Assessing Tunnel Stability and Groundwater Inflows using Remote Techniques

Dr. Lukas U. Arenson, Dr.Sc.Techn.ETH, Derek Kinakin, P.Geo., Mark Pritchard, P.Eng., and Dr. K. Wayne Savigny, P.Eng., P.Geo.

BGC Engineering Inc., Suite 500, 1045 Howe Street, Vancouver, British Columbia, V6Z 2A9, Canada

Tom Edwards, P.Eng.

Canadian National Railway, 10229 127 Avenue, Edmonton, Alberta, T5E 0B9, Canada

Number of words: 5,856

© AREMA 2009 ©
ABSTRACT: Canadian National Railway (CN) operates the Tumbler Subdivision, an 80.8 mile branch line that provides access to coal mines in north-western British Columbia, Canada. Constructed in 1983, the line includes four tunnels. Despite periodic site specific maintenance, natural deterioration of the tunnel support has occurred since construction. Table and Wolverine Tunnels, which are the longer two tunnels at 5.62 miles and 3.67 miles, respectively, also experience large water inflows and winter ice build-up that have accelerated tunnel support and track component deterioration and make track and tunnel maintenance more difficult. In 2007, CN began a program of assessment and remediation of Table and Wolverine Tunnels. The first stage of this work was a survey of the tunnels to quantify tunnel inflow locations, existing support and its condition, and tunnel geometry. Survey was accomplished by geological engineer traverse of the tunnels and by Light Detection and Ranging (LiDAR) and digital thermography survey. A series of stationary LiDAR scans of the tunnels were carried out that provided a detailed digital model for identifying rock support locations and conditions as well as tunnel and track bed geometry. Digital thermography videos were recorded that used the temperature differences between the tunnel walls, ballast, tracks and the running water to provide information on ground water flow. The data was used to assemble condition profiles and sections for the tunnels, assess the practicality and merits of different water control schemes, and recommend specific locations for tunnel stabilization. This paper describes the LiDAR and digital thermography survey of the tunnels, how they were used to quantify the tunnel conditions and provide data for mitigation planning, and the advantages and limitations of these tools for characterization of tunnel condition.

Key words: railway, tunnel, repair, rock fall, water flow, hazard assessment, LiDAR, thermography
INTRODUCTION

Canadian National Railway (CN) is one of the largest Class 1 railways in North America, operating track in Canada and the United States. In 2005, CN became the operator of the former British Columbia Railway (BC Rail) track that included the Tumbler Subdivision. This 80.8 mile long (130 km) subdivision was completed in the fall of 1983 to provide railway access to the coal fields in north-eastern British Columbia (1). The main obstacles to overcome on this route were two mountain ridges of the Rocky Mountains, which necessitated the construction of four tunnels (Figure 1, Table 1). This paper reviews the innovative methods used to assess the structural integrity of the longer two railway tunnels known as the Table Tunnel (5.62 miles) and the Wolverine Tunnel (3.67 miles), as well as water inflow and icing issues. Further, it discusses how data from the remote techniques was used to design and prioritize the proposed rehabilitation measures.

Background and Problems

The tunnels were excavated using traditional drill and blast methods with a horseshoe-shaped cross section 27.5 ft (8.37 m) high by 17.5 ft (5.34 m) wide. The geology of the area is sedimentary and mostly limestone with some quartzite. Some rock bursts were reported during construction, and attributed to high pressures caused by tectonic folding. The maximum overburden is 2,130 ft (650 m) for Table Tunnel and 2,530 ft (770 m) for Wolverine Tunnel, respectively (3).

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. A total of 130 steel sets with timber lagging were installed at two locations over a total length of 460 feet (140 m) in Table Tunnel. The tunnels were originally configured for electric trains, and are

© AREMA 2009 ©
unventilated and unlit. CN currently operates the line with diesel locomotives, and it is Occupancy Control System (OCS) territory.

