Ontario's Reduced Load Period (RLP) Onset and Removal Prediction Model

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ABSTRACT

In the spring, the frost formed in the pavement subsurface structure starts thawing and pavement becomes weaker. Heavy loads on the weakened roads can cause substantial damage and lead to pavement life reduction or road failure. To ensure the integrity of roadway structures during spring-thaw season, the Ontario Ministry of Transportation (MTO) and municipalities in Ontario enforces reduced load restriction on certain provincial highways and municipal roads in according with the Highway Traffic Act.

Currently, most municipalities implemented a fixed-date approach for the reduced load period (RLP). However, concerns have been raised by municipalities and the trucking industry that this fixed RLP does not accurately reflect the actual spring-thaw condition. In an effort to reduce economic red tape and hardship for the trucking industry and to support the municipalities in protecting their road infrastructure, the MTO propose a calibrated predictive approach for determining the start and end dates of the RLP. This predictive approach utilizes representative weather data and the response of pavement structure.

Based on assessment of the RLP protocols from MTO and neighboring agencies, the MTO suggests dividing the province into four RLP zones and employing the Cumulative Thawing Index (CTI) method to forecast the start and removal dates of the RLP. This paper outlines the rationale behind the proposed methodology, which involves utilizing field measurement such as subsurface temperature, moisture content, borehole data, and pavement deflection to establish CTI thresholds for each specific zone's start and removal dates. This paper also highlights the calibration, verification, recommendations, and the subsequent steps necessary for implementing the proposed RLP management solution, which seeks to strike a balance between the requirements of trucking industry and the objectives of road agencies.

1.0 INTRODUCTION AND OBJECTIVE

During the spring-thaw season, the pavement structure experiences thawing of frost and gradual accumulation of water in the subsurface layers. This saturation weakens the pavement's bearing capacity, which can lead to reduced pavement life or even road failure. However, potential damages caused by freeze-thaw-cycles can be mitigated by imposing axle weight restriction during this period.

The Ontario Ministry of Transportation (MTO) and municipalities have the authority, as per the Highway Traffic Act, to enforce a reduced load period (RLP) to protect roads that are not designed or constructed to withstand full loads throughout the year, particularly during the spring-thaw period. The RLP is typically implemented between March 1 and June 30. However, the determination of the RLP varies between MTO and municipalities due to jurisdictional differences. MTO determines the RLP based on factors such as highway location, regional pavement performance, weather conditions, field observations, and the 2012 Ontario's RLP Onset and Removal Prediction Model (MTO RLP Prediction Model) developed specifically for highways in Northern Ontario. On the other hand, most municipalities in Ontario impose a fixed start and end date for the RLP on their roads.

In recent years, concerns have been raised by municipalities and the trucking industry regarding the fixed-date RLP method, as it does not accurately represent the actual spring-thaw conditions. There is a need for a more optimized approach to determine the timing of RLP. In 2021, a review of the 2012 RLP Prediction Models was conducted, resulting in the development of a new RLP Prediction Model calibrated for the entire province. This calibrated approach, based on zones, aims to streamline the RLP determination process between MTO and municipalities, promoting consistency across Ontario.

2.0 APPROACH

The overall approach of the RLP prediction model development contains the following progressive steps:

1. Conduct a literature review to examine existing practices in both Ontario and neighboring jurisdictions in order to identify the best practices to determine RLP.
2. Establish RLP zones for Ontario to regionalize the RLP start and end date criteria.
3. Collect borehole data, air temperature, subsurface condition data, and pavement deflection measurements for the development of RLP prediction model.
4. Analyze the collected data and develop, calibrate, and verify the CTI Thresholds, and select the best fit CTI equation.
5. Provide recommendation and implementation plan for updated MTO RLP Prediction Model, along with outlining the necessary next steps.

By following this approach, the proposed RLP prediction model will offer a more refined and systematic methodology for determining the optimal timing of the reduced load period. This approach will contribute to minimizing potential damages to the road infrastructure during the critical spring-thaw season while considering the interests of both the trucking industry and road agencies.

3.0 LITERATURE REVIEW

3.1 RLP Current Practices in Ontario and Neighboring Agencies

Ontario's is bordered by the province of Quebec to the east, Manitoba to the northwest, and the state of Minnesota to the southwest. These transportation agencies also implement RLP during the spring thaw season, although their criteria for determining RLP start and end dates differ. A comparison of RLP criteria among these agencies is summarized in Table 1.

Table 1. Summary of RLP Start and End Date Criteria between Agencies

Agencies	RLP Start Date Criteria	RLP End Date Criteria
Ontario (MTO)	• Freeze/thaw depth at Seasonal Load Adjustment (SLA) sites • Use CTI, thresholds at 47°C-day for Northeast Region (NER) and at 14°C-day for Northwest Region (NWR) • Site observation, historical date, air temperature	• Site observations (pavement and subsurface condition) • Historical data • Approximately 5 to 10.6 weeks from the RLP start date
Minnesota (MnDOT)	• Use CTI, threshold at 25°F-day • Forecast of warmer temperature	• Site Observations • 3 weeks after complete thaw • Not exceeding 8 weeks from RLP start date
Quebec	• 30% of stations within one thaw zone have reached thaw depth of 30 cm	• 5 weeks after 50% of stations within one thaw zone have reached thaw depth of 90 cm
Manitoba	• Use CTI, threshold at 15°C-day • Continuous rise of temperature	• CTI, threshold at 440°C-day • Continuous rise of temperature • Approximately 12 to 13 weeks from RLP start date

The 2012 MTO CTI Equations and thresholds were developed based on studies conducted under the MTO Highway Infrastructure Innovations Funding Program (HIIFP) for Northern Ontario. These equations, along with the calibrated region-specified thresholds, were adopted to predict the RLP start date in Ontario NER and NWR of Ontario, respectively. The thresholds indicate the depth of thaw penetration, such as 30 cm for NER and 15 cm for NWR. Previous studies have shown that a significant strength reduction occurs when the thaw depth reaches 30 cm, and a refreeze period of 4 days has no effect on pavement strength [1].

The original MnDOT CTI equation, developed based on a MnDOT study conducted in 1999, has undergone several improvements [2]. The study suggested that the CTI equation and threshold developed by the Washington State Department of Transportation (WSDOT) could be customized to suit Minnesota's condition for predicting the RLP start date. The CTI start date threshold of 25°F-day indicates thaw penetration to a base depth of approximately 150 mm. Additionally, Falling Weight Deflectometer (FWD) deflection data was used to assess base layer strength recovery, which influenced the determination of the RLP end date. Results showed that at least 50 percent of base strength recovered two weeks after the end of thaw, and subgrade strength increased within three weeks after complete thaw. Based on these findings, an eight-week duration of RLP was suggested, as it typically took eight weeks for the pavement base layer to recover during the spring-thaw period [2] [3].

In Manitoba, FWD tests conducted between 2010 and 2013 on eight pavement sites (five asphalt concrete and three asphalt surface treated pavements, thicknesses from 25 to 130 mm). The test results demonstrated a significant increase in FWD peak deflection when the thawing started in the pavement base course, regardless of the base course depth. The average CTI corresponding to substantial FWD deflection increase was 12°C-days, aligning closely with the CTI start date criteria of 15°C-days prescribed by the Manitoba Method. For the end date criteria, FWD recovery, stabilized moisture content at 1 m subsurface depth, and thaw depth of 1.2 m was assessed. After data calibration, it was concluded that an RLP of 57 days (8.1 weeks) would capture 95% of expected recovery, corresponding to a calibrated CTI value of 438°C-days, supporting the selected end criteria of 440°C-days in the policy [4] [5].

