MONITORING AND ACCESS MANAGEMENT OF RESOURCE ROADS WITH INSTRUMENTATION

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ABSTRACT

Keywords: Climate change, data acquisition system, instrumentation, resource road, spring load restriction (SLR), threshold.

Forest transportation operations are facing challenges such as having larger road networks to manage because of dispersed harvest patterns, climate changes forcing more hauling to take place under wet road conditions, shortages of gravel, more worn-out roads without a budget to rebuild, and the use of larger heavier trucks. This provides an opportunity for the use of instrumentation with sensors and data acquisition systems to allow real-time monitoring of road conditions that, when tied to threshold values, can be used to manage access and control road operating costs. This research study will describe the link between road material and road performance as well as different types of instrumentation (how and why they are used). It will discuss a case study performed by FPInnovations that used instrumentation to test if the installation of insulation within the road structure of a weak and wet section of the road will improve road strength and performance in the spring by preventing the road from freezing and thawing. Other uses of instrumentation on resource roads will also be discussed as well as the use of instrumentation in defining start and end dates for spring thaw load restrictions (SLRs) on low-volume highways and resource roads across Canada.

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INTRODUCTION

Masses of unpaved roads are built by the Canadian forest industry each year to create access to forest resources for harvest. Many of these forest roads are encountering reductions in bearing capacity and increasingly frequent access interruptions due to excess water in roadbeds combined with climate change and substandard management, construction, and maintenance practices (Thiam et al. 2022). Even more challenges faced by forest transportation operations include larger road networks to manage because of dispersed harvest patterns, climate changes forcing more hauling to take place under wet road conditions, shortages of gravel, more worn-out roads without the budget to rebuild, and use of larger heavier trucks (Thiam et al. 2022).

Logging companies across Canada are encountering an increasing rate of difficult road conditions, many of which are attributed to seasonal interruptions. These seasonal interruptions typically are caused by weak sections of road during the non-frozen seasons and the thawed sections of road during the frozen seasons. A wet and weak road section is defined as a section of a resource road, not in a wetland, that periodically or continuously loses its ability to provide access because of excess water flowing to the site and(or) poor ability to drain (Thiam et al. 2022).

FPInnovations has conducted several studies on said wet, weak sections of resource roads, in cooperation with logging companies that are encountering transportation inefficiencies due to seasonal interruptions in efforts to develop cost-effective strategies and techniques that will improve road quality and maintain an efficient flow of transportation on their resource roads.

Real-time monitoring with instrumentation is important and can be used as a tool in managing and improving weak sections of resource roads. Instrumentation technology has the potential to be used in making critical road management decisions as it can reduce transportation costs, improve transportation efficiency and road reliability, reduce safety-related risk, quantify climate changes and create warning thresholds for road management (Markle et al. 2019).

This study focuses on the importance and relevance of instrumentation to forest road management and how collected data through instrumentation with sensors can be used in making road construction and road management decisions. This study will describe how instrumentation can be used for road monitoring, identify the different types of sensors that may be used and how to select the appropriate type, discuss the link between road material conditions and road performance, and discuss and describe the field test site that was established on Mawn Road in the Thunder Bay Region.

HYPOTHESIS

I hypothesize that the use of instrumentation on forest access roads can provide data that is useful for making critical road management decisions to prolong access and control road operating costs.

OBJECTIVES

The objective of this project is to trial the use of instrumentation with sensors and data acquisition systems to monitor real-time road conditions of forest access roads and determine how the acquired data may be used to manage access and control road operating costs.

This report describes the technologies trialled and the field installation performed in the Thunder Bay Region in the fall of 2022. It also highlights the potential for the use of instrumentation in making access road management decisions.

BACKGROUND LITERATURE

The condition of a road's infrastructure can have a serious impact on a road's safety, driving comfort, rolling resistance and overall road performance. (Masino et al. 2017). The application of real-time monitoring instrumentation on forest roads can be used in researching environmental sustainability and climate change mitigation, road user safety, transportation efficiency and management decision support in forest harvesting operations (Markle et al. 2019). The prospect of climate change means that current assumptions about future climatic conditions could be false which could result in poor infrastructure planning leading to premature deterioration or failure of road infrastructure (Mills and Audrey 2002). Fluctuations in temperature, freeze-thaw cycles, permafrost degradation, reduced ice cover and construction season length and quality are consequences of climate change that have to potential to negatively affect the service life and quality of transportation infrastructure (Mills and Audrey 2002). Real-time monitoring of forest road conditions can also be used as decision support regarding transportation safety and efficiency. Generating road quality characteristics using sensors and data acquisition instrumentation can be used to develop analyses on road infrastructure capital investments, risk assessments and road use agreements and determine how to optimize infrastructure efficiency while in compliance with weight and dimension regulations, seasonal transportation restrictions, and premiums (Markle et al. 2019).