**Water and Ice**

No major problems were reported during construction of the tunnels in 1982/83, and the geological conditions encountered generally coincided with expectations. However, water inflow recorded was often larger than anticipated. Cementitious grouting was utilized to locally reduce water flow, but reportedly with limited success (Joe Rotzien, personal communication). 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 (Figures 2 & 3). However, these measures had limited success and the tunnel has large ditch water flows that, in places, put the track at risk due to scouring (Figure 4).

Shortly after beginning operation, severe problems occurred in the tunnels because of ice build-up in the winter in portions of the tunnels closer to the portals. During an initial rehabilitation stage in 1984, insulation panels were installed within about 0.25 to 0.30 miles (400 to 500 m) from the portals into the tunnels. These 2 inch (50 mm) thick Ethafoam 220 flexible foam insulation panels were installed in an effort to insulate seepage inflow and reduce ice build-up on the tunnel walls and crown, and also to help direct seepage from the crown of the tunnel into the ditches. The Ethafoam panels were bolted to the walls and crowns of the tunnel with short machine threaded bar and resin anchoring. Further, doors were installed at both portals of both tunnels to reduce air flow and hence ice formation. Because of logistic and technical problems, use of the doors was soon discontinued.

The success of the Ethafoam 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 have detached from the walls and crown because of (Figure 5):

- ice action and spalling of the rock mass caused the bolt anchor zone to fail;
• the nut came off, likely as a result of ice expansion and thawing coupled with vibration; or
• ice formation behind the panels ripping the insulation from the bolt support.

Even though some of the insulation panel bolt plates show corrosion, this does not appear to be a significant cause of insulation anchor failure. Fallen or hanging panels may impact the clearance available for trains and will reduce the efficiency of the insulation system (Figure 6). In addition to the ice build-up on the tunnel walls, ice build-up in the ballast near the portals accelerates track component wear and is a major concern for tunnel operation.

Support Conditions

Visual inspections showed that the rock mass integrity of the tunnels is generally good with the exception of freezing of water inflows promoting ravelling deterioration, and some specific locations of dilated rock mass. In most cases, shotcrete is not cracked or spalling, and dilation of rock mass in the walls or spring-line area was not noted. This either indicates that the original rock support generally continues to function, or the original rock support was overdesigned and the rock mass would be stable with less support than installed.

An exception was noted at locations where mesh was anchored with split sets and not shotcreted. Some split set bolt plates were found on the track that had failed by corrosion of the split set bolt near the bolt plate. Similarly, some mesh had been lost to corrosion.

Logistics and Methods

While the general problems of water 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 was lacking. Any work to characterize conditions in the tunnels and prioritize work was constrained by:

• the length of the tunnels requiring characterization;
• unpredictable train traffic of up to five trains per day and the requirement that tunnel
characterization not interfere with train traffic schedules;
  • long train control track blocks, which necessitated clearing the track well in advance of a trains arrival;
  • the tunnels being unlit, and unventilated. The lack of ventilation meant that up to 2 hours were required following a train before the Table Tunnel could be entered, and 1 hour was required for Wolverine Tunnel.
  • soot blackening rock and features, making it hard to distinguish geologic structure, and tunnel geometry; and
  • insulation panels occasionally coinciding and covering areas of poorer rock quality.

In order to create a scaled characterization of the conditions of the tunnels, a method that could collect the maximum amount of information efficiently in the short blocks of time available between trains and under poor light conditions was needed.

GENERAL INSPECTION APPROACH

Based on the initial studies of available information, a concept for a field investigation was developed. The main goal of the investigation was to gather baseline information that could be used to prioritize measures to reduce water inflow problems and reduce ice build-up, and prioritize locations for tunnel support remediation. The characterization plan included:
  • Visual inspections, including still pictures;
  • Infrared thermography videos; and
  • LiDAR scans to create a digital model of the tunnels.

Visual Inspections

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. Water flow measurements in the ditch were also carried out at discrete locations to help quantify the amount of water flowing within the tunnel and how that flow changes along the tunnel. Geologic structure and tunnel support were also visually reviewed.

**Infrared Thermography**

Infrared images were used to obtain a qualitative overview of water inflows into the tunnel and how the water flows in it. Differences between the tunnel wall temperature and the groundwater temperature allowed locations of water flow to be identified, making it possible to “see” the water flow rate based on its thermal response.

