Designing Rehabilitation Measures for the CN Tumbler Tunnels in Northern British Columbia using Remote Techniques

L.U. Arenson¹, D. Kinakin¹, M. Pritchard¹, K.W. Savigny¹, T. Edwards²
¹BGC Engineering Inc., Vancouver, BC, Canada; ²Canadian National Railway, Edmonton, AB, Canada

1. INTRODUCTION

Canadian National Railway (CN), one of the largest railways in North America, became the operator of the former British Columbia Railway (BC Rail) in 2005. This includes tracks of the Tumbler Subdivision, a 130 km long section completed in the fall of 1983 that provides railway access to the coal fields in north-eastern British Columbia [1, 2]. The main obstacles to overcome on this route were two mountain ridges of the Rocky Mountains, which necessitated the construction of four tunnels (Fig. 1).

The two longer tunnels on the subdivision are Table Tunnel (9.05 km) and Wolverine Tunnel (5.94 km). The tunnels were excavated using traditional drill and blast methods with a horseshoe-shaped cross section 8.37 m high by 5.34 m wide. The line runs geographically east-west through the mountain ridges with designed grades of up to 0.3% in the two tunnels peaking approximately in the middle of Table Tunnel. Water is therefore running towards both portals in Table Tunnel, but only from the track-south to the north portal in Wolverine Tunnel. The tunnels were originally configured for electric trains but are currently operated with diesel locomotives and are unventilated and unlit. The geology of the area is sedimentary and mostly limestone with some quartzite. The maximum overburden is 650 m for Table Tunnel and 770 m for Wolverine Tunnel, respectively. Some rock bursts were reported during construction, and attributed to high pressures caused by tectonic folding. Bedding trend is approximately perpendicular to the tunnel alignments, with varying bedding dips. Rock support installed during construction included spot and pattern fully resin grouted threadbar bolts, welded wire mesh supported with threadbar bolts and covered by shotcrete, mesh installed with split set bolts and not shotcreted, and steel sets with timber lagging. Water inflow recorded during construction was often larger than anticipated. Cementitious grouting was utilised to locally reduce water flow, but reportedly with limited success. In addition to the initial grouting trials, wooden wedges were used to fill joints and drainage pipes were installed to release the water pressure in the rock. However, measures to reduce water inflow into the tunnels had limited success and the tunnels have large ditch water flows that, in places, put the track at risk due to scouring.
Figure 1. Map of British Columbia showing the location of the Tumbler Tunnels [1, 2].

Shortly after beginning operation, severe winter ice build-up on the walls and crown of the tunnels near the portals occurred. Insulation panels were installed in an effort to insulate seepage inflow and reduce ice build-up, and also to help direct seepage from the crown of the tunnel into the ditches. The success of the 50 mm thick Ethafoam 220 (closed cell Polyethylene foam) insulation panels is limited because of the ability for cold air to penetrate at joints between panels and cause ice formation behind the panels. Some panels had detached from the walls and crown and were affecting the clearance available for trains and reducing the efficiency of the insulation system (Fig. 2). Fallen or hanging panels and accelerated track component wear were concerns for tunnel operation.

Figure 2. Hanging insulation panels close to the north portal of Wolverine Tunnel.

Initial inspections concluded that the rock mass integrity of the tunnels is generally good with the exception of frost weathering promoting ravelling deterioration, and some specific locations of dilated rock mass. While the general problems of inflow, icing, and local support issues were understood, detailed scaled information on magnitudes and locations of problems, or of the actual tunnel as-built grades and geometry, were not available. The work to characterise conditions in
the tunnels and prioritise work was constrained by the lengths of the tunnels, unpredictable train traffic, train control track blocks, the tunnels being unlit, and unventilated, soot blackening rock and features, and insulation panels occasionally covering areas of poorer rock quality. Therefore, a method that could collect the maximum amount of scaled information efficiently in the short time blocks available between trains and under poor light conditions was needed.

This paper discusses the remote techniques used to assess the conditions of the two long tunnels, including the data analysis, limitations and future potential of the remote techniques, and a discussion of initial mitigation measures. Additional details on the tunnels and the assessment methods, in particular costs and time requirements, are presented in Arenson et al. [3].

