

Thermal imagery and lidar monitoring of ground instability on the Alaska Highway, southwestern Yukon

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Abstract

Permafrost is integral to the landscape of the Yukon, and influences hydrology and ecology, and impacts infrastructure. Accelerated permafrost thaw due to climate change poses significant challenges, particularly for the Alaska Highway, a vital transportation route. This study investigates how thawing permafrost may relate to ground instability, resulting in cracks and deformations along the highway. Thermal infrared imaging, and light detection and ranging (lidar) mounted on remotely piloted aircraft systems (RPAS), along with ground surveys, were completed at three localities along the Alaska Highway between the White River and the community of Beaver Creek, Yukon. Through these surveys, temperature variations and topographic changes were examined. At many locations, the damage is characterized by a 1 to 2 m-wide subsidence feature running longitudinally along the middle of the highway. Associated with these zones of subsidence are potholes, as well as longitudinal and transverse cracks. In places, the system of cracks extends to the edge and shoulder of the highway, suggesting that the cracks and deformation are currently active features.

Plain language summary

To better understand the damage to a part of the Alaska Highway in the Yukon caused by permafrost thaw, a series of drone-based surveys were conducted along the highway between the White River and the community of Beaver Creek. Three sites were surveyed where road damage is extensive; two sites had various engineered structures installed to help dissipate heat in the shallow subsurface, whereas the third site did not have any such structures. Drone-based thermal infrared imaging and lidar surveys were used to map the detailed thermal and topographic expression of the road surface, and each site was also surveyed on the ground. In the central part of the road, where damage was obvious, the surveys mapped a principal depression roughly parallel to the highway, containing more localized and deeper depressions that were slightly cooler than the surrounding road surface. Drone-based surveys offer rapid and cost-effective means of surveying and assessing critical infrastructure such as highways.

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Introduction

Permafrost, the layer of permanently frozen ground that persists year-round in polar and subpolar environments, constitutes much of the Yukon landscape. As a defining feature of northern environments, permafrost is essential to the stability of soils and ecosystems in this region. As global temperatures rise, northern regions of Canada, including the Yukon, are experiencing increasingly rapid permafrost degradation, posing significant challenges to the environment, ecosystems, and local communities. Although permafrost thaw is a natural phenomenon, the current accelerated rates of warming have intensified this process, causing ground instability and enhanced erosion. Permafrost thaw is currently causing landslides (e.g., Patton et al., 2021), impacting groundwater systems (e.g., Wiebe et al., 2024), enhancing riverbank erosion (e.g., Geyman et al., 2024), and affecting infrastructure such as pipelines, roads and buildings (e.g., Hjort et al., 2022).

In the Yukon, permafrost conditions (i.e., thickness, ice content and temperature) vary widely within the continuous, discontinuous and sporadic permafrost zones (Lipovsky et al., 2022). This variation, combined with local factors such as variations in surficial materials and ground ice distribution, leads to complex patterns of thaw and associated ground movement. The effect of permafrost degradation on infrastructure, particularly in regions with discontinuous permafrost, is highly unpredictable without detailed geotechnical investigations. Roads, buildings and pipelines rely on stable ground for safety reasons. As the frozen ground thaws, it can no longer support the weight above, resulting in sinkholes, ground subsidence, thermokarst features (Jorgenson, 2022), and differential settling in areas where ground ice content is not uniform. This instability is a critical concern for the Alaska Highway, which serves as an essential transportation corridor linking communities in southern Canada and Alaska. Along the Yukon segment of the Alaska Highway, ground instability caused by permafrost thaw is manifested as cracks and dips in the road surface, endangering drivers and requiring costly and frequent repairs to the highway. The section of the highway between the White River and the community of Beaver Creek is particularly vulnerable due to a combination of permafrost and buried glacial ice (Calmels et al., 2015) near the last (McConnell) glacial limit (Bond et al., 2008).

Conventional methods for assessing ground stability, such as manual surveys, are limited in their ability to monitor changes over large, remote areas where

these methods do not easily capture subsurface thermal changes. As a result, there is an urgent need for innovative approaches that can efficiently and accurately assess permafrost stability across different and challenging landscapes.

The principal objective of this study was to assess the surface conditions of the road at several sites along the Alaska Highway (Fig. 1). To do this, two surveys were completed to evaluate the road surface: thermal infrared imaging, and light detection and ranging (lidar) mounted on remotely piloted aircraft systems (RPAS). By combining the thermal infrared and lidar datasets, this study offers a novel means of quantifying permafrost-related ground instability. This approach not only highlights current areas of concern but also establishes a baseline for monitoring future changes.