The link between road material conditions and road performance

Road material conditions are altered with changes in soil moisture content and frost depth which can be linked directly to road performance. Understanding the influence of moisture on different road materials and investigating the relationship between road moisture content and road strength is critical in monitoring the performance of low-volume forest roads. As described in *Paige-Green (2003)*, there is a direct relationship between road moisture content, road material density, and overall road strength. Therefore, when choosing materials for road construction it is important to understand the density, permeability, and drainage characteristics associated with the material. Low-permeability materials minimize the flow of water into the base or subbase of a road but will retain water within the structure for a long period of time while highly permeable materials are often associated with quick, more frequent increases in moisture content (Paige-Green 2003). As a common trend, most road materials show a consistent decrease in road strength as moisture content increases. Where road drainage is unsatisfactory, or the water table becomes too high, significant increases in subgrade moisture content are inevitable and the increased moisture in the road will result in road failure (Paige-Green 2003; Paige-Green 2009).

Colder weather conditions in the winter bring forth additional road maintenance requirements and higher levels of deteriorating road conditions due to frost build-up in the road subsurface. Negative effects on road quality caused by frost can be classified as frost heave, road softening, frost boil, and stone migration (Alzubaidi 1999). Frost heave occurs when water is drawn upward from the frost zone and freezes to ice. Layers of ice, varying in thickness, form beneath the road surface. Roads in areas with a high water table are susceptible to the rapid formation of thick ice layers forming above the water table. Roads built with fine-grained materials such as sand and silt are more susceptible to frost heave than those built with gravel. When the water freezes, it expands. During the spring thaw, frost heave can cause a road surface to rise to 50 centimetres, deteriorating the road surface and making driving conditions unsafe (Alzubaidi 1999). Road softening occurs during the early thaw period and is even more prominent in conjunction with heavy rainfall or high levels of meltwater. Following the frozen period where the frost prevented drainage through the road structure, thawing of the frost results in the accumulation of water on the road surface making it soft and susceptible to deep rutting by heavy vehicles (Alzubaidi 1999; Persson 1993). Frost boils commonly form on unpaved forest roads during the late stages of the spring thaw. Frost boils form when thick ice layers within the road structure thaw and release significant amounts of water that eventually burst through the road surface due to heavy traffic “pumping” the water out (Alzubaidi 1999).

<u>Using Instrumentation with Sensors to Monitor Resource Roads</u>

Instrumentation with moisture sensors, thermistors, and a connected data acquisition system data logger in remote data logger housing (RDH) can be used to effectively monitor forest road performance by collecting soil moisture and temperature data within the road structure and precipitation data at the road location (Markle et al. 2019). Soil moisture and temperature profiles are created using soil moisture and temperature data that has been collected below the road surface at specific depths and at specific time intervals. This data can then be comprised into a graph to create a visual profile of the data collected (Figure 1).

