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Introduction to Tire Pressure Control Systems (TPCS) and synthesis of key research findings in highway and urban applications

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Reserved for FPInnovations, Feric Division staff and contract cooperators

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Introduction

Tire Pressure Control Systems (TPCS) were introduced to North American truck-based industries in the early 1990's and their numbers and applications have grown considerably since that time. The road impacts of trucks with reduced tire inflation pressures have been researched primarily by forestry-related organisations (i.e., USFS, Skogforsk, and the Forest Engineering Research Institute of Canada, now known as FPInnovations-Feric Division); recently, however, additional interests have become involved as this technology is transitioned into highway and urban applications (Figure 1).

In March 2008, FPInnovations – Feric Division presented an update on TPCS research to the Engineering and Research Support Committee (ERSC) of the Council of Deputy Ministers Responsible for Transportation and Highway Safety. At the presentation it was proposed that FPInnovations prepare a primer and synthesis of key research findings about TPCS used in on-highway and urban environments.

Objectives

The objectives of this document are to:

- Provide an introduction to TPCS and describe their costs and benefits.
- Describe existing theory of tire inflation pressure on truck–road interaction.
- Synthesise key findings from trials of reduced inflation pressures on pavement damage and vehicle performance.
- Summarise the special case of TPCS use on thaw-weakened roads.

Figure 1. TPCS on cement mixer in Québec.

TPCS configuration, operation, and safety features

TPCS configuration

TPCS are on-board electro-mechanical systems that permit a vehicle operator to monitor and adjust (inflate/deflate) tire inflation pressures even when the vehicle is in motion. TPCS consist of three main assemblies: a cab-mounted operator control, a valve control assembly, and air transfer plumbing to the tires. The cab-mounted operator control displays the current tire inflation of each group (channel) of tires controlled, alerts the operator of TPCS-related safety concerns, and allows the operator to select between pre-programmed operating modes (e.g., highway loaded, secondary road unloaded). The valve control assembly measures the inflation pressure of each channel and varies its pressure by deflating and inflating within strict parameters defined by the operator control. Air for inflations (and deflations in the case of the Roadranger TPCS) is taken from the vehicle's compressed air supply but only after the air brake system requirements are fully met. Air supply lines for each channel link the valve control assembly to the associated tires. Non-driven axles are all plumbed internally. The Dana Spicer Roadranger TPCS (Spicer® TPCS) features entirely internal drive axle plumbing while the TPC International TIREBOSS™ TPCS has externally routed drive tire air supply lines (Figure 2). Steering axle tires on North American trucks are typically not equipped with TPCS because their loading is relatively heavy and constant, and this limits the opportunity for pressure variation if the truck is equipped with conventional tires.

TPCS cost

The cost of a TPCS varies with make, number of channels, and number of tires in each channel. Installed cost before tax of a TIREBOSS™ TPCS ranges from approximately C$10,500 (for tandem drive axles only) to C$22,500 (for an 8-axle B-train with drive and trailer channels and the recommended air dryer upgrade).