Methodology

Study area

Three areas along the Alaska Highway between the White River and the community of Beaver Creek were selected as study areas (Fig. 1). The areas that were selected are part of a section of the Alaska Highway that is in relatively poor condition, and road degradation is characterized by deformation and features such as potholes, longitudinal cracks, and dips on the road surface. Study Area A (KM 1841) is situated at 'the Dry Creek site location' where the Yukon Department of Highways and Public Works (HPW) has installed a series of thermosiphons to help dissipate heat and protect ice-rich permafrost in the shallow subsurface (Reimchen et al., 2009; SRK Consulting, 2018). Study Area B (KM 1865) is located 5 km south of the community of Beaver Creek and is a second highly engineered site. Since 2008, various heat dissipation mitigation techniques have been monitored to determine which configuration is most efficient and cost effective (Doré et al., 2005; López et al., 2024). Study Area C (KM 1862.5) is a section of badly damaged road without engineering mitigations, located 2.5 km south-southeast of Study Area B.

Remotely piloted aircraft systems (RPAS) instrumentation

This study used thermal infrared imaging and lidar deployed on remotely piloted aircraft systems (RPAS), colloquially referred to as drones. The use of RPAS equipped with thermal infrared cameras enabled a non-intrusive examination of the surface, targeting

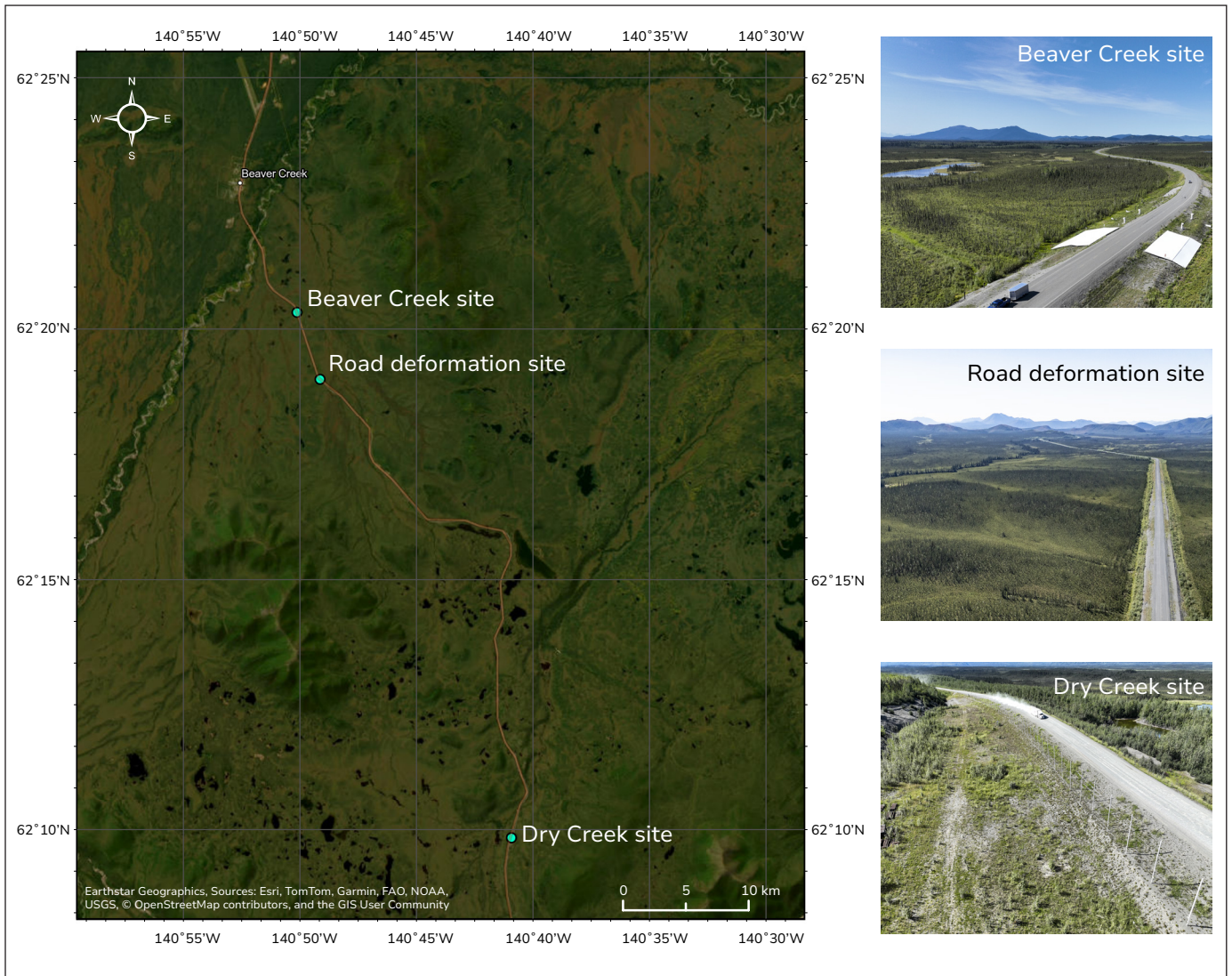


Figure 1. Regions of interest along the Alaska Highway (Study Area A: Dry Creek site; Study Area B: Beaver Creek site; Study Area C: Road deformation site).

