Alignment of Weight Restrictions on Nine-Month Primary Highways to Mitigate Climate Impacts of Earlier Spring

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ABSTRACT

Saskatchewan's Ministry of Highway and Infrastructure (MHI) has a highway vehicle weight management system to maximize highway infrastructure utilization for economic activities while protecting highways to ensure a longer service life. The provincial highway system is generally managed in three allowed vehicle weight categories: i) Primary highways with year round access, ii) secondary highways that are weight restricted during early spring, and iii) nine-month primary highways that allow primary weight for 9 months and secondary weight for the remaining three spring months. The categories were established according to highway pavements' structure capability to handle vehicle weight. The weight restriction on secondary and nine-month primary highways is mainly to protect these lower standard pavements from spring-thaw damage. The secondary highways are subject to the spring weight restriction based on weather triggers (thermistor data). However, to allow for planning freight operations, the nine-month primary follows a fixed schedule where the weight is reverted to secondary for three spring months every year.

In recent years, spring has been observed to frequently occur earlier than the set date for the nine-month primary highways to revert to secondary weights. The spring road restrictions based on weather has been triggered earlier for the secondary highways. This has caused some noticeable discrepancy in the way the weight restrictions are managed in the spring for highway network. For instance, a nine-month primary highway adjacent to a secondary highway could still be allowing primary loads in early spring, while the secondary highway is already under the spring load restriction. A similar discrepancy arises when the rural municipal roads could allow primary loads in late spring while the nine-month primary highways are still under the mandatory three-month secondary weight reversion. This later start of weight restrictions for nine-month primary highways may also contribute to early pavement failures.

MHI conducted a study to evaluate if the timing of the three-month secondary weight reversion for nine-month primary highways could be changed to align better with early spring-thaw period. Extensive analysis of historical temperature data, historical spring weight restriction dates, and Benkelman Beam Deflection data from various locations in the province was conducted. The study concluded that due to the different geographical and climatic conditions in the province, highways in the south of the province are more vulnerable from early spring-thaw than those in the north. While the current timing of the three-month secondary weight reversion for nine-month primary highways creates an unacceptable risk for highways in the south, they were found adequate for highways in the north. As a result, a new policy has implemented the secondary weight reversion 15 days earlier for nine-month primary highways in the south than in the north.

INTRODUCTION

Significant portions of highways in the USA and Canada have a high vulnerability to natural deterioration mechanisms during early spring (Figure 1). During spring, pavement layers generally are in a saturated, weakened state due to partial thaw conditions and trapped water, which results in increased damage and shorter service life unless the loads are reduced. The load carrying capacity of the road is reduced due to excess moisture from spring thaw. Much of the damage that occurs to the pavement is related to the magnitude and frequency of the load applied and the stiffness of the materials (Ovik, van Deusen, & Siekmeier, 2000). A handful of heavy vehicles travelling on these compromised pavements can inflict comparable damage as that over one entire year (Kestler, Knight, & Krat, 1988).

Spring thaw timing depends on the location of the site, solar radiation, drainage, air temperature, rainfall, soil type, moisture and thermal properties. In general, the pavement thaws from the surface, down. Due to changes in weather during the spring, the temperature of the surface layer begins to rise. This initiates the thawing of the aggregate base layer. For a flexible pavement with fine-grained subgrade, the moisture in the base becomes trapped between two impermeable layers: the asphalt concrete layer and the frozen, fine-grained subgrade layer. Since the excess water cannot drain easily, the base layer decreases in stiffness and is considerably softer during the spring thaw period.

Daily Thawing Index

$$TI_i = \left(\frac{T_{maximum} + T_{minimum}}{2} - T_{reference}\right)$$

Where: TI_i = daily degree days above freezing point (^oC.day)

$T_{reference}$ = reference freezing point air temperature (^oC)

$T_{maximum}$ = maximum daily air temperature (^oC), and

$T_{minimum}$ = minimum daily air temperature (^oC)

Cumulative Thawing Index

$$CTI = \sum_{i=1}^{n} TI_i$$

Where: n = the number of days over which the thawing index is summed over.

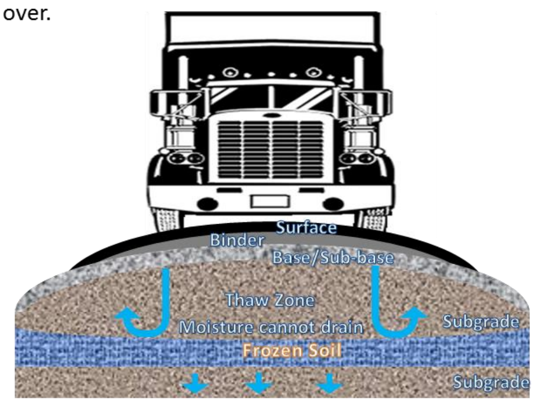

Figure 1: Spring Thaw – vehicle loading is not distributed as per design resulting in deformation and deterioration. The most common measure of when thawing takes place is by calculating the Cumulative Thawing Index as it uses readily available air temperatures instead of in-situ highway measurements (MHI, 2016).

Most jurisdictions around the world, that experience sub-zero temperatures in winter, have some form of weight restrictions applied to protect the highways. In Canada, all provinces and territories have implemented weight restrictions. In Saskatchewan, most secondary highways have a Spring Road Restriction (SRR) imposed based on climatic triggers for the onset of spring (Figure 2). SRRs are placed as a method of protecting the base layer from higher loads during the spring-thaw period.