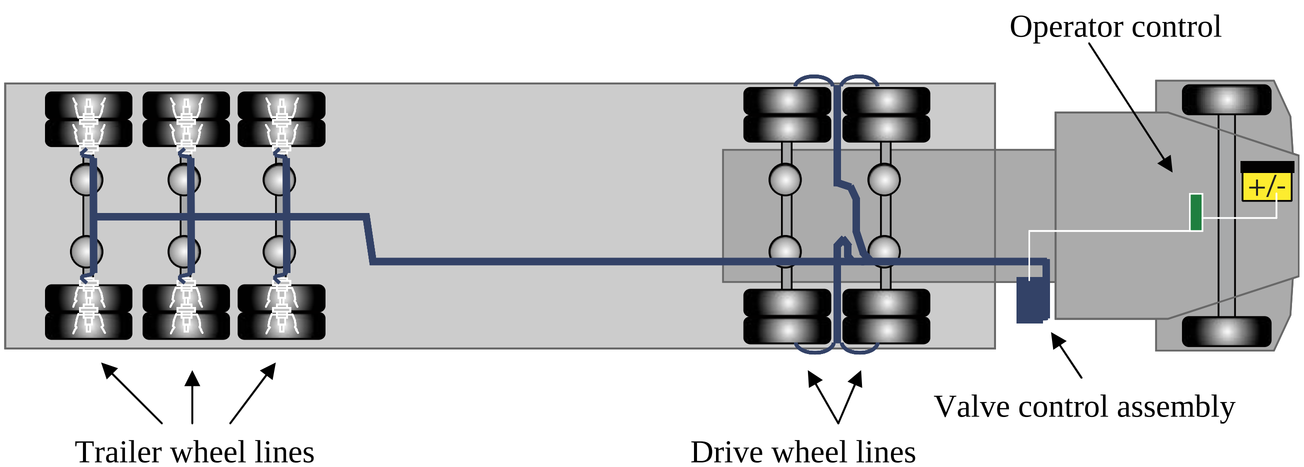

Figure 2. TIREBOSS™ TPCS 2-channel configuration.

TPCS operation

TPCS is a mature technology that was specifically developed for use with commercial trucks. TPCS evolved from the simpler Central Tire Inflation Systems (CTIS) used on tactical wheeled military vehicles around the world. There are numerous manufacturers of CTIS; however, only two companies manufacture and distribute TPCS in North America: Tire Pressure Control International Inc. and Dana Spicer Corporation. Almost all TPCS utilised in Canada are manufactured by Tire Pressure Control International Inc. and approximately 1000 of their TIREBOSS™ TPCS are currently in service in Canada. Commercial applications in North America include log hauling, wood chip transport, concrete transport (transit mixers), sand and aggregate transport, equipment transport (low beds, float trucks), oilfield equipment transport trucks, petroleum tankers, and agriculture trucks.

Tire overheating (and catastrophic failure) may result from prolonged, excessive flexing of the tire carcass such as can occur if a tire is underinflated for its loading or travel speed. Tire manufacturers recommend setting tire inflation for the specific operating speed and tire loading in order to optimise tire performance, safety, and life. Commercial truck duty cycles involve travel at different speeds when laden and unladen creating numerous opportunities for varying tire inflations. TPCS provide the most convenient and efficient way to do this. TPCS tire inflation settings are typically based on minimum cold inflation values recommended in manufacturers' load/ inflation tables (Tire and Rim Association, Inc. 2008).[1] The Tire and Rim Association has also published two tables especially for radial tires used off-highway at reduced inflation pressures at 80 km/h (50 mph) and 56 km/h (35 mph) (Tire and Rim Association, Inc. 2007). Recommended inflation pressures range between 25 psi and the maximum pressure marked on the tire sidewall (e.g., 120 psi) (Figure 3). Trucks without TPCS typically operate at 100–105 psi, or higher, in order to meet the most demanding requirements of their haul cycle (i.e., high speed, heavily loaded operation). TPCS are recommended for use with tubeless, new or retreaded, radial tires (Cohn 1991). Tube type tires or bias ply tires in dual assemblies can be damaged when operated at reduced inflation pressures and so are not recommended for use with TPCS.

[1] The Tire and Rim Association Inc., representing almost all rubber manufacturers selling tires in North America, annually update load/inflation/speed settings for their tires in the year's 'Tire and Rim Association Inc. Year Book' and in the 'Engineering Information' book.