potential hotspots. Lidar provided a high-resolution 3D representation of the surface topography, allowing for precise detection of structural deformations, including depressions, potholes and cracks. Together, these technologies provide a comprehensive approach to analyze both the thermal and topographic properties of the ground surface.

Thermal infrared imaging

The thermal infrared imaging study was designed to collect data at night to minimize interference from solar heating, which makes inferences about the thermal emission of the ground surface difficult. By collecting thermal infrared imagery during the night, the analysis

of temperature variations becomes more accurate. The thermal imaging data were collected using two RPAS equipped with different thermal infrared cameras. These cameras operate in the longwave infrared range, recording radiation emitted from the ground.

The first thermal camera was a DJI H20T, with a wavelength range of 8 to 14 μm , flown 45 m above ground level onboard a DJI M300RTK RPAS. The second, a DJI Zenmuse XT-R, with a wavelength range of 7.5 to 13.5 μm , was flown 25 m above ground level onboard a DJI M100 RPAS. Thermal infrared images were captured at regular intervals along each path. The different flight altitudes were selected to provide a series of images with different and complementary

spatial resolutions. The RPAS were flown along predefined flight paths using flight control software (DJI Pilot 2 for the M300 and Pix4D Capture for the M100). The M300 flights covered a series of 11 to 12 overlapping flight paths with 80% front and sidelap to ensure full coverage of the study areas, whereas the M100 flights covered smaller and more focused areas. For the M100, flight number 1 was performed at Study Area A, flown 55 m above ground level, and an area of 206 by 114 m was surveyed, creating five parallel lines. Flight number 2 at Study Area B was sectioned into two separate flights, both flown 25 m above ground level. The first flight flew parallel to the road, creating four parallel lines, and the second flight flew perpendicular to the road, creating six parallel lines. Flight number 3 at Study Area C flew two lines parallel to the road, and were 25 m above ground level.

Lidar survey

To complement the thermal infrared data, lidar was acquired to capture detailed topographic information across the study areas. Lidar technology uses pulses of light from a laser to generate precise 3D measurements of surface features by calculating the return time of each pulse. Lidar has the potential to identify and quantify temporal changes in topography, such as surface subsidence or the formation of cracks, which are characteristic of ground instability seen on the Alaska Highway. In this study, a DJI L1 lidar system was used, mounted on the DJI M300 RPAS. Flown at 70 m above ground level, 7 to 10 parallel flight lines (50% overlap) were needed at each of the three sites. Repeat surveys will be performed in the summer of 2025 to detect any changes to the road surface of the highway.

Ground truthing

For each study area, a detailed ground survey was conducted, noting important features such as cracks, areas of subsidence, potholes and drainage zones. Photographs were taken of key representative features, and the locations of these features were marked at each site.

Data analysis

A preliminary analysis was conducted of the thermal infrared, lidar and ground survey data collected in August 2024. These results are presented below, including a focus on Study Area B. In the future, a quantitative comparison will be made between the thermal infrared and lidar data collected in the summers of 2024 and 2025

for the three study areas. A comprehensive analysis of the data will also be conducted, whereby the thermal infrared images will be overlain onto a 3D lidar model to create a unified visualization of conditions along the highway. This integration will allow for a comparative analysis, where zones of thermal differences may be examined alongside corresponding topographic changes.

Results

A preliminary examination of the thermal infrared images and lidar data collected in August 2024 reveals potential indicators of permafrost-related ground instability. Although further quantitative analysis is necessary, an initial visual inspection suggests a correspondence between observed ground deformations and temperature anomalies.

The thermal infrared image presented in Figure 2 was obtained on August 9, 2024, from Study Area B using the XT-R camera. The red to white colours represent the road, whereas the darker colours correspond to the embankment and an open area beyond, which are several degrees cooler. Due to the adjustment of the image's emissivity for asphalt ($\epsilon = 0.93$; Engineering Toolbox, 2024) to highlight variations in the road surface, the temperature displayed for the vegetation (which generally has an emissivity closer to 0.98) appears cooler than it actually is. The road surface is thermally heterogeneous. A main central depression is well displayed, characterized by numerous lineations that are parallel to subparallel to the road. These lineations represent fractures and cracks. The warmest areas of the road surface tend to be on either side of the central depression, although warm temperatures are also present within the depression itself. Small potholes within the depression are well displayed and are slightly cooler than the rest of the depression.