The critical time for SRR is when the pavement first thaws and the stiffness of the base layer is low. Thus proper measurement and prediction of freeze-thaw events is crucial to a successful weight restriction strategy. The exact time at which load restrictions should be implemented and removed depends on many factors such as pavement structure, soil type, traffic, topography, frost depth, air temperature and drainage conditions. However, for a weight restriction policy to be implemented successfully it must be as simple as possible, yet include the most important factors common to the greatest numbers of roadway miles (Ovik, van Deusen, & Siekmeier, 2000).

Spring Road Restrictions on Secondary Highways

In Saskatchewan, the Spring Road Restrictions (SRRs) for the secondary weight highways are implemented based on recommendations made by district operations managers. There are fifteen districts in the province – Buffalo Narrows, La Ronge, Meadow Lake, Prince Albert, Tisdale, Yorkton, North Battleford, Saskatoon, Wynyard, Kindersley, Carlyle, Swift Current, Moose Jaw, Regina, and Weyburn. Based on local climatic conditions, each of these districts can have a different start date for the SRRs.

The SRRs are implemented through ministerial orders and communicated through MHI's Highway Hotline. Ideally, longer SRRs will provide better protection for pavements. However, longer SRR will be inconvenient for economic activities and increase transportation costs, which may not be acceptable. It is very important to start the SRRs at the right time, since the SRRs only last for six weeks in Saskatchewan. To start the SRRs too early or too late will likely miss part of the time when the highways require protection.

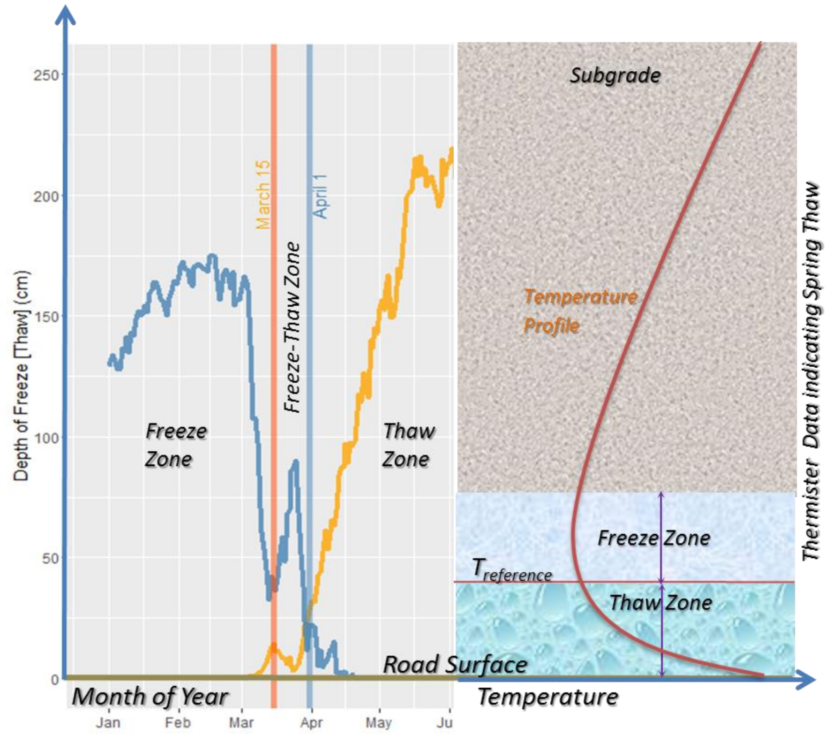

Figure 2: Aggregated data from 22 thermistor stations across the province indicates that the spring thaw occurs between early March and April every year.

The scope of this study assumed that the technology for relating frost and thaw depths to weather station data is sufficiently advanced and the various correlations between freezing and thawing indices and the structural weakening are sufficiently accurate for determining real time onset of thaw. A cursory evaluation indicated that the implementation and removal of various weight regimes (winter weights and spring road restrictions) were generally in accordance with climatic triggers based on temperatures. Therefore, this study will use the historical implementation dates as a guide to evaluate the timing of secondary weight reversion for the nine-month primary highways assuming that the SRR dates have been set properly.

For each district, 20 years of historical data was evaluated to determine if some of these districts could be clustered together in groups based on the similarity of spring road restrictions. These natural climatic clusters were evaluated using statistical k-means. The fifteen districts could be grouped into three clusters/groups based on their similarity of dates in implementation and duration of SRRs.

South Cluster: Carlyle, Kindersley, Moose Jaw, Regina, Swift Current, and Weyburn.
Central Cluster: North Battleford, Saskatoon, Wynyard, and Yorkton.
North Cluster: Buffalo Narrows, La Ronge, Meadow Lake, Prince Albert, and Tisdale.

According to Sauchyn, et al. (2009), Saskatchewan can be divided into four climatic zones. From Figure 3, it is observed that these zones can form a natural clustering mechanism to group different regions to align the SRRs.

