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Spring load restriction methods: A comprehensive review

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ABSTRACT

In cold regions, the seasonal freeze–thaw cycles constitute a significant challenge for pavement, leading to structural impairments and diminished long-term performance. During winter, the frozen water and ice formations increase pavement stiffness and bearing capacity. However, during the spring thaw, the liquid water above the frozen layer can be trapped by the impermeable frozen soil. This leads to a reduction in soil shear strength and pavement bearing capacity, resulting in deformations and damage to the roads. To mitigate these costs, Spring/Seasonal Load Restrictions (SLRs) policies have been implemented to limit axle loads and protect roads during the thaw-weakening. The success of SLR policies depends on an accurate estimation of the start date and duration of the reduced bearing capacity period. SLRs should also strike a balance between minimizing pavement damage and allowing traffic to flow freely as possible. This paper presents a comprehensive review of the existing SLR practices ansssociated with their underlying mechanisms and different categories. SLR practices in Northern America are also summarized to evaluate the industry standards. In-depth discussions are added at the end based on this review to highlight the knowledge gaps and drawbacks of the current state of the practice.

Introduction

The occurrence of seasonally frozen ground is observed in 51 % of the land area located in the Northern Hemisphere[29]. The freeze–thaw seasons in these areas are detrimental to long-term pavement performance and impose significant costs on the economy[46,47,51,60,64]. In early winter, i.e., freezing season, the in-situ pore water[10]and water sucked from deep locations in the pavement structure and subgrade soils freeze[11,70,71], which can temporarily increase stiffness and the load bearing capacity[80,81,131]. In the following thawing stage in spring, thawing starts from above and below the frozen layer. The resultant liquid water above the frozen layer may be trapped in the thawed layer, sandwiched by the above pavement and the below impermeable frozen soil[6,13,27,34,38,130]. The soil then becomes temporarily saturated with water with high pore water pressure, which reduces the shear strength of the soil. The loss in shear strength disables the soil to support the above pavement, leading to thaw-weakening[127]. The bearing capacity suffers significantly under these circumstances, and the pavement becomes susceptible to structural damage and deformations [42,58].

The AASHTO research program in the U.S. estimated that 60 % of annual distress occurred in the springtime when the relative amount of traffic was 24 %[142]. Paved roads with thin overlays may lose more than 50 % of their bearing capacity during the spring thaw, whereas gravel roads, built without sufficient base course thickness, may lose 70 %[56]. Under such conditions, the absence of proper support from underneath can lead to permanent cracks and structural damage when heavy freight vehicles traverse the road[88]. Such issues are especially obvious in secondary (low-volume) roads, e.g., county roads, city streets, and farm-to-market roads[11].

This infrastructure damage caused by the thaw weakening prompted state and local government agencies to adopt a proactive strategy to mitigate these costs. An example of such efforts is Seasonal (or Spring) Weight (Load) Restriction (SWR or SLR) practices, which limit the axle loads. SLRs have been widely adopted in the U.S. to protect the roads and the local economy. SLR practices consider the variation of road-bearing capacity in freeze–thaw seasons, especially thaw-weakening during the annual spring thaw and strength recovery period[149].

Despite the widespread adoption of SLR policies and their proven role in mitigating road damage and economic losses, the literature

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remains fragmented, focusing on specific regions or methods without a unified synthesis. Moreover, advancements in predictive technologies, data analytics, and the evolving impacts of climate change on freeze–thaw cycles necessitate an updated and thorough review. Current studies fail to adequately address these developments or offer practical recommendations for improving policy outcomes.

This review addresses these gaps by synthesizing SLR practices, examining their mechanisms, methodologies, and regional adaptations. It aims to consolidate current knowledge, highlight best practices, and identify knowledge gaps. By focusing on emerging technologies and future challenges, this review seeks to support policymakers and engineers in enhancing the resilience of road networks in cold regions.

SLR Policies in Cold Climate Countries

Overview

One of the biggest indicators of pavement performance is its bearing capacity[20,67–69]. During winter, stiffness increases due to ice formations that bond soil particles. This is not critical in a structural sense since the overall bearing capacity of the pavement increases, leading to Winter Weight Premium (WWP) practices. In spring, however, thawing ice can saturate the soil and decrease its bearing capacity significantly. The spring thaw is followed by a period of gradual recovery, which depends on soil type, frost depth, water content, and drainage conditions [28,59,85]. Therefore, the reduced bearing capacity period consists of spring thaw followed by the strength recovery period[95,98,101,102]. SLR policies aim to estimate the start date and duration of the reduced bearing capacity period.

Countries such as the United States, Canada, Norway, Sweden, Finland, and France utilize SLR policies to mitigate spring-thaw road damage and extend road lifespan [76,110,113,115,117,122]. These policies, which are critical for balancing damage prevention with traffic flow, vary in implementation and impact[72,76]. A World Bank report indicated SLR resulted in significant cost savings in Europe. The United States typically enforces SLR for 8 weeks or more starting in late February or early March, while Canada focuses SLR on non-primary highways. France, after a costly winter in 1962—1963, established weight limits between 3.5 and 9 tons for road safety. Finland achieved $25 million in savings in 1998 with its SLR approach [56]. Norway removed SLRs in 1995, investing in road maintenance instead. Sweden bases its SLR decisions onroad behavior analysis and frost depth measurements, closing specific roads during the thaw period.

Enforcing premature SLR policies imposes unnecessary economic costs on carriers and shippers due to additional distances traveled or reductions in truckloads, while late SLR enactment leads to pavement damage[76]. Since the first SLR enactment in Minnesota in 1937, SLR practices have been continuously developed. Typical SLR practices can be grouped into three categories: fixed dates, observations such as water seeping out of cracks and rutting, and quantitative methods. The quantitative methods can be further classified into six categories: (1) frost tube monitoring – SLR is set on and off according to critical depths, (2) temperature measurement with thermistors/thermocouples, (3) moisture measurement from Time Domain Reflectometry (TDR) or Frequency Domain (FD) sensors, (4) deflection that calculate the stiffness of pavement and subgrade using Falling Weight Deflectometer (FWD) or Light Weight Deflectometer (LWD), (5) Freezing/Thawing Index or other weather data, i.e., air/pavement temperature or freezing/thawing indices calculated with the temperature to analyze the accumulation of freezing or thawing in the pavement and subgrade [148,12], and (6) mechanistic models, e.g., MEPDG [64], CHEVRON (Everseries)-USDA/FS, UNSAT-H (RC1619) and ECIM/Clarus Initiative[36]. The current state of the practice will be discussed in the following sections.

