Evaluating Tire Pressure Control Systems (TPCS) To Improve Productivity and Mitigate Pavement Damage

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ABSTRACT

The imposition of seasonal load restrictions (SLR) on the thaw-weakened secondary roads interrupt the transportation of raw materials to processing facilities; for the forestry industry in particular, this has very significant impacts on productivity and costs. FPInnovations-Feric Division (Feric) has investigated the potential for Tire Pressure Control System (TPCS)-equipped trucks to travel with full, legal loading during the SLR period without accelerating road damage. The TPCS monitors and adjusts the inflation pressure of the trucks' tires from within the truck's cabin.

This paper describes an investigation to determine whether TPCS can be used to mitigate traffic generated damage to secondary roads and also reduce the need to implement load restrictions.

The methodology, design, and instrumentation of the two test sites in Dryden and Chapleau, Ontario are presented. Repeated Portable Falling Weight Deflectometer (PFWD) testing is being carried out at these sites and initial results of this examination and associated impacts of environment and traffic on the road are presented. This study also involves looking into the reliability of using the PFWD, offering lower cost alternative, instead of the FWD to monitor pavement strength and identification of the SLR period.

The use of innovative sensors and data collection techniques are proving to be very informative and advancing pavement engineering knowledge. Moreover, the paper presents a protocol for examining the TPCS technology for addressing the timber industry in crisis, reduced road maintenance budgets, and global warming increasing road damage.

237 words

BACKGROUND

The imposition of seasonal load restriction on the thaw weakened secondary roads interrupts the transportation of raw materials to processing facilities; for the forestry industry in particular, this has huge impacts on productivity and costs. In addition, transportation agencies such as the Ministry of Transportation of Ontario (MTO) are investigating the use of in situ sensors and Road Weather Information Systems (RWIS) to reduce the Seasonal Load Restriction (SLR) period. Nonetheless, restrictions are still imposed. TPCS can potentially enable trucks to still run at full loads or slightly reduced loads by utilizing TPCS. These trucks maintain a low tire pressure to reduce the truck impact and anticipated damage to the pavement. The idea behind the flattening of the tires is that the contact area of the tire with the pavement surface will increase. Thus, allowing the legal weight being transferred to the pavement and the underlying layers over a comparatively larger area. A common consensus has been developed around Canada about the phenomenon which claims negligible damages to the pavement.

This study involves a partnership with the Ontario Ministry of Transportation (MTO), Forest Engineering Research Institute of Canada (Feric), Ontario Ministry of Natural Resources (MNR) and the Centre for Pavement and Transportation Technology (CPATT).

The Forest Engineering Research Institute of Canada (FERIC) had been investigating the potential for shortening the weight restriction period (i.e. lengthening the period for hauling with full legal weights) on secondary roads by hauling with trucks having TPCS technology. These trucks could resume hauling on thaw- weakened pavements without accelerating pavement damage. From 2000 to 2003, FERIC used this modeling process to conduct full-scale tests on a variety of thin pavements in British Columbia, Canada [Bradley 2006]. During these tests, fully loaded log trucks were able to haul during the last three to five weeks of the weight restriction period with no measurable increase in pavement rutting or cracking. In 2004, The British Columbia Ministry of Transportation introduced a program to exempt trucks operating with TPCS from seasonal load restrictions on approved roads in British Columbia ***(1)***. FERIC, in cooperation with several forestry companies, conducted operational hauling under the new program in spring 2004 and 2005. The operation experienced from two to eight weeks extra hauling during the weight restriction periods. This study is aimed at quantifying the results that can further be adopted as guidelines for adoption.

The work done in British Columbia and elsewhere provides a basis for this study into the applicability of TPCS usage in Northern Ontario. In addition, work was carried out last year by FERIC in conjunction with MTO. This work is referred to as Phase 1 while the new CPATT/MTO/FERIC/MNR is referred to as Phase 2.

OBJECTIVES OF THE STUDY

Roads represent the largest in-place asset value of transport infrastructure in most countries. Keeping this asset from depreciating below some specified level while at the same time providing a desired level of service to the road users, presents a major challenge. The study is aimed at exploring a quantifiable solution to this challenge. Traffic loading, environmental conditions, subgrade soil, construction, and maintenance quality are among the various factors, which influence pavement performance. Environmental conditions can have a particularly significant impact on how well pavements will perform. Pavement designers need to pay special attention to various environmental design considerations such as freeze thaw cycles, spring thaw weakening and frost susceptible soils.

The primary goal in implementing Seasonal Load Restriction (SLR) and Winter Weight Premium (WWP) is to strike the right balance between minimizing maintenance costs associated with road damage, and minimizing economic loss due to restricting weights for trucks. Start and end dates must be properly administered. Inaccurately determining either SLR or WWP may lead to premature damage and result in higher maintenance costs or reduced economic activity.

In addition to the SLR and WWP policies, there are potential technologies which can be utilized that potentially mitigate damage. The proposed approach by FERIC to minimize pavement damage during the load restricted period involves the use of the TPCS technology. TPCS is a technology that adjusts truck tire pressures to minimize the impact of axle loads on weight restricted, thin pavement roadways during the spring thaw season.

Highway 630, in Mattawa-North Bay is the preliminary test site to examine the spring-thaw pavement weakening. Theoretically, reduced tire pressure should lower the potential for fatigue cracking on thin asphalt pavement structure. However, its potential to reduce the anticipated structural damage due to poor subgrade conditions, particularly for surface treated pavements, needs to be evaluated further. Past studies have shown that varying the tire inflation pressure only effects stresses at the asphalt pavement base layer. The only way to reduce the phenomenon of secondary rutting, which results from weak sub-grade, would be to reduce loads.