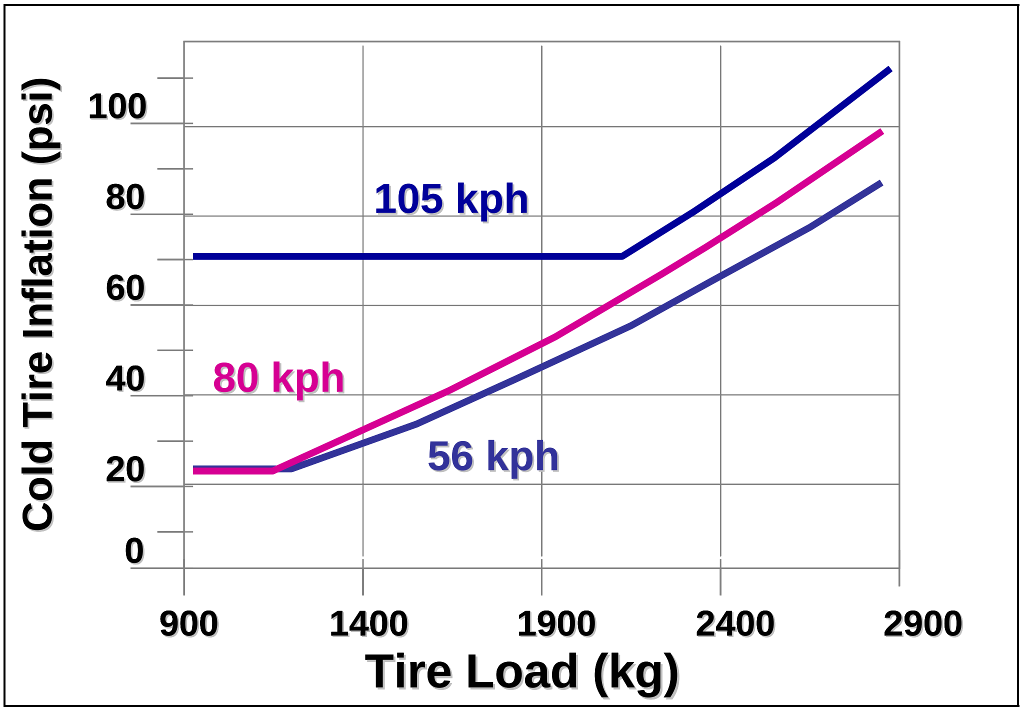

Figure 3. Tire manufacturer-recommended inflations for various loads and three operating speeds (*source: Tire and Rim Association, Inc. (2007) and Tire and Rim Association, Inc. (2008)*).

Vehicle safety and TPCS

TPCS provide for increased vehicle safety by continuously maintaining manufacturer-recommended tire inflations and thereby providing optimal traction and braking under all operating conditions. TPCS balance inflation pressures between all tires on an axle or in an axle group and this prevents tire over-loading and over-heating, and associated pavement damage. Tire damage from road hazards is increased in off-highway travel; however, operating with reduced inflation substantially increases a tire's resistance to punctures and tread face damage (Clark 1993). Reducing tire inflation has been found to reduce peak drive axle torque and thereby lessen the risk of drive line failures under poor traction conditions (Simonson 1994).

TPCS have been developed for commercial trucks operating on public highways and incorporate safety features not found in CTIS. The Society of Automotive Engineer's CTI Subcommittee was commissioned in 1992 with preparing a recommended practice for the design and performance of CTIS/TPCS. The recommended practice was never completed, however, the TIREBOSS™ TPCS and the Spicer® TPCS incorporated much of the intent and have since exceeded some recommendations. TPCS monitor system status continuously and alert the operator about the following unsafe conditions:

- *Vehicle overspeed condition.* If the vehicle's speed exceeds the set point for the current selected tire pressure mode, the operator receives a visual and audible alert to slow down or select a higher pressure mode. If the vehicle continues to speed for a specified period, typically 30–60 seconds, the TPCS will automatically increase the tire pressures to a more appropriate pressure mode.

- *Low air brake supply.* The supply of compressed air to the vehicle air brake system always has priority over the TPCS so that braking is never compromised by TPCS function. Air is available for tire inflations only when the vehicle's air brake pressure is above a safe level (typically 100 psi). If the air brake pressure falls below this level, the driver is alerted and the air supply is shut off to the TPCS.
- *Loss of tire pressure.* If a channel detects an unexpected drop in pressure caused by supply line or tire leaks, the operator is alerted. The operator is directed to immediately stop the vehicle in a safe location, check tire condition, and find and repair the source of the leak. Wheel end shut-off valves are used to isolate the tires on the leaking channel and prevent further tire deflation.
- *Valve closed condition.* The TIREBOSS™ TPCS detects line restrictions and wheel-end valves that have been left closed, and alerts the driver to this condition. The Spicer® TPCS has automatic wheel-end valves that are normally closed.
- *Secondary inflation mechanism.* TPCS have valve stems to permit the manual filling of tires in the event of a TPCS system failure.
- *Tire heat build up.* If tire pressure rises during operation above the maximum pre-set limit for the selected pressure mode, the operator will be alerted that the tires have overheated. Excessive pressure rise (e.g., more than 10–15% of cold inflation) can result from improperly selected pressure settings or from a failure of other vehicle components, such as the brakes overheating. Only TIREBOSS™ TPCS has this feature.
- *Load sensing feature.* TIREBOSS™ TPCS has the capability to sense whether a truck is loaded or not based on drive axle air suspension pressure. Only the appropriate pressure modes are made available for operator selection (i.e., unloaded pressure modes cannot be selected if the truck is loaded).