Canada

In this section, details of SLR regulations in the provinces of Canada are presented in Fig. 1, which is mainly based on the fixed dates and frost tube monitoring to determine the implementation and removal of SLR. The province of Alberta has a network of 70 frost probe stations that use frost probes/tubes to monitor frost and thaw depths throughout the province. In Alberta, SLRs are weather-dependent and are imposed when the thaw depth reaches 25 cm. Also, the government of Alberta publishes a road ban list each year for major highways and restricts the axel weights to 75 % or 90 % of normal permitted values[4].

The province of British Columbia has an SLR program that divides this province into 28 regions with different road and weight restrictions. British Columbia uses 91 frost probe stations that measure pavement surface temperature and temperature beneath the road surface to forecast the pavement's strength loss during periods of extended thawing, primarily in the spring season [137]. The province of Manitoba publishes a SLR policy each year based on the data from the previous year. The Manitoba SLR policies divide this province into four climate zones and post-fixed start and end dates for each of them. These dates are presented in Table 1. Manitoba has two restriction levels based on the type of road and reduces the axle loads from 90 % (level 1) to 65 % (level 2) of maximum allowable weights.

The province of New Brunswick also uses fixed dates to impose SLR policies. In northern New Brunswick, SLR policies come into effect on March 8th and continue until May 23rd. In southern regions, the SLR period is from March 1st until May 16th. Legal axle weights are also published each year to denote roads that are exempt from these policies and the axle load limits for the roads that are not exempt [20].

The province of Nova Scotia divides the counties into two groups for SLR purposes and offers its website app that provides a graphic representation of the seasonal restrictions on all provincially-owned roadways. For both groups, the SLR begins on February 27th, but depending on the county, it lasts until April 17th or May 1st. This policy also exempts some roads from the SLR policy [125]. The province of Ontario divides its roads into three schedules with fixed start and end SLR dates [109,114]. All schedules start on March 1st, the first one ends on April 30th, the second one ends on May 31st, and the third one ends on June 30th [103].

The government of Quebec divides this province into three thaw zones with fixed SLR dates presented in Table 2 [110]. Depending on changes in weather conditions, the start and end of the load restriction period can be moved ahead or postponed. This ensures the road network's protection during periods of reduced bearing capacity.

In Saskatchewan, road restrictions are implemented starting from the first week of March, initially affecting the Southwest regions. This is subsequently expanded to encompass the remaining areas over two to

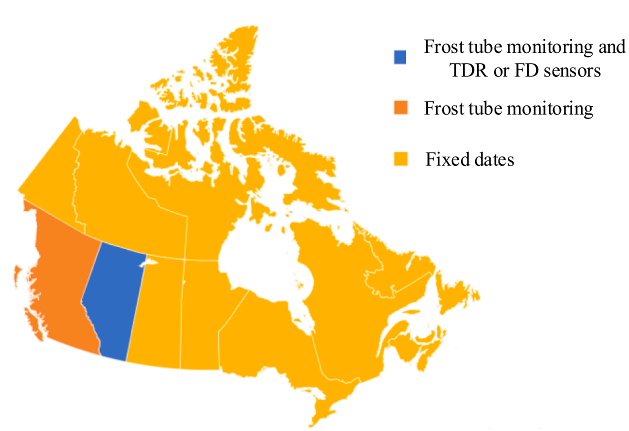


Fig. 1. Seasonal weight restriction policies in Canada.

Table 1
SLR dates for the province of Manitoba.

Climate Zone	Earliest Start Date	Latest End Date
1A	March 1	May 29
1B	March 6	May 31
2	March 6	May 31
3	March 12	June 10

Table 2
SLR dates in Quebec.

Thaw Zone	Earliest Start Date	Latest End Date
1	March 4	April 12
2	March 18	May 10
3	March 18	May 17

three weeks. During the restriction period, which lasts until the end of June, updates on road restrictions are issued by the government every Tuesday and Friday [50].

United States

Fig. 2 shows the SLR practices in the United States. Maine Department of Transportation (DOT) has 5 regions and has transitioned from traditional visual observations to using a statewide model based on the Cumulative Freezing Index (CFI) and the Cumulative Thawing Index (CTI) to determine SLR dates. Besides, Maine DOT developed a freeze–thaw chart that helps district engineers determine when to impose and lift SLRs. The district engineers also rely on experience and judgment for removing weight restrictions. This means that although imposing SLRs is based on CTI indices, visual observation, and CTI indices are used together to decide the most appropriate and business-friendly times for lifting the restrictions.

New Hampshire is also divided into six districts. SLRs are most common in four of these districts, i.e., districts one through four. Each district decides on the frost laws in their jurisdictions based on visual observation and experience. The restrictions are mostly placed on a list of unbuilt roads that are visited each year by the district engineers who look for signs of spring thaw, such as water coming out of the cracks. The restrictions are lifted when the engineers decide that drainage conditions have improved.

The states of Massachusetts, Rhode Island, New York, and Vermont do not have statewide SLRs. However, municipalities can decide to impose restrictions within their jurisdictions.

Illinois does not have state-wide weight restrictions, but the state allows counties to post restrictions between January 15 and April 15. It is up to the counties to decide what methods they use to determine SLR dates. The usual techniques used are visual observations, weather forecasts, and field tests, i.e., auger for frost depth, to decide if a road should be posted. The most prevalent method used, however, is visual observation.

In Wisconsin, a webpage has also been developed to convey SLR policies for five regions of the state (WisDOT). SLRs take effect typically from early March until the second week in May and are based on the load and road types [144]. Similar to the Michigan Department of Transportation (MDOT), WisDOT's SLR program uses temperature forecasts, frost and thaw depths, and Road Weather Information Systems (RWIS) stations to determine SLR dates based on the modified version of the Minnesota Department of Transportation (MnDOT) model for use in Wisconsin [35,145].

Michigan has adopted one of the most intricate and innovative solutions by investing in RWIS and improved freeze–thaw models to predict pavement conditions. MDOT utilized a web-based tool, i.e., MDOTSLR, that automatically draws data from ground temperature sensors, frost tubes, and weather stations to generate site-specific freeze–thaw index values to assist SLR decision-making [82,92]. It is worthwhile to point out that the MnDOT and MDOT efforts, which employed real-time field data and web-based apps, represent the most cutting-edge SLR practices in the U.S. and the world.

The state of Minnesota is also divided into 6 zones and there is a 3-day advance notice policy to post road restrictions. Therefore, the SLR start date is determined using measured and 3-day forecasted air temperatures when it is indicated that the CTI will exceed 25°F degree-days and longer-range forecasts indicate continued warmth. The SLR end date is determined using frost depth, forecasted daily temperatures, and soil moisture content[33,97].

North Dakota DOT (NDDOT) uses a combination of temperature probes in the base layer, temperature forecasts, and FWD to determine SLR dates. When low daily temperatures approach 32 °F (0°C) and high daily temperatures reach the upper 30 s°F (−1.111 °sC) to 40 s°F (4.444 °sC), road restrictions are planned. FWD measurements are combined with long-range weather forecasts and moisture conditions to provide the basis for lifting SLRs[100].