Transports Québec has collected frost depth and pavement deflection data from road weather stations throughout the province for 15 years. A Technical Information Bulletin published in 1996 reported that the pavement deformations pronounced at thaw depth of 45 cm. The pavement started losing its bearing capacity at an average depth of 30 cm and slowly recovering at 90 cm [6]. Their Thaw Report stated that the load restriction period for one particular thaw zone should begin when 30% of stations reach a thaw depth of at least 30 cm and end five weeks after 50% of stations reach a thaw depth of 90 cm, accounting for the recovery period [7].

In summary, the common criterion for determining the RLP start date is the CTI threshold, although the equations and thresholds vary among agencies. Daily maximum and minimum air temperatures and reference temperatures (set by the agency) are required as an input parameter for CTI calculations. For RLP end date, Manitoba employs CTI threshold, while other agencies rely on site observations and thawing conditions. The use of CTI for determining the RLP end date simplifies the prediction process by utilizing measured and forecast daily maximum and minimum air temperatures as roadway inputs.

3.2 Seasonal Load Adjustments (SLA) Sites in Ontario

MTO operates a network of Road Weather information System (RWIS) stations across the province to monitor weather and pavement conditions. These stations support MTO maintenance staff in making proactive and appropriate road maintenance decisions. Currently, MTO has approximately 177 RWIS stations equipped with sensors to measure relative humidity, air temperature, subsurface temperature (at depth of 40 cm and 150 cm), and pavement surface conditions. Among these stations, 15 are designated as Seasonal Load Adjustment (SLA) sites. SLA sites have additional sensors, including multiple subsurface temperature sensors at various depths between 5 and 255 cm, and subsurface moisture content sensors at depths of 15, 45, and 100 cm. Sensor readings are typically recorded at 10-minute or 1-hour intervals. As of 2022, nine SLA sites are in Northern Ontario and additional six SLA sites were installed in 2021 in Southern Ontario. The approximate locations of all SLA sites are depicted in Figure 1 for Northern Ontario and Figure 2 for Southern Ontario.

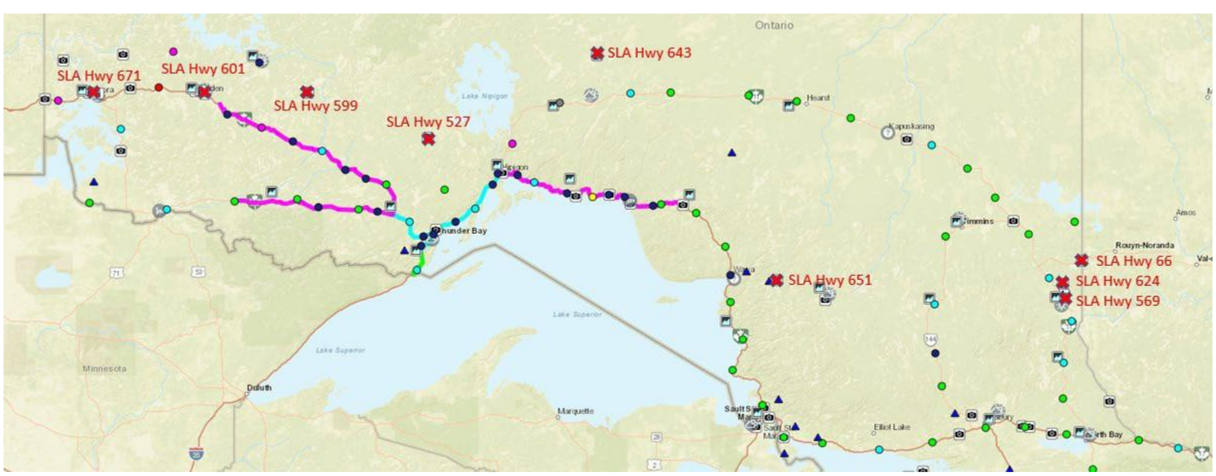

Figure 1. SLA Sites located at Northern Ontario

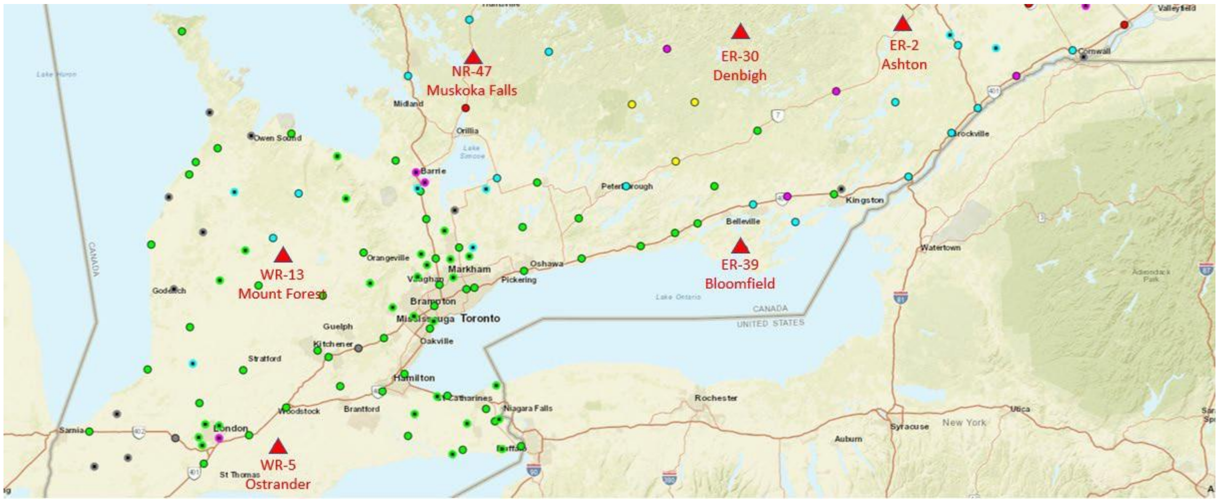

Figure 2. SLA Sites located at Southern Ontario

4.0 MTO RLP ZONE ESTABLISHMENTf

The duration of the RLP is determined by the recovery of pavement strength during the spring-thaw season, which is specific to each location. In Quebec, three thaw zones have been established since 1991, taking into account geographical information, regional frost depth, thaw trends, spring weather conditions, and the heavy vehicle traffic [8].

A similar approach was followed to establish MTO RLP zones, considering diverse climate patterns and geographical variation across the province. These zones were primarily developed based on frost penetration depths, predominant subgrade soil types, and the MTO Performance Graded Asphalt Cement (PGAC) Zone Map. Final adjustments were made considering the coverage of SLA site locations and the municipal boundaries.

MTO has created two frost penetration depth contour maps; one for Southern and another for Northern Ontario, as shown in Figure 3. Frost depth contours exhibit significant variations from north to south, with depths ranging from 1.0 to 2.0 m in Southern Ontario and 1.8 to 3.2 m in Northern Ontario [9] [10].