Tire changes at reduced tire inflation

Tire contact footprint

As a radial tire's inflation pressure is lowered, its contact area lengthens but does not widen. The Forest Engineering Research Institute of Canada and Toyo Tire Canada measured increases in footprint area of 67%, 89%, and 115% when tire sidewall deflections were increased from 8.5% to 15%, 23%, and 30%, respectively, for a 11R24.5 Toyo M503 drive tire (Bradley 1993). The US Army Corps of Engineers (COE) at Waterways Experiment Station measured an average increase of 54% in footprint area when sidewall deflections were increased from 10% to 21% for 11R24.5 Michelin XZY drive tires (Grau 1993).

Reducing tire pressure not only increases the tire–soil contact area but it also reduces the unit shear stress applied to the road surface. When the road surface is able to withstand the reduced shear forces, the tire is able to develop more traction with less wheel slip and less road damage. The softer tire sidewall and longer tire contact patch also serve to reduce cycle bearing loads transmitted to the road. These are the main reasons for promoting reduced inflation pressures for use on unpaved roads (Simonson 1994).

Soil shear continues to decrease until the contact print has approximately doubled in length.[2] Researchers have found that lowering tire pressures results in 12–18% lower tire slip (Nevada Automotive Test Center 1987). The reduced wheel slip results in significant traction improvements; improvements of 17–39% have been reported for various axle loadings and surface conditions (Bradley 1993; Ashmore and Sirois 1987; Sturos et al. 1995).

Michelin reported that at reduced inflation pressure, the stress distribution in a tire carcass changes and this can strongly influence tire life (Clark 1993). Reducing tire inflation lessens stresses in the tread face and improves the tire's resistance against punctures and against tread wear and cutting.

Tire contact footprint stresses

The increase in contact area with reduced tire inflation proportionately reduces the average contact pressure developed below the tire. The vertical contact pressure distribution generally is not uniform across either the length or width of the contact area, as illustrated in the 3-dimensional pressure plot of the contact area (Figure 4). The highest vertical stresses were in the middle and/or sides of the tire footprint and this distribution changed with inflation pressure and tire load. Different tire brands have different stress distributions.

Yap (1988) notes that tire loading typically influences shoulder-region contact pressures whereas inflation pressure influences centre-region contact pressures. Goodyear found that the maximum level of vertical contact pressure was about twice the tire inflation pressure. At reduced inflation pressures, the vertical pressures under the tire contact area are distributed more uniformly and peak values are decreased.

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[2] Kathleen Kreyns, USDA Forest Service. Personal communication, May 1994.

As tire load increases, the portion of the contact patch that carries vertical load grows longer. For example, Douglas et al. (2003) reported that a 4.6 kN load on a European radial truck tire at 100 psi (690 kPa) was carried by the leading 100-mm-long part of the 500-mm-long contact patch. The vertically loaded portion of the contact patch doubled in length when either tire load was quadrupled (to 19.6 kN) or inflation pressure was decreased to 15 psi (100 kPa). The vertically loaded portion of the contact patch quadrupled in length when both load was quadrupled and inflation pressure was decreased to 15 psi.