South Dakota DOT monitors daily high and low temperatures, calculates CTI and CFI, and relies on visual observations and experience of its field personnel to determine SLR start and removal dates[126]. The highway maintenance authorities may decide to restrict roads based on the mentioned criteria between February 15 to April 30.

Idaho Transportation Department (ITD) has an elaborate SLR

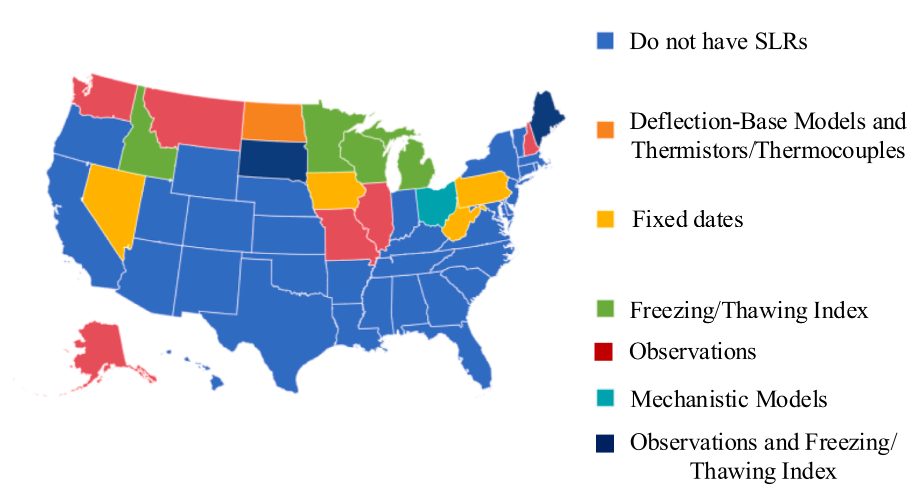


Fig. 2. Seasonal weight restriction practices in the USA.

program based on CTI indices. ITD limits individual axle weights and speed during spring thaw and has a 3-day notice period. ITD imposes weight restrictions on the day that CTI is equal to or greater than 25 °F (−3.889°C)-days and is expected to increase in the following 3-day forecasts. The ITD has 4 levels of weight restrictions depending on the amount of moisture, temperature conditions, and the severity of frost heave and breakup[57]. ITD also imposes speed restrictions on the posted roads to further mitigate the damage caused by spring thaw. The decision regarding lifting these restrictions is made by the districts. However, restrictions should last no more than 8 weeks.

Fixed Dates and Observations

Traditional methods like fixed dates and observations count on engineers' experience and visual inspections in situ. Fixed dates are established based on long-term experience. However, due to annual fluctuations in freezing and thawing cycles, potential damage may still occur despite these precautions[39]. Conversely, these fixed dates may sometimes lead to unnecessary restrictions, even when conditions are conducive to driving activities without causing harm to the roadways. Although simple to implement, the fixed dates category presents a challenge. In contrast, observations involve field personnel actively monitoring the roads for signs of deterioration, such as water seepage from cracks, and other indicators of pavement distress. These methods also allow for the detection of more severe damage, including significant rutting, cracking, or the disintegration of asphalt. The primary limitation of observation is that it often results in the recognition of the problem only after the damage has already been inflicted on the pavement. Additionally, most states in the U.S. and Canada require three to five days' notice before applying SLRs which exacerbates this issue[95].

For example, the SLRs in Maine were placed based on visual observations such as water pumping from cracks or roadway frost deformation[88]. As summarized in the classic report of Mahoney et al. [86], many agencies initiated limits based on judgments, which could range from evidence of water at the surface (indicating a saturated base) to signs of cracking (which is too late) or simply rely on an established date. Due to these reasons, more and more agencies are switching to or planning to switch to quantitative SLR decision algorithms from traditional methods like fixed dates and observations.

Quantitative SLR Methods

This section introduces quantitative SLR methods that employ various technologies and data analysis models to make predictive assessments of pavement condition, incorporating measurements of frost depth, soil temperature, moisture content, pavement deflection, and weather indices. By quantifying the critical factors that affect pavement strength during thaw cycles, these approaches enable more precise management of SLRs, potentially reducing both road damage and economic costs associated with overly conservative or delayed SLR applications.

The foundation for some of the approaches often lies in heat balance principles, such as the Saarelainen heat balance equation [122], which models the energy fluxes and phase changes in seasonally frozen soils. This equation accounts for thermal gradients, moisture migration, and latent heat exchanges, providing insights into the timing of thaw initiation and recovery. By integrating such theoretical frameworks, researchers can accurately predict critical transitions in soil shear strength and bearing capacity, ensuring the timely imposition and removal of SLRs.

The general idea for the quantitative SLR methods is that the SLR placement corresponds to the time when the continuous thawing starts in the subgrade soils[10], which is illustrated by the grey square (Fig. 3). This moment signifies when the bearing capacity of the pavement begins to diminish, necessitating the implementation of SLRs to prevent damage. Conversely, the SLR removal should take place after the thawing depth meets the freezing depth in the thawing season, i.e., the black square. The SLR placement and removal was also adopted by Chapin et al. [25].

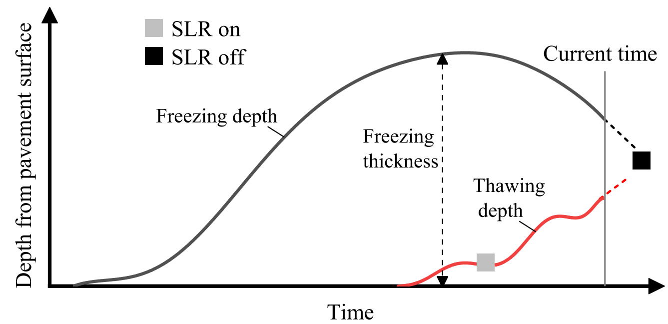


Fig. 3. SLR decisions based on freezing/thawing depth predictions.

Frost Tube Monitoring

Frost tubes are used to directly determine the freezing and/or thawing depth[146]. The freezing or thawing depth is used to determine when to apply load restrictions and to determine their duration. Michigan DOT measures soil freezing and thawing manually using frost tubes installed throughout the state. Frost tubes are embedded in the ground and filled with a solution that changes color when it freezes and returns to its original color when it thaws[92], as shown in Fig. 4. The color changes in the solution correlate well with the phase changes of the porewater in the surrounding soils[89]. The tubes are checked periodically to determine how far down-freezing temperatures have penetrated the soil. By filtering through vast amounts of data, engineering models are developed to better predict pavement and subsoil conditions and changes. Backed up by data from frost tubes and other indicators, these models assist in determining the optimal dates for placing and lifting SLRs anywhere in Michigan[92]. Specifically, the initiation of SLRs aligns with the onset of continuous thawing in the subgrade soils, marked by a significant indicator as shown in Fig. 3. The cessation of these restrictions is advised once the thawing depth equates to the freezing depth during the thawing season.