**LiDAR Scan**

Light Detection and Ranging (LiDAR) survey was carried out to produce a three-dimensional, scaled, digital model of the tunnels that was used to assess the current condition in the tunnels. Insulation panels, drainage pipes, rock fall, bolts, mesh and other structural elements, as well as spalling, ravelling, overbreak or local instabilities could be identified in the LiDAR 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. The LiDAR surveyed extent of installed insulation further helped in identifying the penetration of icing into the tunnels.

**THERMOGRAPHY**

**Overview**

Infrared cameras allow measurement of the temperature of a surface. In the fall and winter, the cool air blowing through the tunnel cools the rock surfaces below the temperature of the
groundwater entering the tunnels, providing a temperature contrast that can be recorded when
the ground water reaches the tunnel walls. The temperature of the ground water is also an
indirect parameter for the flow rate. The water temperature of slow flowing inflows is closer to
the tunnel wall temperature than if there is a large inflow. Further, it is possible to record wetted
rock surfaces and the flow of the water can be tracked along the ditch as well as underground
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.

A FLIR ThermaCAM P65HS was used for this project with the scans carried out in
November when the air temperature outside the tunnels was below zero centigrade. The
infrared video were used to quantify the water inflow on a scale of one to eight, with one being a
minor inflow (e.g. wet walls) and eight being a sever inflow (e.g. a flowing drain hole ). In total,
five infrared traverses were carried out through the Table and the Wolverine Tunnels with
driving speeds between 10 and 20 mph. Some traverses had temperature ranges that
automatically changed according to the rock surface temperature, whereas others had fixed
temperature ranges.

**Thermography Results**

A selection of images from the infrared videos for both tunnels is presented in Figure 7. A
qualitative inflow chart was created using these images and the scaling method described
above. These charts are shown in Figure 8 for Table and Wolverine Tunnels. Run No. 4 was
judged as the most reliable because of its high resolution and focused images. The temperature
was set to automatic range and the driving speed was 14.6 mph. Problems with the infrared
camera resulted in some poorly focused traverses on subsequent recordings that used fixed
temperature ranges. However, even from these images it was possible to derive some
information about the water flow in the Table Tunnel.

The qualitative water inflow graphs in Figure 8 were overlaid with physical water flow measurements that were carried out in the tunnel by estimating the ditch flow cross section area and measuring the water flow rate. The Table Tunnel has a summit at Mile 36.70 that creates a water flow divide; water flows from this location towards both the north and south portals. On the south side of the divide, the main flow occurs in the east ditch, whereas the main flow was recorded in the west ditch on the north side of the divide. The Wolverine Tunnel has a downward gradient from the south to the north portal, and water flow was only recorded in the west ditch. The east side of the tracks was dry except for some local water accumulation with water seeping through the ballast to the west side of the track. The crosses in the figures represent qualitative water inflow characterizations that were made based on visual inspections.

Discussion of Results

Table Tunnel

Several zones can be distinguished where water enters the tunnel. However, some of the features found are wet cracks where water drips out of the rock and don’t add much to the general flow through the tunnel. Based on the qualitative observations and the flow measurements in the ditches, 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:

- South: Mile 34.65 to 34.90 and Mile 35.05 to 35.25
- North: Mile 36.62 to 36.71 and Mile 37.20 to 38.30 with increased inflow at Mile 36.71, Mile 37.18, Mile 37.62, Mile 37.72, Mile 37.91, and Mile 38.17.

The ditch water flow measurements show more than 0.44 gal/min (0.1 m³/s) is added to the flow between Mile 35.10 and 35.40. However, further down gradient towards the portal, lower total
ditch flow was measured (e.g. Mile 35.10). Assuming that the measurements are accurate, there are two possible explanations for this apparent flow loss: some water escapes the tunnel through a system of cracks and fractures before Mile 35.10, e.g. between Mile 34.65 and 34.90, or a significant amount of water is flowing in the ballast that was not measured by the ditch flow measurements. The infrared camera showed evidence of water flow in the ballast under the track, even though the water could no longer be traced thermally once its temperature reaches the temperature of the surrounding ballast. It was concluded that the apparent loss of cumulative flow in the graphs was caused by an increasing amount of the flow being within the ballast as the flow increases, and therefore not measured by the ditch cross section flow measurements. It is also partly attributed to the margin of error in estimating the ditch flow.