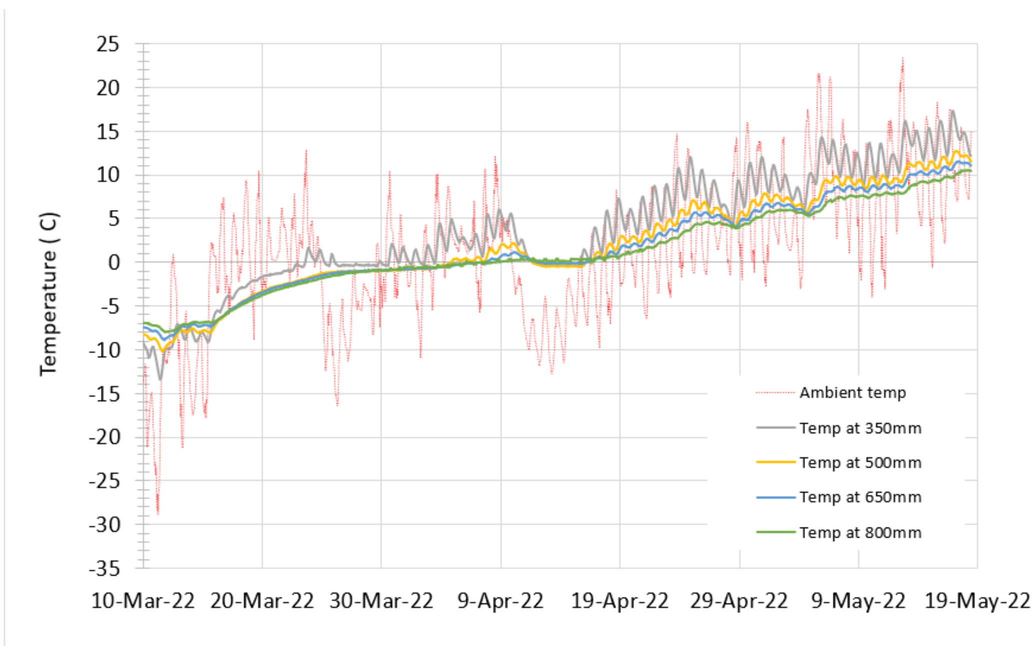

Figure 1. Roadbed thawing in insulated SK resource road during spring 2022.

Soil moisture and temperature profiles of forest road structures and monitoring of road site precipitation have the potential to be used within the forestry and logging industry to analyze the relationship between these factors and overall road quality, performance, and serviceability and to further use this information to develop plants of action in an attempt to extend hauling seasons and improve overall transportation efficiency and safety on forest access roads.

Different instrumentation types and monitoring techniques may be chosen based on project monitoring objectives, cost, accuracy, reliability, type of data collection, ease of installation, data frequency, and reusability. Availability is also a common factor that may determine the type of instrumentation used in a road monitoring project. Two common types of instrumentation used to monitor road structure characteristics are subsurface thermistors and soil moisture sensors. Other examples of instrumentation used to monitor road performance and serviceability include radio frequency identification (RFID), cameras, onboard computers in logging trucks, and all-weather stations (Markle et al. 2019).

Subsurface thermistors are used to monitor temperatures below the road's surface. Subsurface thermistors are most used to monitor low-volume roads in areas that are subject to seasonal freezing and thawing. Subsurface temperature data can then be used to determine when the road freezing or thawing, by watching trends in temperature fluctuate above or below zero degrees Celsius (Kestler et al. 1999; Kestler et al. 2001; Kestler et al 2007). Temperature thermistors are most commonly installed in a roadbed in a single vertical sequence or "stack" of 4 to 10 thermistors roughly equally distributed from the road surface down to a depth of 1 to 2 m. . Thermistor stacks with 5 thermistors and 16m of tail wire, such as the instrumentation installed by FPInnovations at the Mawn Road test site, cost approximately $700CAD (Lakewood Systems Ltd. 2023). Soil moisture sensors are used to monitor moisture content in road subgrade and soils. Like subsurface temperature sensors, moisture sensors are commonly used to monitor low-volume roads subject to seasonal freezing (Kestler et al. 1999; Kestler et al. 2001; Kestler et al 2007). Designs for moisture sensors may vary but one common design, such as the one used by FPInnovations at the Mawn Road test site, had a ruggedized design made to withstand harsh conditions, and equipped with two pointed stainless-steel probes. Single moisture sensors of this type and with 12m of tail wire cost approximately $300CAD each (Lakewood Systems Ltd. 2023). The measurements made with thermistors and moisture sensors can be collected by a roadside data acquisition system. The data logger installed within the remote datalogger housing (RDH) is a small computer used to gather and store sensor readings. These readings are set to be collected at regular intervals (e.g., each hour). The collected data within the data acquisition system can be downloaded manually, by cellular network, or via satellite uplink (Lakewood Systems Ltd. 2023).