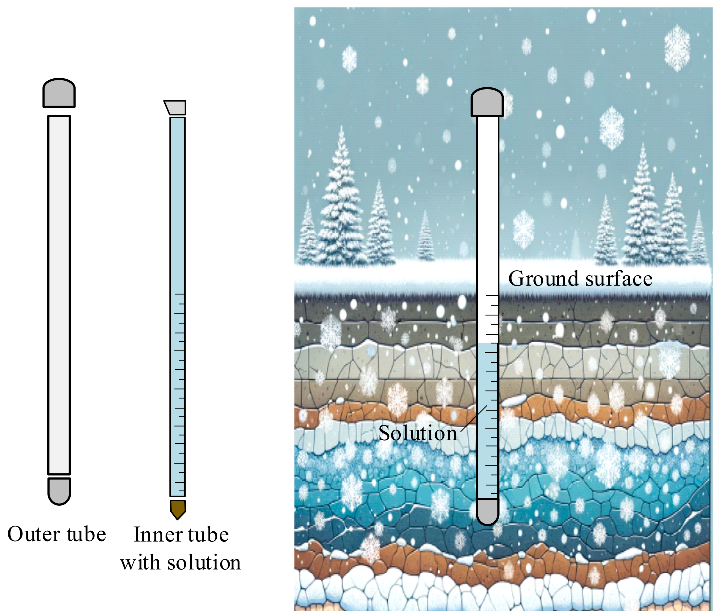
Temperature Measurement with Thermistors/Thermocouples

From the temperature data collected by thermistors or thermocouples, freezing and thawing depths can be inferred and SLR dates can be determined similar to the methods using frost tubes. Although other methods like infrared thermography and fiber optic sensing exist, thermistors and thermocouples are widely used due to their reliability, cost-effectiveness, and suitability for localized freeze–thaw monitoring. Barcomb [14] carried out a test in northwestern Montana, Canada, focused on determining the critical temperature at which thawing begins. The temperature at which thawing starts was found to be around 31.7 °F (−0.2°C). Data from individual sensors on a thermistor string were aggregated to produce a weighted average. Graphs of these average readings from individual installations were used to easily identify warming trends. By applying a trend line to the temperature plots and extending it to the thaw point, an estimate for the onset of thawing at the site could be made. These interpreted trends, along with weather forecasts, were used to predict when break-up would occur. The decision to restrict a section of road was made when one or more strings indicated thawing temperatures at the sensor just below the asphalt pavement.

Moisture Measurement from TDR or FD Sensors

TDRs are used to monitor the moisture content in pavement layers

(a)



(b)

Fig. 4. Frost tube placed in the ground: (a) in-situ test picture in Wisconsin (https://www.wearegreenbay.com/weather/beyondtheforecast/wisdot-uses-frost-tubes-to-help-determine-frozen-road-declarations/); and (b) schematic picture.

[53]. The real-time moisture content data from TDRs and the development of precise local models could be used to determine the start and end dates of SLRs. These models take into account moisture dynamics within the pavement structure, allowing for more accurate predictions of when pavements are most vulnerable to damage and when SLR should be implemented to mitigate these risks.

Although other methods such as neutron probes and dielectric sensors are available, TDR and FD sensors are emphasized due to their widespread use, ability to provide real-time data, and suitability for localized monitoring in pavement layers. Asefzadeh et al. [8] conducted a test in Edmonton, Alberta, Canada, using the fully instrumented integrated road research facility (IRRF) test road. Time domain reflectometers (TDRs) are utilized to collect real-time data on the variation of moisture content within the pavement layers, particularly the subgrade, to determine the SLR.

Deflection-Based Models

In this sub-section, different deflection-based models for pavement performance evaluation are explored. Resilient modulus is a common metric for evaluating the bearing capacity of soil under freeze–thaw cycles and its stiffness. Researchers have tried to measure the loss of strength in different soils during spring thaw or after freeze–thaw cycles. For example, Simonsen et al. [131] studied five different soils under freeze–thaw cycles and observed that the resilient modulus of these soils decreased by 20 %-60 %. The lower bound of this range belongs to the coarser soils with fewer fine particles, i.e., gravelly sand, and the upper bound belongs to fine sands. Johnson [61] conducted laboratory-resilient modulus tests with silty soils during freeze–thaw cycles. These tests measured resilient modulus as low as 2 MPa in the thaw period and 100 MPa after full recovery, meaning that the resilient modulus can decrease to 1 %-2% of its original value. Cole et al. [37] and Berg [15] reached similar conclusions when they studied freeze–thaw effects on soils: the resilient modulus increased by two or three times after the soil recovered, and the recovery process can be modeled using soil moisture. To develop new SLR models in practice, the stiffness or bearing capacity of pavement is estimated using load tests such as FWD or LWD. The next section discusses these models.

Falling Weight Deflectometer (FWD)

Field testing could provide highly credible data, as it reflects real-world conditions and ground behavior under actual load scenarios [32,78,79]. Studies have shown that FWD is the most effective non-destructive test for deflection measurements[41]and can be used on all pavement types[133]. FWD is a diagnostic tool used to evaluate the structural integrity and performance of pavement by simulating the impact of vehicle loads on the road surface. As shown in Fig. 5, FWD operates by dropping a known weight from a specific height onto a pavement surface and measuring the deflection (bending) of the pavement under this load. This non-destructive testing method provides valuable information about the pavement's load-bearing capacity and the stiffness of its materials, including the subgrade and base layers. Many studies indicated that FWD is superior to other tests in simulating the moving wheels of a vehicle due to its transient impulse load [31,84,87,134]. Moreover, the measurements are based on the actual pavement response and various loads can be applied to evaluate the stress–strain models[44,104]. Due to these advantages, FWD has been frequently utilized to measure the structural capacity of pavements during the spring thaw.

For example, Bilodeau and Doré [18] used FWD on two road sections to monitor spring thaw and the evolution of pavement response in this period. These two sections had similar structures except for the asphalt concrete thickness of 100 mm and 200 mm. The results showed that only 1–2 % of the damage happened in the winter and the rest happened during spring and summer. Also, fatigue damage happened three times faster for the thinner pavement and the final fatigue damage was 31 % higher for this pavement. In a different application, Park and Kim [106] employed FWD to develop a predictive model for the remaining life of flexible pavements.