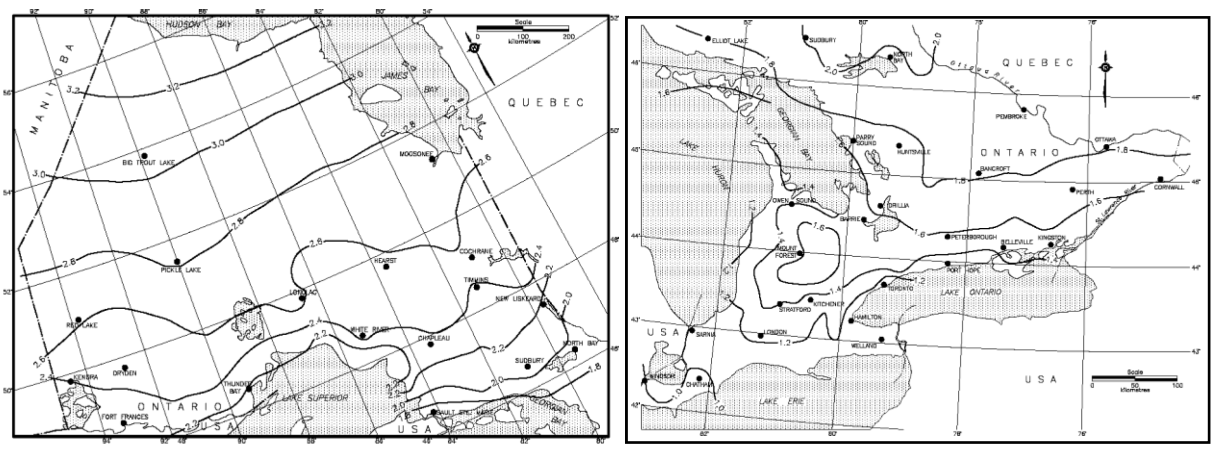

Figure 3. Foundation Frost Penetration Depths for Northern (left) and Southern (right) Ontario

The three PGAC Zones in Ontario were developed based on temperature contours from available weather data, in conjunction with the relationship between pavement and air temperature as established by the Long-Term Pavement Performance (LTPP) studies [11]. In 1960, the Soil Associations of Southern Ontario published a map that divided the region into areas with dominant soil types for Southern Ontario. Although the soil types have been categorized into great details, a boundary can be observed that the north part of Southern Ontario has dominantly medium to coarse textured soils formed on stony till, bedrock or with Precambrian rock; while the south part has most soils sitting on clay, silt or sand and gravels [12]. This boundary generally matches with the Ontario PGAC zone border between Zone 2 and Zone 3 as seen in Figure 4.

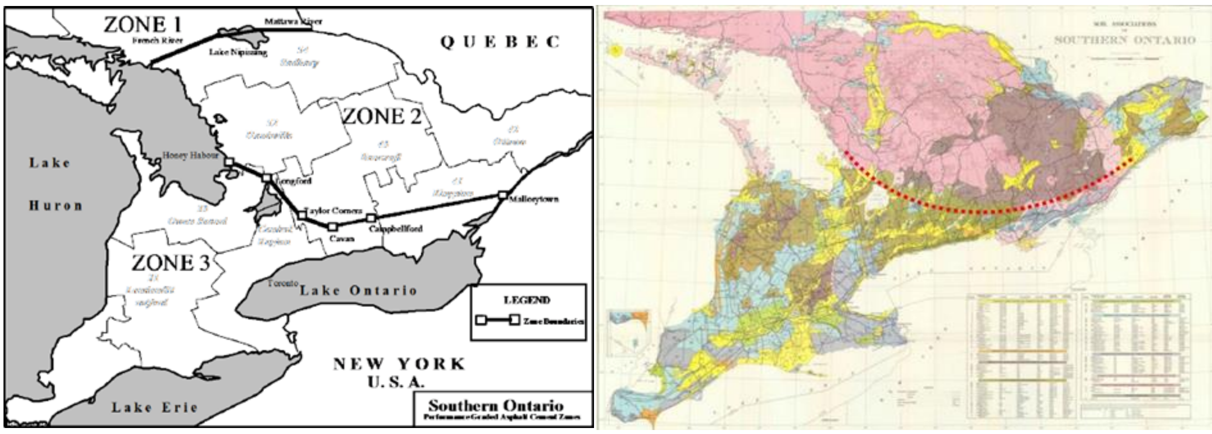

Figure 4. MTO PGAC Zone Map (left) and Dominant Soil Families in Southern Ontario (right)

Based on review of the above information and taking the SLA site coverage and municipality boundaries into consideration, the MTO RLP Zone below was established. Ontario was divided into 4 zones as shown in Figure 5. The number of SLA sites and approximate frost depth range for the corresponding zone is shown in Table 2.

Figure 5. MTO RLP Zones

Table 2. MTO RLP Zones

	RLP Zone 1	RLP Zone 2	RLP Zone 3	RLP Zone 4
Number of SLA Sites	5	4	3	3
Approximate Frost Penetration Depth	2.4 to 3.2m	2.0 to 2.4m	1.6 to 2.0m	1.0 to 1.6m

5.0 DATA COLLECTION AND INTERPRETATION

5.1 Borehole Information

Boreholes were obtained between April and June 2022 to determine the pavement structure and subgrade type for each of the SLA sites. Table 3 summarizes the pavement structure at each SLA site. Based on the borehole data, the surface course at the SLA sites consists of either asphalt or surface-treated material with a thickness ranging from 20 and 325 mm. The minimum depth to the base layer from the surface is 25 mm. Most SLA sites have gravel, sand, and/or silt subgrade, except for Hwy 66 and Hwy 569, which have clay subgrade where the subsurface moisture will take longer to drain.

Table 3. Pavement Structure and Subgrade Types of the SLA Sites

RLP Zone	SLA Sites	Thickness of Pavement Layers (mm)								Subgrade Type
		Asphalt	Surface Treated	Granular Base	Select Subgrade Material	Asphalt	Select Subgrade Material	Granular Subbase	Total	
1	Hwy 527	60		200				740	1000	Sand with Silt and Gravel
	Hwy 599		25	300					325	Sand with Gravel/Gravelly Sand
	Hwy 601		25	200				375	600	Silty Clay & Sand/Clay with Sand
	Hwy 643	45		150				305	500	Gravelly Sand/Sand with Gravel
	Hwy 671		20	200					220	Silty Sand/Sand and Silt
2	Hwy 66	230						200	430	Clay and Silt with Trace of Sand
	Hwy 569		25	230	355	50			660	Clay and Silt with Trace of Sand/Gravel
	Hwy 624		25	230		50	455		760	Silt with Some Clay with Trace of Sand/Gravel
	Hwy 651	50						865	915	Encounter Bedrock or Boulders at 0.915 m
3	ER-2 Ashton	250		180				260	690	Sand to Silty Sand with Traces of Gravel
	ER-30 Denbigh	90		190				250	530	Sand with Gravel with Traces of Silt
	NR-47 Muskoka Falls	140			240	50		1370	1800	Sand and silt with Trace of Gravel/Clay
4	ER-39 Bloomfield	110		300				500	910	Silty Sand with Traces of Gravel
	WR-5 Ostrander	325		175				> 1500	2000	Not Encountered within 2 m
	WR-13 Mount Forest	265		185				750	1200	Silty Sand

5.2 Air Temperature and Subsurface Condition Data

During the period between January and June 2022, recorded air temperatures, subsurface temperatures, and subsurface moisture content readings were collected for each SLA site from the RWIS database. These readings were aggregated and presented in Table 4, showing the daily maximum and minimum air temperatures, daily average subsurface temperatures, and daily average subsurface moisture contents. To illustrate the freeze-thaw progression across subsurface depths, a color-coded daily average subsurface temperature profile was created. In this representation, the orange color indicates thaw condition (i.e., subsurface temperature ≥ 0°C), while the blue color represents frozen condition (i.e., subsurface temperature < 0°C).

In the provided example, the pavement underwent a thawing phase to a depth of 15cm below the surface, starting on March 20 and lasting for two consecutive days. Afterward, due to a decrease in air temperature, the pavement experienced two days of refreezing. This was followed by a brief period of one-day thawing, succeeded by eight days of refreezing. As the ambient temperature increased again, the pavement resumed thawing from April 2 onwards until it reached a complete thaw phase on May 8. Additionally, gradual bottom-up thawing was observed as the air temperature continued to rise.