However, there is some consensus among pavement experts that the reduction of surface contact stresses may be beneficial in terms reducing fatigue cracking as well as the surface distress associated with the tire-pavement contact stress. There is no standard model (similar to the Asphalt Institute fatigue model) available for evaluating the ELSYM-5 computer software program in combination with the Asphalt Institute (AI) structural failure criteria which is only suitable for asphalt pavements. Extending this analysis to surface treated pavements may not be appropriate. Secondly, this analysis relies on measured FWD deflection measurements which may not be economical for use on a routine basis either by public sector agencies or by private industry.

Hence, in order to validate and develop an adoptable strategy towards allowing CTI/TPCS use commercially in Northern Ontario, with more insight and knowledge of pavement conditions; this study will account for all relevant parameters like behavior of different pavement layers with changing weather conditions and true comparison with ARWIS. This will enable the research team to establish benchmarks using less costly engineered technology like Portable Falling Weight Deflectometer which has compatible results as the Falling Weight Deflectometer (FWD).

PFWD has shown good reliability for seasonal stiffness variations and can be compared well with FWD on asphalt surfaces ***(2)*****.** The approach in this study is to identify and quantify the potential of effectiveness of the use of PFWD for surface treated roads with specific application to monitoring CTI/TPCS on Northern Ontario's roads.

NORTHERN ONTARIO'S LOW VOLUME ROADS

The 500 and 600-series secondary highways of Northern Ontario are subjected to SLR imposition during the spring-thaw period. These highways carry less than 1,000 vehicles per day which are part of the province's 3,715 long network of low volume roads ***(3)***. Most of these highways are rural remote access roads for industries and resources and are subject to less frequent but heavy traffic loading. Besides carrying heavy axle loads they are also experiencing variations in moisture contents and temperatures. These intensive fluctuations in moisture contents and temperatures play a vital role in the premature deterioration and design failure.

These low volume roads constitute about 20 % of the total provincial road network and are not constructed to resist the frost action in the pavement structures such as other high volume roads like the 400-series and the King's Highway ***(3)***. In order to prevent this asset from deterioration and avoiding huge maintenance cost's, the MTO uses the technique of imposing SLR when the pavement structure is considerable weak during the spring-thaw period.

PAVEMENT STRUCTURE OF LOW VOLUME ROADS IN ONTARIO

Low volume roads in Ontario generally have similar base-down-to-subgrade structural layers and only differ in the surface nature ***(4)***. Apart from a few roads, which are still gravel-surfaced since their construction in the 1950s, most of Ontario's secondary highways have been rehabilitated or re-constructed several times since 1985 and are now paved with asphalt-concrete ***(3)***. Also, thin bituminous surface treatments can be found on some portions of roads where the renovation of pavements surfaced with old asphalt concrete or the use of sealing coats was needed. Typical distresses associated with these flexible pavements are: rutting (permanent deformation), surface roughness, thermal fracture (transverse cracking) and fatigue cracking, which comprises top down cracking (longitudinal cracking) and bottom-up cracking (reflective cracking) ***(5)***.

THE FREEZE-THAW PHENOMENON

A flexible road normally transfers traffic loading vertically from one structural layer down to another in such a way that the whole pavement structure bends without rutting or breaking. It can also be interpreted as the loads are uniformly distributed over the structural layers of the flexible pavement. During winter, the pavement structure, mainly in Northern Ontario freeze from the surface to the subgrade. The available moisture in the pavement structure upon freezing behaves anomalously and the pavement structure experiences a volumetric expansion called frost heave. Provided this condition remains stable, the road exhibits increased strength that can even justify the allowance of overloaded commercial vehicles. However, warmer winters and/or the arrival of spring cause temperatures in the soil to oscillate around the freezing point with more or less amplitude and frequency. As a result, the pavement reaches a critical state where its upper layers are thawed while the lower ones are frozen. Water trapped between these layers saturates the structure and renders it unable to transfer traffic loading properly, and pavement deformation occurs. The deterioration is most dramatic when the freezing front penetrates into a fine graded, frost susceptible soil, as frost heave is amplified, and the damaging effects of pumping due to partial thawing and saturation are aggravated ***(6)***.

SPRING LOAD RESTRICTIONS (SLR) AND WINTER WEIGHT PEMIUMS (WWP)

SLR in Ontario

Seasonal load restrictions are imposed each year on low volume routes designated as "Schedule 2 Highways", usually throughout March, April and May ***(7)***. Although the SLR periods are commonly called "half load periods", section 122 of the *Highway Traffic Act* ***(8)*** specifies the load restriction limit to be 5,000 kg per single axle. Vehicles exceeding this limit have to take alternative routes or be subject to the penalties described in the *Act*. Also, oversized load permits, often called Winter Weight Premiums (WWPs), that are usually allowed as long as the pavement structure is frozen and thus assumed to be able to cope with higher loads, are restricted during an SLR period.

