Impact of Climate Change in the Implementation of the Seasonal Weights in Manitoba

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ABSTRACT

Seasonal weights are implemented in Manitoba to minimize the pavement damage due to traffic loading in spring and to improve the productivity of the trucking industry during the winter. This paper presents the implication of early or late start and end of seasonal weights to the pavement's service life. Several scenarios that could impact the life of the pavement during the implementation of seasonal weights were identified. The seasonal variation of pavement stiffness was determined from FWD data collected in different seasons from instrumented test sites. These stiffness values were used to estimate the critical strains in the pavement at different temperature conditions using mechanistic analysis assuming elastoplastic properties of the materials. The reduction in the life of the pavement when seasonal weights are not implemented on time was estimated using the Asphalt Institute, Miner's Hypothesis and MEPDG models. The results indicate that significant reduction in the life of the asphalt pavement occur when spring restrictions are not implemented on time. The results of the study can be used to justify revision to the existing policy on SWR and WSW.

INTRODUCTION

Manitoba Infrastructure implements seasonal weight restrictions to protect its weak pavements from undue damage during the spring thawing periods. The department also allows trucks to haul additional weights in the winter when the pavement is sufficiently frozen. The department uses the Cumulative Thawing Index (CTI) to implement the Spring Weight Restrictions (SWR) and to end the Winter Seasonal Weights (WSW). The Cumulative Freezing Index (CFI) is used to start the WSW. The WSW is allowed when the CFI is -160 °C-days or December 1, whichever comes first and is terminated when the daily high air temperature exceeds zero °C or when the CTI exceeds zero °C-days but not before the end of February. The SWR starts when the CTI reaches 15 °C-days and ends when the CTI reaches 440 °C-days. However, SWR does not start before March 11. The duration of the SWR is limited to 56 days and it does not extend beyond May 31. These air temperature indices for starting and ending the seasonal weights were developed based upon internal research and experience, and research by other highway agencies. The earliest or latest start or end dates are based on historical data and/or past practices to help trucking industry in advance planning of their works.

Significant temperature variation had been observed in the province in the last few years. The early spring of 2014 experienced a consistently below freezing average daily air temperature resulting to a CTI remaining at zero for a longer period and delaying the imposition of the SWR. However, during this period, pavement thaws during the daytime due to increased solar intensity, solar duration and daytime high above zero air temperatures, and refreezes at night due to cold weather. This results in increased number of freezing and thawing cycles which are not accounted for by the air temperature indices such as the CTI or a positive air temperature. In 2015, the milder temperatures in November and December in southern Manitoba have triggered several cycles of freezing and thawing in the pavement after the start of the WSW on December 1st. The trigger CFI was reached on December 23 (i.e., WSW was allowed 23 days early) in the southern zone and on December 11 (i.e., WSW was allowed 11 days early) in the northern zone than when CFI reached the target. In 2016, the trigger CTI for imposing the SWR reached on March 6 in the southern zone and SWR was imposed on March 11 (based on the earliest start date in the policy) i.e., five days later. The maximum 56 days of SWR duration requires removing SWR on May 5 or earlier. However, the trigger for ending the SWR reached on May 11. The trigger CTI for starting the SWR reached on March 14 in the northern zone. However, the trigger CTI for ending the SWR is expected to reach on May 17. These usual variations of the time when CFI and CTI reach the targets are considered to be associated with the effect of climate change.

OBJECTIVES AND APPROACH

The main objective of the study is to assess the impact of climate change in the implementation of the spring road restrictions and winter seasonal weights in Manitoba's provincial highway network system. The approach taken includes:

- Estimation of material properties including the stiffness of each of the pavement layers and the subgrade using the FWD deflections measured in different seasons of the year. These were used as inputs in the load deformation analysis.
- Evaluation of historical climate and pavement stiffness data, and determination of scenarios of early or delayed start or end of the SWR and WSW due to climate change that could possibly affect the life of the pavement.
- Perform mechanistic analyses of pavement response to changes in the weights and pavement stiffness due to varying seasons.
- Develop models for estimating the rutting and critical strains in the pavement using layer thicknesses and FWD deflection data.
- Predict the remaining life of existing pavements in terms of the number of load repetitions to rutting and fatigue failures and determine the type of pavement distress that will trigger pavement failure.
- Determine the conditions that will impact the service life of the pavement due to variations in the timing of implementation of the seasonal weights.

REVIEW OF RUTTING AND FATIGUE CRACKING MODELS

Pavement rutting is a surface depression at the wheel path. It is the accumulation of the irrecoverable strains in the pavement layers and subgrade due to load repetitions over time. Fatigue cracking, on the other hand, is a series of interconnected cracks caused by fatigue failure of the HMA surface under repeated traffic loading. A number of existing models that can be used to estimate the number of load repetitions to fatigue and rutting failures are summarized in Table 1.

The MEPDG rutting models are presented in the review for comparison with other models but were not used in the analysis due to inadequate parameters of the base and the subgrade.

DESCRIPTION OF TEST SECTIONS

The study sites consist of highway sections that represent the three (3) weight classifications of roads in the Province, namely, RTAC routes, A1 highways and B1 highways. RTAC routes include all expressways as well as primary and secondary arterials that are generally structurally capable of carrying the specified maximum axle loads for RTAC. Weaker pavements generally are classified as either A1 or B1. In the spring, weight restrictions are imposed on weak pavements at two levels of restrictions depending on the structural strength of the pavements. The Level 1 restrictions reduce the allowable axle weights to 90 percent of the normal weights while Level 2 restricts the axle weights to 65% of the maximum allowable weight. Weak pavements that are classified as RTAC are restricted only to Level 1 in the spring.

Table 1: Models for estimating the number of load repetitions to fatigue and rutting failures

Models	Number of load repetitions to fatigue failure, N_f	Number of load repetitions to rutting failure, N_r
Miner's Hypothesis	$N_f = 2.83 \, x \, 10^{-6} \left({}^{1}/_{\varepsilon_t} \right)^{3.148}$ $where: \ \varepsilon_t = tensile\ strain\ at\ the\ bottom\ of\ AC$	$N_r = 6.026 \, x \, 10^{-8} \left({}^{1}/_{\varepsilon_v} \right)^{3.87}$ $where: \varepsilon_v = \ compressive\ strain\ on\ top\ of the\ subgrade$
Asphalt Institute	$N_f = 0.0796 \, x \, (\epsilon_t)^{-3.291} \left({}^{1}/_{E_1} \right)^{-0.854}$ $where: \ \varepsilon_t = tensile\ strain\ at\ the\ bottom\ of\ AC$ $E_1 = modulus\ of\ the\ AC$	$N_r = 1.36 \, x \, 10^9 x \, (\epsilon_v)^{-4.477}$ $where: \varepsilon_v = \ vertical\ compressive\ strain\ on\ top\ of\ the\ subgrade$
Mechanistic-Empirical Pavement Design Guide (MEPDG)	$N_{f-HMA} = k_{f1}(C)(C_H)\beta_{f1} \, (\epsilon_t)^{k_{f2}\beta_{f2}} (E_{HMA})^{k_{f3}\beta_{f3}}$ where: $k_{f1} = 0.007566, k_{f2} = -3.9492; \ k_{f3} = -1.281$ (global field calibration coefficients) $\beta_{f1,}\beta_{f2,}\beta_{f3} = local\ calibration\ factors = 1.0$ $C = \ 10^M; M = 4.84 \left(\frac{V_{be}}{V_a + V_{be}} - 0.69 \right)$ For bottom up or alligator cracking: $C_H = \frac{1}{0.000398 + \frac{0.003602}{1 + e^{11.02 - 3.49 H_{HMA}}}}$ For top-down or longitudinal cracking: $C_H = \frac{1}{0.01 + \frac{12}{1 + e^{15.676 - 2.8186 H_{HMA}}}}$	$\Delta_{p(HMA)} = \varepsilon_p h_{HMA} = \beta_{1r} k_z \varepsilon_{r(HMA)} 10^{k_{1r}} n^{k_{2r}\beta_{2r}} T^{k_{3r}\beta_{3r}}$ $\Delta_{p(soil)} = \beta_{s1} k_{s1} \varepsilon_v h_{soil} \left({}^{\varepsilon_0}/_{\varepsilon_r} \right) e^{\left({}^{\rho}/_{n} \right)^{\beta}}$ where: $k_{r1} = -3.35412, k_{r2} = 0.4791; \ k_{r3} = 1.5606$ (global field calibration coefficients) $\beta_{r1,}\beta_{r2,}\beta_{r3} = local\ calibration\ factors = 1.0$ $k_z = (C_1 + C_2) 0.328196^D$ $C_1 = -0.1039(H_{HMA})^2 + 2.4868 H_{HMA} - 17.342$ $C_2 = -0.0172(H_{HMA})^2 - 1.733 H_{HMA} + 27.428$ $log\beta = -0.61119 - 0.017638 W_C$ $\rho = \ 10^9 \left[\frac{0.0075}{1 - (10^9)^\beta} \right]^{1/\beta}$ $W_C = water\ content, \%$