The lidar point cloud density ranged from 30 to 230 pts/m². Lidar data from the same locality as the thermal infrared imagery discussed above also reveals a central area of the road surface containing irregular features (Fig. 3). The main longitudinal depression feature, having a depth of 10 to 15 cm and width of 1 to 3 m, is clearly present in at least two areas of the point cloud. Within the depression, a series of smaller, darker features represent potholes and other locally deeper areas of the depression. The two cross sections contrast a 37 cm vertical difference in cross section A, and a 16 cm vertical difference in cross section B. Cross section A traverses one of the larger local depressions.

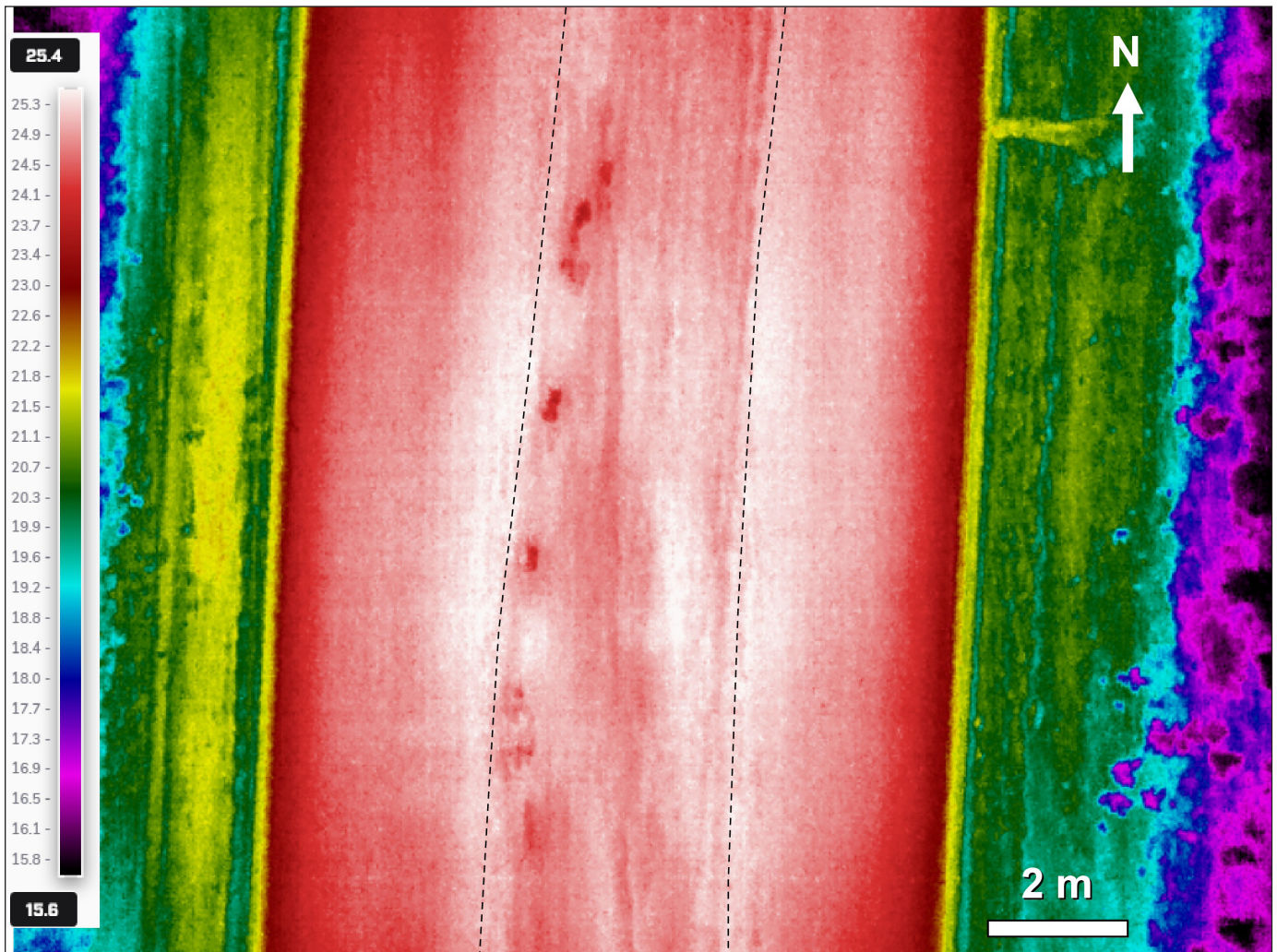


Figure 2. Thermal infrared image from the road deformation site acquired with the XT-R thermal camera from 25 m above ground level, indicating pronounced thermal heterogeneity in the middle section of the road corresponding with the irregular surface topography displayed in Figure 3. The black dashed lines define the main central depression. The red anomalies within the depression correspond to local depressions such as potholes. The left side of the diagram includes temperatures in degrees Celsius and the corresponding colours that are depicted on the image. Analytical parameters used: emissivity 0.93, air temperature 17°C, external optics temperature 17°C, reflected temperature -50°C, relative humidity 69%, and distance 25 m. Note: to prioritize the highway, the emissivity was set to 0.93 (general estimate for asphalt) and other materials with higher emissivity such as vegetation, will be underestimated in temperature.

Areas where thermal infrared imaging indicated lower temperatures appear to correspond with locally deep areas such as potholes in the lidar point cloud. These observations align with findings from Throop et al. (2012), who suggest that there may be similar spatial relationships between ground temperature changes and topographic changes in other permafrost landscapes.

Ground truthing information was collected at all three study areas (Fig. 1), including detailed ground surveys

of each area, enabling detailed observations of the road surface. Figures 4 and 5 demonstrate the magnitude and variability of the road deformation at Study Area B, such as cracks and potholes within larger depression features. These features are all observed on the thermal infrared imagery and lidar point cloud. Other observations include features along the side of the road, such as cracks and drainage zones. These features may help to identify specific areas of weakness along the highway.