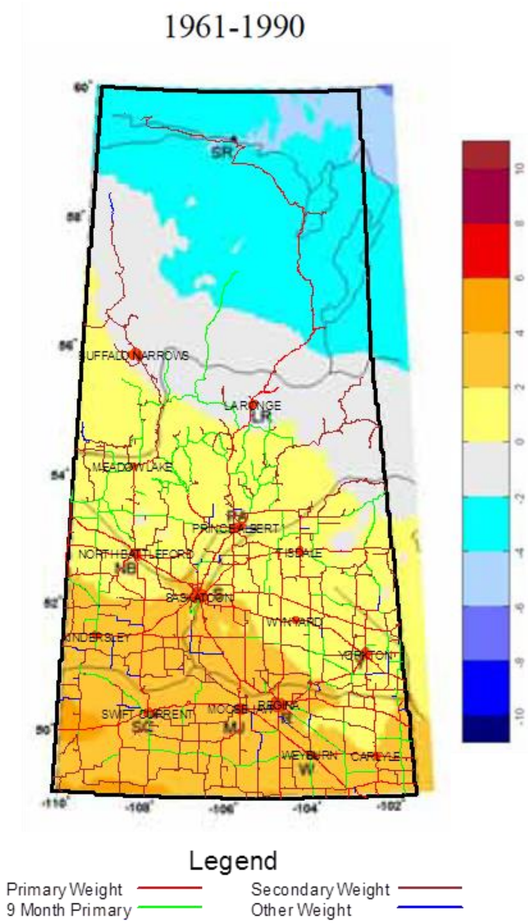

Figure 3: Saskatchewan's climatic zones provide a natural clustering mechanism for the spring road restrictions (adapted from Sauchyn et. al., 2009).

Climate change models described by Sauchyn, et al. indicate that the Saskatchewan's climate is expected to get warmer by 2050 (Sauchyn, et al., 2009). The increase in mean annual temperature is expected to be approximately 2 ^{o}C in each zone (Figure 3). This implies that over the long term spring could start earlier in the different regions.

Winter temperatures across Saskatchewan have been warmer than usual in recent years. It is not certain whether the recent warmer winter temperatures are part of the trend described by Sauchyn, et al. (2009). At present, these changes do not significantly affect the timing of spring. However, it is something that needs to be periodically monitored to adjust the timing of SRRs.

Spring Road Restrictions on Nine-month Primary Highways

The Ministry of Highways and Infrastructure (MHI) implemented major primary weight expansion initiatives in 2006 and 2009 to support economic activities by reducing transportation cost. These initiatives resulted in adding approximately 6,000 kilometers to nine-month primary highways (Liu, 2005), including approximately 3,000 km gravel highways and 3,000 km of pavements (MHI, 2016). As part of the expansion initiative, primary weight loads are allowed for these nine-month primary highways except during the spring-thaw season (April 1st to June 30th) when road structures are in their weakest state.

The nine-month primary highways were not originally designed and constructed to handle primary weights. The decision to allow primary weights on these highways was based on a comprehensive risk assessment of each road segment for their soil conditions, existing structure, past road performance, truck traffic and benefit-cost analysis (Liu, Bell, & Stamatinos, 2007). During the remaining three months in the spring, only secondary weights are allowed on the nine-month primary highways, it is referred as 3-month weight reversion (3MWR) in this paper. The 3MWR significantly reduces the risk of road failures for these highways. However, the date of implementing 3MWRs on the nine-month primary highways was fixed for convenience and easy understanding, not based on climatic triggers, as implementation of the SRRs on the secondary highways.

The neighboring Canadian provinces of Alberta and Manitoba also incorporate seasonal vehicle weight restrictions that are similar to Saskatchewan's practice of imposing spring bans on secondary highways. However, the nine-month primary highway in Saskatchewan is a category that is unique to Saskatchewan and therefore requires a more specialized implementation of the three-month weight-reversion periods.

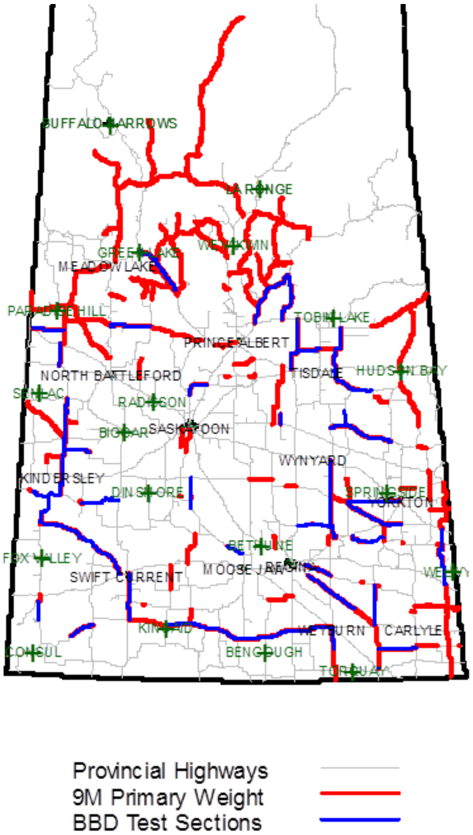

Figure 4: Saskatchewan's climatic zones provide a natural clustering mechanism for the spring road restrictions.