Table 2 gives a summary of the maximum allowable seasonal weights for a single axle for each road classification. The allowable single axle loads were used to estimate the critical strains in the pavement. See Manitoba Regulation 575/88 for additional information on allowable vehicle weights in the province. Also, the implementation of the SWR and WSW varies per zone. The province is divided into two zones, with Zone 1 located in southern Manitoba and Zone 2 in northern Manitoba (Figure 1).

Table 2: Maximum allowable seasonal weights per single axle, kg.

Spring Road Restrictions Levels	**Maximum Allowable Seasonal Weights per Single Axle, kg**		
	RTAC	**A1 Loading**	**B1 Loading**
No Restrictions	9,100	9,100	8,200
Level 1 (90% of AL*)	8,190	8,190	7,380
Level 2 (65% of AL)		5,915	5,330

- AL = Allowable Load

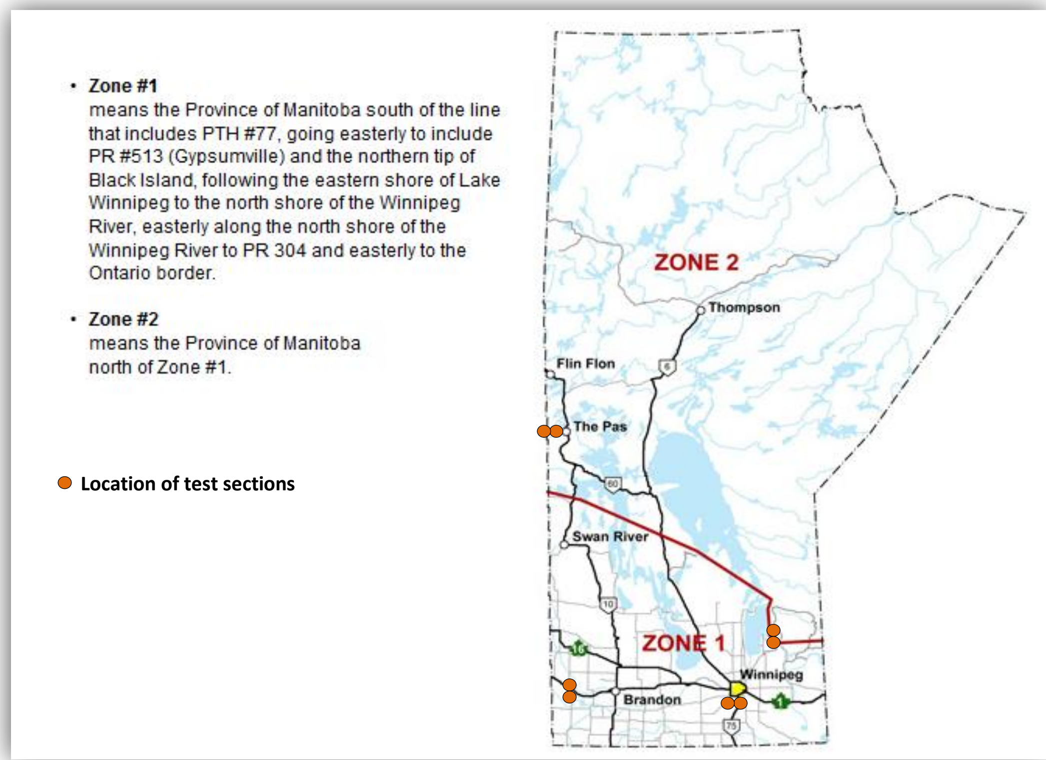

Figure 1: Climate zone map for the implementation of seasonal weights in Manitoba and location of test sections.

During 2011-2013, Materials Engineering collected FWD deflection data from eight (8) test sections located across the province. A summary of the weight classification, levels of restrictions, allowable loads, subgrade type and thickness of the pavement structure at the study sites is given in Table 3. Some of the test sections classified as A1 and B1 are allowed to carry 110% of the allowable weight for RTAC routes during the winter. These roads are classified as winter seasonal RTAC.

Table 3: Test sections, their weight classification, allowable winter loads, level of spring restrictions, pavement structure and subgrade type.

Test Sections	No. of Lanes	Weight Class	SRR Level	Allowable Winter Loads	Subgrade Type	Layer Thickness, mm	
						Base	AC
PTH 59	4	RTAC	None	Plus 10% of AL	Clay	650	150
PTH 11	2	RTAC	L1	Plus 10% of AL	Silty Clay	335	130
PR 283 (Bit)	2	A1	L1	Seasonal RTAC	Clay	300	100
PR 210	2	A1	L1	Plus 10% of AL	Clay	400	100
PR 283 (AST)	2	A1	L2	Seasonal RTAC	Clay	400	AST
PR 256 (Bit)	2	B1	L2	Seasonal RTAC	Silty/Sandy Clay	150	75
PR 304 (AST)	2	B1	None	Seasonal RTAC	Clay	400	AST
PR 256 (AST)	2	B1	L2	Seasonal RTAC	Silty/Sandy Clay	200	AST

ANALYSIS PROCEDURE

Analysis Scenarios

As discussed in the previous section, the implementation of the seasonal weights uses the CFI and CTI to start and end the WSW and SWR. With these indices calculated from the average daily temperatures, the changing pattern of temperature rise and fall could have huge impact on the trigger values. Also, the trigger CTI values may not fit within the specified earliest start, latest end and maximum duration of the SWR. For example, an abrupt increase in the average daily temperature in the spring could result in fewer days of restricted period while a slow rise in temperature could mean longer restriction period. In the early winter, the required CFI may not reach by December 1st due to slow drop of the subzero temperature. Alternatively, if the negative temperatures fall rapidly, this could mean starting the winter weight premium earlier than the time required to develop the needed frost depth for allowing the WSW.