Table 4. Example of Daily Air Temperatures and Subsurface Condition Data (Hwy 599)

Date	Daily Air Temperature, oC			Daily Average Subsurface Temperature (Depth below Surface), °C												Daily Average Subsurface Moisture Content (Depth below Surface), %		
	Average of Daily Min. and Max.	Maximum (Max.)	Minimum (Min.)	5 cm	15 cm	30 cm	45 cm	60 cm	75 cm	90 cm	105 cm	135 cm	195 cm	225 cm	255cm	15 cm	45 cm	100 cm
3/19/2022	1.1	8.9	-6.7	-0.3	-1.0	-1.5	-2.4	-3.1	-4.1	-4.7	0.8	-4.8	-2.2	-0.8	0.7	6	4	3
3/20/2022	1.3	8.0	-5.4	1.2	0.3	-1.1	-1.7	-2.2	-3.0	-3.8	0.4	-4.4	-2.1	-0.8	0.7	6	4	3
3/21/2022	0.0	4.8	-4.8	1.1	0.6	-0.8	-1.3	-1.6	-2.0	-2.8	-0.2	-3.9	-2.0	-0.7	0.7	14	4	3
3/22/2022	-2.4	-0.8	-4.0	-0.2	-0.3	-0.5	-1.0	-1.3	-1.6	-2.2	-2.7	-3.4	-1.9	-0.7	0.7	15	4	3
3/23/2022	-1.8	0.0	-3.6	-0.4	-0.4	-0.7	-0.9	-1.2	-1.4	-1.9	-2.3	-3.0	-1.8	-0.7	0.7	16	4	3
3/24/2022	-2.5	5.8	-10.7	1.0	0.5	-0.7	-1.0	-1.1	-1.2	-1.5	-1.8	-2.5	-1.6	-0.6	0.7	17	4	3
3/25/2022	-4.9	0.0	-9.8	-0.6	-0.4	-0.6	-0.8	-1.0	-1.2	-1.4	-1.6	-2.0	-1.5	-0.6	0.7	18	10	3
3/26/2022	-15.1	-10.6	-19.5	-1.5	-1.1	-0.8	-0.9	-1.1	-1.2	-1.3	-1.4	-1.7	-1.4	-0.6	0.7	17	18	3
3/27/2022	-17.3	-9.9	-24.7	-3.6	-2.6	-1.2	-0.9	-1.0	-1.2	-1.2	-1.4	-1.5	-1.3	-0.5	0.7	14	19	3
3/28/2022	-15.3	-2.2	-28.3	-4.1	-3.2	-1.6	-1.1	-1.0	-1.2	-1.2	-1.3	-1.3	-1.1	-0.5	0.7	12	17	3
3/29/2022	-3.9	2.4	-10.2	-1.6	-1.6	-1.6	-1.3	-1.0	-1.1	-1.2	-1.3	-1.3	-1.0	-0.5	0.8	11	14	3
3/30/2022	-2.6	-1.2	-4.0	-1.2	-1.3	-1.5	-1.4	-1.1	-1.1	-1.2	-1.2	-1.2	-1.0	-0.4	0.8	12	12	3
3/31/2022	-6.5	-2.2	-10.8	-1.6	-1.4	-1.4	-1.4	-1.3	-1.2	-1.1	-1.2	-1.2	-0.9	-0.4	0.8	12	11	3
4/1/2022	-6.5	5.3	-18.3	-1.4	-1.5	-1.5	-1.5	-1.3	-1.3	-1.1	-1.2	-1.2	-0.9	-0.3	0.8	12	11	3
4/2/2022	-0.3	3.3	-3.9	0.3	-0.3	-0.9	-1.2	-1.3	-1.5	-1.3	-1.2	-1.2	-0.8	-0.3	0.9	13	13	3
4/3/2022	-0.6	2.6	-3.8	0.5	0.1	-0.6	-1.0	-1.1	-1.2	-1.3	-1.3	-1.1	-0.8	-0.2	0.9	20	18	3
4/4/2022	0.6	2.8	-1.7	1.0	0.5	-0.5	-0.8	-0.9	-0.9	-1.1	-1.2	-1.1	-0.7	-0.2	0.9	25	24	3
4/5/2022	1.3	4.6	-2.1	1.4	0.9	-0.2	-0.4	-0.5	-0.7	-0.8	-1.0	-1.1	-0.7	-0.1	0.9	32	29	3
4/6/2022	0.4	1.8	-1.1	0.8	0.6	0.0	-0.4	-0.6	-0.7	-0.7	-0.9	-1.1	-0.7	-0.1	1.0	49	28	9
4/27/2022	-1.9	7.1	-10.8	3.9	3.0	1.1	0.3	-0.1	-0.2	-0.3	-0.4	-0.5	-0.1	0.5	1.3	14	12	9
4/28/2022	1.3	9.3	-6.8	5.4	4.6	2.6	1.3	0.1	-0.2	-0.3	-0.3	-0.5	-0.1	0.5	1.3	14	13	9
4/29/2022	4.1	7.6	0.5	6.1	5.6	3.8	2.1	0.5	-0.2	-0.2	-0.3	-0.4	0.0	0.5	1.3	14	12	9
4/30/2022	8.5	13.1	3.8	8.5	7.3	4.6	2.8	1.0	-0.2	-0.2	-0.3	-0.4	0.0	0.6	1.3	14	12	9
5/1/2022	4.3	6.6	2.0	6.0	6.1	5.3	4.0	2.1	-0.1	-0.2	-0.3	-0.4	0.1	0.6	1.3	15	13	10
5/2/2022	2.7	5.4	0.0	5.6	5.1	4.1	3.2	2.0	0.1	-0.3	-0.3	-0.4	0.1	0.6	1.4	15	14	9
5/3/2022	2.8	7.3	-1.7	7.0	6.2	4.5	3.3	2.1	0.4	-0.3	-0.3	-0.3	0.2	0.7	1.4	14	15	9
5/4/2022	4.6	13.2	-4.0	8.9	7.9	5.5	4.0	2.6	1.0	-0.1	-0.3	-0.3	0.2	0.7	1.4	14	15	9
5/5/2022	9.3	18.1	0.5	12.2	10.7	7.5	5.4	3.6	1.7	0.2	-0.3	-0.3	0.3	0.8	1.5	14	16	9
5/6/2022	8.2	17.1	-0.8	14.0	12.8	9.7	7.2	5.0	2.8	1.0	-0.1	-0.2	0.4	0.8	1.5	14	16	9
5/7/2022	12.2	19.7	4.7	14.8	13.7	10.8	8.5	6.3	4.0	2.0	0.5	-0.2	0.4	0.9	1.6	14	16	9
5/8/2022	7.8	9.6	5.9	10.5	11.1	10.7	9.3	7.4	5.1	3.2	1.5	0.1	0.5	1.0	1.7	15	17	8

The weakening of pavement strength occurs when thaw reaches the granular base layer. Therefore, the subsurface temperature sensor closest to the base layer can serve as an indicator for determining the timing of pavement thaw weakening. Based on the borehole data, it was observed that most SLA sites in RLP Zones 1 and 2 have either surface-treated layer with a thickness of 20 to 25 mm or thin asphalt surfacing ranging from 45 to 60 mm. The subsurface temperature sensor positioned 5 cm deep, located at the upper base layer, provides the most reliable indicator for assessing thaw weakening in RLP Zones 1 and 2.