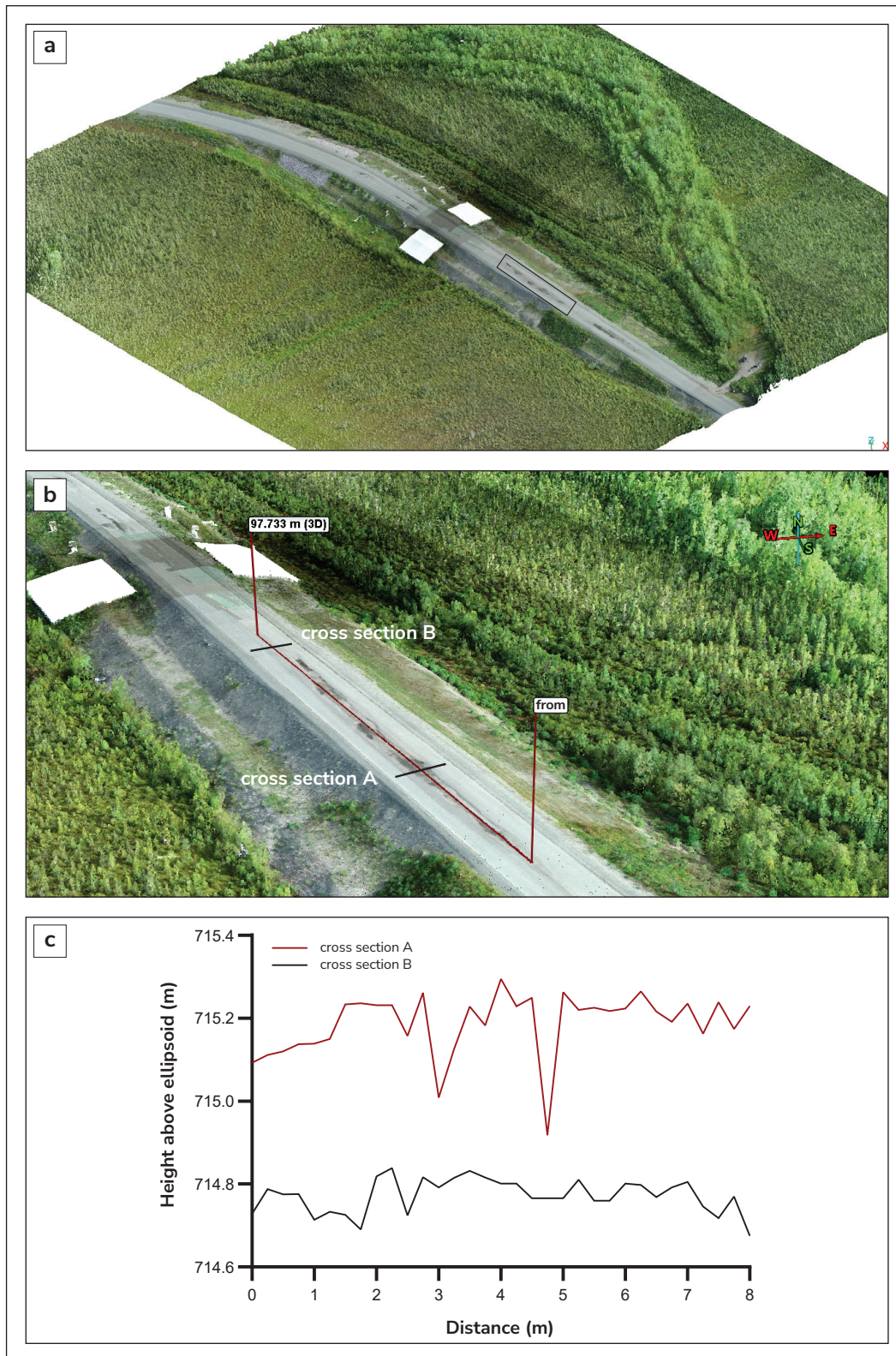


Figure 3. Lidar point cloud from Study Area B. **(a)** Overview of the 650 by 350 m area. The black rectangle is the area visible in **(b)**; **(b)** Close-up view of the highway with a 97.7 m centreline across which 8 m cross sections were extracted. Cross section B does not show major surface deformation. Cross section A traverses the central depression on the highway. **(c)** Elevation across the two cross sections at a resolution of 25 cm. Cross section A has a vertical difference of 37 cm, and cross section B has a vertical difference of 16 cm.



Figure 4. Site survey of Study Area B indicating a longitudinal depression in the central part of the highway (brown area), as well as potholes and other local depressions.

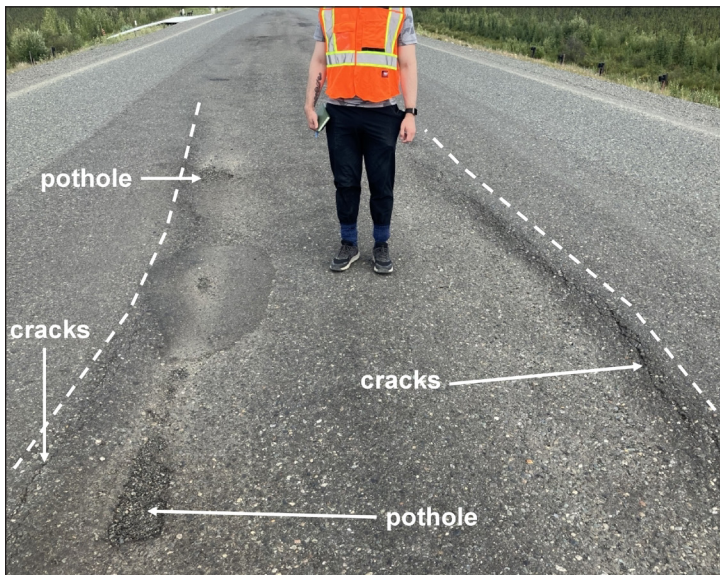


Figure 5. Close-up view of road deformation in Study Area B. A central depression feature is visible (outlined by the dashed white lines), along with potholes and cracks, which define the margins of the depression.

Discussion

This study used thermal infrared imaging and lidar to investigate ground instability along the Alaska Highway. Although this preliminary analysis was largely qualitative, some early results provide insights into the spatial relationship between surface deformations and temperature differences. The correspondence between ground temperatures and surface deformation, as seen from the thermal infrared and lidar point cloud, suggests that ground instability may be driving structural weaknesses along the highway. This discussion explores the implications of these observations, the strengths and limitations of the methods used, and the potential for future research to refine these initial findings.

One of the primary observations from the thermal infrared imaging data is the presence of subtle temperature anomalies in road sections that exhibit visible depressions and cracks. The slightly cooler zones such as potholes in the middle of the highway may indicate that heat dissipation is enhanced from irregular ground that is broken, fractured and deformed in these central areas. In an earlier study at Study Area A, de Grandpré et al. (2012) found a similar central road subsidence was due to groundwater flow. They concluded that permafrost degradation under the damaged road surface was due partly to the road construction and ongoing maintenance, as well as the road cross-cutting the natural groundwater drainage. The comparable surface deformation features and area topography found at Study Area B suggest the causes may be similar.

The thermal infrared image in Figure 2 indicates that the areas of maximum highway damage, as manifested by relatively deep potholes, are reflected by slightly lower temperatures relative to the rest of the road surface. These preliminary results suggest that thermal infrared imaging may serve as a sensitive and early indicator of highway damage. Such surface changes can be valuable for identifying sections of the highway where more thorough investigations may be needed that penetrate deeper in the subsurface. This information could be crucial for road maintenance teams in prioritizing repairs in areas that are most at risk of further thawing.