The implementation of SWR and WSW should be based on the stiffness of the pavement structure at that time. After the review of historical climate and pavement stiffness data, a base (typical) and six alternative scenarios that could possibly impact the life of the pavement were determined. A method to estimate the weighted average strain and stiffness of the pavement layers was developed. The difference in the life of the pavement between the typical (base) scenario and the other six scenarios was calculated. The six scenarios, including the typical condition are summarized in Table 4.

Table 4: Analysis scenarios

Scenario	WINTER	PRE-SPRING	SPRING	SUMMER	FALL	NOTES
T (Base)	90 days	15 days	56 days	174 days	30 days	Typical (base) scenario
1	90 days	15 days	7 days of AL + 56 days of RL	167 days	30 days	SWR imposition is delayed for 7 days
2	90 days	15 days	14 days of AL + 56 days of RL	160 days	30 days	SWR imposition is delayed for 14 days
3	90 days	8 days	56 days of RL + 7 days of late spring modulus	174 days	30 days	SWR removed before summer modulus is reached
4	83 days	15 days	56 days of RL	174 days	30 days + 7 days of WL	WSW allowed before winter modulus is reached
5	76 days	15 days	7 days of AL + 56 days of RL	174 days	30 days + 14 days of WL	WSW allowed before winter modulus is reached
6	90 days	8 days of AL+7 days of WL	56 days of RL	174 days	30 days	WSW is removed at pre-spring modulus
Stiffness	Winter modulus	Pre-spring modulus	Spring modulus	Summer modulus	Fall modulus	Modulus used in the analysis
Duration	Dec 1-Feb 28	Mar 1-15	Mar 16-May 14	May 15-Oct 30	Nov 1-30	365 days total
Load Applied	WL = 110% of AL	AL	RL = 65%-90% of AL	AL	AL	AL=Allowable Load WL=Winter Load RL=Restricted Load

Calculation of Layer Stiffness from FWD Deflection Data

The FWD deflection data collected from the study sites during 2011 to 2013 were used to estimate the stiffness of the pavement layers and subgrade. The backcalculated modulus in each layer of the pavement structure and the subgrade were adjusted to their equivalent laboratory modulus. The adjustment factors are based on the recommendations in the paper titled "Estimating Base Layers and Subgrade Modulii for ME Pavement Design in Manitoba," (Oberez, et.al, 2015).

From the series of FWD deflection measurements done on each test site, the data chosen for the analysis represent the typical deflection readings for the site for that particular season of the year (See Table 5). Six (6) FWD test measurements in spring, late spring, summer, late fall, winter and pre-spring were analyzed. The corresponding layer and subgrade modulii were determined by backcalculation and used as inputs in the mechanistic analysis. The backcalculated modulus in late spring was used to determine the impact of early removal of the restrictions when the modulus of the pavement layers and subgrade were not yet recovered to the summer levels. The late fall modulus was used to determine the impact of allowing the winter weight premium before the required pavement and subgrade stiffness for WSW were attained.

After the removal of the WSW, typically there is a 15-day non-restricted (pre-spring) period where trucks are permitted to haul the allowable maximum loads before the spring restriction starts. Another possible scenario that could impact the service life of the pavement is when temperatures in the late winter are mild enough to weaken the pavement structure but the average temperature is below zero and will not trigger the end of the WSW. The surface of the pavement could already be experiencing partial thawing while WSW is still in place. The pre-spring modulus of the pavement layers and subgrade were used for this scenario.

Table 5: The FWD central deflection measurements (micrometer) at the test sections

Highway Section	FWD Central Deflection, micrometer					
	Early Spring	Spring	Late Spring	Summer	Fall	Winter
PTH 59	236	364	354	341	222	107
PTH 11	277	619	442	367	129	40
PR 283 (Bit)	315	883	760	487	99	31
PR 210	164	910	727	597	94	23
PR 304 (AST)	902	760	876	437	161	64
PR 283 (AST)	1490	2532	1323	925	80	23
PR 256 (Bit)	214	2417	1565	1364	156	76
PR 256 (AST)	245	2057	1415	1124	78	76

Mechanistic Analysis using SIGMA/W (GEOSTUDIO)

The SIGMA/W module of Geostudio 2012 is used to analyze the pavement response to loadings. This software can perform a two-dimensional load deformation analysis using the finite element method

(FEM). The deformation in the pavement is estimated at three (3) defined time steps, with fixed elapsed time of 0.03 second for a total duration of load application of 0.1 second. The FWD test applies the load to the pavement at 0.03 second which translates to a frequency of 33 Hertz. For consistency, the strain calculated at this frequency was used in the stress-strain analysis. The maximum number of iterations for convergence is set at 50 with a minimum displacement difference of 0.001.

The materials for the asphalt, base and subgrade were modeled using the elastoplastic properties of the materials. An elastoplastic material undergoes both elastic (recoverable) and plastic (permanent) deformation during the loading period. A small load applied in the soil resulting into small strains causes the soil to behave like elastic material, and thereafter as the loads and strains increase, the soil behaves like an elastoplastic material (Budhu, 2011).

The inputs for stiffness of the base layer and subgrade were the backcalculated modulii for each season converted to their laboratory modulii. Due to unreasonably high values of the backcalculated asphalt modulus in the winter, the dynamic modulus of the asphalt concrete was used. The dynamic modulus was estimated from the results of the laboratory test based on the temperature of the asphalt layer at the time of FWD data collection. Other material properties such as cohesion, unit weight, Poisson's ratio, phi, and dilation angles are typical values for the type of material.

Tire Contact Area VS. Tire Load

Figure 2 shows the graphical presentation of the relationship between the tire load (kg) and tire contact area (mm^2) for tire pressures of 698 and 346 kPa. The graph was developed using the data from the paper titled "Recommendations to Improve the Productivity of the Manitoba Trucking Industry: Use of Tire Pressure Control Systems (TPCS) during SLR and a Rational Method for Ending SLR", (Kavanagh, L., et. al., 2011). For a given the tire load, the tire contact area was estimated from the correlation shown in Figure 2 and was used to calculate the stress on top of the pavement.

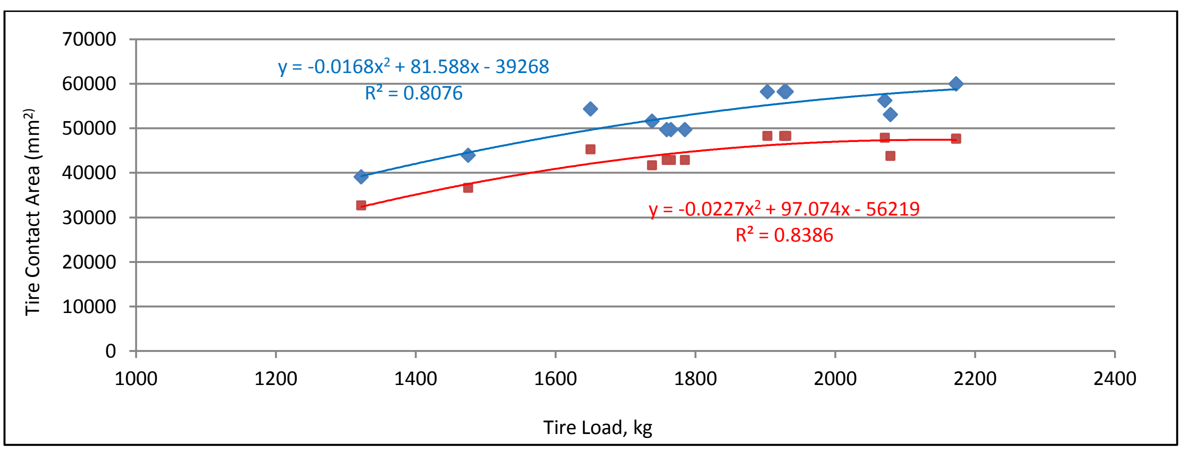

Figure 2: Relationship between tire load, in kg, and tire contact area, in mm^2.