2. REMOTE DATA COLLECTION

A field investigation concept was developed to gather baseline information that could be used to assess the effectiveness of measures to reduce water inflow problems and reduce ice build-up, as well as locations for tunnel support remediation. Three approaches were selected: i) visual inspection, ii) infrared thermography; and iii) ground based stationary Light Detection and Ranging (LiDAR) scans.

Visual inspections included walking and driving engineering assessment, and collection of digital still images. This information helped to identify critical locations for water inflow, zones of ice build-up, and tunnel support issues. Geologic structure and tunnel support were also visually reviewed. Infrared images were used to obtain a qualitative overview of water inflows into the tunnel. Differences between the tunnel wall temperature and the groundwater temperature allowed locations of water flow to be identified, making it possible to rank the water flow based on its thermal response. Finally, stationary, ground based LiDAR survey was carried out to produce a three-dimensional, scaled, digital model of the tunnels. Insulation panels, drainage pipes, rock fall events, bolts, mesh and other structural elements, as well as spalling, ravelling, overbreak or local instabilities could be identified in the digital data. Locations where drainage holes were visible or water deflectors were installed in the crown were used as an additional identifier for water inflow problems.

2.1. Thermography

Infrared cameras allow measurement of the tunnel surface temperatures. The tunnel wall temperatures are generally affected by the outside air temperatures, whereas ground water temperature is controlled by the rock mass and generally shows little variations throughout the year. This difference can be recorded using thermography. Further, it is possible to record wetted rock surfaces and the flow of the water can be tracked along the ditch as well as through the ballast, which would not be possible using only visual imagery. In addition to visualizing water flow, the insulating effect of the Ethafoam panels can be assessed and the functional efficiency of electronic elements, such as radio transmitters, can be checked as they generate heat that can easily be imaged in the tunnel environment. In total, five infrared traverses were carried out through the Table and the Wolverine Tunnels with driving speeds between 15 and 30 km/h using a FLIR ThermaCAM P65HS.

A selection of infrared (IR) images for both tunnels is presented in Figure 3. A qualitative inflow chart by tunnel stationage was created using these images and a scaling method applied to obtain a relative representation of water inflow and flow issues along the tunnels [3].
Examination of the data allowed several zones of water inflow to be distinguished in each tunnel. For the Table tunnel, two major zones of water inflow were identified on the south side of the tunnel, and a number of smaller seepage zones were identified on the north side of the tunnel. Further, the infrared camera showed evidence of water flow in the ballast under the track. It was concluded that the apparent loss of cumulative flow measured in the ditches was caused by an increasing amount of water flow being within the ballast as the overall flow volume increased. Total water accumulation in the Wolverine Tunnel is less than in the Table Tunnel. The Wolverine Tunnel experiences water inflows throughout its length and the ditch flow measurements indicate increasingly higher flows from south to north. Five principal seepage inflow zones were identified. Similar to the Table Tunnel, water flow likely occurs through the ballast and is not picked up with the infrared camera or with ditch flow measurements.

The central sections of the tunnels, in particular the Table Tunnel, did not provide much information using the infrared camera. Reasons may be the dryer conditions, the reduced ability of cold air from the portals to provide a temperature difference between the rock and inflowing water, or poor air ventilation influencing the images due to the warm exhaust of the hi-rail truck.

No mileage counter was linked to the camera for the thermal imaging work, and locations in the video were determined by referencing the time stamp on the video image with the actual tunnel mileage. The driving speed of the hi-rail was kept as constant as possible to allow approximate distance estimates from the video time stamp. Also, structural indicators that provide a thermal signal, such as mounted metal mile markers, catenary hangers, insulation patches or metal deflectors were used to calibrate the distances. Finally, the findings were compared with observations from the visual inspections and the LiDAR scans.