Although FWD offers several benefits for evaluating the structural capacity of pavements during spring thaw it also suffers from notable drawbacks. Firstly, the lack of predictive values during the rapid occurrence of spring thaw limits its effectiveness meaning that several tests are needed for each section of the road at different times[147]. Secondly, FWD measures the deflections at a specific point, and complex soil structures and special variability undermine its reliability. Thirdly, the accuracy of the back-calculation procedure from deflection measurements to pavement moduli is contingent on pavement thickness [107], which is not always available. Finally, the most significant drawback of FWD is that it is heavy equipment that is expensive to operate and requires regular calibration and maintenance to mitigate systematic errors[55]. These limitations render FWD inappropriate for direct application in SLR policies and underscore the need for alternative models that can leverage the advantages of deflection-based models while addressing the challenges mentioned above. Two alternative approaches are available for this purpose: modified versions of FWD that are lighter and more portable, and the use of FWD correlations with more readily available measurements such as temperature and moisture for SLR policies. The following two sections elaborate on these two approaches in detail.

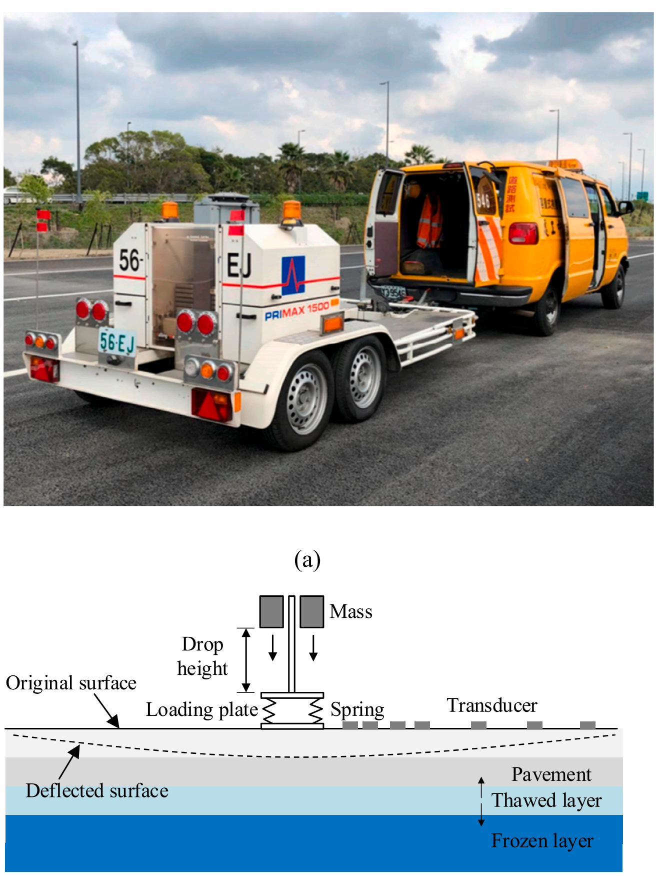


Fig. 5. Falling Weight Deflectometer: (a) in-situ pictures[73]and (b) schematic description of FWD.

FWD Alternatives

Researchers have conducted investigations into the viability of substituting the FWD with simpler and more accessible tests. Some potential alternatives for this purpose include Portable/Light Falling Weight Deflectometers (PFWD/LFWD) or Dynamic Cone Penetrometers (DCP)[132]. Light Weight Deflectometer (LWD) or Light Falling Weight Deflectometer (LFWD) are portable and lighter versions of FWD with smaller impact loads and shallower depths of influence[118]. LWDs have been frequently used as a readily available and easy-to-operate alternative for FWD, especially on low-volume roads[62]. DCP is another popular test due to its simplicity, repeatability of results, low cost, and the ability to provide a continuous measurement of soil strength with depth[21]. Studies have used DCP, LWD, or a combination of them to estimate the resilient modulus and bearing capacity of pavements.

For example, Vuorimies et al. [140] compared the results of DCP, FWD, and LFWD on ten sites between 2012 and 2013. The results showed that there is a threshold *E* modulus measurement for each model, below which the risk and rate of rutting per path increase significantly. The authors concluded that these thresholds could offer a more accurate for the bearing capacity and trafficability of the road if complemented by visual observations and weather forecasts. Kaakkurivaara et al. [63] conducted a similar study to compare DCP, FWD, and LFWD measurements for different roads and moisture conditions. This study was carried out on 35 roads during four years. According to the findings of this study, the use of portable devices such as PFWD/LFWD and DCP may result in overestimations of pavement stiffness. However, the study also revealed that meaningful correlations could be established between the results of these portable tests and those obtained from FWD. Consequently, regression models were constructed to establish relationships between the measurements obtained from different testing devices. The correlations were strong on the wheel path and moderate on center lines. Furthermore, the correlations were better for mineral subgrades compared to peat subgrades and it was concluded that the thickness of the aggregate layer must be added to the regression models to achieve comparable accuracy for peat subgrades. Another important conclusion is that LFWD is suitable for measuring the stiffness of the road surface layer, which is an important aspect of LFWD investigated by many researchers. Although there is not a unanimous agreement on the exact influencing depth of LFWD, estimates mostly fall between 1 [48,129]to 2[99]times the diameter of the loading plate depending on the LFWD designs, static/dynamic loading, and material properties[136].

DCP has been used in studies to determine different characteristics of soil, such as shear strength[9,112], resilient modulus[123], or California Bearing Ratio (CBR)[49,150]. Moreover, some researchers have investigated the relationship between DCP with more refined tests. For example, Abu-Farsakh et al. [1] compared elastic moduli of DCP with FWD and Plate Load Test (PLT) for different materials in field and laboratory tests. They obtained strong empirical correlations between the

DCP resilient modulus and that of FWD, i.e., $R^2 = 0.91$, and good correction between initial and reloading elastic moduli of PLT and DCP, i.e., $R^2 = 0.67$ and $R^2 = 0.78$, respectively. These PLT results are compatible with those estimated by [69]. Another example is a study by Chen et al. [30] that compared the results of 198 DCP and FWD tests and found a correlation for the estimated elastic modulus. The results were promising and were only 10 % and 1.7 % off from Powell et al. [109] results for penetration rates of 10 mm/blow and 80 mm/blow, respectively. Although these FWD alternatives address most of the drawbacks of the FWD test, i.e., enhanced portability and affordability, their automation potential is low. This limitation implies that the tests mentioned above still require human operators and cannot be readily automated through the use of instruments such as thermistors or frost tubes.

Correlation-Based Models

Correlation-based models are developed in three steps. Firstly, a case study is conducted that involves a bearing capacity test, e.g., FWD or other load tests[3], and one or more performance indicators, which are readily available measures such as subsurface temperature. Secondly, the bearing capacity results are analyzed to determine the optimal date for initiating SLR. Finally, a regression analysis is performed to obtain a model that establishes correlations between the bearing capacity and the performance indicator. The process of developing the above models often involves a monitoring and calibration process that links an actual bearing capacity measure to a more accessible and easily measurable performance indicator[93,135].