FINDINGS

Variation of Rutting in the Pavement Layers and the Subgrade

The stress contours representing the typical bulbs of vertical pressures beneath a loaded pavement structure is shown in Figure 3. Each contour label represents the percentages of the applied pressure at those points. The shape and extent of the pressure bulb change by season due to changes in layer modulli and allowable loadings. A sample illustration of the pressure bulb for a thick pavement (PTH 59) is given in Figure 3. As expected, for a thick pavement, the bulb for high vertical pressures is confined at the pavement layers. For thinner pavements and gravel roads, this bulb was observed to be narrower and extended deeper into the subgrade imposing higher pressures and thereby increasing the rutting at the subgrade.

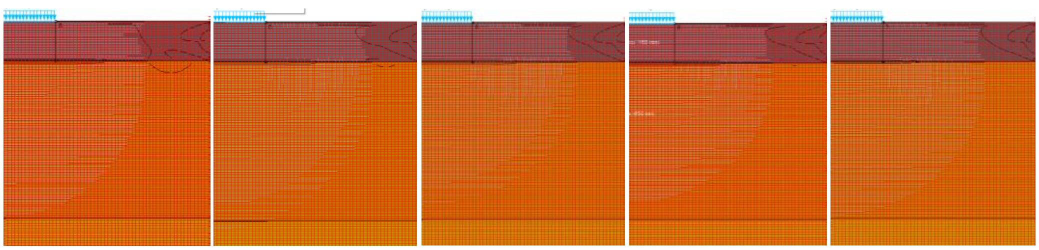

Figure 3: Seasonal changes in the size of pressure bulbs for PTH 59.

The rutting contributions for each layer in the pavement structure and the subgrade were estimated from the total elastic vertical displacements at each node in the finite element model (See Figure 3). For the asphalt layer, the mechanistic analysis showed that 20 to 33 percent of the total rutting could be from the asphalt layer. The results also showed that as the asphalt layer thickness increases, the amount of stress it carries and absorb also increases, thereby increasing its contribution to total rutting. The base layer rutting percentage to total rutting decreases as the base layer thickness increases. The base layer rutting contribution could vary from 31 to 66% of the total rutting. For the subgrade, the rutting percentage is a function of the total thickness of the pavement structure.

The data from the mechanistic analysis were used to develop the preliminary linear regression models for estimating the rutting of the subgrade, base and asphalt layers. The use of these models is limited to a two-layer pavement system and material properties of the pavement layers and subgrade used in the study. The preliminary models are as follows:

1. $Rut_{AC}(\%) = 26.381 + 0.042265t_{AC} - 0.0028448t_{base} - 0.0054497FWD_{cd}$ R^2= 0.805

2. $Rut_{Base}(\%) = 76.296 - 0.297255t_{AC} - 0.063658t_{base} - 0.023725FWD_{cd}$ R^2= 0.995

3. $Rut_{Subgrade}(\%) = -2.6775 + 0.25498t_{AC} - 0.060805t_{base} - 0.029175FWD_{cd}$ R^2= 0.999

where:

$Rut_{AC}(\%)$ = rutting percentage of the asphalt layer from the total rutting

$Rut_{Base}(\%)$ = rutting percentage of the base layer from the total rutting

$Rut_{Subgrade}(\%)$ = rutting percentage of subgrade to the total rutting

t_{AC} = thickness of the asphalt layer, mm

t_{base} = thickness of the base layer, mm

FWD_{cd} = FWD central deflection measured in summer, micrometer

Mechanistic analysis was also performed on AST roads. The results indicate that thick gravel surface could be more efficient in significantly reducing the rutting in the subgrade compared to thin asphalt pavements. The test section in PR 283, located in northwest Manitoba show the highest seasonal variation in rutting for both the base and the subgrade. The early spring rutting show that 100% of the rutting is from the base indicating that the subgrade is still in a frozen state. On the other hand, rutting percentages for the test section in PR 256 did not show high sensitivity to changes in temperature. This could be due to the type of soil and moisture condition of the materials in the base and subgrade. The seasonal variation of the stiffness of a soil is dependent on the temperature, type and moisture content of the soil (Oberez, M., et al, 2015).

The vertical displacement values from the mechanistic analysis were used to develop the preliminary linear regression model to estimate the rutting contribution of the subgrade from the total rutting. The parameters used are the thickness of the gravel surface and the FWD central deflection values.

4. $$Rut_{subgrade}(\%) = 84.457 - 0.12189t_{gravel\,surface} - 0.016974FWD_{cd} \qquad R^2 = 1.0$$

Shear Stress and Strain in the Pavement

A loaded elastoplastic material exhibits both elastic and plastic strains. In the critical state, plastic strain has two components –a deviatoric component and a volumetric component. Volumetric strain is a measure of volume changes and consists of the recoverable strain and the unrecoverable strain. The deviatoric strain or sometimes referred to as resilient strain is a measure of shear deformation of the material without volume change. Figure 4 show that the maximum X-Y shear strains are located at the edges of the loaded strip.

The plots of the X-Y shear strain, deviatoric strain, volumetric strain and maximum shear stress versus depth at the edge of the loaded strip are also shown in Figure 4. From these plots, high shear stresses and deviatoric strains for the AC layer are to be expected at the top and bottom of this layer. The maximum shear stresses at the base and subgrade are insignificant compared to the maximum shear stresses carried by the asphalt layer. The results show that high volumetric changes (from high volumetric strains) are to be expected at the top of the base layer. The asphalt layer show the least amounts of volumetric strain (Figure 4.d).