CASE STUDY

FPInnovations and Resolute Forest Products created a test site north of Thunder Bay on an active secondary haul road (Mawn Road) to assess the ability of two different road insulation technologies to improve road performance in a wet, weak section of road that is highly susceptible to road damage from thaw-weakening in the spring. The performance of the insulation technologies was evaluated using moisture and temperature sensors that were placed within the road structure. The goal of this project was to characterize the site’s temperature and moisture content patterns to allow researchers to compare differences between the insulation technologies and explain observed road performance changes. A secondary goal was to test the constructability and performance of the two insulation technologies used. We hypothesized that preventing the subgrade from freezing and thawing in a traditionally wet site on a resource road would result in improved strength and performance in the springtime.

The test site was divided into three sections, two of which were equipped with different types of insulation and the road structure of the third was left unmodified as a reference control (Figure 2). A site at the roadside was excavated for the roadside datalogger housing (RDH) and it was installed. This is where all the wires from the instrumentation would lead to. Next, a 30cm-deep trench was excavated along the roadside beside each test section and lead to the RDH. The top 30cm of the road surface was then excavated for both test sections so that the insulation boards could be installed at a depth of 30cm. Holes for the thermistor stacks were also dug. Any poor-quality road material that was excavated was trucked to a nearby spur road and discarded. The wires for the thermistors and soil moisture sensors were then routed along the trench from each test section to the RDH. The below-insulation moisture sensors were positioned in the road wheel path and the thermistor stacks in the road centreline. The thermistor stacks were buried vertically with thermistor sensors at depths of 250, 400, 550, 700, and 850 mm below the finished road surface. When all instrumentation was in place, the insulation boards were installed in the 8m by 20m excavated surface of each test section (Figure 3). Holes were cut in the insulating boards to allow the 250mm thermistor on the thermistor stacks to be positioned just above the insulation boards. Now that all sensors are installed into the road structure, the readings from the datalogger were checked to assure everything was reading correctly. With everything placed and functioning, the road structure could be rebuilt. A layer of woven geotextile was placed on top of the insulation to help protect it and then the road was reconstructed and the trenches re-filled using good-quality material from a nearby pit mixed with the original road material.

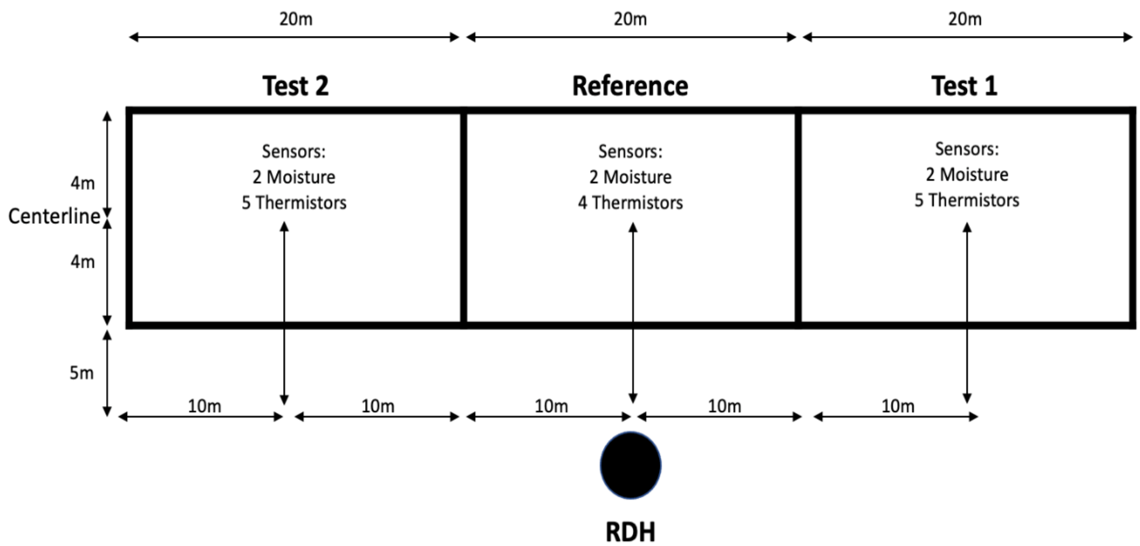

Figure 2. Plan view of the Mawn Road test site.

Figure 3. Southbound view of test section 1 prior to covering the insulating layer.