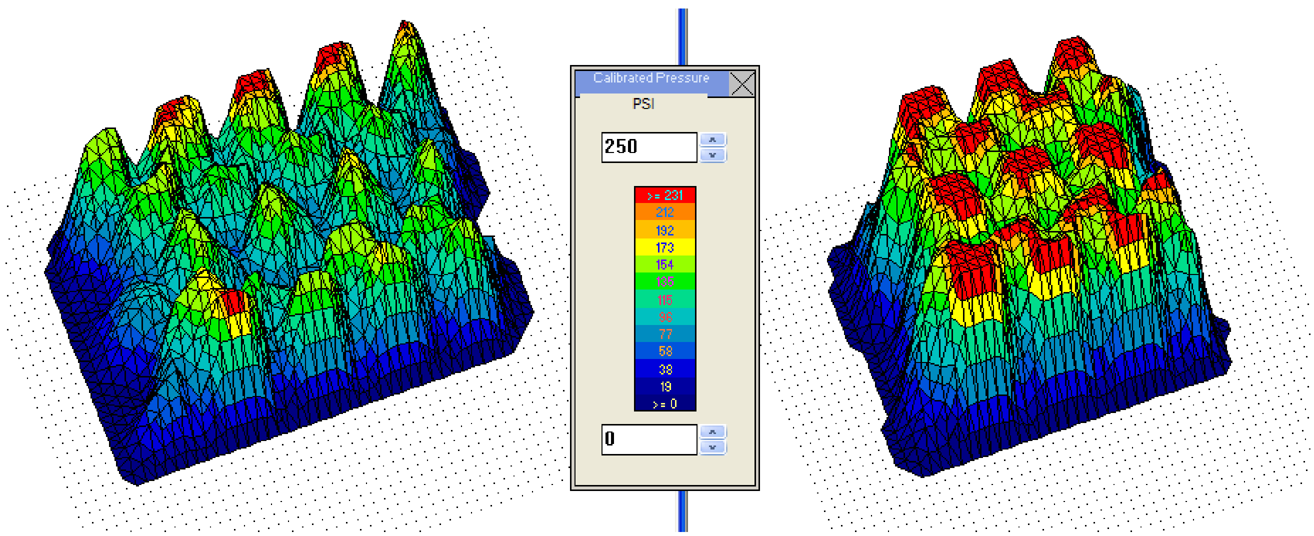

Figure 4. Vertical contact stress distribution at 65 psi (left) and 95 psi (right) for an 11R22.5 tire loaded to 2300 kg.

Tire sidewall effects

As a radial tire's inflation pressure is lowered, its sidewall vertical stiffness (spring rate) decreases. Michelin reported a 38% decrease in sidewall stiffness in an 11R22.5 truck tire when it was deflated from 690 to 480 kPa (100 to 70 psi) (Clark 1993). Reducing sidewall stiffness reduces wheel hop frequency, improves damping ratio, and improves ride.

Greater sidewall deflection increases sidewall stresses and the heat generated when the tire flexes (Clark 1993). Both flexing and heat generation can shorten tire life if not managed carefully. Increased flexing hastens the fatigue of the sidewall belts and can reduce tire recapability. The recapability of tires used in on-/off-highway service, however, is typically controlled by tread face damage rather than sidewall fatigue. Overheating a truck tire can melt the bond between rubber and the structural belts and thereby lead to belt movement or a rupture. Heat generation is proportional to travel speed and tire load, and is inversely proportional to inflation pressure. A TPCS tire heating test found that fully loaded, underinflated truck tires operated at highway speeds heated up relatively slowly but cooled rapidly in response to stopping or slowing down (Ashmore and Smith 1994). Use of tire manufacturers' published load/speed/inflation recommendations controls sidewall deflection, prevents tire overheating, and optimises tire life.

Fuel consumption, handling and braking performance

Fuel consumption

Tire Pressure Control Systems influence fuel consumption in several ways.

- By continuously monitoring, balancing and resetting tire pressures to the programmed pressures, TPCS ensure that the normal leak down by truck tires (e.g., 1 psi per month) is eliminated and that all of the tires—even the hard-to-check (inside) tires—are maintained. This provides direct but unquantified benefits in terms of improved fuel consumption, tire wear and tire maintenance costs. North American tire companies estimate an increase in fuel efficiency of 2% to 10% due to constant inflation maintenance as compared with documented industry maintenance practices (PSI 2008).
- TPCS are typically programmed with manufacturer-recommended inflations for use on- and off-highway. Recommended tire inflations generate design footprint sizes and sidewall deflections that provide optimal all-round tire performance (i.e., an optimal compromise between traction, ride, tire wear, tire life, noise, and heat control and fuel efficiency). Operating a tire on-highway at typical industry inflations (100–105 psi) and loads creates an over-inflated condition that compromises tire performance, accelerates tire wear, and is neither effective nor recommended as a fuel economy improvement method (Kenworth 2006).
- Fuel consumption is strongly influenced by vehicle speed. Bridgestone/Firestone claims that truck fuel consumption increases by 2% for every 1 km/h over 100 km/h. The TPCS's speed monitoring ability "forces" the driver to abide by the programmed maximum speed with an audible overspeed alarm that beeps continuously if the truck speeds. If the TPCS is linked to a datalogger, then the threat of compliance enforcement based on the speed record would also deter speeding.
- When travelling on loose or soft unpaved roadways, fuel consumption is strongly influenced by wheel slip and flotation. Operating at reduced tire pressures reduces wheel slip and motion resistance. Nevada Automotive Test Center (1987) and Kreyns (1994) concluded that operating trucks with reduced tire pressures on unpaved resource roads can result in fuel consumption improvements in the order of 1 to 3%. FPInnovations tests with a TPCS log truck in 2005 confirmed the aforementioned results and measured improvements on a variety of unpaved road surfaces (Table 1).