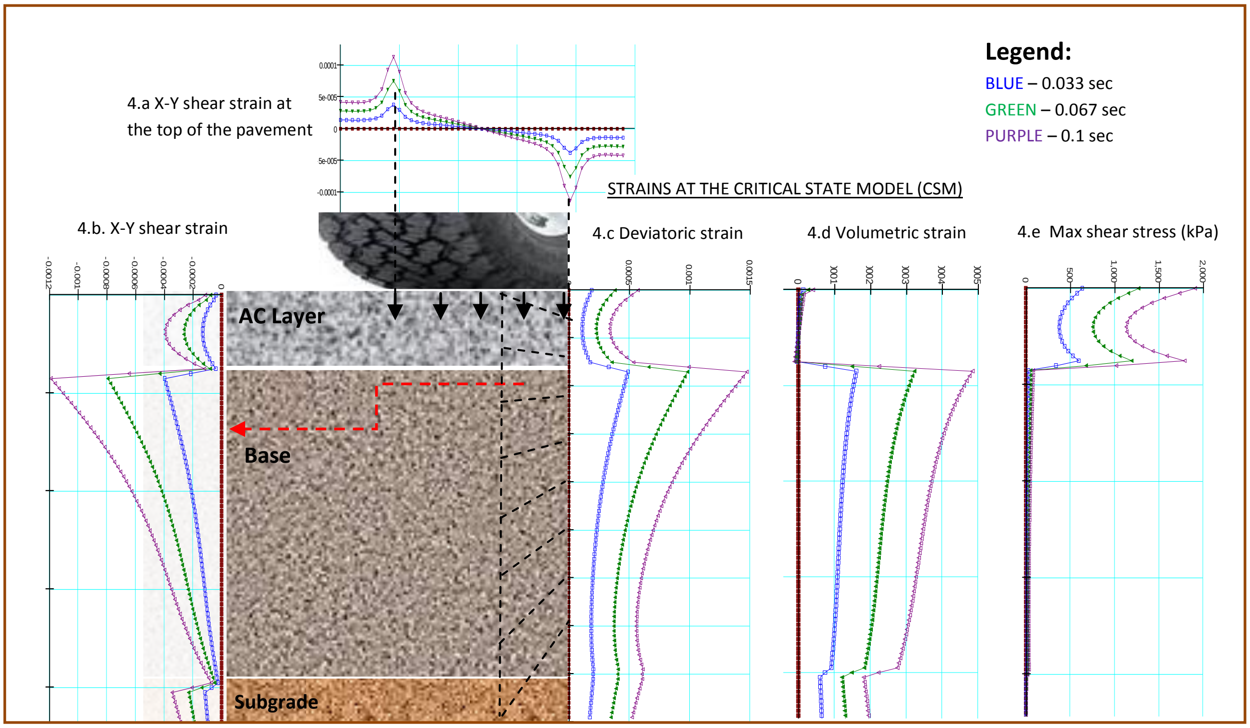

Figure 4: Plots of stress and strains for PTH 59: 4.a X-Y shear strain at the interface of the tire and the pavement; 4.b Plot of X-Y shear strain versus depth; 4.c Plot of deviatoric strain versus depth; 4.d Plot of volumetric strain versus depth and, 4.e Plot of maximum shear stress (kPa) versus depth.

Stress VS. Critical Strains

The critical strains in pavements are the tensile strain (ε_t) at the bottom of the AC layer and the compressive strain (ε_c) at the top of the subgrade (Xu B. Et. al, 2002). The models for estimating the life of the pavement uses the tensile strain (ε_t) at the bottom of the asphalt layer to predict the fatigue failure in the asphalt layer while the compressive strain (ε_c) on top of the subgrade was used to predict the overall rutting performance of the pavement. From Figure 5, the maximum vertical displacement is located at the middle of the loaded section. The displacements and strains along the y axis and strain along the x-axis (Figure 5.b, 5.c, and 5d) at the middle of the loaded strip are presented in Figure 5. The x-strain is compressive at the top of the pavement and tensile at the bottom of the asphalt layer.

To estimate the weighted average critical strains (yearly representative values) from the wheel loads, the relationships between the stress applied and the corresponding strains from the mechanistic analysis for six different pavement sections and seasonal modulii (late fall, winter, early spring, spring, late spring and summer) were developed. The input for stress applied at the top of the pavement was varied from 200 to 800 kPa, with an increment of 200 kPa. The calculated strains from Sigma/W for each stress were plotted. Six (6) plots of the stress-strain relationships were developed for each pavement type. From the plots, the strain for the maximum load allowed during the season was determined and the weighted strain, ε, was calculated using the following equation:

1. $\varepsilon = (\varepsilon_s xS + \varepsilon_f xF + \varepsilon_w xW + \varepsilon_{ps} xPS + \varepsilon_s xSp)/365$

Where:

ε_s, ε_f, ε_w, ε_{ps}, ε_{sp} are strains in different seasons and the subscripts *s, f, w, ps* and *sp* stand for summer, fall, winter, pre-spring and spring respectively.

S, F, W, PS and Sp, are the number of days for each season and varies per scenario as shown in Table 4.

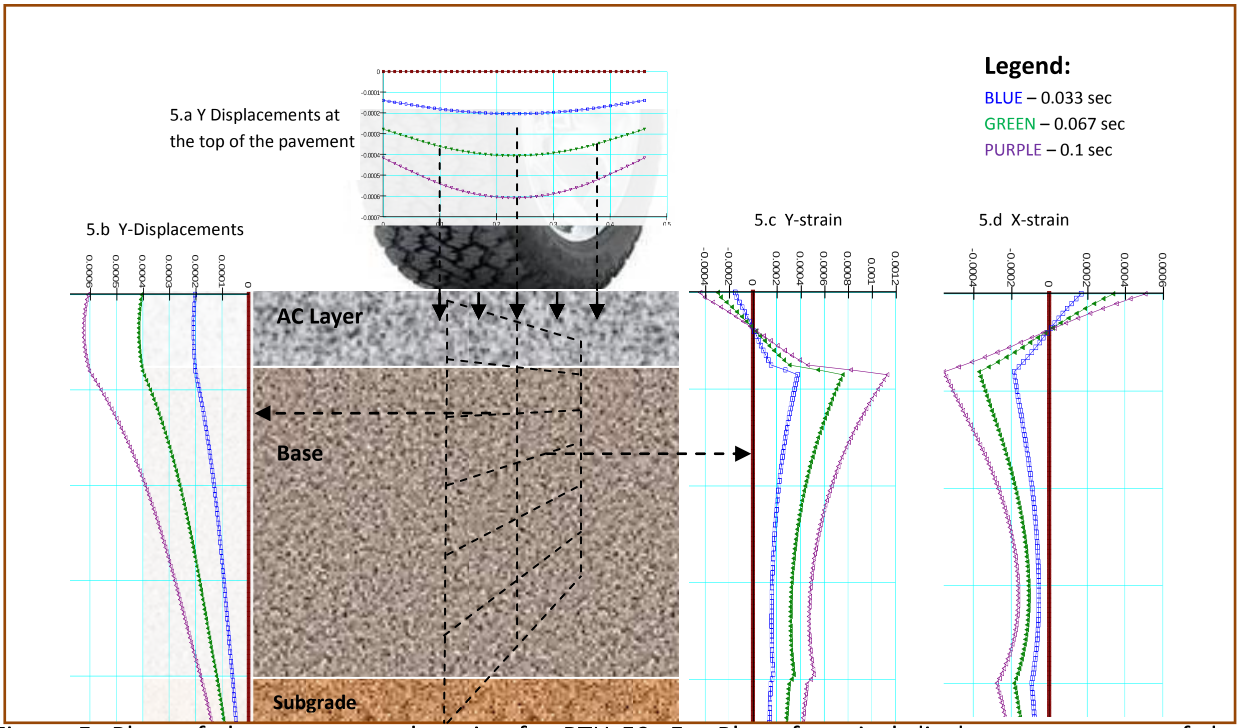

Figure 5: Plots of shear stress and strains for PTH 59: 5.a Plot of vertical displacement at top of the pavement; 5.b Plot of Y displacements versus depth; 5.c Plot of Y-strain versus depth, and; 5.d Plot of X-strain versus depth.

The weighted modulus for each scenario was calculated in the same way.

Using the data from the mechanistic analysis, linear regression models to estimate the tensile strain at the bottom of the asphalt layer and compressive strain on top of the subgrade were developed for asphalt pavements. The parameters included in the preliminary models were the thicknesses of the asphalt and base layers and the FWD central deflection measured in the summer. The models are given below.