**Wolverine Tunnel**

Total water accumulation in the Wolverine Tunnel is less than in the Table Tunnel. The qualitative inflow ratings assigned for the two tunnels should not be directly compared because of the qualitative nature of the water inflow assessment that is relative to each tunnel. The Wolverine Tunnel experiences water inflows throughout its length and the ditch flow measurements indicate increasingly higher flows from south to north. However, individual seepage flows are typically relatively small. Five principal seepage inflow zones were identified:

- Mile 44.20 to 44.50: several locations where water enters the tunnel;
- Mile 44.90: local fault zone with concentrated water accumulation;
- Mile 45.15: valve adds a large flow to the tunnel. It is assumed that the valve drains a number of joints in this zone;
- Mile 45.45 to 45.90: several locations where water enters the tunnel; and
- Mile 46.70 to 46.80: smaller zone with joints where water enters the tunnel.
The maximum flow rate is recorded at Mile 46 and not at the north portal. Similar to the Table Tunnel the water could leave the tunnel through joints after Mile 46, or flow could be occurring through the ballast that was not picked up with the infrared camera or ditch flow measurements. The presence of water inflow through the entire length of the tunnel indicates the tunnel is acting as a groundwater discharge zone through its length. Therefore, flow out of the tunnel is unlikely and the apparent seepage losses are attributed to some of the flow occurring through the ballast and not being measured.

Challenges and Practicalities

The central sections of the tunnels, in particular the Table Tunnel, did not provide much information using the infrared camera. Some of the reasons include:

- Dryer conditions near the groundwater divide in the center of the Table Tunnel;
- Wall temperatures further from the effect of cold air from the portals are higher and closer to the groundwater temperature. This reduced the ability of the thermal imaging to distinguish water from rock; and
- Poor air ventilation influencing the images (focusing issues) due to the exhaust of the hi-rail truck.

For this work, a mileage counter was not directly linked to the camera, and special attention had to be paid to referencing the video image with the tunnel mileage. Several indicators were used. 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 distances on the video. Finally, the findings were compared with observations from the visual inspections and the LiDAR scans.
Time and Cost

The actual recording time for all runs in both tunnels, including setup time, was about 6 hours. However, due to train traffic, the runs were carried out over two days in conjunction with additional visual inspections. The infrared camera was rented for the whole duration of the field work (2 weeks) at a cost of CAD 3,300. Since the videos were recorded in standard AVI format, no additional software was required.

LASER SCANNING

Overview

LiDAR scanning is being increasingly used in many engineering applications. By sending a laser signal and recording its reflective energy it is possible to create a detailed three-dimensional image of the scanned area without the use of a light source. In addition the reflectivity of the surface can be determined. A ground based, Leica HDS-3000 scanner, was used for this project. The scanner was mounted on the back of a hi-rail that was parked at intervals along the track of between 260 and 490 feet (80 and 150 m). The standard instrument spacing was varied to optimize data collection of features in the tunnel that the visual overview traverses had identified as being of interest. Data coverage decreased in between the scanning locations and with increasing distance between scan 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. In particular, the rough tunnel surface produced shades in the scan, which resulted in reduced scan coverage for certain sections.

For each scan location, a series of three to seven individual scans were shot using different scanning resolutions. Higher resolutions were used for the far field to compensate for the spread of the LiDAR points with distance, whereas a lower scanning resolution was used for
the near field. Five spheres with a diameter of about 8 inches (20 cm) were used to stitch the data from two scanning locations together. These perfectly round targets were set at various locations (height and distance) in-between two scans and were always shot in the forward as well the backward direction. Relocation, setup and scanning required approximately one hour at each location.