This improvement can be explained as resulting from both reduced wheel slip (i.e., better traction, less energy is wasted) and less rutting (i.e., less motion resistance) when the truck operates on soft road surfaces. Nevada Automotive Test Center (1987) and Kreyns (1994) found no improvement in fuel consumption on hard road surfaces, such as pavements—likely because the improvements in traction and rutting are minimal on hard surfaces and are cancelled out by the tires' added rolling resistance.

Table 1. Influence of fuel consumption of a TPCS-equipped log truck travelling off-highway (*Carme 2006*)

Road type	Tire pressure (drive tires/ trailer tires)(psi)					
	Unloaded			Loaded		
	TPCS off	TPCS on	Fuel savings (%)	TPCS off	TPCS on	Fuel savings (%)
Good quality gravel	100	55 / 45	6.6	100	80 / 83	2.4
Poor quality gravel	100	27 / 30	5.6	100	80 / 83	2.0
Native with mud surface	100	27 / 30	14.5	100	55 / 55	30.1

Handling

Use of low inflation pressures when loaded and travelling at highway speeds will degrade heavy truck dynamic performance and could create an unsafe condition if the vehicle already has marginal or poor stability. Woodrooffe and Divole (1997) modelled a 9-axle B-train and predicted that reducing drive and trailer tire pressures to 27 and 55 psi, respectively, would moderately degrade some dynamic performance measures, although all measures were still within TAC guidelines. The authors note that the Tire & Rim Association load/inflation guidelines apply to continuous travel at highway speeds and, therefore, vehicles operating at highway speeds over short distances or at reduced speeds over longer distances may be able to do so safely with reduced inflation pressures.

Operation of loaded trucks with reduced inflation pressures at low speeds may experience some added roll when cornering but this, in general, is readily adapted to (Ashmore and Sirois 1987) (Ashmore and Smith 1994). Drivers have found steering control in sharp curves may be influenced by steer tire pressure. Drivers from various tests have noted that high pressure tires may “drift-out” in sharp corners while low pressure tires may give “heavy” or sluggish steering without drift-out.

Braking

Stopping distance for loaded TPCS-equipped logging trucks may be reduced when tire inflation is reduced. Testing found that at reduced inflation pressure, non-locked wheel braking (i.e., ABS or controlled non-panic moderate braking) distances were decreased on loose gravel and dry pavement and were no different on wetted pavement (Smith 1994). Locked wheel braking (e.g., panic stops) testing with a small test vehicle was also conducted. Results indicated that locked wheel braking (e.g., panic stops) might have longer stopping distances at reduced inflations; however, this did not correlate well with the loaded truck stopping distance tests.

Unpublished vibration and stopping distance tests were conducted with a 50-tonne off-highway log truck by FPInnovations in August 2007 on gravel logging roads in British Columbia. The testing found that reducing inflation increased average brake retardation force by 3–8% and peak retardation force by 15–17%. Average axle shock loading also reduced by 8–32% with reduced inflation, and this is believed to be partly responsible for the braking improvement. The driver reported that there was noticeably less trailer wheel lock-up on steep grades with reduced inflations.