2. $\varepsilon_t = -5.0311x10^{-5} - 9.0669x10^{-7}t_{AC} + 5.2058x10^{-7}t_{base} - 6.695x10^{-7}FWD_{cd}$ $R^2 = 0.998$

3. $\varepsilon_c = -6.4648x10^{-4} + 6.0742x10^{-6}t_{AC} - 1.316x10^{-6}t_{base} + 1.9277x10^{-6}FWD_{cd}$ $R^2 = 0.944$

where:

ε_t = tensile strain at the bottom of the asphalt layer

ε_c = compressive strain at the top of the subgrade

Similarly, for AST roads, the model for predicting the compressive strain at the top of the subgrade is given below.

4. $\varepsilon_c = -0.01403 + 1.5113x10^{-5} t_{gravel\ surface} + 1.4686x10^{-5} FWD_{cd}$ R^2= 1.0

Impact of Climate Change on Thick Bitumnous Pavements

Two thick bituminous pavement sections, PTH 59 and PTH 11 were included in the study. PTH 59 (a strong pavement) has no restrictions in spring while PTH 11 (a moderately weak pavement) is restricted to Level 1 (90% of the normal weights). As shown in Table 6, using the AI and Miner's models, thick pavements will most likely fail due to fatigue of the HMA layer. Fatigue cracking at the HMA layer starts at the bottom, where the location of the critical tensile strain is, and develops upwards to the surface of the pavement. The extension of spring season has the highest impact on the life of thick (strong) pavements (>150 mm AC) which is not spring weight restricted. The early removal of the spring restrictions when the pavement and the subgrade are still recovering from the effect of thawing has significant impact on moderately weak pavement on PTH 11. This condition could happen when continuous intermittent high and low air temperatures in early spring causes refreezing of the pavement and/or continuous low temperatures throughout the spring season, thus slowing the thawing of the subgrade which could then delay the time required for the subgrade to recover its strength. This condition could get worse if there is a sudden increase in the air temperature and the required CTI of 440 deg-days to lift the spring restrictions is attained in a very short time. Also, PTH 11 has an older asphalt surface which could have reduced its fatigue resistance thus affecting the bottom layers of the pavement including the subgrade. Allowing the WSW 7-14 days before the required frost depth and pavement modulus is achieved had insignificant impact on the life of the thick pavement sections analyzed.

The estimated number of load repetitions to fatigue cracking using the MEPDG model (See Table 7) is considerably higher compared to those calculated using the models developed by the Asphalt Institute and Miner's Hypothesis. The calculated load repetitions to fatigue failure for PTH 59 for Scenarios 1 to 5 are higher than the typical condition which does not appear to be reasonable. For these five scenarios, the calculated weighted AC modulii are lower compared to the AC modulus for the typical condition and the calculated weighted strains from the mechanistic analyses are higher compared to the strain for the typical condition. A high strain means that there is a reduction in the fatigue life of the pavement for these scenarios. However, the MEPDG model for calculating the number of load repetitions to fatigue failure gives more weight to the AC modulus than the strain that tend to show increase in fatigue life due to the decrease in the AC modulus.

The results also show that the late removal of the winter weight premium could reduce the service life of PTH 59 by 1.4%. For PTH 11, the removal of the spring restrictions when the subgrade is still recovering from the effects of thawing has the highest impact on the service life of the pavement, reducing it by almost 6.9%. The impact of early and delayed implementation of WSW does not have significant impact on the life of the pavement.

Table 6: Estimated number of load repetitions to fatigue and rutting failures for thick pavements using the Asphalt Institute and Miner's models.

Test Section	Pavement Structure	Scenarios	Nf, Number of Load Repetitions to Fatigue Failure				Nr, Number of Load Repetitions to Rutting Failure				NOTES
			Nf_1, AI Model	Change in Nf_1	Nf_2, Miner's Hypo	Change in Nf_2	Nr_1, AI Model	Change in Nr_1	Nr_2, Miner's Hypo	Change in Nr_2	
PTH 59		T	4.24E+06		1.03E+07		7.48E+09		9.54E+08		Typical
	AC (150 mm)	1	4.07E+06	-4.06%	9.88E+06	-4.20%	7.12E+09	-4.80%	9.14E+08	-4.17%	SWR imposition is delayed for 7 days
	Base (650 mm)	2	3.91E+06	-7.90%	9.47E+06	-8.18%	6.78E+09	-9.33%	8.76E+08	-8.12%	SWR imposition is delayed for 14 days
		3	4.03E+06	-5.06%	9.70E+06	-5.99%	7.05E+09	-5.74%	9.06E+08	-4.98%	SWR removed 7 days before summer modulus is reached
	Sub – grade	4	4.34E+06	0	1.03E+07	-0.06%	7.09E+09	-5.24%	9.10E+08	-4.55%	WSW allowed 7 days before winter modulus is reached
		5	4.45E+06	0	1.03E+07	-0.12%	6.72E+09	-10.15%	8.69E+08	-8.84%	WSW allowed 14 days before winter modulus is reached
		6	4.23E+06	-0.44%	1.03E+07	-0.42%	7.24E+09	-3.21%	9.27E+08	-2.78%	WSW not removed for 7 days at pre-spring modulus
PTH 11		T	3.70E+05		9.19E+05		3.44E+06		1.24E+06		Typical
	AC (130 mm)	1	3.64E+05	-1.76%	9.00E+05	-2.03%	3.14E+06	-8.64%	1.15E+06	-7.52%	SWR imposition is delayed for 7 days
	Base (335 mm)	2	3.57E+05	-3.47%	8.82E+05	-4.01%	2.88E+06	-16.39%	1.07E+06	-14.34%	SWR imposition is delayed for 14 days
		3	3.49E+05	-5.71%	8.72E+05	-5.13%	3.02E+06	-12.13%	1.11E+06	-10.57%	SWR removed 7 days before summer modulus is reached
	Sub – grade	4	3.68E+05	-0.68%	9.08E+05	-1.17%	3.41E+06	-0.97%	1.23E+06	-0.84%	WSW allowed 7 days before winter modulus is reached
		5	3.65E+05	-1.35%	8.98E+05	-2.33%	3.37E+06	-1.92%	1.22E+06	-1.67%	WSW allowed 14 days before winter modulus is reached
		6	3.69E+05	-0.41%	9.15E+05	-0.39%	3.42E+06	-0.50%	1.24E+06	-0.43%	WSW not removed for 7 days at pre-spring modulus

Table 7: Estimated number of load repetitions to failure for thick pavements using the Mechanistic-Empirical Pavement Design Guide model.

Scenarios	Test Section	Pavement Structure	Nf	Change in Nf_2	Test Section	Pavement Structure	Nf	Change in Nf_2	NOTES
T	**PTH 59**		3.51E+08		**PTH 11**		6.10E+06		Typical
1		AC (150 mm)	4.38E+08	Increase		AC (130 mm)	5.98E+06	-2.00%	SWR imposition is delayed for 7 days
2		Base (650 mm)	5.53E+08	Increase		Base (335 mm)	5.86E+06	-3.93%	SWR imposition is delayed for 14 days
3			3.72E+08	Increase			5.68E+06	-6.92%	SWR removed 7 days before the summer modulus is reached
4		Subgrade	3.63E+08	Increase		Subgrade	6.06E+06	-0.65%	WSW allowed 7 days before the winter modulus is reached
5			3.77E+08	Increase			6.02E+06	-1.29%	WSW allowed 14 days before the winter modulus is reached
6			3.46E+08	-1.40%			6.07E+06	-0.49%	WSW is not removed for 7 days at pre-spring modulus

Impact of Climate Change on Medium Thick Bituminous Pavements

Medium-thick bituminous pavements are those that have 100 to 125 mm thick AC layer. The MEPDG model for fatigue gives higher estimates on the number of load repetitions to fatigue failure compared to the other two models (See Tables 8 and 9). When applying the MEPDG models, the delay in the imposition of SWR and early removal of the SWR showed reductions in the life of the two medium thick pavement sections i.e., the results are reversed from that shown for thick bituminous pavements. The results for early start and late end of the WSW scenarios also reversed. Table 8 provides a summary of the number of load repetitions to fatigue failure for different scenarios using the MEPDG model.