As stated above, for this study, below-ground moisture sensors and thermistors were used to compare the performance of insulation technologies in improving the structural integrity and overall performance of a weak section of the road. The moisture used in this study collected volumetric-based measurements of moisture within the road surface. The belowground thermistors collected road structure temperatures at several depths beginning at the road surface. The ambient air thermistor fastened to the outside of the remote datalogger housing (RDH) at the roadside collected the air temperature of the road site. The precipitation gauge, also fastened to the RDH, collected rainfall measurements. Each of these measurements (in-situ soil moisture, in-situ roadbed temperatures, ambient air temperature, and rainfall) were collected at 1-hour intervals.

The primary goal of this study was to test whether the addition of insulation technology within the road structure of weak road sections, susceptible to high moisture levels, flood, and frost-related issues, has the potential to become a cost-effective strategy for maintaining road quality and performance by preventing underlying weak soils from thawing and becoming saturated and weak in early spring before generalized thawing has occurred and stopped log hauling. Therefore, through this study, we can monitor the effectiveness of mechanical reinforcement and winter insulation technologies. Following months of data collection, we will be able to analyze the data and draw conclusions from our findings. These results will be shared with Resolute Forest Products and the individuals who work to maintain the road to be used as a decision support tool in planning future maintenance activities and schedules for this section of the road.

(The instrumentation technology used in this study was chosen based on cost, availability, and compatibility with the chosen datalogger communication system (which was also chosen based on cost and availability). The instrumentation used at this test site needed to be able to function in a temperature range of -45° C to 30° C, not require an intensive installation process, and be robust enough to withstand groundwater salt and truck wheel forces near the road surface.

The thermistor sensors used in this study were 44007RC Precision Epoxy NTC thermistors. These thermistors have 5000-ohm resistance at 25° C, have high sensitivity and good long-term stability ratings, have a thermally conductive epoxy coating, and are RoHS compliant (Premier Farnell Ltd. 2008). The thermistors were installed in each of the three test sections. Five thermistors were separated by 150mm in a single cable (a thermistor stack) so that temperature readings could be read simultaneously throughout the road structure.

The moisture sensors used in this study were TEROS 10 moisture sensors which are low-cost durable soil moisture sensors. They have sharp, stainless steel electrical probes between which current through the soil is measured and which help to secure their position in the soil. Their robust epoxy bodies are built to resist extremes of pressure, salt content, and temperature and last a relatively long time in the field. Moisture measurements are representative of the 430mL volume around the probe (Meter Group Inc. 2023). One moisture sensor was installed per test section (3) approximately 30cm below the road surface.

Figure 4. (A) TEROS 10 soil moisture sensor, and (B) five 44007RC Precision Epoxy NTC thermistors arranged in a single cable (or thermistor stack)..

The roadside data acquisition system was equipped with Lakewood Systems Ltd.-developed Prolog software that collects, stores, and allows the user to analyze and chart the data collected from the sensors that were installed at the test site. The data acquisition system comprises a datalogger installed within the remote datalogger housing (RDH). Each sensor is wired to the datalogger, including an ambient temperature thermistor and rain gauge mounted on the side of the RDH (Figure 3). A lithium battery powers the datalogger and sensors. The computer memory collects data until it is full and then starts discarding the first data collected to make room for new data (a first-in /first-out pattern). The datalogger can be downloaded manually by plugging in a laptop to the USB port on the outside of the RDH and then the Prolog software in the laptop detects the datalogger and automatically downloads the sensor readings. A Resolute employee has been doing the manual downloads regularly and forwarding the data to FPInnovations for analysis.

Figure 5. A Lakewood Systems remote data logger housing (RDH) was installed in a trench at roadside and sensor wiring routed to a datalogger inside. A rain gauge and air temperature radiation shield assembly were mounted on the left and right sides, respectively, of the RDH.

OTHER USES FOR INSTRUMENTATION ON RESOURCE ROADS

Monitoring with instrumentation and data logging technology has the potential to be used in various settings by the transportation industry, specifically by the natural resources sector on remote forest access roads. These monitoring systems have the capacity to provide tremendous assistance in improving use safety, maintaining operational productivity, and optimizing the infrastructure service life of forest resource roads. There are many current examples of the forestry and transportation industry using instrumentation monitoring systems. In Quebec, Domtar is using technologies such as radio frequency identification (RFID), cameras, onboard computers, all-weather stations, and roadbed temperature sensors in an attempt to extend the hauling season and improve overall transportation efficiency and safety (Markle et al. 2019). In Alberta, forestry companies have installed thermistor networks to track frost depth penetration for winter haul management (Markle et al. 2019). In British Columbia, the Ministry of Forests, Lands, Natural Resource Operations and Rural Development (FLNRORD) is using technologies such as crack monitoring gauges on cracked bridge abutments and rock faces, traffic counters to record vehicle road use on main resource roads, and all-weather stations (Markle et al. 2019).