THE POLICY CONTEXT

The past few years in Saskatchewan (2013-2016) appeared to be warmer than usual and SRR based on climate has been triggered earlier for the secondary highways. This has caused some noticeable discrepancy in the way the weight restrictions (WRs) are managed in the spring for highway network. For instance, nine-month primary highways adjacent to a secondary highway could be allowing primary weights in early spring, while the secondary highway is already under a SRR. A similar discrepancy arises when the rural municipal (RM) roads could allow primary weights loads in late spring while the nine-month primary highways are still under the mandatory 3MWRs.

Duration of 3MWR

Pavements are designed to carry a load limit to balance economic demand and pavement service life. As the temperature drops in the pavement structure, the moisture that is present will freeze and additional water supply will result in the formation of ice lenses. Melting of such lenses within the pavement structure and subgrade will reduce the load carrying capacity and result in permanent damage (Huen, Tighe, Mills, & Perchanok, 2006). The Benkelman Beam Deflection (BBD) test measures the rebound deflection of a pavement under a standard load and tire pressure. The BBD values reflect the structural capacity of the pavement. The higher BBD values represent weaker pavement structures.

This study has analyzed over 12 years of Benkelman Beam Deflection (BBD) data from relevant highways from the year 2000 to 2012. During this period, MHI conducted around 186,756 BBD tests (3845 trail runs) on different road sections across the province. The tests were mostly conducted to aid in the design of road structures. In this study, this vast data resource was used to provide an insight about when the highways are most at risk of deterioration due to spring thaw. MHI replaced the BBD with the FWD (falling weight deflection) tests in 2012. Though the BBD and FWD are correlated, only the BBD data is used in the interest of facilitating consistent comparison.

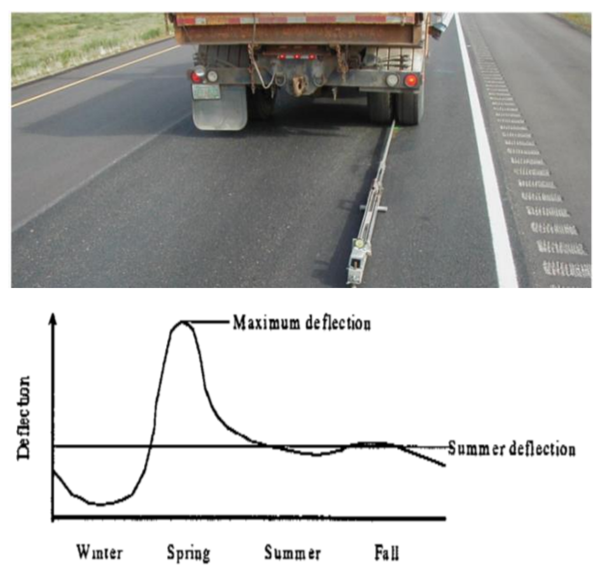

Figure 5: Top - Benkelman Beam Deflection Test Apparatus (Coe, Anthony, & Fuchs, 2013); Bottom - Typical profile of a BBD test over time. (Samson & Frechette, 1995)

Figure 5 shows a typical profile of the BBD over time for a road section. The road section has lower deflection in winter due to the additional strength provided by the frozen subgrade. During spring season, the deflection rises rapidly due to the entrapment of spring thaw water and subsequent loss of load carrying capacity. As the underlying ice melts, drainage of the water becomes possible and the road surface regains its strength.

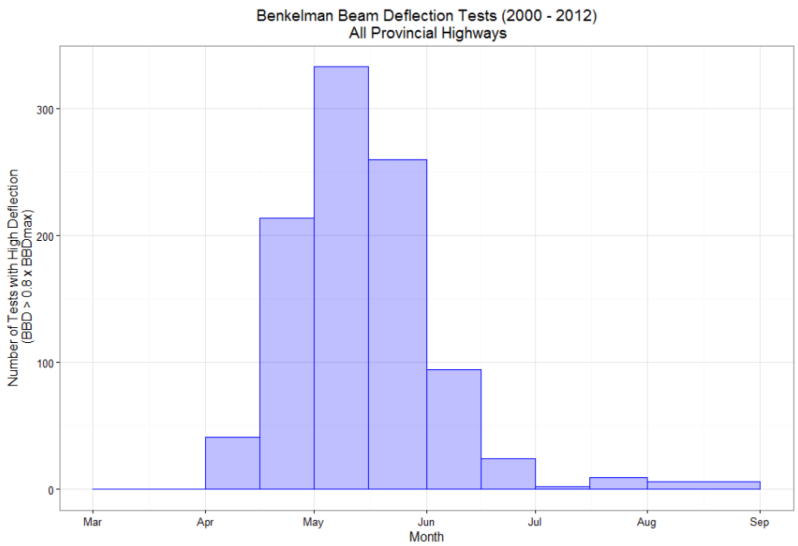

Figure 6: Frequency of occurrence of maximum deflections in BBD tests for all provincial highways. Breaks on the x-axis indicate that the period between April to July has the greatest vulnerability.

The highest risk to infrastructure due to this seasonal behavior of the highways comes during late winter and early spring (especially in regions that allow an increased winter weights). The rapid decrease in strength from winter season to spring season indicates that the accurate determination of the beginning of spring is essential to reduce the pavement damage risk to highways.

On some highway sections (Highway 3 near North Battleford), the deflection behavior is consistent over different years. Other highway sections (Highway 4 near Swift Current), show a varied pattern of deflections, which may indicate large changes in spring temperatures annually, or other factors influencing the BBD (such as soil moisture, soil type etc.). However, the general trend across the different regions indicates a high BBD in spring that rapidly tails off within a few weeks.