Table 8: Estimated number of load repetitions to fatigue failure for thick pavements using the Mechanistic- Empirical Pavement Design Guide (MEPDG) model.

Scenarios	Test Section	Pavement Structure	Nf	Change in Nf	Test Section	Pavement Structure	Nf	Change in Nf	NOTE
T	PR 283		1.03E+06		PR 210		1.32E+06		Typical
1		AC (100 mm)	9.61E+05	-6.70%		AC (100 mm)	1.22E+06	-7.58%	SWR imposition is delayed for 7 days
2		Base (300 mm)	8.95E+05	-13.11%		Base (400 mm)	1.13E+06	-14.39%	SWR imposition is delayed for 14 days
3			9.55E+05	-7.28%			1.23E+06	-6.82%	SWR removed 7 days before the summer modulus is reached
4		Subgrade	1.03E+06	0.00%		Subgrade	1.31E+06	-0.76%	WSW allowed 7 days before the winter modulus is reached
5			1.02E+06	-0.97%			1.30E+06	-1.52%	WSW allowed 14 days before the winter modulus is reached
6			1.03E+06	0.00%			1.30E+06	-1.52%	WSW is not removed for 7 days at pre-spring modulus

When adopting Miner's Hypothesis, the test section on PR 283, which has an older asphalt layer is likely to fail by rutting of the subgrade. The test section on PR 210, which has a newer asphalt layer, could also fail due to rutting at the subgrade but if the spring restrictions are delayed for days, this section could fail in fatigue. The AI model on the other hand predicts that the two pavement sections will fail due to fatigue of the asphalt layer (See Table 9).

The results also show that the delayed imposition of spring restrictions on medium-thick pavements will result to greater damage to pavements with older asphalt surface layer compared to those pavements with newer asphalt overlay. The deteriorated asphalt layer as a result of the aging of the binder and the presence of fatigue and thermal cracks makes the base and the subgrade more vulnerable to higher amounts of rutting.

Table 9: Estimated number of load repetitions to fatigue and rutting failures for medium-thick pavements (100 to 125 mm asphalt layer thickness) using the Asphalt Institute and Miner's models

Test Sections	Pavement Structure	Scenarios	Nf, Number of Load Repetitions to Fatigue Failure				Nr, Number of Load Repetitions to Rutting Failure				Notes
			Nf_1, AI Model	Change in Nf_1	Nf_2, Miner's Hypothesis	Change in Nf_2	Nr_1, AI Model	Change in Nr_1	Nr_2, Miner's Hypothesis	Change in Nr_2	
PR 283 BIT		T	8.31E+04		2.08E+05		1.89E+05		1.01E+05		Typical
	AC (100 mm)	1	7.81E+04	-6.00%	1.95E+05	-6.16%	1.72E+05	-9.02%	9.35E+04	-7.85%	SWR imposition is delayed for 7 days
	Base (300 mm)	2	7.35E+04	-11.53%	1.83E+05	-11.83%	1.57E+05	-17.07%	8.63E+04	-14.94%	SWR imposition is delayed for 14 days
		3	7.77E+04	-6.49%	1.95E+05	-6.38%	1.80E+05	-4.88%	9.72E+04	-4.23%	SWR removed 7 days before summer modulus is reached
	Sub – grade	4	8.26E+04	-0.55%	2.06E+05	-0.75%	1.86E+05	-1.55%	1.00E+05	-1.34%	WSW allowed 7 days before winter modulus is reached
		5	8.21E+04	-1.09%	2.05E+05	-1.49%	1.84E+05	-3.07%	9.88E+04	-2.66%	WSW allowed 14 days before winter modulus is reached
		6	8.25E+04	-0.63%	2.07E+05	-0.60%	1.88E+05	-0.87%	1.01E+05	-0.76%	WSW not removed for 7 days at pre-spring modulus
PR 210		T	9.48E+04		2.40E+05		4.89E+05		2.30E+05		Typical
	AC (100 mm)	1	8.86E+04	-6.56%	2.24E+05	-6.60%	4.87E+05	-0.31%	2.30E+05	-0.26%	SWR imposition is delayed for 7 days
	Base (400 mm)	2	8.29E+04	-12.55%	2.10E+05	-12.63%	4.86E+05	-0.61%	2.29E+05	-0.53%	SWR imposition is delayed for 14 days
		3	9.04E+04	-4.63%	2.28E+05	-4.86%	4.45E+05	-9.02%	2.12E+05	-7.85%	SWR removed 7 days before summer modulus is reached
	Sub – grade	4	9.41E+04	-0.73%	2.38E+05	-0.75%	4.86E+05	-0.66%	2.29E+05	-0.57%	WSW allowed 7 days before winter modulus is reached
		5	9.35E+04	-1.45%	2.37E+05	-1.49%	4.82E+05	-1.31%	2.28E+05	-1.13%	WSW allowed 14 days before winter modulus is reached
		6	9.46E+04	-0.20%	2.40E+05	-0.19%	4.88E+05	-0.22%	2.30E+05	-0.19%	WSW not removed for 7 days at pre-spring modulus

Impact of Climate Change on Thin Bituminous Pavements

Thin pavements have asphalt layers that are less than 100 mm thick. The test section for analysis of the behaviour of thin pavements is on PR 256 located in south western Manitoba. This section was last rehabilitated in 1967. As expected, the results (Table 10) show that this section will likely fail by rutting at the subgrade. With a remaining life of barely 1,000 axle load repetitions when using the Miner's hypothesis model, the life of this section could be reduced by as much as 11 percent if the spring road restrictions is removed earlier than the required time for the pavement and the subgrade to recover from spring thaw weakening.

Both the Miner's Hypothesis and the AI models predict that thin pavements would likely fail by rutting at the subgrade for all scenarios. Extending the winter weight premium had the minimum impact for the pavement condition considered in the analysis. It is suggested that a pavement structure with thin AC and thicker base be analyzed to see whether a thicker base will reverse the failure mechanism, that is, to check whether the failure will be due to fatigue and not rutting of the subgrade. This type of failure may be easier to fix since the damage is confined at the surface of the pavement.

Table 10: Estimated number of load repetitions to fatigue and rutting failure for PR 256, thin pavement (less than 100 mm thick) using the Asphalt Institute and Miner's Hypothesis models.