In contrast, for RLP Zones 3 and 4, the surface course layers of the SLA sites tend to be thicker compared to those in RLP Zones 1 and 2. In these cases, a subsurface temperature sensor placed at a lower depth should be considered as the indicator for thaw weakening. However, when examining the 2022 data presented in Table 5, it is evident that the thawing rate is relatively faster in RLP Zone 3 and 4. An average duration of 6 days was observed for the thaw to penetrate from the 5cm depth to the full depth in Southern Ontario, while it takes 54 days in Northern Ontario. The difference arises from a combination of higher rate of warming in the south and the bottom-up thawing effect that expedites the overall thawing process. Due to the shorter duration of the thawing period in these zones, it is recommended to utilize the subsurface temperature sensor placed at a depth of 5 cm for determining thaw weakening.

Table 5. Number of Days required from "thaw at 5 cm" to "complete thaw"

MTO RLP Zone	SLA Sites	Maximum Frost Depth, m	Date of Thaw to 5 cm	Date of Complete Thaw	Number of Days required from "Thaw to 5 cm" to "Complete Thaw"
1	Hwy 527	1.95 m	02-Apr-22	12-May-22	40
	Hwy 599	2.25 m	02-Apr-22	08-May-22	36
	Hwy 601	1.5 m	16-Mar-22	17-May-22	62
	Hwy 643	2.55 m	23-Mar-22	12-May-22	50
	Hwy 671	1.95 m	19-Mar-22	03-May-22	45
2	Hwy 66	2.25 m	06-Mar-22	30-May-22	85
	Hwy 569	1.35 m	18-Mar-22	14-May-22	57
	Hwy 624	1.65 m	18-Mar-22	09-May-22	52
	Hwy 651	1.25 m	18-Mar-22	14-May-22	57
3	ER-2 Ashton	0.9 m	07-Mar-22	20-Mar-22	13
	ER-30 Denbigh	1.05 m	07-Apr-22	11-Apr-22	4
	NR-47 Muskoka Falls	1.13 m	16-Mar-22	18-Mar-22	2
4	ER-39 Bloomfield	1.05 m	07-Mar-22	08-Mar-22	1
	WR-5 Ostrander	0.9 m	06-Mar-22	16-Mar-22	10
	WR-13 Mount Forest	1.05 m	15-Mar-22	20-Mar-22	5

In addition to monitoring air and subsurface temperatures, graphical representation of the daily average subsurface moisture readings was employed to analyze the drainage condition over time. During the spring-thaw season, the subsurface underwent thawing both from the top down and the bottom up, driven by elevated air temperature and the release of latent heat in the subgrade soil. Typically, the subsurface moisture content increases during spring thaw to reach the maximum moisture content (i.e., peak), and then it starts draining until it reaches a stabilized condition. This rate of moisture content change can be rapid or gradual, depending on factors such as depth, freeze-thaw front, and subsurface material properties.

Figure 6 illustrates an example of moisture drainage trend over time, as recorded by three subsurface moisture content sensors placed at the depth of 15 cm, 45, cm, and 100 cm. According to the observation from subsurface temperature condition (Table 4) and moisture content profiles, top-down thawing starts when the air temperature increases during the spring thaw season. As a result, the moisture content at 15 cm, 45 cm, and 100 cm start increasing around March 20, March 24, and April 5, respectively. They then reach their respective peaks around April 6, May 24, and April 7. It is noted that the 100 cm depth reached its moisture peak sooner than the 45 cm depth, as this middle zone at 45 cm depth is experiencing thawing from both bottom up and top down. Subsequently, a draining phase commenced and continued until the moisture content stabilizes on June 2, June 29, and June 23, corresponding to the depth of 15 cm, 45, cm, and 100 cm, respectively.

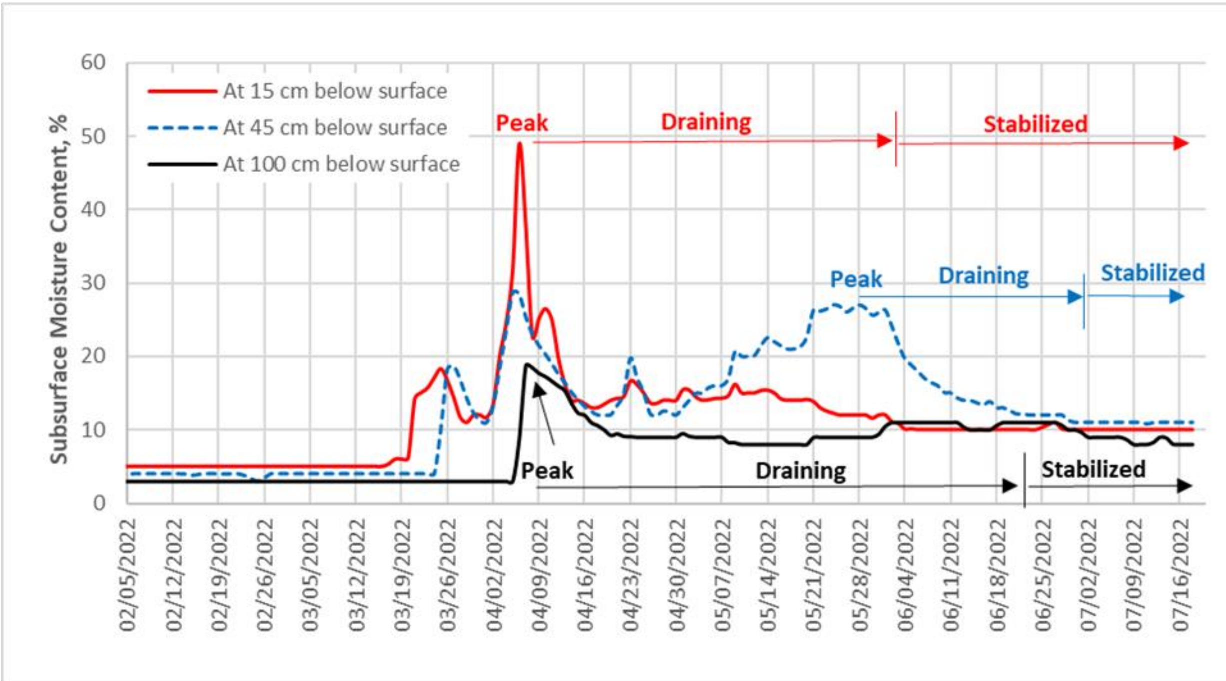

Figure 6. Example of Daily Subsurface Moisture Content Drainage Trend (Hwy 599)

5.3 Pavement Deflection Data

During the spring 2022, FWD testing was carried out at 15 selected SLA sites to assess the recovery condition of pavement strength within the four RLP zones. Between March and June 2022, each site underwent two to four rounds of FWD deflection basin testing. The FWD tests were conducted on the wheelpath of the lane closest to the SLA sites. At each SLA site, a total of three test points, approximately 1 m apart, were examined along the wheelpath. To ensure consistency, the location of these three test points was marked on the pavement, ensuring the tests were consistently performed at the exact same locations for each round (Figure 7).

Figure 7. Example of FWD Testing Location along the Wheelpath

FWD data analysis was performed to determine the normalized deflection for each site, with higher deflection meant weaker pavement strength. The average normalized deflection reading for each round is presented in a graphic format to determine the progression of pavement strength recovery. Due to limited rounds of FWD testing performed, some assumptions of the observations and interpretations were made. Three scenarios of trends were observed and interpreted from the deflection readings as shown in Figure 8.