SLR and WWP Practices in Canada

A market scan for Transport Canada in 2005 summarized the various methods used in Canada for determining start and stop dates for load restrictions ***(6)***. The imposition of WWP is most typically done by fixed date across Canada, except in Alberta where frost depth and the number of days with temperatures less than 00C are used. Pavement structures that should receive an SLR schedule are normally identified using design and strength criteria, such as whether or not the frost penetrates down to a frost susceptible subgrade soil. Quantitative methods have progressively been introduced to complement and address limitations of the traditional expert judgment and historical records used in the decision-making process. Calendar-based imposition systems use fixed start dates derived through analysis of historical thaw data and do not take into consideration annual fluctuations. Used alone, visual observations and engineering judgment often fail to prevent the pavement damage that has been initiated in the lower layers to propagate up to the surface. In an effort to address these concerns, Manitoba, British Columbia, Québec and Alberta have recently adopted more quantitative approaches based on the monitoring of deflection and the use of threshold values (suspected to be associated to strength shifts) to trigger and lift SLR. Other analytical approaches include the use of measured and predicted temperatures as inputs for empirical-mechanistic indicators of the road's strength, such as the thaw index used in Minnesota and in Manitoba. More recently, British Columbia's truckers have shortened SLR periods through the use of Central Tire Inflation (CTI) system to abide by "reduced tire-pressure" periods.

REDUCED TIRE PRESSURE

Preliminary work in Canada and the U.S. on the use of reduced tire pressure has been encouraging to create more road-friendly trucks. Reduced tire pressure increases the footprint of the tire, which reduces the potential horizontal and vertical strain that are applied to the road surface, allowing heavier loads to be carried without increasing the damage to road structure***(6).***

A Central Tire Inflation (CTI) system allows drivers to monitor and modify tire pressures from within their cab. In addition, the use of a Global Positioning System (GPS) on the truck and a data logger allows the tracking of vehicle location and associated tire pressure. The British Columbia Ministry of Transportation adopted the use of CTI in 2004 as a means of allowing hauling through part of the SLR period. B.C. has a TPCS SLR Program by which trucks operating with tire pressure control systems (TPCS) are exempted from weight restrictions on approved routes, after road strength has recovered to a surface rebound of 1.5 mm. This haul resumption rebound applies to all truck configurations and roads, and is calculated as the average plus two standard deviations (x+2S) from a 10-point Benkelman beam test on the weakest part of the route. The haul resumption rebound is based on results from a mechanistic analysis of critical road strains conducted by FERIC, using typical truck configurations and road structures. B.C.'s restrictions are typically lifted after a surface rebound of 1.25 mm is reached so the program offers significant gains to participants. CTI systems were found to improve ride, traction and mobility ***(1)***.

FOCUS OF THE RESEARCH

This paper focuses on introducing the use of Central Tire Inflation (CTI) technology during the SLR period on low volume roads of Northern Ontario.

This study is directed at providing a realistic and straight forward approach. To fulfill the proposed approach, to realize the objectives, and to be able to achieve continuity with the research team, a two year frame was suggested to accommodate climatic conditions at a given set of loading pattern.

Phase 1 which was completed by FERIC/MTO on the project, successfully demonstrated the use of TCPS technology yet it was not done in a commercial setting. Moreover, Highway 630 in Mattawa-Ontario was surveyed for visible distresses only in the absence of any in-ground sensors, Road Weather Information System (RWIS) and weather related data. Hence, in order to validate and develop an adoptable strategy towards allowing CTI/TPCS use commercially in Northern Ontario, with more insight and knowledge of pavement conditions; the study has now accounted for all relevant parameters like behavior of different pavement layers with changing weather conditions. Therefore, two additional test sites; Highway 651 in Chapleau and Highway 601 in Dryden Ontario are instrumented with thermistor strings, soil moisture content probes, relative air and humidity probes to monitor the variations due to the changes in weather and soil moisture levels. It is also aimed at introducing the confident use of Portable Falling Weight Deflectometer for monitoring the spring rebound instead of Benkelman Beam and trailer mounted Falling Weight Deflectometer. The analysis and correlations have enabled us to establish benchmarks using less costly engineered technology like the Portable Falling Weight Deflectometer which has compatible results as the Falling Weight Deflectometer (FWD).

The PFWD has shown good reliability for seasonal stiffness variations and can be compared well with FWD on asphalt surfaces ***(2).*** The approach in this study is to identify and quantify the potential of effectiveness of the use of PFWD for surface treated roads with specific application to monitoring CTI/TPCS on Northern Ontario's roads.

MONITORING PAVEMENT STRENGTH THROUGH NON DESTRUCTIVE (NDT) TESTING TECHNIQUES DURING SLR

There a number of ways to evaluate pavement strength using the Benkelman Beam (BB), the Falling Weight Deflectometer (FWD), and the Dynaflect. These fall under the non-destructive techniques since field deflection measurements are recorded without damaging the pavement structure. Different agencies use one with the FWD being the one choice of the above devices after fixing certain threshold deflection value for imposing and lifting SLR. These readings need to be calibrated to a reference temperature and either converted to a strength measurement or used as they are. For agencies that are moving from one analysis method to another, a correlation factor between the different types of equipment readings also needs to be completed. The Benkelman beam rebound is a static measurement of road strength while the Falling Weight Deflectometer is an impact load and the Dynaflect is a vibratory load measuring device. The idea of correlating a dynamic deflection with a static deflection is open to criticism because the two methods represent two different patterns of behavior (Transport Canada 2005). Nevertheless, if the dynamic system is used simply as a faster means of obtaining a number which can be correlated to a number obtained from a static system then the idea is not as faulty. Roads regulators in B.C., Alberta and Saskatchewan have tried unsuccessfully to determine reliable calibrations so that they could move from static to dynamic methods without losing the benefit of historical static measurements. Because of the calibration problem and because each method has strengths and weaknesses a variety of methods are used by Canadian regulators (e.g., B.C., Saskatchewan and Manitoba use BBR while Alberta uses FWD).