Scenario	Pavement Structure	Nf, Number of Load Repetitions to Fatigue Failure				Nr, Number of Load Repetitions to Rutting Failure				Notes
		Nf_1, AI Model	Change in Nf_1	Nf_2, Miner's Hypothesis	Change in Nf_2	Nr_1, AI Model	Change in Nr_1	Nr_2, Miner's Hypothesis	Change in Nr_2	
T		3.72E+03		9.23E+03		9.11E+02		1.01E+03		Typical
1	AC (75 mm)	3.45E+03	-7.19%	8.59E+03	-6.95%	8.79E+02	-3.50%	9.75E+02	-3.03%	SWR imposition is delayed for 7 days
2	Base (150 mm)	3.21E+03	-13.72%	8.00E+03	-13.28%	8.48E+02	-6.85%	9.46E+02	-5.95%	SWR imposition is delayed for 14 days
3		3.43E+03	-7.77%	8.48E+03	-8.05%	7.90E+02	-13.21%	8.90E+02	-11.53%	SWR removed 7 days before summer modulus is reached
4	Sub-grade	3.72E+03	-0.08%	9.17E+03	-0.64%	9.05E+02	-0.68%	1.00E+03	-0.58%	WSW allowed 7 days before winter modulus is reached
5		3.72E+03	-0.15%	9.11E+03	-1.28%	8.98E+02	-1.35%	9.94E+02	-1.16%	WSW allowed 14 days before winter modulus is reached
6		3.72E+03	-0.07%	9.22E+03	-0.07%	9.10E+02	-0.08%	1.01E+03	-0.07%	WSW not removed for 7 days at pre-spring modulus

Impact of Climate Change on AST Roads

The AST roads are gravel roads treated with two applications of chip seal at the surface. Some of these roads are allowed to carry RTAC loadings in the winter. In the absence of models for determining the rutting of the subgrade, the Asphalt Institute and Miner's models were used to predict the number of load repetitions to failure for gravel roads. It is recommended that the results be validated by actual performance in the field.

Table 11: Estimated reduction in the service life of AST road due to subgrade rutting failure.

Scenario	PR 256		PR 283		PR 304		Notes
	Change in Nr_1 (AI Model)	Change in Nr_2 (Miner's Hypo)	Change in Nr_1 (AI Model)	Change in Nr_2 (Miner's Hypo)	Change in Nr_1 (AI Model)	Change in Nr_2 (Miner's Hypo)	
1	-1.55%	-1.34%	0.78%	0.67%	-4.25%	-3.69%	SWR imposition is delayed for 7 days
2	-3.08%	-2.67%	1.56%	1.35%	-8.29%	-7.21%	SWR imposition is delayed for 14 days
3	-6.37%	-5.53%	-8.70%	-7.57%	0.23%	0.20%	SWR removed 7 days before summer modulus is reached
4	-2.68%	-2.32%	-3.82%	-3.31%	-4.51%	-3.91%	WSW allowed 7 days before winter modulus is reached
5	-5.27%	-4.57%	-7.46%	-6.49%	-8.78%	-7.64%	WSW allowed 14 days before winter modulus is reached
6	-0.03%	-0.03%	-0.33%	-0.28%	-0.82%	-0.71%	WSW not removed for 7 days at pre-spring modulus
	Structure Base Subgrade	 200 mm Silty clay	Structure Base Subgrade	 400 mm Clay	Structure Base Subbase	 400 mm 300 mm Crushed rock	These gravel roads are treated with double chip seal.

The province may allow early and end late of the winter seasonal weights in the northern Manitoba (Zone 2) because cold temperatures generally start earlier and remain colder for longer period than the southern zone. Similarly, the SWR can start later and end later in the northern zone. Typically there is one week difference in start and end dates of the WSW and SWR. In the northern zone, winter conditions usually are longer (early start and late end). An early removal of the spring restrictions when the subgrade is still recovering, such as the case of PR 283, can result in a high reduction in the pavement life for this scenario. The results also show that the early implementation of WSW could create more damage on AST roads. Unlike asphalt pavements, the surface of AST roads could be subject to more deformation such as chipping and other forms of surface deformation when higher loads are applied and the temperature at the surface of the road is just above the freezing temperature.

PR 304 is a seasonal RTAC route consisting of a thick gravel base of 400 mm, underlain by a 330 mm of crushed rock on a clay subgrade. This road is equally sensitive to the delay in the imposition of spring restrictions and the early implementation of the winter seasonal weights. From the results, thick gravel roads could effectively reduce the impact of removing the spring restrictions earlier than the time required for the subgrade to recover its modulus.

SUMMARY OF FINDINGS AND RECOMMENDATIONS

While there is a need to verify the results of the simplified mechanistic analysis, the calculated percent reduction in the pavement life for the different scenarios identified in the study could provide an indication of the extent of damage, and its impact on the service life of the pavement when the seasonal weights are not implemented on time. The following are the findings and recommendations:

Findings:

1. The mechanistic analysis using Sigma/W and the AI and Miner's pavement distress models to estimate the life of the pavement provide reasonable prediction of the pavement behaviour and failure mechanism under load.
2. The preliminary models show that rutting and critical strains in the pavement layers and the subgrade may be estimated from the thickness of the asphalt and base layers, and the FWD central deflection readings measured in summer.
3. All pavement structures show significant reduction in pavement life when the spring restriction is not imposed on time.
4. When applying the Asphalt Institute and the Miner's Hypothesis models to estimate the number of load repetitions to rutting and fatigue failure, the results showed that thick pavements will likely fail by fatigue failure while medium-thick pavements will fail either by fatigue cracking or rutting at the subgrade. Thin pavements are likely to fail by rutting at the subgrade.
5. All models show that the service life of the asphalt pavement sections analyzed could be significantly reduced when the SWR is removed earlier than the time required for the subgrade to recover from the effects of thawing.
6. Pavement sections with older asphalt surface layer are more susceptible to increased damage than those with newer asphalt surface when the SWR is not implemented timely.
7. All the asphalt pavement sections analyzed did not show sensitivity to an earlier implementation or delayed removal of WSW. This could be due to the fact that asphalt binders become stiffer as

the temperature drops and the impact of the additional load in the winter is not high enough to cause damage in the pavement.

8. Gravel roads show high sensitivity to untimely implementation of both the SWR and WSW.

Recommendations:

The latest/earliest start and earliest/latest end dates of the WSW and SWR and the specified maximum duration of the SWR should be revised to account for the impact of climate change and protect the pavements from undue damage. The air temperatures indices (CTI and CFI) used to implement the seasonal weights in the Province may require a review to take into account the effects of intermittent rise and fall of temperature every year due to climate change at the start and during the spring restriction period. Since all the pavement structures analyzed also showed sensitivity to an early removal of the SWR, a detailed review of the required time for the subgrade to recover from the effect of thaw-weakening in spring should be conducted. Further review/refienement of the developed models and field verification of results are also recommended.

REFERENCES:

AASHTO Guide for Design of Pavement Structure. AASHTO, 1996.

L. Kavanagh, A. Shalaby, and Q. Liu. *Recommendations to Improve the Productivity of the Manitoba Trucking Industry: Use of Tire Pressure Control Systems during the SLR and a Rational Method for Ending SLR*. July 2011.

B. Xu, S. R. Ranjithan, and Y. S. Kim. *New Relationships Between the Falling Weight Deflectometer Deflections and Asphalt Pavement Layer Indicators*. In Transportation Research Record 1806, TRB, Washington D.C. 2002.

Mechanistic-Empirical Pavement Design Guide -A Manual of Practice. American Association of State Highway and Transportation Officials, August 2015, Second Edition.

M.E. Oberez, A. Ahammed, S. Hilderman, S. Kass. *Estimating the Base Layers and Subgrade Modulii for ME Pavement Design in Manitoba, 2015 Annual Conference of the Transportation Association of Canada Charlottetown, PEI,* September, 2015.