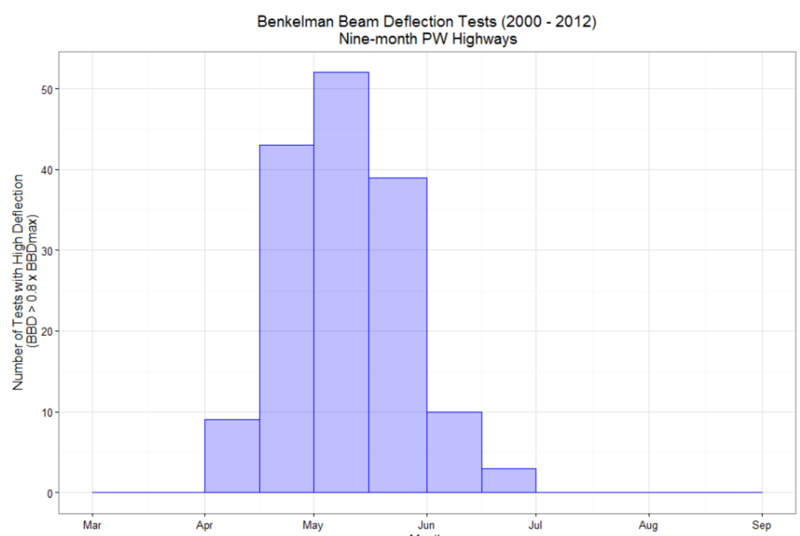

Figure 7: Frequency of occurrence of maximum deflections in BBD tests for nine-month primary highways. Breaks on the x-axis indicate that the period between April to July has the greatest vulnerability.

In design of road structures, the BBD test is used essentially to determine the thickness of pavement overlay required for the design load. Since MHI has maintained high-quality digital records of this data, it was possible to conduct system-wide, long-range analytics to determine the spring-thaw vulnerability as well. The entire BBD test data was aggregated to determine the maximum deflections over each test trial, for each year and for each road segment. Using this aggregated data, the time of the year that this maximum deflection occurred could be obtained.

Figure 6 shows the frequency of high BBD deflections that occurred in a given time. High BBD is defined as when the BBD is above 80% of maximum measured BBD for that trial run. It is observed that most of the high BBD tests occurred during mid-April to mid-June, with the highest occurring in May.

The absence of data in March does not indicate that this period is completely risk free. Past experience showed lower possibility of high BBD in March and thus the BBD tests were usually initiated in April or May. Similarly, data is not available after August for the same reason. This means that the road strength after its lowest point (highest BBD) will recover gradually, and the recovery time period is at least two weeks after the peak, which leads to the normal road strength can be reached at around the middle of June for the vast majority of highways.

A similar analysis was conducted for a subset of the data that included only the nine-month primary highways (Figure 7). This is done to see if there is any substantial difference in behavior compared to the overall system. The results indicate that the nine-month primary highways have the highest deflections in April, May and June. These deflections are reduced to approximately 20% of the maximum deflection within two weeks. The BBD data analysis clearly shows that the 9-month primary highways as a whole do need three months lowered vehicle weight during the spring thaw time to protect these pavements.

Evaluation of Historical Spring Restrictions

The implementation dates of winter weights and spring road restrictions (SRRs) for each district were obtained from MHI Highway Hotline records. The SRR dates were available for twenty years (1996 to 2016). The implementation dates for winter weights were available for eleven years between 2005 and 2016. For all these districts, the 3MWRs on the nine-month primary highways was implemented between April 1st and June 30th of each year since 2006.

For all highways in Saskatchewan, freezing of the subgrade provides an additional support to the highways during winter. To take advantage of this increased strength, most highways allow an increased weight during periods of winter when the subgrade is frozen (winter weights). The decision to start the winter weight period is based on triggers based on cumulative freezing index. Similarly, a cumulative thawing index is used to estimate the end of the winter weights and the start of the spring road restrictions (TAC, 2016). Figure 8 shows the variability of the onset of spring in the three cluster regions (south, central and north) of Saskatchewan. The decision to implement SRRs are recommended by the district operations managers and implemented through Minister's Order pursuant to Section 35(1) of "The Highways and Transportation Act, 1997" (Government of Saskatchewan, 1997).

Figure 8 gives a summary of the SRRs implemented in different regions across the province. The box plot for each region shows the quantiles (25, 50 and 75 percentile) of the range of SRR implementation dates. Generally, 75% of the SRRs are implemented after March 10th in the south cluster; after March 15th in the central cluster and after March 25th in the north cluster. Therefore, historically there is a difference of around 15 days between the implementation of SRRs in the south and the north cluster.

More importantly, for the south cluster, the difference between the start of SRR on the secondary highways and the start of the 3MWR on the nine-month primary highways is about 21 days. This means that for two third of a month, the weight restrictions determined through weather triggers on secondary highways is not being implemented on an adjacent nine-month primary highway. Similar discrepancies exist in the central and north cluster where the weight restrictions are out of phase by 15 and five days respectively.