Ride and vibration

Ride and vehicle vibration has been found to be substantially improved by the use of reduced tire inflation pressures. Reducing radial truck tire inflation pressure increases the tire's spring rate (load-induced deflection) but the damping rate remains largely unaffected. Nevada Automotive Test Center (NATC) measured a reduction in truck vibration in the key vibration ranges that influence whole body bounce and operator ride quality. Nevada Automotive Test Center (1987) reported a range of ride improvement for test trucks at reduced inflations compared with normal, highway inflation—one-sixth the vertical energy on a smooth asphalt surface and one-seventh the vertical energy on 5-cm-high washboard. All NATC test drivers reported that ride was significantly improved at reduced inflations, laden or unladen. Compared to the truck using normal highway inflations during a closed loop test, NATC's reduced inflation truck experienced one-fourth the component failures and one-eighth the associated parts and labour cost. A Canadian operational trial similarly found that the number and severity of vibration-related repairs on a test vehicle with reduced drive tire inflations were reduced by 30% and 26%, respectively, and ride was noticeably improved (Bradley 1993).

Altunel and de Hoop (1998) analysed vibration data from a 1989 CTI closed loop test and reported that the use of reduced tire inflations decreased vibration levels in the driver seats from 10 to 25%, depending on pavement thickness and surface type. Ride improvement felt at the driver's seat was improved with reduced inflations in steering and drive axle tires but lowering trailer tire inflation had little influence. "Back slap" felt at the driver's seat is a result of the truck frame flexing vertically—predominantly in response to vertical motion of the steering and drive axles; back slap is reduced most strongly by lowering the inflation of the rearmost drive axle tires.[3] Granlund (2004) measured vibration and ride differences of a TPCS-equipped log truck travelling on five different classes of Swedish roads. Driving comfort was noticeably improved with optimised tire pressures and the level of vibration at the driver's seat was reduced by 4% to 14% (as per ISO standard 2631-1). Vibration in the vertical plane—which is most relevant to driver comfort—was between 5 and 10% lower when the TPCS was activated. The greatest improvements were obtained when the truck was unloaded and travelling on a pot-holed gravel road at speed, and when the truck was loaded and travelling slowly.

Concordia University instrumented an urban bus to see whether TPCS could improve ride quality for public transit users. The TPCS was programmed with tire pressure settings that, for a given speed, generated nearly constant sidewall deflections and contact areas regardless of passenger load. Researchers predicted that optimal tire pressures could yield significant benefits in terms of ride vibration and dynamic pavement loads (Rakheja and Wang 2006). Ride improvement was most noticeable on rough roads, and when lightly loaded or unloaded. Reductions in axle acceleration of up to 38–43% root mean squared (RMS) were measured. The shock motions measured under discrete road discontinuities, such as expansion joints, showed the most significant reductions in peak accelerations of the body and the axles with lower pressure.

Subsequent research conducted by Bodycote Testing Group, and funded by Transport Canada and the Transportation Development Centre, measured substantial reductions in chassis component vibration, loads and stresses when inflation pressures were reduced from 110 psi to 75 psi. These reductions can

[3] Doug Jones, Product Engineer, Michelin Americas Research & Development Corporation. Personal communication, May 1994.

be expected to reduce fatigue and increase life of chassis components. Bodycote predicted a 71% increase in overall bus service life when empty and a 97% increase when lightly loaded (Leslar and Fereday 2008). Apart from fewer, shorter unscheduled service interruptions and longer bus life, the improved ride may permit the use of lighter weight, lower cost, structural components. Reduced pavement damage, improved ride quality for passengers and the driver, optimal tire performance, less service interruption, and lower life cycle costs may create sufficient incentive for transit companies to implement TPCS.

Potential economic and safety benefits of TPCS

Public benefits

TPCS-SLR policies will promote several important economic and safety benefits for a province. Monitoring trip data in an incentive trucking program leverages enforcement activities, provides data for other transportation-related programs, and creates a model for regulators to encourage the adoption of other new technologies. Although the TPCS SLR hauling program was developed with the intention of providing provinces with an alternative to seasonally weight restricting trucks, it also has the potential to have a major impact on road life if TPCS use were extended into other periods of vulnerability when restrictions are not used, such as late spring or during mid-winter thaws. Use of TPCS on urban transit buses could be expected to yield lower stresses on the vehicles and on the pavement.