A mobile LiDAR system (5) was considered as an alternative to the fixed discrete scan location approach. Although the scanning time would have been significantly shorter, data resolutions would have been much lower. In addition, the stationary scanner could be placed at locations of interest for obtaining optimal resolution, and locations of major water inflows could be avoided. A mobile scanner could have been affected or even severely damaged by the amount of water that infiltrated the tunnel at certain sections.

LiDAR Scanning Results

A series of LiDAR scan images of the tunnels are presented in Figure 9a through Figure 9e. The data collected with the LiDAR scanner can be used in a variety of ways. As shown in Figure 9, details of tunnel geometry and support features can be examined and inventoried in three-dimensional real-scale without the constraints of trying to do detailed inventory work on site. Virtual, three-dimensional (3D) walk-throughs can be carried out and 3D point cloud surfaces of the tunnels can be examined from different orientations and measured. This detail and scale would not be possible with traditional photography. Exposed mesh or missing bolt plates that would have been difficult to visually assess because of the flat black soot coating in the tunnel are apparent on the LiDAR images.

In addition to the advantage of viewing the tunnel surface from different angles, the major advantage in the LiDAR scan lies in the availability of a digital scale model of the tunnel. The digital information can be extracted and used for further analyses. Distances can be measured, such as the length of tunnel construction blasting rounds, or the size of a safety bay. The ability
to include the track bed and measure distances to the tunnel wall from the track centerline was
used to determine available horizontal width for the design of an improved ditch drainage
system. Examples of cross sections that were created for this assessment are shown in
Figure 10. The cross sections are generated by using 1.5 feet (0.5 m) thick segments of LiDAR
points along the track, and some show the catenary system that is still installed in the tunnels
from the period of electric train use. Generally, the laser signal does not reflect from the water
surface, and the survey could not image the ditch invert through water. However, occasionally
the angle of incidence allowed a penetration through the water and a reflection from the rock
wall below the water level or from the invert of the ditch. Even though only a few points were
collected like this, it provided some additional information on the ditch geometry. This was
useful as it confirmed there was the potential to achieve greater ditch depth through the tunnels
as part of improving ditch flow capacity.

The LiDAR data was also used to determine the actual grades in the tunnel by graphing
LiDAR points from the top of rail. It was noted that the grades are steeper than the tunnel
design. The Table Tunnel was excavated using two headings from either portal, and the scans
suggest that adjustments to the grade were made so that the two approaches would meet as
planned. This information on tunnel gradient also helped with estimates of the available flow
capacity of potential drainage improvements.

**Discussion of Results**
The digital model derived by the LiDAR scans provided valuable data for the assessment of
conditions within the Wolverine and Tumbler Tunnels. The scans provided three-dimensional
scaled data on tunnel geometry and features that included the track bed and were sufficiently
detailed that they could be used for office assessment of support characteristics, insulation
assessment, and designs for ditch modifications. When combined with the visual assessment of
tunnel support concerns and the thermography data, plan and profile views of the tunnels could

© AREMA 2009 ©
be 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 diesel coating conditions encountered in the tunnel. Similar information would have required washing of the tunnel followed by inspection with a man-lift, accompanied by a light plant.

Challenges and Practicalities
The major challenges of using the stationary LiDAR survey for underground tunnel scanning on this project included logistical challenges and locally limited point cover due to shadow effects. Train traffic and limited accessibility greatly reduced the data collection time available each day. Because of the remote location of the tunnels in northern British Columbia, daily demobilization, remobilization and standby accounted for a large part of the daily field time. Further, scan targets had to be mounted (e.g. screwed to a tie) so that they would not move when trains passed and did not affect train clearance. The confined nature of a tunnel is also a problem for good point coverage in sections with overhanging elements or rough surfaces. Data shadows are created when the laser beam is at a shallow angle of incidence to the tunnel wall, and protrusions in the wall block the beam from reaching areas of the wall. Coverage can be improved by having shorter distances between the individual scans, but this increases the scanning costs. To minimize 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. It should also be considered, though, that having a shallow angle of incidence between the survey beam and the wall can occasionally improve data collection. An example of this is data that was collected from behind insulation panels and within rock joints that would not have been obtained at a greater angle of incidence or with a system that was always oriented perpendicular to the tunnel
alignment. In one instance, the LiDAR “saw” behind an insulation panel and delineated a developing chimney in the tunnel crown. Data gaps were also caused by the hi-rail truck at the location of the scanner. However, since the track geometry was not the focus of the scope of work, these short gaps were acceptable.