Bridges

As used by FLNRORD in British Columbia, monitoring the structural condition and performance of bridges with instrumentation monitoring systems can provide bridge managers/ owners with useful data to help manage their use. The use of diagnostic instrumentation and the monitoring of bridges are helpful for making accurate structural condition assessments and performance evaluations which would be helpful in further modelling and defining load ratings. The evaluation of structurally deficient bridges is an economic and engineering requirement before planning or making any decisions regarding preventative measures or improvement. Therefore, field diagnostic technologies are indispensable tools that enable and support field-calibrated modelling, analysis, identification and load rating (Farhey 2005). Stream flow gauges can also be used to measure storm flows in small forest streams and provide valuable data with which to estimate the hydrology of that or nearby streams when designing stream crossings.

Culverts

In comparison to bridges, culverts are simpler structures and do not require the same level of inspection and monitoring. A potential monitoring strategy might include a moisture sensor linked to a telemetry system and flashing light. When a culvert gets plugged and water pools against the upstream side of the road, the moisture sensor would indicate that the roadbed is saturated and send a warning to the road manager. The road manager would then come and inspect and(or) send equipment to clean the debris or ice out of the culvert and restore drainage. Meanwhile, the moisture sensor would also turn on the flashing light so that road users would be warned of a potential washout and hole in the road (Personal communication. Allan Bradley. FPInnovations, March 2023).

Platooning trucks

Truck platooning is the newly developed transportation strategy wherein a platoon or sequence of two or more trucks travel closely together with only the first truck having a driver and the following truck(s) being controlled by that driver using automated driving technology. The potential benefits of truck platooning include lower fuel consumption, improvements in productivity (i.e, fewer drivers required), fewer accidents, safer traffic, less road congestion, and reduced carbon emissions (Janssen et al. 2015). In a truck platoon, the lead truck will have a scanning sensor pack on the cab roof that maps the roadway in 3D and virtually places waypoints for the rest of the platoon to follow. Using a variety of sensors, it tries to see the road at all times. The following trucks receive the 3D map and waypoints to navigate to. They also scan the roadway behind the lead truck to ensure that no new hazards have appeared (Janssen et al. 2015). However, there are some challenges to this current system at night or in rainy, snowy, or dusty conditions.

The system's satellite connection also faces issues with losing connection under overpasses, through tight canyons or between tall buildings. System designers in current platooning trials are adding sensors in the road under bridges and overpasses and in downtown cores to help platooned trucks to navigate there (Vu and Johnsson 2019). Such technologies show great potential for the future of logging transportation for increasing worker efficiency and increasing road safety of resource roads.

DISCUSSION: USING INSTRUMENTATION AS A DECISION SUPPORT TOOL

The use of instrumentation in the monitoring of resource roads is being continuously researched, practiced, and improved. Instrumentation monitoring can be used as an effective decision support tool for forest and road managers to make decisions on how to manage and maintain resource roads. Using instrumentation monitoring as a decision support tool in making decisions regarding the building of roads and road infrastructure and has the potential to increase transportation efficiency, increase the efficiency of the allocation of road-building materials, improve road quality, and improve road safety. Two major examples of how instrumentation monitoring can be used as a tool to make management decisions are with enforcing spring-thaw load restrictions on low-traffic highways and/or forest access roads, and with road maintenance frequency and allocation.

Spring thaw load restrictions are used to prevent road damage - notably deep subgrade failures in gravel roads and pavement cracking and rutting in low-standard highway pavements. When implemented properly, the practice of load restrictions (the limiting of truck weights), reduces springtime road structure damage (Kestler et al. 2007). The technique and success (in minimizing road damage and economic impact) of spring load restrictions vary appreciably as the use of load restrictions is only effective in preventing road damage if the timing is predicted carefully. Some agencies use qualitative techniques, such as the implementation of road restrictions when road thawing is observed. Another common practice is to use predetermined dates for load restrictions. Neither of these methods is particularly efficient in minimizing damage and road damage often occurs regardless of the load restriction efforts (Kestler et al. 1999; Kestler et al. 2007).