The research proposal submitted to the MTO proposes the use of less costly device called the Portable FWD (PFWD) instead of the trailer mounted FWD. An attempt has been made to correlate the Portable Falling Weight Deflectometer (PFWD) to the FWD and then to the BB. Various agencies still use the Benkelman Beam Rebound (BBR) value as a basis for establishing spring load restrictions. Manitoba Transportation and Government Services (MTGS) have continued to improve and modify its spring load restriction practices since 1997 as detailed in [MTGS 2004]. The system uses a combination of Benkelman Beam Rebound Existing (BBRE) measurements to determine when the pavement is in the weakest state. Pavements more than 15 years in age and Asphalt Surface Treatments warrant spring load restrictions when the BBRE is more than 1.5 mm. Pavements 15 years in age or less warrant spring road restrictions when the BBRE is more than 1.65 mm.

British Columbia's Ministry of Transportation also uses BBR to establish spring load restrictions. The restrictions are based on 50 to 60 pavement sections that were monitored for several years during the spring thaw in the late 1970s. Each test section had ten test points and was tested every week from the start of thaw to the end of the pavement recovery period. The evaluation network was reduced in the early 1990s to approximately 30 sections. In addition to taking BBR measurements, frost tubes and thermometers were installed. The maximum rebound (adjusted to 10°C) was set at 1.6 mm while others are established at 1.25 mm. The B.C. system establishes spring load restrictions based on structural capacity, the conditions from the previous fall and whether or not it was wet or dry, amount of snow cover during winter and temperature during the spring including timing and duration of any warm weather. The main highways are usually restricted to 100 percent of the legal axle load, secondary highways to 70 percent of the load and roadways in poor condition to 50 percent, with details being made available on the British Columbia Ministry of Transportation website.

PORTABLE FALLING WEIGHT DEFLECTOMETER (PFWD)

The PFWD has shown promise as a tool for seasonal stiffness measurements and can be compared well with FWD on asphalt surfaces ***(2)*.** The Falling Weight Deflectometer is a device capable of applying dynamic loads to the pavement surface, similar in magnitude and duration to that of a single heavy moving wheel load. The response of the pavement is measured in terms of vertical deformation, or deflection, over a given area using seismometers. Thus, the use of FWD enables for the determination of a deflection basin caused by a controlled load. FWD generated data combined with layer thickness, can be confidently used to obtain the 'in-situ" resilient elastic module of a pavement structure. The two common types of FWDs used in data collection are the Portable Falling Weight Deflectometer (PFWD) and the Falling Weight Deflectometer (FWD). The University of Waterloo, Centre for Pavement and Transportation Technology (CPATT) is using Dynatest KPI 100 portable falling weight deflectometer for deflection data collection. FERIC has also used the similar instrument while evaluating pavement strength of our preliminary test site in Mattawa-Ontario. The portable Falling Weight Deflectometer PRIMA100 - FWD is a handy instrument for on-site measurement of stiffness in terms of Elastic Modulus of the pavement structure layers to minimize risks and optimize quality.

The PFWD's were investigated as a tool to aid in determining when to impose weight restrictions on low-volume roads during the spring thaw ***(2)***.

The PRIMA 100 FWD equipment enabling high quality data collection is very low and means a tremendous cost reduction as on-site analysis of collected data allows immediate information. Site locations can be captured by means of GPS (Geographic Positioning System), which enable presentation of data in maps or general plans of site. The data transfer system of the new generation of PFWD is very flexible and allows for wireless transfer of data. The portable FWD PRIMA 100 is powered by four 1.5 volt standard AA batteries and no extra power supply is needed. PRIMA 100 standard model has one centre geophone. Moreover, PFWD directly measure stiffness of pavement systems and compacted layers which is needed for mechanistic pavement design. The results of the first drop should always be neglected. It is recommended that the results from drops two through six be averaged to obtain results that are representative of a test location ***(2)***. Table 1 summarizes the advantages and disadvantages of the PFWD and the FWD.

Table 1*: PFWD versus FWD*

Device	Advantages	Disadvantages
PFWD	• Easy to use • Portable • Data easily interpreted • Follows seasonal stiffness changes in pavements	• Inexpensive • Need to establish values and accuracy testing • Not very durable • Records deflection and modulus at a maximum of three sensor offsets
FWD	• Simulates vehicular loads with various weights • Multi-purpose pavement applications, ranging from unpaved roads to airfields. • Accurate and fast (up to 60 test points/hr). • Records deflection/modulus at maximum of nine sensor offsets.	• Expensive • Requires a vehicle in addition to the instrument • Requires complex soft wares to interpret data

CORRELATION BETWEEN PORTABLE FALLING WEIGHT DEFLCTOMETER (PFWD), FALLING WEIGHT DEFLCTOMETER (FWD), AND BENKELMAN BEAM (BB)

The study requires the evaluation of the pavement structure through Non Destructive Testing (NDT) by using the Falling Weight Deflectometer. The DOT in British Columbia Canada is evaluating the pavement structure through wide use of the Benkelman Beam readings of 1.5 mm to 1.25 mm in order to impose and lift the SLR during the spring-thaw period. The Benkelman Beam records deflections due to the application of static loads and does not simulate vehicular rolling load. In addition, the use of Benkelman Beam is very costly whereas the FWD is cost effective and its advantage of simulating vehicular rolling load supersedes the use of the Benkelman Beam. Besides using the FWD, CPATT has proposed the use of PFWD instead of the FWD due to the following advantages.