To improve the accuracy of linking the scans it would have been better to use the same targets for the compilation of more than two scans. However, due to the scanning distances chosen and the logistical challenges this was not feasible.

The vibration of the running hi-rail truck and a portable generator used to provide power for the laser scanner also caused some problems to the LiDAR scanner. The vibrations disrupted the scanner, and scanning could only be carried out with the generator unloaded from the truck. Finally, better lighting would have allowed the optical lens on the scanner to be used to collect regular photographs in conjunction with the LiDAR scanner. These photographs could have 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. Six Gigabytes 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 (e.g. 6). Ideally, all unwanted elements could be stripped from the model (e.g. wires, catenary supports, people, the truck, survey targets) to examine the rock surface. Manual cleaning of the data to produce a bare tunnel model is possible, but was not necessary for this assessment since the critical elements could easily be identified without data cleaning.

While it was possible to see geologic structure (joints, faults) in the LiDAR, and software tools to measure structural orientations from LiDAR data exist, this was not attempted. Being able to visualize the structural geology features controlling stability at a location was sufficient
for preliminary stabilization planning, and, as the areas involved are small, if quantitative structural geology measurements were required they could be collected manually.

**Time and Cost**

It typically took about one hour to complete a scan at one location, which included relocation, setting up targets, scanning five to seven sections with different resolutions and scanning the targets at a higher resolution. However, significantly more field time was required due to standby time for train traffic and to wait for the tunnels to clear of smoke. In addition, hi-rail support and flagging was provided by local track maintenance personnel, and some standby time was incurred when other track maintenance priorities occurred during the survey program. The whole survey program, thermography included, took about three weeks. The total costs for the laser scanning, including post processing by the surveyor, were CAD 123,000, or CAD 13,000 per mile. However, true scanning costs without standby time were about CAD 6,500 per mile, i.e. 50% of the total cost. Post processing was in the order of 15% of the true scanning costs. Data post processing mainly included compiling the scans into a single point cloud model, i.e. merging forward and backward scans with the help of the spherical targets.

**COMBINED TUNNEL ASSESSMENT**

The visual inspections, infrared thermography, and LiDAR scans collected by BGC in Winter 2007/08 for the CN Tumbler Subdivision Table and Wolverine Tunnels were used to develop current condition drawings of the tunnels and potential rehabilitation measures. Current condition drawings were prepared for both tunnels that illustrate the water flow data summarized on Figure 8, identified prioritized locations for support mitigation, and identified prioritized insulation and drainage improvement areas. The scalable data from the LiDAR survey allowed
the potential effect on ditch flow of ditch improvement concepts to be confirmed, and preliminary quantities for mitigation measures to be developed.

CONCLUSIONS AND FUTURE DEVELOPMENT

Infrared thermography and ground based, stationary LiDAR were used to assess the conditions of two tunnels on the CN Tumbler Subdivision in north-western BC, Canada. The tunnels inspected have lengths of 5.62 miles (9.05 km) and 3.67 miles (5.91 km), respectively. Using ground based LiDAR and/or thermography for a tunnel application appears to be unusual. There are very few reported applications known to the authors (7). This study has shown that these techniques can be valuable tools for characterization 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 qualitative quantities, as well as identifying flow within the ballast (underground) in some circumstances. Recording velocities of up to 20 mph make this method very efficient, with best results obtained where the rock surface temperature is at least 3 degrees Fahrenheit different from the ground water temperature. Consideration should be given to the seasonal variation of rock surface temperature through the tunnel versus groundwater temperature when planning to use thermal mapping. Depending on the location within the tunnel the ideal season may vary. By running infrared scans at different times during the year changes in flow intensity as well as temperature could be assessed. 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 tools to work with the data and present the data. For this study, the LiDAR data was used as a rapid way to collect a detailed image of the tunnel that could be used as a visualization tool to examine and measure locations of interest in detail, and for creating
sections and profiles of the tunnel. However, we believe there is additional potential for the use of LiDAR in tunnel environments. This would require developing tools that allow the LiDAR data to more automatically be cleaned to achieve a bare rock model, and be better presented in a traditional two-dimensional (paper) format. For tunnel work, paper drawings are typically done with tunnel layout drawings that “roll out” the tunnel so that the walls and the crown can be seen together on a drawing. To do this, additional software tools will be required that consider the overhanging nature of a tunnel. Further it should be possible to automate the creation of cross sections and determination of tunnel volume. Creating plots, such as cross sectional area against tunnel mileage, could be a significant improvement in methods to assess excavation volume and overbreak for contracts administration. It would also benefit operations when clearances need to be checked. By overlaying data sets collected at different dates, it would also be possible to identify changes to the tunnel geometry occurring with time.