Lidar data can complement thermal infrared data by providing a precise, high-resolution micro-

topographic view of the road surface. In this study, lidar data revealed cracks and other deformations along a central depression structure on the Alaska Highway (Fig. 3). Further spatial analysis of the point clouds will likely reveal that surface deformations are not uniform, but vary significantly in size and distribution, with certain areas displaying more pronounced instability than others. These can be particularly interesting in the context of highway management because the work can be focused on high-risk areas. These variations may be linked to differences in local permafrost conditions, soil composition or drainage patterns, all of which can influence how thaw affects ground stability (de Grandpré et al., 2012).

The use of RPAS-based lidar appears to be advantageous for monitoring a focused section of the highway. Unlike ground-based survey methods, which can be time-consuming and limited in scope, RPAS-mounted lidar allows for rapid assessment of surface changes across the study area. A typical survey takes less than 30 minutes for an area of 650 by 350 m. This capability is particularly useful for monitoring infrastructure in remote northern regions, where field access may be limited. By capturing detailed topographic data over time, lidar can help track the progression of ground instability, identify areas where deformation is increasing and support proactive maintenance strategies.

Several limitations of this study should be noted. First, the analysis was limited to surface observations, and without subsurface measurements, the exact depth and extent of permafrost thaw is uncertain. Borehole data from the Yukon Geological Survey's permafrost database could complement these surface observations by providing a clearer picture of subsurface conditions and analysis (Douglas et al., 2021). Incorporating subsurface data would also help validate the thermal anomalies observed. Field-based validation of the surface temperature would allow further refining of the estimate of emissivity for the asphalt under various surface conditions. This would ensure a more accurate estimate of the surface temperature.

Additionally, seasonal variations in ground temperatures may be important (Douglas et al., 2021). Conducting thermal infrared imaging during the different seasons would provide a more comprehensive dataset to capture any seasonal variability that may be present. Repeating the lidar over similar time intervals could also enable a more robust assessment of the rate and extent of surface deformation over time, supporting an analysis on the impacts permafrost may have on the

highway, and the degradation in the permafrost caused by the presence of the highway.

Lastly, the preliminary observations suggest a correspondence between thermal anomalies and surface deformations, but further quantitative analyses are necessary to establish a definitive link. These analyses could also be expanded to assess how different factors, such as soil type, moisture content and vegetation cover, influence the observed patterns of temperature and deformation, providing a more nuanced and in-depth understanding of permafrost dynamics and ground instability.

Concluding remarks and future work

As climate change continues to affect the Yukon, understanding the consequences of such change and its effects on the landscape will be crucial for building resilience. The Alaska Highway, like many structures in northern Canada, will increasingly require proactive measures for maintenance and adaptation to minimize risks associated with permafrost thaw. By identifying vulnerable sections of the highway and contributing to models for permafrost thaw, this research can help support the development of mitigation strategies. These strategies may include using materials and engineering techniques adapted to shifting ground conditions, such as thermosiphons, as well as developing early-warning systems to monitor temperature and ground movement in critical areas.

This research is significant for several reasons. First, it contributes to a deeper understanding of permafrost dynamics specific to the Yukon, where permafrost conditions are highly variable and sensitive to environmental change. Second, by focusing on the Alaska Highway, this study addresses challenges for a major transportation corridor that has great economic importance for the region. Ground instability along this highway disrupts not only local travel, but also broader supply chains that extend into the Yukon and beyond. Finally, the use of RPAS technology represents an innovative step in monitoring infrastructure in permafrost regions. These tools offer practical advantages over conventional methods, providing safer, more efficient and more extensive coverage for these types of areas.

This study provides preliminary insights into the use of thermal infrared imagery and lidar to assess permafrost-related ground instability along a segment of the Alaska

Highway in the Yukon. Although quantitative analysis is pending, initial observations indicate a correspondence between ground temperatures and surface deformations. These findings suggest that thermal changes could serve as early indicators of road damage and possibly permafrost thaw, whereas lidar can effectively capture the physical surface characteristics of this instability. Together, these techniques offer a promising approach to identifying and monitoring areas of infrastructure vulnerability in permafrost regions.

Future work is three-fold:

1. The three sites along the Alaska Highway will be resurveyed in summer 2025, to compare with the 2024 results, and to observe any changes that may have occurred on the road surface over the course of a year.
2. A detailed analysis of the thermal infrared imagery and lidar data will be completed to examine any differences in a quantitative fashion.
3. Since landslides are common features in the Yukon (e.g., Huscroft et al., 2004), a new demonstration project will be initiated in July 2025 using an automated drone system, the DJI Dock 2, to observe and monitor the unstable Miles Ridge landslide area near Koidern and the White River. This active landslide area is very close to the Alaska Highway, hence is cause for concern. Daily automated RPAS missions will be conducted of the landslide using visual and thermal infrared cameras during the summer from July to September.