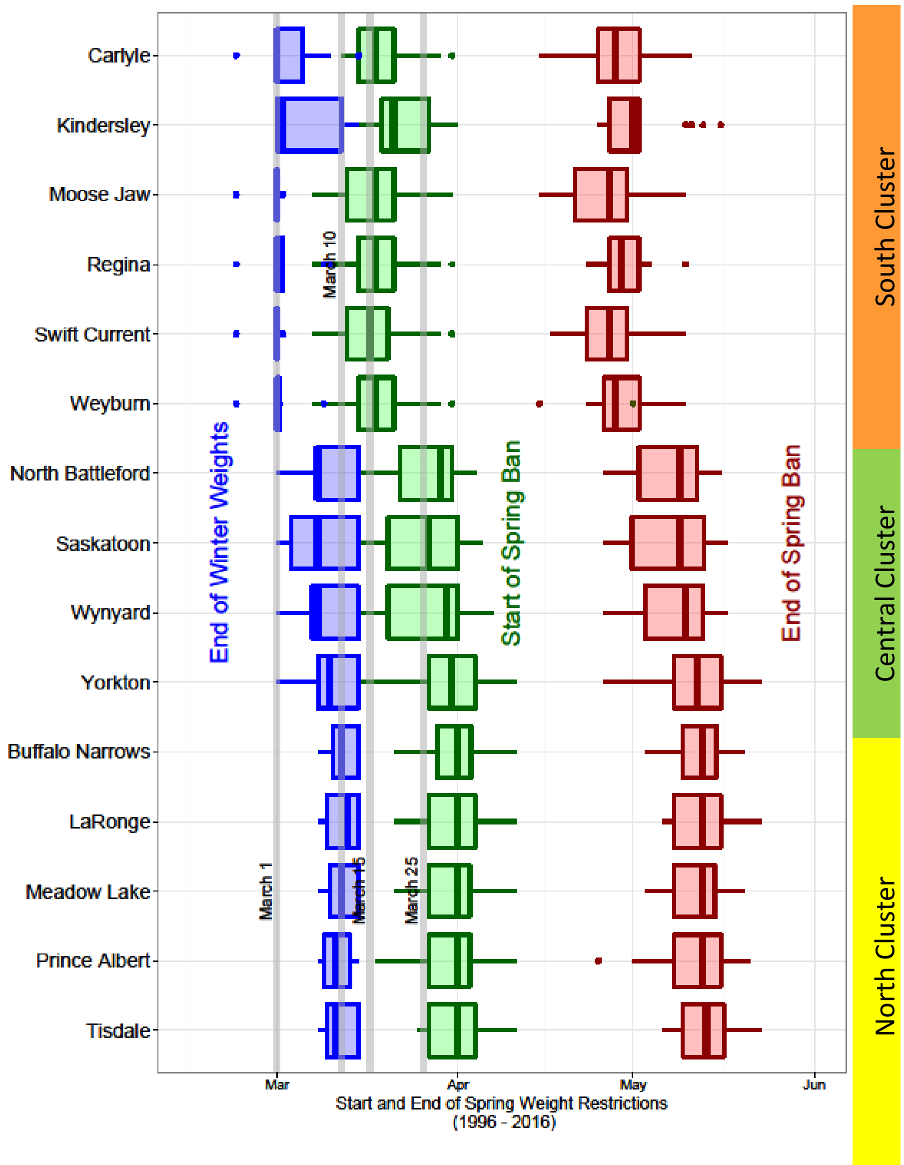

Figure 8: Regional variability in the onset and end of weight restrictions and spring road ban.

The nine-month primary highways are also being loaded with primary weights during early spring (as determined by the implementation of the SRR via climatic triggers on adjacent secondary highways). Loading with primary weights during this period leaves the highways vulnerable to spring thaw induced deterioration.

Impact of Warm Weather in Spring

Recently, the weather appeared to be warmer than normal. To evaluate this, 50 years (1966 - 2016) of minimum, maximum, and mean daily temperature data for each of the fifteen districts was collected (Environment Canada, 2016). Using this data, an expected pattern of mean, minimum, and maximum daily temperatures was developed. Recent weather pattern was similarly obtained using temperature data for the past three years (2013 -2016).

The average temperature as well as the daily range for 50 years of historical data is shown as a shaded blue area in Figure 8. This was compared to the recent temperature (shaded red area). By superimposing these two patterns – 50 year historical and three year recent – it is possible to visually determine whether there are significant differences between the long term and recent climate that needs to be considered.

For all 15 districts, the recent weather pattern showed higher temperatures peaks in winter compared to the 50-year historical pattern. The winter temperatures in recent years have been higher.

Even though higher than normal winter temperatures were observed in recent years, the mean temperatures were below the freezing temperatures. Therefore, the higher winter temperatures did not affect the timing of the SRRs. However, even though these are still sub-zero temperatures, they might affect the speed of thaw. Therefore, this changing weather pattern needs to be observed and evaluated periodically to ensure that the SRRs are aligned with the changing weather patterns.