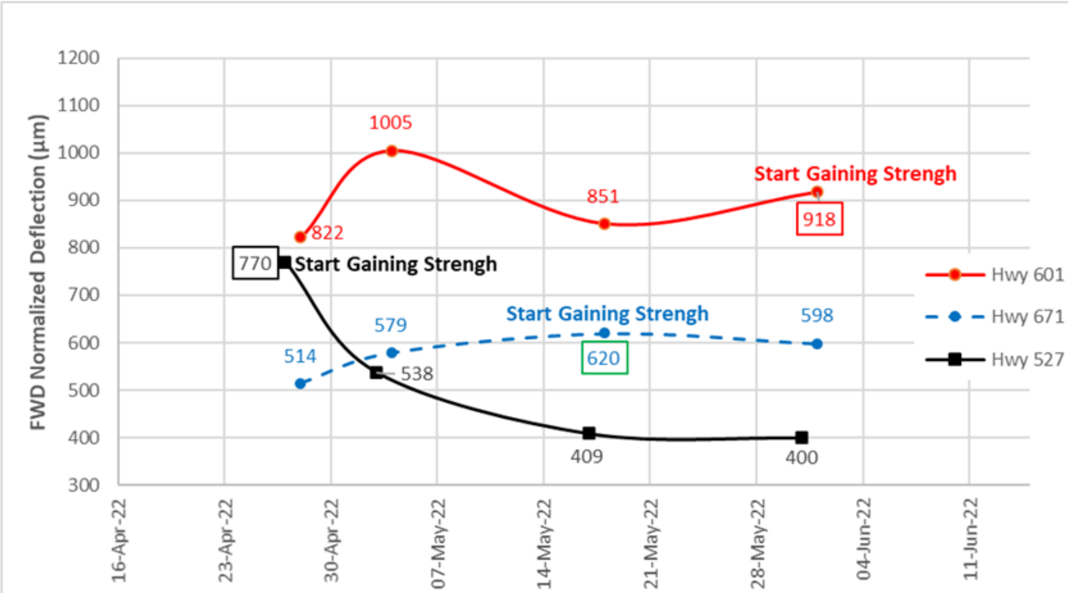

Figure 8. Example of Pavement Strength Recovery Trends

On Hwy 601, the deflection trend displayed an initial increase from the first round to the second round, followed by a decrease in the third round, and a subsequent increase in the last round. This trend suggests that the pavement had not yet reached its full-strength recovery period at the last round of testing. On Hwy 671, the deflection trend showed an increase in deflection readings up to the peak, followed by a subsequent decrease. In this case, the pavement strength recovery period commenced sometime after the peak deflection point. On Hwy 527, displayed a continuous decrease in deflection readings, indicating that the pavement strength recovery period had already peaked at the first round of testing.

6.0 RESULTS AND ANALYSIS

6.1 RLP CTI Start Date Threshold Determination and Best-Fit CTI Equation Selection

The subsurface temperature sensor located at the depth of 5 cm was selected to provide early indication of thawing or start of pavement weakening. The RLP CTI start date threshold was established as the date when thawing is observed at the 5cm-depth subsurface temperature probe. Based on this criterion, the following steps were used to determine and verify the RLP CTI start date thresholds. In order to select the best fit CTI equation for each RLP Zone, the analysis was completed on the four RLP prediction models – MTO NER, MTO NWR, MnDOT, Manitoba:

1. Utilize the daily maximum and minimum air temperatures to calculate the daily CTI using different CTI equations (i.e., MTO NE & NW, MnDOT and Manitoba).
2. Determine the first date after January when the subsurface temperature sensor at a depth of the 5 cm registers a reading of 0°C or higher for three consecutive days.
3. Identify the corresponding CTI value for each SLA site based on the date found in Step 2.
4. Review and analyze all corresponding CTIs and back-calculate the CTI start date threshold for

each RLP Zone to match the closest actual date of reaching “thaw to 5 cm” (i.e., date found from Step 2 for each site). To be conservative, the predicted start date shall be either on or earlier than the actual “thaw to 5 cm” date, and the earliest date of all the SLA sites within the zone should be used.

5. Verify the CTI start date thresholds using 2021 data (RLP Zone 1 and Zone 2 only).
6. Compare results from all CTI models to select the best fit CTI equation and determine the RLP start date CTI threshold for each RLP Zone.
7. Compare the predicted RLP start date from the calibrated best fit CTI equation against the current MTO NER and NWR CTI prediction models, RLP start date algorithms used by other jurisdictions, and MTO Operations’ RLP start dates.

Figure 9 presents an example of the results obtained from Steps 1 to 3. The daily maximum and minimum air temperatures were used to calculate the daily CTI using four CTI equations. In this example, the first date at which the subsurface temperature sensor reading indicated “thaw to 5 cm” (i.e., ≥ 0°C) for three consecutive days was on April 2. The corresponding CTI value was then read from the graph for each CTI equation.

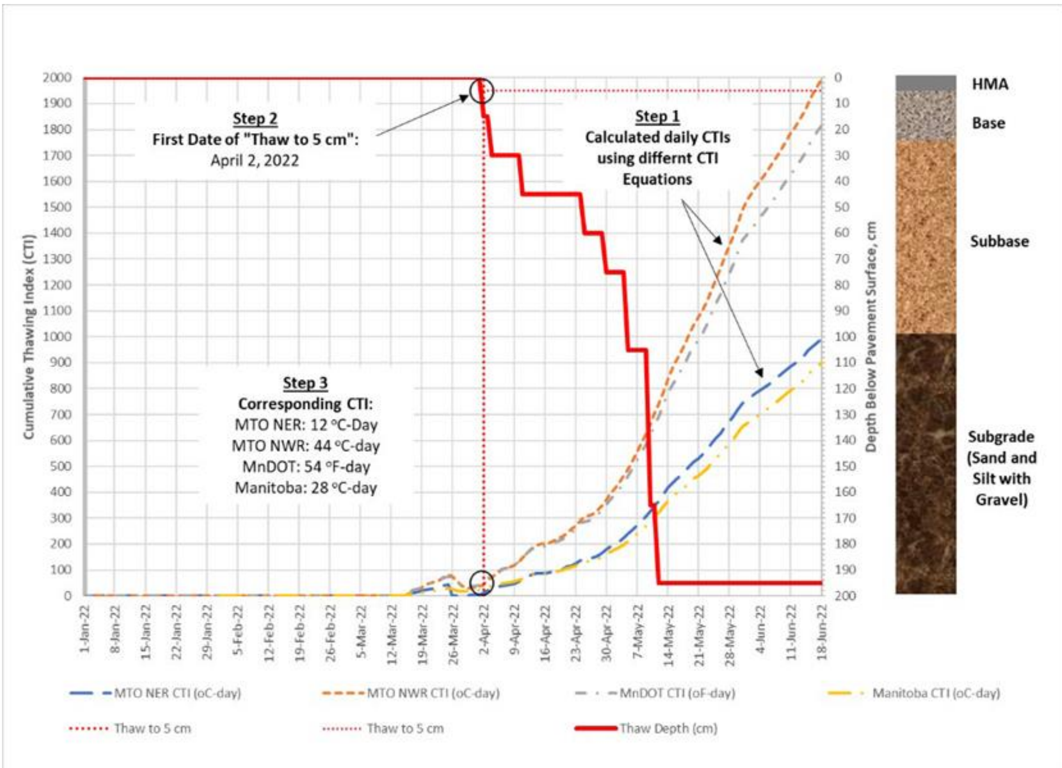

Figure 9. Example of RLP CTI Start Date Determination Results from Steps 1 to 3 (Hwy 527)

Upon obtaining the corresponding CTIs from Step 3, the CTI start date thresholds for each RLP zone were determined in Step 4. This analysis was conducted separately for each RLP zone and the four RLP prediction models. The CTI start date thresholds were back-calculated to predict the closest RLP start date that aligns with the actual start date of “thaw to 5 cm”. To be conservative, the CTI start date threshold determination considered predicted start dates were either on or earlier than the actual “thaw to 5 cm” date, selecting the earliest date within the zone.