- Easy to use
- Portable
- Data easily interpreted
- Follows seasonal stiffness changes in pavements
- Cost effective

Hence, an attempt has been made to correlate the PFWD to the Benkelman Beam through the intermediary FWD device to monitor and evaluate the pavement stiffness similar to B.C's threshold deflection values for imposition and lifting of the SLR in Northern Ontario. A correlation has already been established by Washington State DOT Materials Laboratory in 1982 between the BB and FWD

Highway 630 in Mattawa North Bay was initially tested on two different days through using the FWD and PFWD. The road consists of six test sections where each section has 30 points at an interval of 3 meters. Linear correlations are developed between the two devices for both deflection and elastic/composite modulus by taking the average of the two days. Table 2 summarizes the pavement structure details.

Table 2: ***Highway 630 Pavement Structure***

Section	Surface Treatment	Upper Binder Layer	Granular Base	Lower Binder Layer	Granular (mm)			Total Pavement Thickness (mm)
					Granular A 'Base'	Granular 'B' Subbase	Total	
1	30			110	270		270	410
2	60		300	80	390	170	560	1000
2	20	80	250	60	210		210	620
3	20	110	150	140	100		100	520
4	40		210	70	430	250	680	1000
5	70				170	370	540	610
6	20		180	100	310		310	610

(A) FALLING WEIGHT DEFLECTOMETER (FWD) VERSUS PORTABLE FALLING WEIGHT DEFLECTOMETER (PFWD)

The following equations based on linear relations made on best R^2 values have been derived for the two different devices based on deflection tests conducted on Highway 630 Mattawa-Ontario. The tests were conducted on April 23, 2007 and May 7, 2007. The results are averaged for both deflection and modulus values.

1. Deflection, Do (um)
   $[FWD]_{Do} = 3.002\ [PFWD]_{Do} - 315.55$ (1)

2. Modulus of Elasticity, Eo (MPa)
   $[FWD]_{Eo} = 1.7991[PFWD]_{Eo} - 33.6955$ (2)

(B) BENKELMAN BEAM TO FWD

According to Washington State DOT Materials Laboratory in 1982-1983, the following relations are being used for correlating the Benkelman Beam with the Falling Weight Deflectometer.

$BB = 1.33269 + 0.93748\ [FWD]_{Do}$ (3)

Where BB = Benkelman Beam Deflection (inches x 10^{-3})
FWD = FWD center-of-load deflection (inches x 10^{-3})

According to the condition in this case, "the threshold rebound value by the Benkelman Beam testing is kept be 1.5mm", therefore the corresponding deflection values for FWD are calculated as under.

BB = 1.5 mm = 1.5/ (10 x 2.54) = 0.059 inches = 59 inches x 10^{-3}

Inserting this value of BB in Equation 3,

$59 \times 10^{-3} = 1.33269 + 0.93748\ [FWD]_{Do}$

Or $[FWD]_{Do}$ = 61.5131 inches x 10^{-3}

Converting (inches x 10^{-3}) into (mm x 10^{-3}),

$[FWD]_{Do} = 1562.4327 \times 10^{-3} = 1562.43$ (um)

(C) BENKELMAN BEAM TO PFWD

In terms of BB deflection (Do) of 1.5 mm, the corresponding deflection for the PFWD is calculated as under.

According to Equation 1,

$[FWD]_{Do} = 3.002\ [PFWD]_{Do} - 315.55$

Inserting the value of $[FWD]_{Do}$ = 1562.4 (um) = 1.56 mm

$[PFWD]_{Do}$ = 625.57 (um) =0.62 mm

Similarly the corresponding PFWD value with the BB value of 1.25 mm for lifting the SLR is calculated to be 500 um or 0.50 mm.

Resultantly, the above correlations indicate that for a BB value of 1.5 mm deflection the corresponding value of FWD deflection should be 1.56 mm, and that of the PFWD should be 0.62 mm. Or if we round of the numbers we get the following inter conversion relation 1.5 mm of BB deflection =1.5 mm of FWD deflection = 0.6 mm of PFWD deflection.

LINEAR REGRESSION MODEL BETWEEN FWD AND PFWD

Table 2 summarizes values of the pavement composite layer modulus (E_o), and Resilient Modulus (M_R) of subgrade for Highway 630 on April 23, 2007 and May 7, 2007. The composite layer modulus (E_o) is recorded directly from the FWD or PFWD data while the values for resilient modulus of the subgrade are derived through back calculation as described in AASHTO Guide for Design of Pavement Structures.

Figures 1 and 2 demonstrate the correlation between the FWD and PFWD's resilient modulus M_R. The R-squared value for M_R between the two devices on April 23, 2007 is 0.62 and it is 0.38 on May 7, 2007. Literature review of the past researches show the same or slightly lesser R-squared values for thin asphalt surface treated roads. The reason behind this being the fact that the FWD which has the capacity of simulating heavier vehicular loads (40-80 KN) indicates a representative value of the subgrade modulus. On the other hand the PFWD which is sometimes also called the Light Weight Deflectometer (LWD) can simulate loads from 15 -20 KN. Though the above fact is inevitable yet regression model is linear and is relied upon for interpreting the correlation for the study.