Even though significant developments are to be expected in the future, LiDAR and thermography survey, as demonstrated by this work for the CN tunnels, are worthwhile tools to maintenance personnel and engineers to consider for tunnel characterization.

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


© AREMA 2009 ®
### TABLE 1 - Overview Tumbler Sub Division Tunnels.

<table>
<thead>
<tr>
<th>Tunnel Name</th>
<th>Tunnel Length</th>
<th>Start at</th>
<th>End at</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mile</td>
<td>km</td>
<td>mile</td>
</tr>
<tr>
<td>Table Tunnel</td>
<td>5.622</td>
<td>9.047</td>
<td>34.065</td>
</tr>
<tr>
<td>Wolverine Tunnel</td>
<td>3.674</td>
<td>5.913</td>
<td>43.677</td>
</tr>
<tr>
<td>km 80 Tunnel</td>
<td>0.167</td>
<td>0.269</td>
<td>49.552</td>
</tr>
<tr>
<td>km 86 Tunnel</td>
<td>0.227</td>
<td>0.365</td>
<td>53.494</td>
</tr>
</tbody>
</table>

### LIST OF TABLES

TABLE 1 – Overview Tumbler Sub Division Tunnels.
Figure 1 – Map of British Columbia showing the location of the Tumbler Tunnels (2).

Figure 2 – Drainage pipes dewatering into the ditch and ballast Mile 35.46, Table Tunnel.
Figure 3 – Drainage valve draining into the ditch and the ballast (Wolverine Tunnel).

Figure 4 – Scouring of the ballast due to water flow in the ditch and water fall into the Table Tunnel, Mile 39.07.
Figure 5 – left: Extensive ice formation approximately 1 km from the East portal of Table Tunnel during mid-December 1983 (4). Right: Ice buildup behind insulation panels in km 80 Tunnel, a 270m long tunnel just North of Wolverine Tunnel.

Figure 6 – Hanging insulation panels close to the north portal of Wolverine Tunnel.
Figure 7 – Screen shots from infrared movies in Table and Wolverine Tunnel.

a) Various Water inflows into Table Tunnel.

b) Ditch water flow on the right hand side of the tunnel. Effect of insulation can be seen on the left side.

c) Examples of water inflow and ditch runoff in Wolverine Tunnel.

d) Water running through the ballast from one side to the other in the Wolverine Tunnel. This would not have been seen on a visual picture.
Figure 8 – Summary of water inflow for Table Tunnel (a) and Wolverine Tunnel (b). The filled circles are relative flow interpretations made from infrared run No. 4, which was judged as the most reliable recording. Open circles are relative flow interpretations from the remaining runs and the crosses are relative inflow estimates made during visual inspections. The blue line indicates cumulative water flow measured in the ditches. Note that Table Tunnel has a summit and there is flow towards both portals, whereas Wolverine Tunnel grade descends from the south to the north portal.
Figure 9 – Examples of raw images of LiDAR scans used to identify tunnel support concerns.

a) Table Tunnel Mile 38.17. Looking north, showing detail available from the LiDAR of the track, road bed, tunnel walls, and steel sets.