### 2.2. Laser Scanning

A ground based, Leica HDS-3000 scanner, was used for this project to create a detailed three-dimensional digital model of the tunnels (Fig. 4). Forward and backward scans were taken at intervals along the track of between 80 and 150 m. Data coverage decreased from over 2000 points per square meter to less than 10 points per square meter in between the scanning locations. This is because of increasing spread of the laser scan points with distance from the scanner combined with the flattening of the reflection angle with distance down the tunnel causing data shadows. High LiDAR point density surveys of spherical targets were used to stitch the data together and form a single 3D digital model for each tunnel.
The LiDAR data captured tunnel geometry and support features for later examination. Using the data, virtual three-dimensional (3D) walk-throughs could be carried out and 3D point cloud surfaces of the tunnels could be examined from different orientations and measured. In addition to the advantage of viewing the tunnel surface from different angles, the major advantage in the LiDAR scan was the availability of a digital scale surface model of the tunnel and the ability to extract pieces of the digital information for further analyses. The LiDAR data also imaged the top of rail, and was used to determine the actual grades in the tunnel. This information on tunnel gradient, combined with LiDAR cross-section information on the ditch and track-bed geometry, was used to estimate available flow capacity of proposed drainage improvements. When combined with the visual assessment of tunnel support concerns and the IR data, plan and profile views of the tunnels were created that indicated ditch flow, priorities for tunnel support mitigation and insulation repair, and overall tunnel geometry. A specific advantage of this data was that it allowed areas to be examined in more detail at any time without additional field investigations. Further, the digital model often revealed information that would not have been identified visually due to the lighting and soot coating conditions encountered in the tunnels. Similar information would have required washing of the tunnels followed by inspection with a man-lift accompanied by a light plant.

2.3. LiDAR Digital Data Analysis

Having a complete set of digital data of the tunnel geometry allows for several analyses to be carried out. Figure 5 shows a tunnel cross section compiled from LiDAR point data over a 25 cm long tunnel segment. When combined with a design clearance envelope, discrepancies between the actual tunnel cross-section and the reference cross-section can be examined (Fig. 6). Such cross-section overlays indicate where the as-built cross-section differs from the design profile, and can be used to assess tunnel clearance. However, no software is currently available that allows automatic generation of such cross-sections. Since the centre lines of the tops of tracks are three dimensional lines, it would be useful to have a function for the reference cross-section that is automatically generated based on the track geometry identified in the scans. In addition, tools to automate cleaning of the LiDAR data to remove elements that are not part of the tunnel wall would be valuable. Currently, catenary systems, cables or any other element in the data that are not part of the tunnel wall or crown need to be manually identified and removed from the data set in order to generate clean cross sections. Figures 5 and 6 show how a radio cable connector can affect the analysis.

Similar to the cross-section generated using a reference design clearance envelope (Fig. 5), whole wall sections can be plotted using the LiDAR data available. Such a pseudo-topography is presented in Figure 7 where the differences between the smooth surfaces of the insulation panels and the rougher rock surface can clearly be identified. Ideally, tools would be available to work with tunnel LiDAR data to automate the process of creating a traditional tunnel "roll-out" drawing that shows features of the tunnel circumference in a two dimensional graph (e.g. circumference...
position versus tunnel stationage. Even though it would be helpful to generate such continuous plots, this could not be easily achieved because of the difficulties indicated above. The changing reference line and elements hanging in the tunnel would require significant manual work to achieve a roll-out drawing.

Figure 5. Tunnel cross section based on LiDAR data points of a 25 cm thick tunnel length. The thin line represents a reference design cross section (e.g. clearance). Scale is in metres.

Figure 6. Discrepancy between actual tunnel wall and reference line for the tunnel walls and crown (top) and the bottom below top of track (below).

Figure 7. Example of a wall section (14 m x 6 m) contour plot. White represents areas closer to the reference line and green areas are farther away. Rectangular outlines are insulation panels.

2.4. Limitations of LiDAR Collection

In some locations, shadow effects limited point cloud cover. LiDAR coverage can be improved by having shorter distances between the individual scans, but this increases the scanning time and costs. To minimise scanning cost while maintaining adequate data quality, it is important to first visually determine where closer survey spacing is required, either because of irregularities in the tunnel, or because a section is considered important for stability or other assessment. Some errors may be generated when stitching the various scans together using the targets. Additional targets and a conventional survey of these targets would have allowed an improved integration of the LiDAR data into the real world. Finally, better lighting would have allowed the optical lens on the scanner to be used to collect photographs that could have been used as overlays for the point clouds to add information.
The lengths of the two tunnels produced an amount of digital data that was challenging to manage and extract specific information from with current desktop computational capacities. 6 GB of raw LiDAR data were produced for the two tunnels. In addition, no commercially available software was found that could be used to strip unwanted information from the data to create a “bare tunnel” model if desired, as is common practice for aerial LiDAR where bare earth models can be derived by stripping vegetation [4]. Ideally, all unwanted elements could be stripped from the model (e.g. wires, catenary supports, people, the truck, survey targets) to better examine the rock surface. Manual cleaning of the data to produce a bare tunnel model is possible, but was not considered necessary for this assessment since the critical elements could easily be identified without data cleaning. A Microsoft Access database and a self-developed Python programme were utilised for data management. Being able to visualise the structural geology features controlling stability at a certain location was sufficient for preliminary stabilisation planning. As the areas involved are small, quantitative structural geology measurements could be collected manually if required.