Figures 3 and 4 demonstrate a similar linear correlation for layer composite modulus with R-squared values of 0.47 and 0.62 for the data recorded on April 23, 2007 and May 7, 2007. Equation 1 is derived by averaging the two linear models shown in Figures 1, 2, 3, and 4.

Table 2: Averaged Pavement Layer Modulus and Resilient Modulus

SEC	April 23,2007				May 7, 2007			
	PFWD M_R (MPA)	FWD M_R (MPA)	PFWD Eo (MPA)	FWD Eo (MPA)	PFWD M_R (MPA)	FWD M_R (MPA)	PFWD Eo (MPA)	FWD Eo (MPA)
1	24	28	151	302	27	20	151	320
2	25	24	151	228	26	17	157	268
3	21	15	127	141	24	15	143	234
4	18	14	110	125	18	11	112	177
5	20	14	120	134	21	13	113	215
6	21	16	171	195	29	14	180	283

Six sections are selected in a length of about nine kilometers road. Sections are selected and laid out jointly with FERIC. Sixty points are marked at an interval of 3 meters in each section as shown in Figure 12; 30 points each in north and south bound. The two devices used were CPATT's Prima 100 PFWD and Applied Research Associate's trailer mounted FWD.

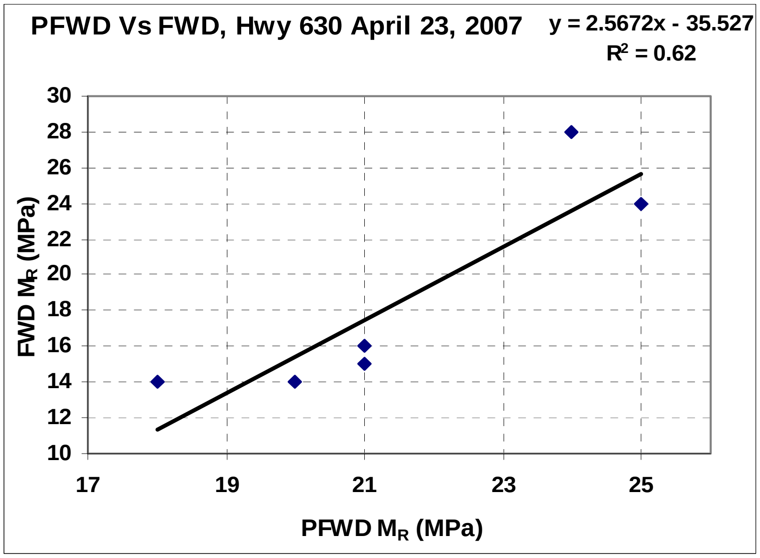

Figure 1: ***PFWD versus FWD, Subgrade Resilient Modulus-Highway 630***

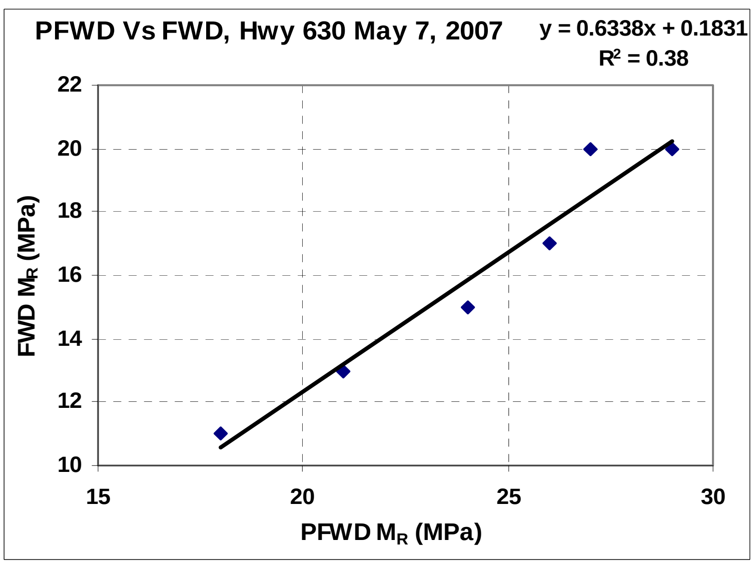

Figure 2: ***PFWD versus FWD, Subgrade Resilient Modulus-Highway 630***

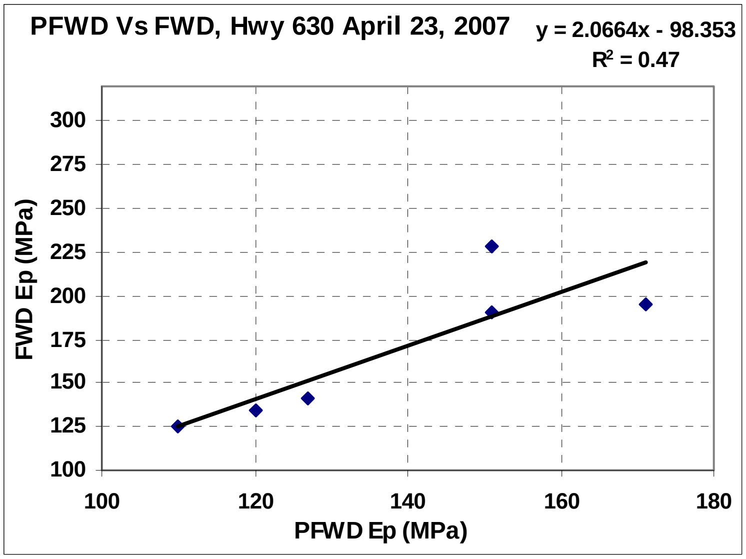

Figure 3: ***PFWD versus FWD, Layer Composite Modulus-Highway 630***

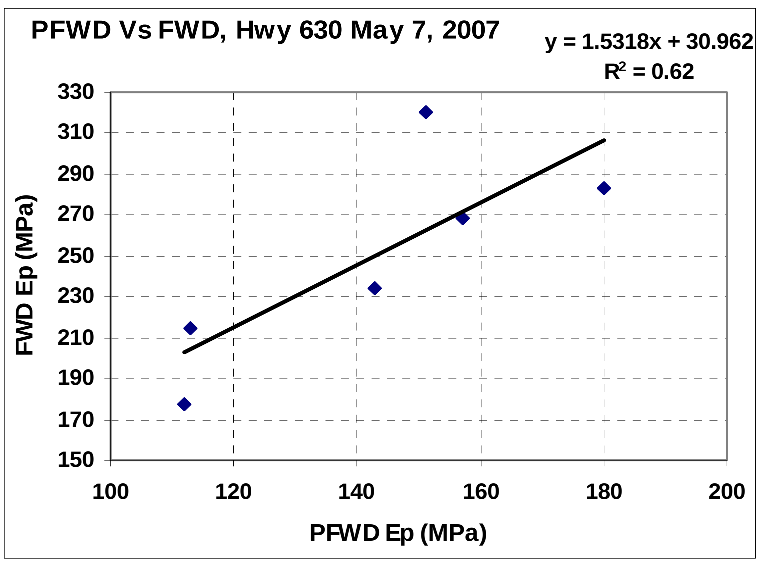

Figure 4: ***PFWD versus FWD, Layer Composite Modulus-Highway 630***