Mile 38.59

Mile 38.60

b) Table Tunnel Mile 38.59 and Mile 38.60. Upper image is a view looking down on the tunnel showing the ravelling sections (yellow elliptical features). The two lower images are views looking north from inside the tunnel to the crown. The images show lineaments indicating raveling and shotcrete failure in a thin strip. Some shotcrete is still intact in the crown at Mile 38.60. A communication cable and the inactive catenary system cable can be identified in these images.
c) Table Tunnel Mile 39.07. View looking west at tunnel wall showing local rock failure on an approximately 10 ft long section. Detail is sufficient to distinguish geologic structure and potential modes of further rock fall.

d) Wolverine Tunnel Mile 45.18. View looking south showing scouring in the ditch. Note the survey detail that is available of the rails positions relative to the tunnel wall and ceiling. This allows details of tunnel clearance to be examined from the data.
e) Wolverine Tunnel Mile 46.50. View looking at crown of the tunnel showing survey delineation of incomplete shotcrete cover (indicated by arrows). The image also shows effect of different scanning resolutions.

Figure 10 – Cross sections extracted from LiDAR scans. The design cross section is included for reference.
LIST OF FIGURES

Figure 1 – Map of British Columbia showing the location of the Tumbler Tunnels (2).
Figure 2 – Drainage pipes dewatering into the ditch and ballast Mile 35.46, Table Tunnel.
Figure 3 – Drainage valve draining into the ditch and the ballast (Wolverine Tunnel).
Figure 4 – Scouring of the ballast due to water flow in the ditch and water fall into the Table Tunnel, Mile 39.07.
Figure 5 – left: Extensive ice formation approximately 1 km from the East portal of Table Tunnel during mid-December 1983 (4). Right: Ice build up behind insulation panels in km 80 Tunnel, a 270m long tunnel just North of Wolverine Tunnel.
Figure 6 – Hanging insulation panels close to the north portal of Wolverine Tunnel.
Figure 7 – Screen shots from infrared movies in Table and Wolverine Tunnel.
  a) Various Water inflows into Table Tunnel.
  b) Ditch water flow on the right hand side of the tunnel. Effect of insulation can be seen on the left side.
  c) Examples of water inflow and ditch runoff in Wolverine Tunnel.
  d) Water running through the ballast from one side to the other in the Wolverine Tunnel. This would not have been seen on a visual picture.
Figure 8 – Summary of water inflow for Table Tunnel (a) and Wolverine Tunnel (b). The filled circles are relative flow interpretations made from infrared run No. 4, which was judged as the most reliable recording. Open circles are relative flow interpretations from the remaining runs and the crosses are relative inflow estimates made during visual inspections. The blue line indicates cumulative water flow measured in the ditches. Note that Table Tunnel has a summit and there is flow towards both portals, whereas Wolverine Tunnel grade descends from the south to the north portal.
Figure 9 – Examples of raw images of LiDAR scans used to identify tunnel support concerns.
  a) Table Tunnel Mile 38.17. Looking north, showing detail available from the LiDAR of the track, road bed, tunnel walls, and steel sets.
  b) Table Tunnel Mile 38.59 and Mile 38.60. Upper image is a view looking down on the tunnel showing the ravelling sections (yellow elliptical features). The two lower images are views looking north from inside the tunnel to the crown. The images show lineaments indicating raveling and shotcrete failure in a thin strip. Some shotcrete is still intact in the crown at Mile 38.60. A communication cable and the inactive catenary system cable can be identified in these images
  c) Table Tunnel Mile 39.07. View looking west at tunnel wall showing local rock failure on an approximately 10 ft long section. Detail is sufficient to distinguish geologic structure and potential modes of further rock fall.
  d) Wolverine Tunnel Mile 45.18. View looking south showing scouring in the ditch. Note the survey detail that is available of the rails positions relative to the tunnel wall and ceiling. This allows details of tunnel clearance to be examined from the data.
  e) Wolverine Tunnel Mile 46.50. View looking at crown of the tunnel showing survey delineation of incomplete shotcrete cover (indicated by arrows). The image also shows effect of different scanning resolutions.
Figure 10 – Cross sections extracted from LiDAR scans. The design cross section is included for reference.

© AREMA 2009 ®