Salour and Erlingsson [124] studied the spring thaw effect on a 100-mm hot mix asphalt course on a gravel base and a sandy gravel subbase. They used moisture probes, frost rods, and groundwater level rods to monitor the pavement. The FWD was conducted using a 50 KN load pulse on a 300-mm diameter plate. They observed a significant decrease in the unbound layer stiffness, with a 63 % reduction in the subgrade and a 48 % reduction in the granular layer. Finally, they used the collected data to develop a moisture-stiffness model for the granular layer and the subgrade, providing a model that predicts stiffness based on a more accessible measurement, such as temperature. Another example is Calhoon et al. [22] who studied the correlation between pavement performance and seasonal moisture variation using Falling Weight Deflectometer (FWD) and Ground Penetrating Radar (GPR). They observed significant reductions in pavement stiffness during spring thaw and validated the strong correlation between GPR-based moisture measurements and FWD-derived structural capacity parameters. While they did not develop a predictive model, their findings support the use of GPR as an efficient tool for monitoring seasonal moisture fluctuations and identifying critical sections for FWD testing.

Models Based on the Freezing/Thawing Index

Several agencies in the U.S. and Canada have performed research for applicable roadway monitoring and SLR practice[45,54,90,96,146]. Such efforts are generated primarily based on the freezing/thawing indices, which have been successfully adopted by state DOTs: (1) FHWA-Washington State DOT (WSDOT) model, (2) Minnesota DOT (MnDOT) model, (3) MIT model, (4) South Dakota DOT (SDDOT), and (5) USDA-NHDOT. The comparison of different models for calculating freezing and thawing indices using real data are as shown in Table 3.

FHWA-WSDOT Model

The FHWA-WSDOT model[86,119]is one of the first quantitative SLR decision algorithms based on freezing and thawing indices. Before this model, field personnel would determine the location, time, and duration of SLRs based on air temperature. The load restrictions in this model are between 40 % to 50 %[120]. The reports suggested that surface thickness, moisture conditions, and subgrade type are also important to consider. Therefore, the location of the SLR policies was selected based on these criteria[118]. They also reported that surface deflection data can be a useful measure and spring deflections greater than 45–50 % of summer deflections indicate the need for SLRs. Despite this, the authors opted for a more straightforward measurement that is widely available, i.e., air temperature. This is due to the limited availability of deflection measurement equipment.

This model directly estimates the SLR duration (days) for fine-grained soils using the following equation[86,119]:

$$\text{Duration} = 25 + 0.01\,(FI)$$

where TI is estimated from a regression equation,

$$TI \simeq 0.3\,(FI)$$

MnDOT Model

The MnDOT model[105,139]is an adaptation of the WSDOT model and provides an alternative for predicting the beginning and duration of the spring thaw period. The MnDOT model was developed from case studies of fifteen flexible road sections and is based on actual and forecasted air temperature. This report found a major drawback in the SLR practices at the time: there was typically a week or more delay in SLR enactments from when they should have been posted. The authors of this report argue that each day of delay in SLR implementation is equivalent to damages caused by 28 days of reduced loads at the end of SLR. Therefore, this model is primarily focused on estimating the best SLR initiation dates, and the duration of SLR is fixed at 8 weeks. It was observed that the equation that WSDOT developed for the thawing index predicts thawing too late for Minnesota. The solution was to adopt a floating reference temperature that adjusts dynamically based on the current date. Specifically, the reference temperature, T_{ref} is 32 °F (0°C) during January. In February, the reference temperature is decreased by 2.7 °F (−16.28°C) during the first week to account for the solar gain, followed by a weekly decrease of 0.9 °F (−17.28°C) thereafter. This approach ensures that the reference temperature remains in sync with the current weather conditions. The MnDOT model recommends SLR initiation when the three-day weather forecast indicates that the CTI will

Table 3
Comparison of models based on the freezing/thawing index.

Model	Key Feature	Calculation Basis	Advantages	Disadvantages
FHWA-WSDOT	Quantitative SLR decision based on freezing/thawing indices	Air temperature	Straightforward, uses widely available air temperature data	Limited by availability of deflection measurement equipment
MnDOT	Adapts reference temperature to current weather conditions	Actual and forecasted air temperature with dynamic reference temperature	More accurate start dates for SLR, accounts for solar gain	Fixed duration of SLR may not be suitable for all conditions
MIT	National model in Canada, adapts to climate change	Pavement strength with FWD correlated with CTI	Considers changing climate, uses FWD for pavement strength	Requires FWD for pavement strength assessment
SDDOT	Simple model based on min and max air temperatures	Minimum and maximum air temperatures	Effective for identifying thaw periods, simple to use	May not be as accurate without calibration
USDA-NHDOT	Estimates pavement temperature from air temperature using Summer and Winter n-factors	Air temperature with sinusoidal adjustments	Accurate for determining SLR start dates, includes sinusoidal temperature adjustments	Modified Berggren equation may be less accurate than other models for SLR removal

surpass 25 °F (−3.889°C)-days, and extended forecasts predict continued warmth. The CTI can be calculated for any given day using:

$$CTI_n = \sum_1^n (\text{Dailly Thawing Index} - 0.5 \times \text{Daily Freezing Index})$$

Where Daily Freezing and Thawing Indices (DFI and DTI) can be obtained based on maximum and minimum daily temperatures, i.e., $T_{\max}$ and $T_{\min}$, from three possible scenarios:

1. When $\left\{\frac{T_{max}+T_{min}}{2} - T_{ref} < 0^\circ \mathrm{F}\right\}$ and $\left\{CTI_{n-1} \leq 0.5 \times (32^\circ \mathrm{F} - \frac{T_{max}+T_{min}}{2})\right\}$
2. ⇒ Significant thawing has not yet occurred ⇒ DTI = 0 °F −days, DFI = 0 °F −days
3. When $\left\{\frac{T_{max}+T_{min}}{2} - T_{ref} > 0^\circ \mathrm{F}\right\}$
4. ⇒ Thawing in progress ⇒ DTI = $\frac{T_{max}+T_{min}}{2} - T_{ref}$, DFI = 0 °F-days
5. When $\left\{\frac{T_{max}+T_{min}}{2} - T_{ref} < 0^\circ \mathrm{F}\right\}$ and $\left\{CTI_{n-1} > 0.5 \times \left(32^\circ \mathrm{F} - \frac{T_{max}+T_{min}}{2}\right)\right\}$
6. ⇒ Pavement is refreezing ⇒ DTI = 0 °F-days, DFI =$32^\circ \mathrm{F} - \frac{T_{max}+T_{min}}{2}$

where CTI_{n-1} is the cumulative thawing index for the previous day.