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References

- Bond, J.D., Lipovsky, P.S. and von Gaza, P., 2008. Surficial geology investigations in Wellesley basin and Nisling Range, southwest Yukon. In: Yukon Exploration and Geology 2007, D.S. Emond, L.R. Blackburn, R.P. Hill and L.H. Weston (eds.), Yukon Geological Survey, p. 125–138.
- Calmels, F., Roy, L.P., Laurent, C., Pelletier, M., Kinnear, L., Benkert, B., Horton, B. and Pumple, J., 2015. Vulnerability of the north Alaska Highway to permafrost thaw: A field guide and data synthesis. Northern Climate ExChange, Yukon Research Centre, Whitehorse, Yukon, 130 p., https://www.yukonu.ca/sites/default/files/inline-files/permafrost_report.pdf
- de Grandpré, I., Fortier, D. and Stephani, E., 2012. Degradation of permafrost beneath a road embankment enhanced by heat advected in groundwater. Canadian Journal of Earth Sciences, vol. 49, no. 8, p. 953–962.
- Doré, G., Beaulac, I. and Shur, Y., 2005. Performance of the Alaska Highway Beaver Creek area. Faculté des Sciences et de Génie, Université Laval, Final Report GCT-04-17, 108 p.
- Douglas, T.A., Hiemstra, C.A., Anderson, J.E., Barbato, R.A., Bjella, K.L., Deeb, E.J., Gelvin, A.B., Nelsen, P.E., Newman, S.D., Saari, S.P. and Wagner, A.M., 2021. Recent degradation of interior Alaska permafrost mapped with ground surveys, geophysics, deep drilling, and repeat airborne LiDAR. The Cryosphere, vol. 15, no. 8, p. 3555–3575.
- Engineering Toolbox, 2024. Surface emissivity coefficients, https://www.engineeringtoolbox.com/emissivity-coefficients-d_447.html [accessed 2024/12/08].
- Geyman, E.C., Douglas, M.M., Avouac, J.P. and Lamb, M.P., 2024. Permafrost slows Arctic riverbank erosion. Nature, vol. 634, no. 8033, p. 359–365.
- Hjort, J., Streletskiy, D., Doré, G., Wu, Q., Bjella, K. and Luoto, M., 2022. Impacts of permafrost degradation on infrastructure. Nature Reviews Earth & Environment, vol. 3, no. 1, p. 24–38.
- Huscroft, C.A., Lipovsky, P.S. and Bond, J.D., 2004. A regional characterization of landslides in the Alaska Highway corridor, Yukon. Yukon Geological Survey, Open File 2004-18, 65 p., report and CD-ROM.
- Jorgenson, M.T., 2022. Thermokarst. Treatise on Geomorphology (Second Edition), vol. 4, p. 392–414.

- Lipovsky, P.S., Humphries, J.K., Stewart-Jones, E.T. and Cronmiller, D.C., 2022. Yukon permafrost database: A new baseline data resource. *In: Yukon Exploration and Geology 2021*, K.E. MacFarlane (ed.), Yukon Geological Survey, p. 37–49.
- López, X., Bilodeau, J.-P., Doré, G. and Lemieux, C., 2024. Long-term evaluation of mitigation techniques used for permafrost thermal stabilization at the Beaver Creek (YT) experimental road site. *In: 12th International Conference on Permafrost*, Whitehorse, Yukon, p. 240–247.
- Patton, A.I., Rathburn, S.L., Capps, D.M., McGrath, D. and Brown, R.A., 2021. Ongoing landslide deformation in thawing permafrost. *Geophysical Research Letters*, vol. 48, no. 16, e2021GL092959.
- Reimchen, D., Doré, G., Fortier, D. and Walsh, R., 2009. Cost and constructability of permafrost test sections along the Alaska Highway, Yukon. *In: 2009 Annual Conference and Exhibition of the Transportation Association of Canada-Transportation in a Climate of Change*, p. 1–20.
- SRK Consulting, 2018. Design report highway stabilization kilometre 1840+500 – 1840+899 (Dry Creek). SRK Consulting (Canada) Inc. Project 1CG023.004, 99 p.
- Throop, J., Lewkowicz, A.G. and Smith, S.L., 2012. Climate and ground temperature relations at sites across the continuous and discontinuous permafrost zones, northern Canada. *Canadian Journal of Earth Sciences*, vol. 49, no. 8, p. 865–876.
- Wiebe, A.J., McKenzie, J.M., Hamel, E., Rudolph, D.L., Mulligan, B. and de Grandpré, I., 2024. Groundwater vulnerability in the Yukon and Northwest Territories, Canada. *Hydrogeology Journal*, vol. 32, no. 2, p. 341–346.