Recommended Policy Option

The duration, timing and harmonization of the weight restrictions across different jurisdictions is an evolving situation. Each jurisdiction across Canada has a different practice based on the considerations of factors such as transport demand, cost, risk and preservation needs of typically weak pavement structures. The policy options for the alignment of weight restrictions identified for consideration in this project

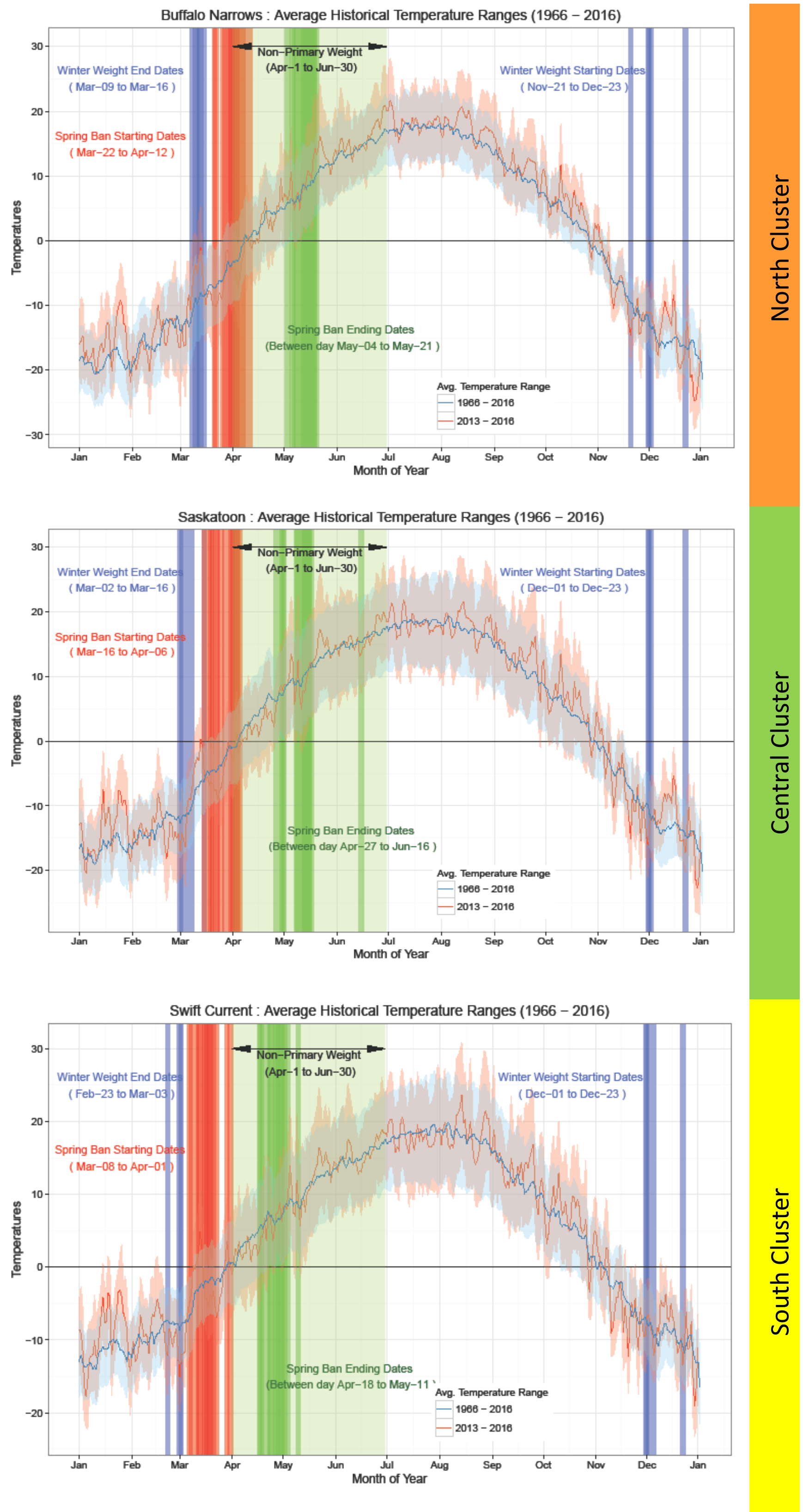

Figure 9: Comparing recent climatic triggers for the SRRs

were guided by two principles:

1. The spring-thaw impacts on the affected highways will be reduced, or at least not increased.
2. The best solutions for alignment will be provided without an undue increase in complexity for road users and resource requirement for the MHI's operational staff.

Three main options have been considered in the policy analysis, including status quo, and moving the three month secondary weight reversion time earlier for all 9-month primary highways, and considering 9-month primary highways in different regions and to move the three months secondary weight reversion time earlier in different regions according to their local weather conditions. All options are identified such that no additional resources would be required in the implementation. These options can be implemented within a quick timeframe through the normal business and communication channels of MHI.

The TAC (2016) guidelines recommend that flexible starts to SRRs be implemented rather than across-the-board restrictions. While this is rational and reasonable for pavement protection, and implementable in geographically smaller provinces, it is difficult to implement in a large province like Saskatchewan. If every highway link needs to be assessed individually and different SRR is imposed on individual highways based on minor differences in thawing indices, a significant amount of work would be required and large inconvenience would be created for road users. This study has tried to balance the flexibility of starting SRR to reflect local spring thaw conditions and highway network operation efficiency by combining the fifteen districts into three geographical clusters that will conveniently align with Saskatchewan's natural climatic zones.

Therefore, the recommended policy option tried to use the natural clustering of regions within Saskatchewan to provide regional flexibility without undue complexity. One operational challenge for the option is that highway corridors do not stop at zone/cluster/region boundaries. This makes the implementation and communication of the 3MWRs difficult for the MHI operators and tedious and complex for the road users.