MIT Model

The MIT model[19]developed by the Manitoba Department of Infrastructure and Transportation (MIT) is a national model in Canada for starting and ending SLRs. The authors believed that the fixed dates that are based on historical data are not adequate due to the changing climate of Canada, which resulted in shorter and warmer winters[19]. This model determines the pavement strength with FWD and correlates it with CTI. The SLR policies start when CTI reaches 59 °F (15°C)-days and ends 56 days later or when CTI reaches 662 °F (350°C)-days. MIT uses the following definition of CTI[43]:

$$CTI = \sum \textit{Daily Thawing Index} = \sum [T_{ref} + \frac{T_{max} + T_{min}}{2}]$$

where $T_{\text{ref}} = 35.06$ °F (1.7°C) starting March 1 and increases by 32.108 °F (0.06°C) per day until May 31 (32 °F (0°C) from June through February in the following year).

It is important to note that CTI is never negative in the MIT model, so it will be reset to zero for negative values. Moreover, if $\frac{T_{max}+T_{min}}{2} < 0$, the daily thawing index equation will be modified to $[T_{ref} + \frac{T_{max}+T_{min}}{4}]$.

SDDOT Model

Similar to MnDOT, SDDOT[143] found the air temperature to be an effective measure in identifying thaw periods. Wilson [143] performed a series of field tests and developed a model based on minimum and maximum air temperatures. He also evaluated whether another model, i.e., speed restriction, would be more effective than SLR policies but found that speed restrictions are, in fact, harmful to the pavement. It was recommended in this study to use WSDOT equations for South Dakota as well after calibration [138].

USDA-NHDOT Model

The USDA-NHDOT model [16,64] is based on a USDA study in Minnesota and Ohio which is also tested on two sites in New Hampshire and Vermont[16]. The air temperature was used alongside Summer and Winter n-factors were applied to FI (Freezing Index) and TI (Thawing Index) to estimate sinusoidal pavement temperatures from sinusoidal air temperature [77,83]. The difference between the sinusoidal temperatures of air and pavement was then used to estimate the pavement temperature from air temperature measurements. It was found that this model is accurate for determining SLR start dates in New Hampshire. For SLR removal, however, it was found that the Rutherford et al. [119] model was more accurate than the proposed Modified Berggren equation [5].

Mechanistic Models

Enhanced Integrated Climatic Model (EICM).

EICM [74] is a one-dimensional heat and moisture flow climatic finite difference model that was created as part of the Mechanistic-Empirical Pavement Design Guide (MEPDG) by AASHTO[7]. This model is the result of integrating an infiltration and drainage model [116], a climatic material-structure model[40], and a frost heave and thaw settlement model[52]. The inputs of this model are environmental conditions, and the outputs are changes in the properties of the unbound materials. More specifically, this model takes air temperature, precipitation, relative humidity, wind speed, percent sunshine, groundwater table depth, and thickness of pavement layers as inputs and calculates temperature, pore water pressure, water content, frost heave, frost depth, thaw depth, and resilient modulus for the pavement structure [66]. It is noteworthy that the EICM comes with default values that can be used in instances where input data is unavailable. However, it should be emphasized that utilizing these default values can lead to a decrease in the accuracy of the predictions. Additionally, the calculations performed by the ICM are not limited to granular materials; it can analyze various types of pavement and soil systems, accommodating different material properties and configurations.

EICM has been utilized in different studies to evaluate its performance in different climatic patterns and sites. For example, Ahmed et al. [2] evaluated the predictive capabilities of EICM for subsurface temperature and moisture conditions in New Jersey. It was found that no strong and consistent correlation can be found between the predicted and field-measured values. Quintero [111] conducted a similar study in Ohio and concluded that the temperature predictions by EICM were in good agreement with instrument-measured data, whereas the moisture variation data exhibited irregular and poor correlations. Howayek et al. (2016) investigated the impact of soil input parameters on the predicted resilient modulus in four sites in Indiana. The results showed that the water table depth is the most influential parameter and water table depth has no impact on the predicted resilient modulus. In another study, McCartney et al. [91] investigated the EICM model for the state of Arkansas. The results indicated that while head flow predictions were acceptable, pore water pressure predictions were inaccurate.

TEMP/W model

The Finite Element Program TEMP/W, as described in studies conducted by Lakehead University under contract with the Ministry of Transportation Ontario [23,24,26,108], is a two-dimensional finite element software program used to estimate frost and thaw penetration, subsurface temperatures, moisture contents, and ice contents beneath pavements. It is particularly valuable for determining when to place and remove SLRs by utilizing data output from the computer program. TEMP/W requires initial temperature and moisture conditions as well as lower boundary temperatures with time. It can use measured lower boundary conditions or an assumed constant temperature at a certain depth.

In addition to TEMP/W, other finite element methods (FEM) offer robust capabilities for modeling freeze–thaw processes and supporting SLR decisions. The Enhanced Integrated Climatic Model (EICM) is commonly employed within the Mechanistic-Empirical Pavement Design Guide (MEPDG) and integrates heat and moisture transfer simulations to predict subsurface conditions such as frost depth and thaw depth. COMSOL Multiphysics provides a flexible framework for simulating coupled thermal and hydraulic processes with complex boundary conditions, while PLAXIS offers specialized tools for thermo-hydro-mechanical interactions in geotechnical systems. For open-source alternatives, OpenGeoSys (OGS) and FEniCS are particularly noteworthy. FEniCS, for example, allows for custom implementation of governing equations, enabling tailored simulations of frost and thaw phenomena under diverse climatic scenarios. These tools complement TEMP/W by addressing specific needs, offering scalability, and enabling advanced coupling mechanisms for research and practical applications.

Thermo-Hydro-Mechanical (THM) Analysis.

Thermo-Hydro-Mechanical (THM) analysis provides a comprehensive framework for evaluating the interactions between temperature, moisture, and mechanical behavior within pavement structures [12,13,52,80,130,147]. By integrating heat transfer, moisture migration, and mechanical stress–strain relationships, THM models simulate the complex processes that occur during freeze–thaw cycles, including temperature distributions, water content changes, and their effects on pavement performance.

For example, Liu and Yu [80] developed a coupled THM model to simulate frost-induced stresses and moisture migration in pavement structures. These models have been instrumental in providing insights into how water redistribution and frost heave influence the mechanical behavior and structural integrity of pavements, particularly during freeze–thaw cycles. Other studies have extended THM analysis to optimize SLR policies by incorporating localized climatic data and soil properties, thereby improving the accuracy of predictions related to frost depth, thaw depth, and pavement resilience.