Table 3 summarizes the deflection recorded by the PFWD and FWD on Highway 630 on the two dates mentioned in the table. Figure 5 and Figure 6 shows the correlation trend and R-squared values. The correlation gives R-squared value of 0.81 and 0.62 on April 23, 2007 and May 7, 2007 respectively. The relation is linear and the regression model developed is averaged to derive Equation 1.

Table 3: ***Averaged PFWD and FWD Deflections on Highway 630***

SECTION	4/23/2007		5/7/2007	
	PFWD Do (um)	**FWD Do (um)**	**PFWD Do (um)**	**FWD Do (um)**
1	369	522	330	550
2	369	714	330	680
3	446	1131	372	773
4	495	1256	454	1018
5	442	1159	386	821
6	313	843	290	658

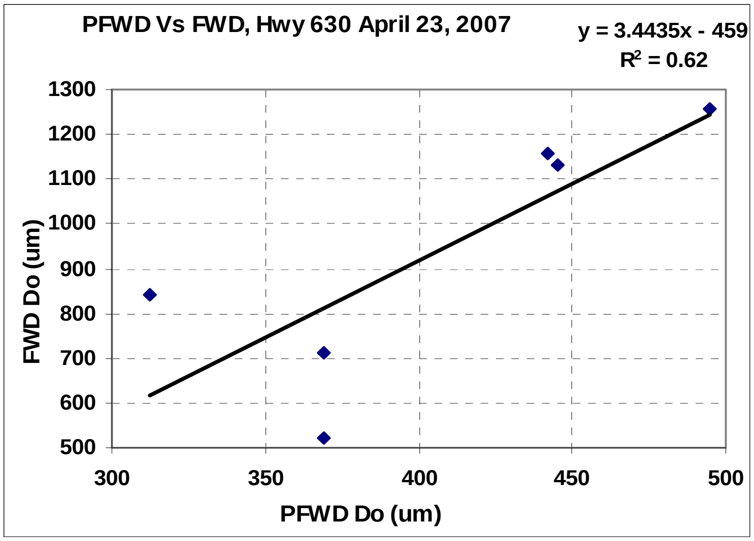

Figure 6: ***FWD versus PFWD for Deflection Do-Hwy 630***

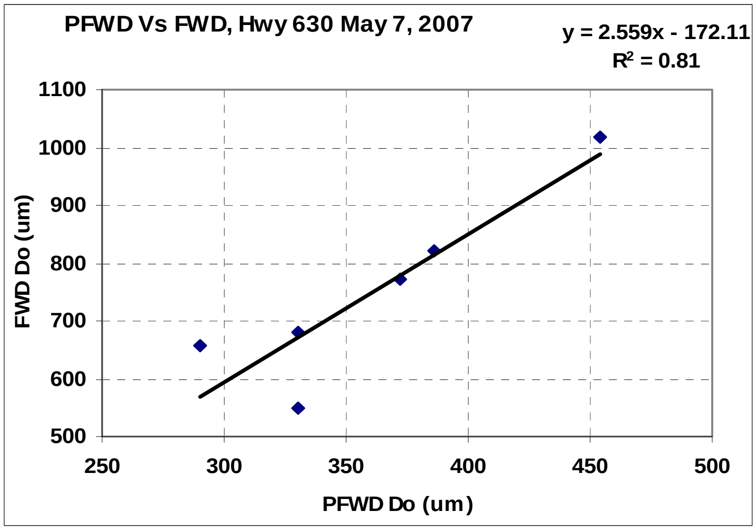

Figure 5: ***FWD versus PFWD for Deflection Do-Hwy 630***

INNOVATIVE USE OF INSTRUMENTATION

Highway 651 and Highway 601 are instrumented to monitor in-situ freezing and thawing progression in the pavement structure with variable climatic conditions especially the change of universal global warming. Thermistor strings, relative humidity (RH) probes-air temperature sensors and water content gauges were installed at the two locations. The data loggers are programmed to record real time data after every hour which is downloaded to a computer via a cable or it is retrieved through a high profile flash memory card. The research is on-going and this real time data will be analyzed and finally compared with the ARWIS data. The variability will be quantified and tools will be developed to project and convert the ARWIS data to real time data.