The results indicated that the CTI start date threshold could be harmonized across all RLP zones, suggesting that a single CTI start date threshold could be applied to all four RLP zones. However, the CTI start date thresholds for the four models differed and are listed in the top portion of Table 6. The table also displays the number of days deviated from the predicted RLP start day (using the CTI start day threshold) to the actual "thaw to 5 cm" date. The objective was to holistically calibrate the RLP start date, minimizing the number of days that predicted a later start than actual "thaw to 5 cm" start date. As indicated in Table 6, the proposed CTI start date threshold effectively minimized the occurrence of positive values, meaning the predicted RLP starts later than the actual thaw start day were minimal.

Table 6. RLP CTI Start Date Thresholds and Corresponding Deviations

		CTI Equations			
2022 Data	**CTI Equation:**	**MTO NER**	**MTO NWR**	**MnDOT**	**Manitoba**
MTO RLP Zone	**CTI Start Date Threshold:**	8 °C-day	11 °C-day	18 °F-day	8 °C-day
	SLA Sites	**Number of Days from the Date of Actual "Thaw to 5 cm"**			
1	Hwy 527	-16	-16	-16	-16
	Hwy 599	-17	-16	-16	-16
	Hwy 601	0	0	0	0
	Hwy 643	-5	-4	-4	-3
	Hwy 671	-3	-3	-3	-3
2	Hwy 66	11	11	11	11
	Hwy 569	-1	-1	-1	-1
	Hwy 624	-1	-1	-1	-1
	Hwy 651	-1	-1	-1	-1
3	ER-2 Ashton	0	0	0	0
	ER-30 Denbigh	-22	-22	-22	-21
	NR-47 Muskoka Falls	-9	-9	-9	-9
4	ER-39 Bloomfield	0	-25	-1	0
	WR-5 Ostrander	0	0	0	0
	WR-13 Mount Forest	1	-8	-8	-8
Note:	positive day (+) means predicted RLP starts later than actual thaw to 5 cm zero day (0) means predicted RLP starts on the same day as actual thaw to 5 cm negative day (-) means predicted RLP starts earlier than actual thaw to 5 cm				

After establishing the CTI start date threshold, the accuracy of the thresholds was verified using historical data in Step 5. However, due to the SLA sites in RLP Zones 3 and 4 being installed in the summer to late 2021, the availability of spring-thaw data for those sites was limited. Therefore, verification process focused solely on the 2021 data for RLP Zones 1 and 2. The result as presented in Table 7 revealed that all the predicted RLP start dates either matched or preceded the actual start dates, confirming the precision of the CTI start date thresholds.

Table 7. Verifying RLP CTI Start Date Thresholds and Corresponding Deviation using 2021 Data

		CTI Equations			
2021 Data	**CTI Equation:**	**MTO NER**	**MTO NWR**	**MnDOT**	**Manitoba**
MTO RLP Zone	**CTI Start Date Threshold:**	8 °C-day	11 °C-day	18 °F-day	8 °C-day
	SLA Sites	**Number of Days from the Date of Actual "Thaw to 5 cm"**			
1	Hwy 527	0	-8	-8	-8
	Hwy 599	-1	-1	-1	-1
	Hwy 601	0	0	0	0
	Hwy 643	0	-1	-11	-1
	Hwy 671	-2	-2	-2	-1
2	Hwy 66	-7	-17	-17	-17
	Hwy 569	-10	-9	-10	-9
	Hwy 624	-10	-10	-10	-10
	Hwy 651	0	-10	-10	-10
Note:	positive day (+) means predicted RLP starts later than actual thaw to 5 cm zero day (0) means predicted RLP starts on the same day as actual thaw to 5 cm negative day (-) means predicted RLP starts earlier than actual thaw to 5 cm				

On comparing the RLP start date prediction generated by the four CTI models in Step 6, it was observed that the predictions were very similar, with many cases yielding identical results (refer to Table 6 and Table 7). However, when considering the complexity of the CTI models, the Manitoba CTI equation stand out as relatively simpler. From this evaluation, it is recommended to adopt the calibrated Manitoba CTI equation with RLP CTI start date threshold of 8°C-day for all MTO RLP Zones.

To validate the predicted RLP start date, the best fit CTI equation (i.e., Calibrated Manitoba Model) was compared against other RLP start date policies and RLP start dates implemented by MTO Operations in Step 7. The overall result, as presented in Table 8, indicate that the predicted start dates from other models were either the “same day” or “later than” the predicted RLP start date obtained using the Calibrated Manitoba Model. This outcome aligned with expectation, as the threshold used in this analysis was calibrated to the thaw depth of 5 cm, while the RLP start date thresholds employed by the MTO CTI Model, MnDOT Model, and Manitoba Model were calibrated based on the initiation of thaw weakening at depth around 15 to 30 cm. As a result, it is advisable to utilize a more conservative CTI start date threshold to effectively capture the normal top-down thawing occurring at 5 cm (carefully selected to suit Ontario’s condition as described in Section 5.2).

Table 8. Compare RLP CTI Start Date Prediction with other Start Date Policies (Step 7)

MTO RLP Zone	**Predicted RLP Start Date from Calibrated Manitoba Model**	**MTO NER**	**MTO NWR**	**MnDOT**	**Manitoba**	**MTO Operations**
		Start Date Prediction is				
1	16-Mar-22	5 days later	the same	the same	2 days later	5 days later
2	17-Mar-22	6 days later	the same	the same	1 days later	1 days earlier
3	07-Mar-22	12 days later	1 days later	1 days later	4 days later	9 days later
4	06-Mar-22	12 days later	23 days earlier	1 days later	1 days later	N/A

6.2 RLP CTI End Date Threshold Determination

The change of pavement deflection, thaw depth progression, and the subsurface moisture content drainage conditions are the indicator values used to determine the pavement strength recovery condition during the RLP. The RLP CTI end date threshold was established as the date when both pavement deflection and moisture content in granular base layer show a decrease. Based on these criteria, the following steps were used to determine and verify the RLP CTI end date thresholds for each RLP Zone using the Calibrated Manitoba Model:

1. Determine the date when the pavement enters the period of gaining strength (i.e., pavement deflection is decreasing) based on FWD results.
2. Check if the date determined from Step 1 is showing “draining” or “stabilized” condition for the subsurface moisture at all depths
3. Identify the corresponding CTI with the date that is found from Step 1 for each SLA site
4. Review and analyze CTI values and back-calculate to determine the CTI end date threshold for each RLP zone.
5. Compare the predicted RLP end date with RLP end date algorithms used in other jurisdictions and MTO Operations.
6. Provide recommendations for the RLP end date CTI threshold for each RLP Zone.

Figure 10 illustrates an example of the results obtained from Steps 1 to 3. In this example, the pavement starts gaining strength after May 18, 2022. On this date, the subsurface moisture content at all three depths showed a draining condition and the corresponding CTI value was 481°C-day.