3. COMBINED TUNNEL ASSESSMENT AND MITIGATION MEASURES

The visual inspections, IR, and LiDAR scans collected in Winter 2007/08 were used to develop current condition drawings of the two tunnels and potential rehabilitation measures. Drawings were prepared that illustrate water flow data, prioritised locations for support mitigation, and prioritised insulation and drainage improvement areas. The scalable data from the LiDAR survey was used to design ditch flow improvement concepts and assess the potential benefit of those concepts.

In 2008 and 2009, CN initiated mitigation measures to improve tunnel safety and control water flow. Insulation panel were reattached and scaling and renewal of tunnel support were completed at critical sections. The excessive flow of water in the ditch along the track that at times flooded the ballast was mitigated by improving the ditch flow capacity. This was done by installing low height modular concrete gravity retaining walls for the ballast shoulder that effectively widened and deepened the ditch. At the north end of Wolverine Tunnel 300 Jersey barriers (3000 feet) were installed on the West side of the tunnel. These have proven effective in lowering the ditch water level and slowing degradation of the ballast (Fig. 8). The digital model of the tunnel provided valuable information on the available space (channel width and track height) and tunnel grade that confirmed the practicality of this design. Further, ice build-up in the ballast close to the portals was reduced because of increased flow and reduced water in the ballast. Additional ditch improvement and other repair work will be carried out in the future based on the priorities identified during this assessment.

![Figure 8. Ditch cross-section improvements.](image)
4. CONCLUSIONS AND FUTURE POTENTIAL

Infrared thermography and ground based, stationary LiDAR were used to assess the conditions of two railway tunnels in north-western BC, Canada. The study has shown that the techniques can be valuable characterisation tools in a tunnel environment, especially when access restricts available data collection time in a tunnel, and where lighting is poor. Thermography successfully allowed differentiation of tunnel surface flow locations and a qualitative estimate of flow quantities, as well as identified flow within the ballast. The method is very efficient, with best results obtained where the rock surface temperature is at least 2°C different from the ground water temperature. By running infrared scans at different times during the year, changes in flow intensity as well as temperature could be assessed. Also, monitoring flow changes seasonally would help determine the ideal rehabilitation measures. The major challenges with LiDAR scans are data management of the data produced, and having adequate post-processing tools to work with and present the data. For this study, the LiDAR data was used as a rapid way to collect a detailed 3D image of the tunnel that could be used as a visualisation tool, and for creating sections and profiles of the tunnel. However, we believe there is additional potential for the use of LiDAR in underground environments. However, this would require developing special software tools that allow the data to be cleaned to achieve a bare rock model more automatically, make it easier to combine design and LiDAR survey cross section data, and facilitate two-dimensional presentation of the data, on tunnel layout drawings. To do this, engineering requirements for the data need to be communicated to the surveyors that generally collect and work with these data. Such tools could also be valuable for assessing excavation volume and overbreak for tunnel construction contract administration. They could also benefit operations when clearances need to be checked or changed. By overlaying data sets collected at different dates, it would also be possible to identify changes to the tunnel geometry with time.

As demonstrated by this work on the CN Tumbler tunnels, thermography and LiDAR can be successfully used to characterise tunnel conditions and aid in design rehabilitation measures. These are worthwhile tools for maintenance personnel and engineers to consider for tunnel characterisation. We expect future development of software tools to manage the data in an underground setting will only improve the applicability of these techniques.

5. ACKNOWLEDGEMENT

The authors would like to thank CN for the opportunity to work on this project, their permission to publish results from the work, and for their tremendous support in the field. The LiDAR scanning was carried out by Peter Nicol, Summit Metrology Inc., Vancouver BC.

REFERENCES