TIRE PRESSURES AND PAVEMENT PERFORMANCE

The effects of tire pressure on pavement performance with regards to fatigue and rutting failure depends generally on two pavement properties: pavement thickness and stiffness of the base and subgrade layers. In the studies reviewed, asphalt pavement thickness ranged from 25 mm to 250 mm. With regard to fatigue failure, when asphalt concrete pavement thickness is in excess of 100 mm the effects of tire pressure on tensile strains were found to be relatively minor. Roberts found that for asphalt concrete pavement thickness 100 mm or greater, the effect of tire inflation pressure on tensile strains was less than ten percent ***(9)***, while Sebaaly reached the same conclusion noting that the effect of inflation pressure was as low as one percent for asphalt layers with thicknesses of 100, 150, and 300 mm ***(10)***. Hence, this and many more studies regarding the subject have potentially encouraged us to explore the effects of reduced tire pressure on surface treated “Schedule 2 Highways” performance.

In addition to this, CTI-Trials on the Highway 630 in Phase 1 of the study have shown good results with trucks hauling with the TPCS installed with full legal loads and varying tire pressures. FERIC’s report IR-2006-12-22 concludes that initiation of a TPCS technology in Ontario and thereby promote an economic advantage for industry and small communities, and enhance public safety on the highway while safe guarding public investment in the infrastructure.

TIRE PRESSURE AND WHEEL LOAD

Tire influences the quality of surface (wearing) coarse. In fact the magnitude of the vertical pressure at any depth of soil subgrade or pavement section depends upon the surface pressure as well as on the total wheel load.
The equation for vertical stress computations under a uniformly distributed circular load based on Boussinesq’s theory is given by:

$$\sigma_Z = q\,[1 - z^3 / (a^2 + z^2)^{3/2}] \qquad \textbf{\textit{(11)}}$$

Here σ_Z = Vertical stress at depth z,

q = Surface pressure or contact pressure, and
a = Radius of loaded area.

Using the above equation, the variation of vertical stress σ_Z with depth is plotted as given in Figure 6.

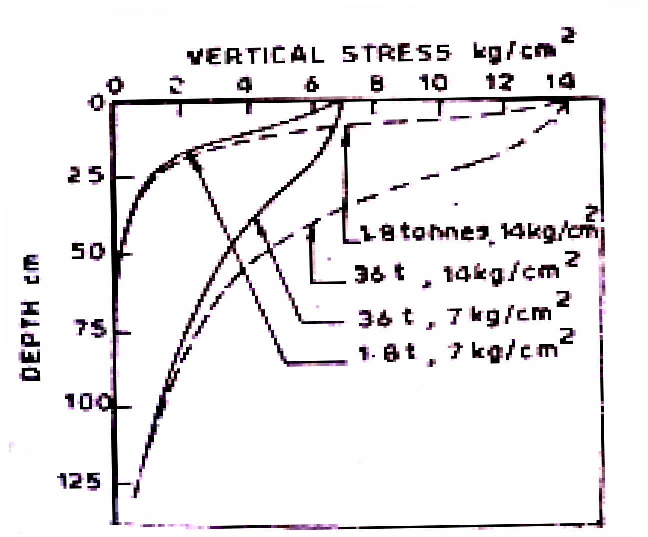

Figure 6: ***Vertical Stress Distribution (11)***

As seen from Figure 6, the influence of tire pressure is predominating in the upper layers. At a greater depth the effect of tire pressure diminishes and the total load exhibits a considerable influence on the vertical stress magnitudes. Tire pressure of higher magnitudes therefore demand high quality materials in the upper layers in pavements. The total depth of pavement is however not influenced by the tire pressure. With constant tire pressure, the total load governs the stress on the top of the subgrade within allowable limits. This also implies that narrow concentrated rolling load as that of a horse driven cart will produce very high stresses on the pavement surface. This demands the use of very strong and hard aggregates for the wearing surface of the pavement. However, the stresses at a lower level of the cart wheel are negligibly small as the gross load is very small.

CONCLUSIONS

The conclusions arrived at until now, in this study, are not yet definitive due to the fact that the study requires a one more year of exercising the unto date findings. Nevertheless, unto date conclusions are summarized as follows.

- The PFWD can be used to determine in-situ strength and provides benefits due to its portable nature. However, it does need to be examined still over a range of conditions.

- The in-situ strength monitoring with the help of innovative use of instrumentation like pavement temperature and soil moisture probes will help determine the best time to apply SLR and CTI.
- It is recommended that the "Schedule 2 Highways" that are used as accesses to industries and resources be instrumented.
- The CTI-Trial scheduled during this spring on Highways 601 and Highway 651 is expected to prove beneficial both to DOT, Forestry and Trucking Industry.
- The research team will continue to determine the best time to use CTI.

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