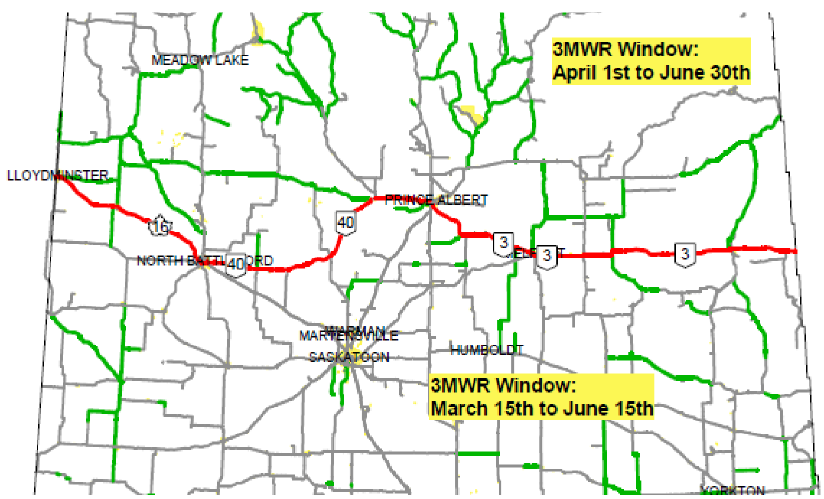

Figure 10: Recommended policy – Two windows of 3MWRs on nine-month primary highways.

The key for the policy recommendation is to properly balance among factors of satisfying transportation demand of economic activities, reducing pavement deterioration risk, lowering implementation complicity and costs for agency and road users.

Due to the different geographical and climatic conditions in the province, the southern district highways are most vulnerable from early spring-thaw than the northern districts. While the current implementation of the 3MWRs creates an unacceptable risk for the southern districts, they were found generally adequate for the northern districts. However, the complexity of implementation and communication is quite high as there is the difficulty of drawing a boundary of areas for all nine-month primary highways to follow a particular cluster and the difficulty for communication to truckers/shippers as the rules for all primary weight highways have been uniformly applied province-wide so far.

After detailed network analysis and consultation with regional staffs, a highway corridor that was selected as a delineator between the northern and southern regions was identified and accepted. It is proposed that the northern cluster will remain the status quo for the 3MWRs window (1st April to 30th June), while the southern cluster will move the 3MWR window 15 days earlier (15th March to 15th June) to reflect the previously identified timing for the beginning of thawing. Figure 10 Shows the highway corridor that divides the south and north regions for the timing of implementing the three month secondary weight reversion for the nine-month primary weight highways.

This recommended policy has achieved the closest alignment as the 3MWR period mostly overlaps the SRR periods in all regions while keeping the vehicle weight management for nine-month primary highways in the spring as simple as possible. Table 1 provides a summary of policy options for re-aligning the timing of secondary weight reversion for nine-month primary Highways.

Table 1: Summary of Policy Options for re-aligning the timing of secondary weight reversion in the spring for nine-month primary Highways

Criteria	Status Quo Option	Earlier 3MWRs Option	**Recommended option**
Acceptability	Out of phase – not acceptable	May be acceptable	Acceptable
Highways Risk	Not properly aligned – high protection risk	reduced risk	Lowest risk
flexibility to reflect regional weather conditions	Not flexible	Not flexible	Moderately flexible
Implementation Complexity	easy	Easy to understand	Low complexity
Communication Strategy	need to explain why not change	Highway hotline, wt. map, web site	Highway hotline, some int. stakeholder input
Implementation Cost	need to explain why not change	Low	Low
Potential long-term road costs	have costs	Reduced	Reduced
Road Users – Simplicity of understanding	some complaints	simple	slightly lower simplicity
Road Users – Business Planning	Low acceptance – some complaints	Similar to status quo	Slight increase in complicity –for north –south movement
Road Users – Long term benefits	May increase road deterioration	Will reduce early spring deterioration	Will reduce early spring deterioration
Alignment with secondary SRRs	No change – not aligned	Improved alignment	More improved alignment

The recommended policy option envisions a staggered implementation of the 3MWRs across two clusters. Regional differences in climate triggers for SRRs within each cluster were often insignificant. This can be used to reduce the complexity of potentially managing 15 districts down to two clusters. The recommended policy option provides the maximum possible alignment of the 3MWRs and the SRRs across the province. It also provides the necessary flexibility for individual clusters to have appropriately spaced 3MWRs based on their historical record of climatic triggers for implementation of SRRs.

CONCLUSIONS

Saskatchewan is a geographically large province with considerable difference in climate in the north and the south. The recommended policy change takes into account the climatic differences in the north and the south of the province and their impact on pavement deterioration, while also maintaining the original intent of the nine-month primary highways in providing the expanded level of primary weight access for transportation and economic activity across Saskatchewan.

This recommended policy will reduce the existing vulnerabilities during early spring in the implementation of 3MWRs on the nine-month primary highways. The policy option will also keep the complexity of the policy and its impact on transport operations to a minimum.

The policy was implemented and communicated to stakeholders through highway vehicle weight maps, web site, Highway Hotline, etc. and many stakeholder groups.

A continuous monitoring of nine-month primary highways is required during the implementation of the new policy to promote compliance and avoid unforeseen negative impacts.

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