Other Models

Several other studies provided nuanced approaches to limit spring thaw damage. For example, Kestler et al. [65] proposed a combination of shortened SLR policies and reduced the tire pressure in the latter parts of the SLR period to increase the pressure area underneath tires which subsequently decreases pressure. Connor et al.[102] developed a decision support system using remote sensing and spatial information technology to collect subsurface temperature data for real-time frost and thaw depth analysis, aiding State Departments of Transportation in timely and efficient road maintenance decisions. This system integrates database design, data collection methods, and technology to automate decision-making during critical spring-thaw periods. Kraatz et al. [72] demonstrated the potential of using Soil Moisture Active Passive (SMAP) satellite data to accurately determine freeze–thaw conditions on roads, offering a promising approach to inform the timing of seasonal load restrictions and improve transportation asset management practices. Another model is Percostation [121]which is a real-time monitoring system based on dielectric value, electric conductivity, and temperature profile. All three of these measurements are utilized to determine the amount of free water in the pavement, i.e., moisture level, and pavement bearing capacity is then estimated based on that[141].

Future Research Directions

Building on the comprehensive review of Spring Load Restriction (SLR) practices, this study identifies several key areas for future research and development to address the knowledge gaps and improve current practices. Current SLR models heavily rely on historical data or simplified indicators such as air temperature and frost depth. Developing machine learning models that integrate multi-source data such as Road Weather Information Systems (RWIS), satellite remote sensing, and Internet of Things (IoT) sensors could significantly enhance prediction accuracy and decision-making for SLR policies. These models can offer more precise, dynamic predictions of thaw-weakening and recovery periods, potentially enabling more targeted and efficient SLR implementations. While this review highlighted the widespread adoption of SLR policies across North America and Europe, significant variability exists in their application due to differences in climate, soil, and road design. For instance, Canada's use of frost tubes and Finland's integration of localized climate data demonstrate the benefits of region-specific approaches. Future studies should explore the customization of SLR models to accommodate local soil properties, drainage conditions, and freeze–thaw cycles, ensuring more accurate and cost-effective decision-making.

The environmental and economic impacts of SLR policies were not deeply analyzed in this study. Future research should aim to quantify the carbon emissions associated with road damage and repair during the spring thaw, as well as the economic costs imposed on freight and transportation industries due to SLR restrictions. Sustainability-focused models that balance infrastructure protection with economic efficiency can provide a more holistic framework for policy-making. This review underscored the importance of accurate monitoring technologies, such as frost tubes, TDR sensors, and FWD measurements. While these methods provide critical data, emerging technologies like remote sensing from Soil Moisture Active Passive (SMAP) satellites or ground-penetrating radar (GPR) could enable real-time, large-scale monitoring of pavement conditions. Research should focus on integrating these technologies into existing frameworks to improve data accuracy and accessibility.

The review acknowledged that climate change-induced variability in freeze–thaw cycles presents a significant challenge to traditional SLR models. Recent studies, including Daniel et al. [39] and Sias et al. [128], emphasized that climate change is altering the timing and intensity of thaw periods, leading to increased road damage and reduced service life. For example, Sias et al. [128] projected shifts in frost-thaw timing across New England using 19 climate models, with a reduction in frozen periods of up to four weeks under RCP 4.5 by the end of the century. Similarly, Basit et al. [17] developed predictive models in Ontario, Canada, incorporating climate change scenarios and found that SLR periods are expected to shrink by 2100. These findings highlight the need for adaptive SLR policies that incorporate real-time climate projections and localized conditions.

Further research should explore how advanced technologies like intelligent transportation systems[98] and real-time monitoring of pavement conditions can support dynamic SLR policy adjustments. The integration of data from sensors, RWIS stations, and remote sensing platforms can provide decision-makers with actionable insights to mitigate risks associated with climate variability. Additionally, there is a need for field validation studies in diverse regions to test the applicability of these models under varying environmental conditions and infrastructure types. Such efforts would improve the generalizability and reliability of SLR practices globally.

By addressing these areas, future research can bridge the gaps identified in this study, advancing the precision and effectiveness of SLR practices. Incorporating sustainability considerations, climate adaptation strategies, and advanced monitoring technologies will ensure that transportation infrastructure remains resilient and efficient in the face of evolving climatic challenges.

Discussion

Although state DOT efforts, such as models and apps from MnDOT and MDOT, have presented state-of-the-art solutions to SLR decision-making, the current SLR practices can be improved further in several key aspects.

First, local adaptation of established models is crucial but usually overlooked. Many county road engineers use the FHWA model, which was developed based on pavement and weather conditions in the state of Washington in the 1980 s and thus can lead to errors ranging from days to months when applied in different locations and weather conditions. Consequently, these errors have significant implications: the load restrictions not only fail to prevent pavement damages, but they also pose additional costs to the economy due to the additional distance traveled or fewer truckloads to comply with the restrictions. These errors have a significant repercussion: although load restrictions limit truck loads and impose costs to the economy, they fail to prevent intended pavement damages. Thus, from a cost/benefit perspective, lifting SLR would be the optimal course of action. Therefore, it would be reasonable to lift SLRs altogether in this scenario.

Second, most SLR decision algorithms have yet to fully harness the potential of data. There is extensive data from RWIS, field measurements, and remote sensing due to the efforts by state DOTs to build up data infrastructures such as RWIS and MDSS; however, most SLR decision-makers still primarily rely on fixed dates for SLR initiation. As we enter the era of data, we must improve the utilization of data to fully leverage its potential.

Third, the performance of pavement structures, especially their frost susceptibility and stiffness variation, is still not adequately considered. Most models including the latest MDOT2019 model still assume without in-depth investigations that SLR starts when the thawing depth reaches a certain depth, e.g., 0 or 4 in., and the pavement structure is the weakest when freezing and thawing depths converge. Many other studies focused on the variation of the pavements' performance with time or temperature via FWD and LWD measurements, but such efforts have not been well integrated into SLR decision-making procedures.

Last but not least, more comprehensive and accurate data from the field is still needed despite data available from various sources, including RWIS. For example, subsurface temperatures from RWIS may be measured at locations far off the road, which cannot reflect the conditions of the base, subbase, and subgrade due to different heat transfer mechanisms caused by pavement layers and snow coverage. It would be beneficial to develop a more customized, accurate, site-specific, and autonomous decision-making support system by improving all the above aspects, especially with a good understanding of the frost susceptibility of pavement structures.

CRediT authorship contribution statement

Muchun Liu: Writing – original draft, Visualization, Resources, Methodology, Investigation, Formal analysis, Conceptualization. **Behnam Azmoon:** Writing – original draft, Formal analysis, Data curation, Conceptualization. **Mohammad Hossein Tavakoli Dastjerdi:** Resources, Methodology, Data curation. **Aynaz Biniyaz:** Software. **Zhen Leo Liu:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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