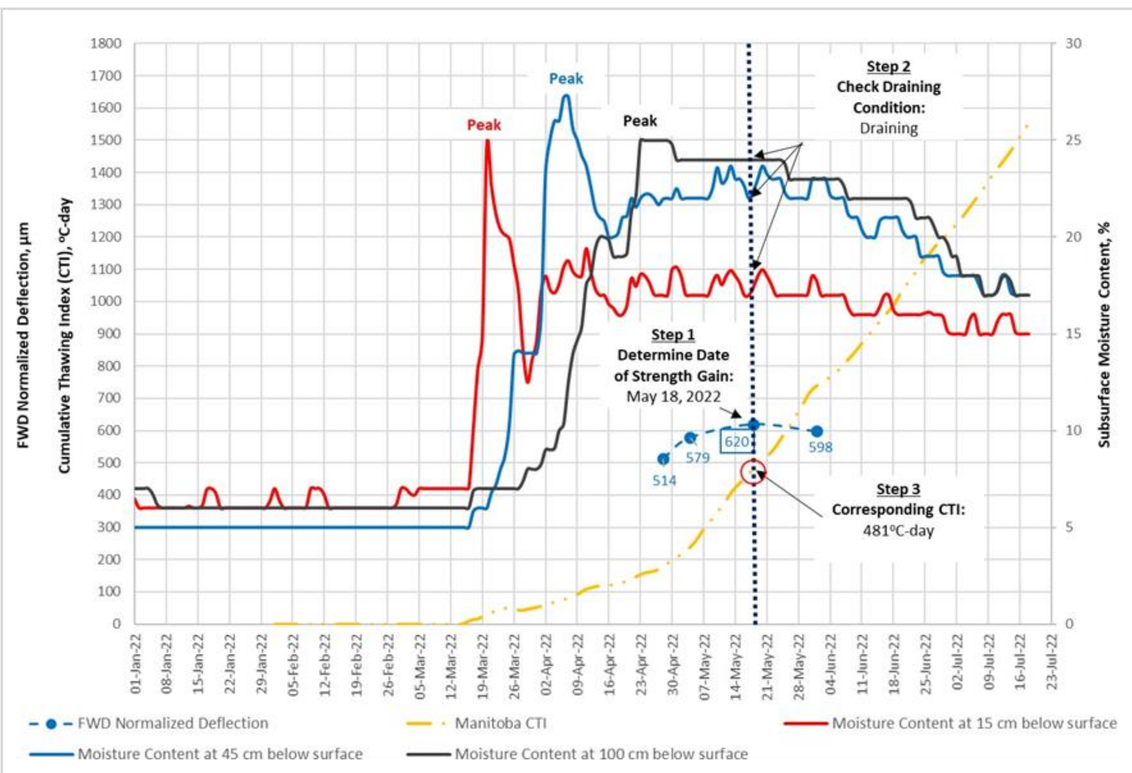

Figure 10. Example of RLP CTI End Date Determination Results (Hwy 671)

After collecting the corresponding CTI in Step 3, the analysis to determine the RLP end date thresholds was carried out in accordance with Step 4. To maintain a conservative approach, the highest CTI value among all SLA sites within each zone was selected as the initial RLP end date CTI threshold for that zone. The predicted RLP end date using these initial CTI end date thresholds indicates the point at which all SLA sites within the zone would reach the pavement strength recovery period. Considering the strength recovery trend and engineering judgement, it is recommended to set the CTI end date thresholds for RLP Zones 1, 2, 3, and 4 at 700°C-day, 700°C-day, 560°C-day and 290°C-day, respectively. Additionally, the moisture content drainage condition was verified to be at either "draining" or "stabilized" condition.

Next, in Step 5, the predicted RLP end dates were compared with the RLP end date determined by other jurisdictions and the RLP end dates implemented by MTO Operations. The overall result, as showed in Table 9, indicate that the predicted end dates from other jurisdictions and MTO Operations align either with or precede the predicted RLP end date obtained from the Calibrated Manitoba Model. This demonstrated that the prediction from the Calibrated Manitoba Model prediction is more conservative when compared to the other methods for determining RLP end dates.

Table 9. Comparison of RLP CTI End Date Predictions (Step 5)

MTO RLP Zone	RLP CTI End Date Threshold (°C-Day)	MTO RLP End Date	MnDOT	Quebec	Manitoba	MTO Operations
			End Date Prediction is			
1	700	07-Jun-22	the same	2 days later	17 days earlier	14 days earlier
2	700	31-May-22	20 days later	16 days later	16 days earlier	7 days earlier
3	560	14-May-22	12 days earlier	2 days later	6 days earlier	2 days later
4	290	28-Apr-22	18 days earlier	the same	12 days later	N/A

7.0 ONTARIO'S RLP PREDICTION MODEL RECOMMENDATION AND IMPLEMENTATION

The analysis from this study suggested that the Calibrated Manitoba Model can be used to predict the RLP onset and removal dates for the highways located at both Northern and Southern Ontario. Based on the review of the current RLP prediction models and policies from MTO and other jurisdictions, the following is recommended for use to set the start and end dates of RLP for the four MTO RLP zones.

1. Obtain 7-day forecast daily maximum and minimum air temperatures from designated weather station for the SLA sites, starting from February 1 of each year.
2. Calculate the CTI using Equation below:

Set $CTI = 0^oC\text{-}day$ on February 1 of each year, calculate the CTI on February 2 of each year as follow:

$$CTI_i = TI_{i-1} + TI_i$$

$$Reset\ CTI\ to\ 0^oC\text{-}day \qquad when\ \ CTI < 0^oC\text{-}day$$

$$TI = (0.5\ \times T_{Air}) + T_{Ref} \qquad when\ \ T_{Air} < 0^oC$$

$$TI = T_{Air} + T_{Ref} \qquad when\ \ T_{Air} \geq 0^oC$$

$$T_{Air} = \frac{T_{Max} + T_{Min}}{2}$$

$$T_{Ref} = 0.06^oC\ on\ February\ 1\ and\ increase\ by\ 0.06^oC\ daily\ until\ May\ 31$$

$$T_{Ref} = 0^oC\ from\ June\ 1\ to\ January\ 31$$

$$T_{Max} = Maximun\ Daily\ Air\ Temperature\ in\ Degree\ Celcius$$

$$T_{Min} = Minimum\ Daily\ Air\ Temperature\ in\ Degree\ Celcius$$

3. Update the forecast daily maximum and minimum air temperatures with the measured daily maximum and minimum air temperatures when it is available.
4. Monitor if any SLA site within zone showing forecast of CTI will exceed the threshold as per Table 10.

Table 10. CTI Start and End Date Thresholds

MTO RLP Zones	**1**	**2**	**3**	**4**
CTI Start Date Thresholds	8 °C-day	8 °C-day	8 °C-day	8 °C-day
CTI End Date Thresholds	700°C-day	700°C-day	560°C-day	290°C-day

5. Recommend starting the RLP on the first date when any SLA site within RLP zone exceed the CTI start date threshold for three consecutive days.
6. Recommend ending the RLP on the date when all the SLA site within RLP zone exceed the CTI end date threshold.

An excel spreadsheet has been developed for this MTO RLP Prediction Model and it is available for the MTO maintenance staff and municipalities to use as hosted by Good Roads. Municipalities can also opt to apply the RLP start and end dates based on the four MTO RLP zones to provide regional zonal consistency.

8.0 CONCLUSION

After review and reassessment in 2021, the 2012 Ontario's RLP Onset and Removal Prediction Model, originally designed for Northern Ontario, underwent significant updates. With the inclusion of additional test data and information from SLA sites, a new RLP prediction model specific to Ontario's conditions was developed. This updated model was based on Manitoba CTI equations, but customized and calibrated with Ontario's local condition. To ensure widespread understanding and utilization of this model, training sessions and conferences were conducted to disseminate the knowledge and information to the ministry's internal staff, industry stakeholders, and municipalities.

The development of the model relied on slightly over a year's worth of data from 2022. However, ongoing calibration and algorithm refinement will be conducted to enhance its accuracy and effectiveness. In particular, for RLP Zone 1, which currently has SLA sites predominantly located in the southern part of the zone, the inclusion of additional SLA sites in the middle of the zone is being considered to achieve better coverage and representation.

In the spring of 2023, the updated MTO RLP prediction model will be implemented for the first time. Collaborating with the Good Roads, the model will be distributed to trucking industry and municipalities for practical application. Continuous calibration and refinements of the model will be undertaken as necessary, with the aim of improving the accuracy and efficiency of the RLP algorithms. This ongoing effort seeks to minimize the load restriction period while ensuring the necessary protection and maintenance of infrastructure.

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