Previously, spring load restrictions were implemented each year during a predetermined time frame in many Canadian provinces; however, in some jurisdictions engineering judgement was also used and took into account local weather conditions (Canada Cartage 2021). Despite the imperfect success rate of load restrictions in preventing road damage during thawing conditions, research continues in an effort to improve this technique because spring road damage remains a major transportation and road maintenance issue in locations with freezing winter seasons.

The provinces of Alberta, Saskatchewan, Manitoba, Ontario, and New Brunswick now use rational methods based on road temperature monitoring networks and(or) observed weather and known relations between weather and freezing/thawing to start and end winter weights and start spring load restrictions (SLR). Ontario and Manitoba have rational methods based on weather and road strength recovery relations to end SLR while

British Columbia, Alberta, Saskatchewan, and New Brunswick use non-destructive strength testing to determine when the roads are strong enough to remove spring load restrictions. The Ontario MTO recently introduced a new Excel program for municipalities and the MTO to use for setting and removing SLR that features updated weather-road relations and 4 climatic zones. Quebec does not allow winter weights but does start SLR based on weather and does strength testing to end SLR (Thiam and Bradley 2018).

Many studies on the effects of spring thaw on road damage have been completed as being able to link seasonal weight programs to climate change is critical in protecting road pavements (Kestler et al. 1999; Kestler 2003; Kestler et al, 2007). These studies focussed on the effects of spring thaw on low-volume paved roads. Each of these studies defined the road damage factor as the ratio of the number of loads to reach failure under normal summertime conditions to the number of loads to reach failure under freeze-thaw conditions. These studies found that road damage begins with the beginning of thaw and peaks mid to late spring when thaw depth reaches approximately 45cm beneath the road surface. This damage includes cracking, rutting, frost boils, and other road damage that severely decreases road quality, road safety, and transpiration efficiency.

The use of instrumentation monitoring with below-ground thermistors and soil moisture sensors has the potential to improve the spring load restriction technique to an efficiency level that will yield success in preventing road damage during the spring season. Alternatively, to using predetermined dates in scheduling annual spring load restrictions, temperature and moisture data collected through belowground instrumentation can be used quantitatively to accurately determine when the thaw begins, how deep the thaw has penetrated the roadbed, and therefore, when to implement load restrictions.

Below-ground temperature readings can be used as an accurate tool for determining spring thaw trends beneath the road surface. Temperature data from a series of thermistors stations in an area or region can be compiled to produce a weighted average that can be used to identify warming trends and impose spring load restrictions (Barcomb 1988). Below-ground soil moisture sensors measure the soil's volumetric water content. Because the dielectric constant of water is so much greater than that of dry soil, the contribution of moisture to the overall dielectric constant of the soil-water-air mixture dominates and the percentage of water, by volume, within the soil can be determined (Kestler et al. 1999). Once excess moisture has dissipated from the road structure, the degree of road damage probability can be expected to decrease. Therefore, the Kestler et al. 1999 study made the conclusion that thermistors within the road structure can be used to quantitatively determine an effective start date for load restrictions and soil moisture sensors within the road structure can be used to quantitatively determine when restrictions can be strategically removed. With the use of these instrumentation tools, road damage can be minimized while maintaining transportation efficiency.

CONCLUSION

Many unpaved resource roads are built each year in Canada to provide access to forest resources. Due to increases in storm intensity and frequency in many areas with climate change and due to poor drainage and substandard management, construction, and maintenance practices, these roads may experience decreases in bearing capacity which leads to road damage and access challenges. This is especially evident in the springtime when roads become thaw weakened and highly susceptible to deep structural damage from heavy trucks.. This study was able to highlight the various opportunities for instrumentation to be used as a tool to better understand the link between road material conditions, road strength, and road performance. Instrumentation has proven potential to be used as a tool to monitor road, bridge and culvert conditions as well as to be used in managing spring load restrictions for low-volume road networks that will effectively preserve road quality and performance during the spring season.

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