Truck-based industry benefits

Forest companies operating TPCS-equipped trucks during the SLR period may experience very significant savings accruing from the improved access to fresh fibre, reduction in the size of mill yard inventories, and flexibility to reschedule winter activities to the spring. In general, the use of TPCS has been found to reduce resource road grading requirements, aggregate loss and breakdown, and aggregate base requirements (Légère and Mercier 2005). Oilfield companies have experienced improved access to site locations, better vehicle utilisation and reduced impact on fields during land spraying operations. Concrete companies have experienced improved access and minimised damage to rural roadways, reduced vehicle extraction costs and savings in vehicle maintenance.[4]

Vehicle owner benefits

When associated with an incentive program, use of TPCS may result in significant economic benefits by extending the operating season, increasing payloads, and increasing the revenue earned by the vehicle. This will decrease both (fixed) ownership costs and operating costs. It may make it easier to attract and retain quality operators also as a result of the improved vehicle ride and health benefits, and the increased revenue from more hauling days and fewer delays.

[4] Brian Spreen, TPC International Ltd. Personal communication, December 2008.

TPCS offers improved vehicle safety by balancing and maintaining tire pressures, and by optimising traction and braking under all loading conditions. Increased sidewall deflection improves ride noticeably as well as reduces vibration-related damage to truck and trailer components and cargo. Increased sidewall deflection and tire contact area improves traction and mobility on soft terrain and low traction surfaces, and this may prevent drivetrain damage caused by shock loading associated with wheel slippage. Improved mobility on soft or poor traction surfaces also will increase fuel efficiency, reduce cycle times, and reduce delays and truck damage associated with vehicle assists. Fuel economy and tread wear are improved through the maintenance of tire manufacturer's recommended inflations both on- and off-highway. Tire life is extended through the reduction of tread face damage from road hazards. The ability to monitor trip data, as required under existing provincial TPCS SLR programs, can be used by owners to monitor and train drivers, and assess cycle times.

Tire inflation pressure influence on truck–road interaction

Pavement stress and strain

The change in a tire's contact area with tire pressure significantly alters the distribution of vertical stresses felt by a road surface. The highest vertical stresses are in the middle and/or sides of the tire imprint and this distribution changes with inflation pressure and tire load.

Tielking and Roberts (1987) reported that vehicle speed has almost no impact on vertical contact stresses but has a strong effect on longitudinal and transverse stresses. When a tire is rolling freely, longitudinal shear stresses develop in the middle of the contact patch, resulting in a double reversal of the longitudinal stresses from the leading edge to the trailing edge (Figure 5). As a point on the outer rib of the tire rolls into the contact patch, it is pushed toward the centre, and therefore transverse stresses also develop the contact patch. Longitudinal and transverse contact stresses are affected by tire construction (radial or bias ply), with transverse stresses being less for radial tires.

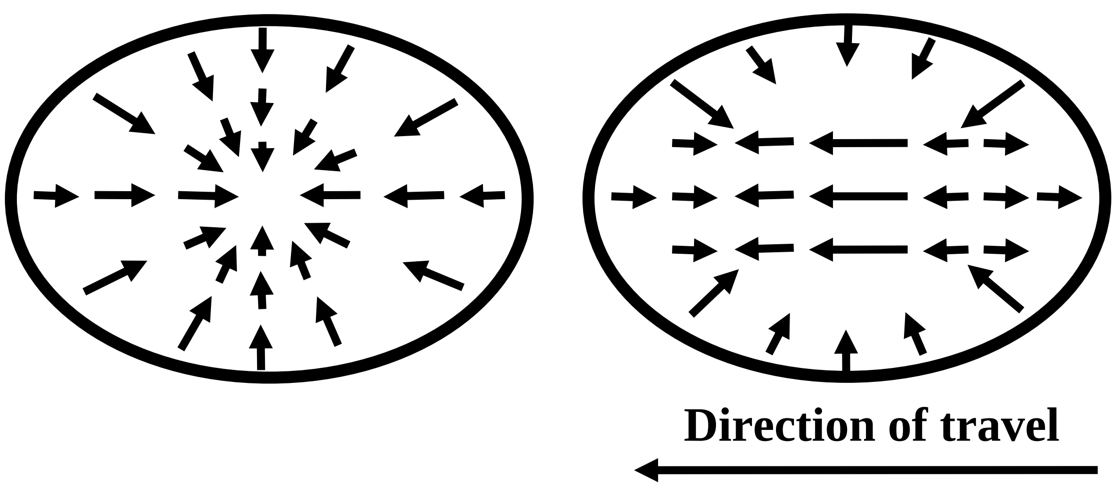

Figure 5. Stresses imposed on the road surface within the contact patch of a static (left) and a free rolling tire (right)(*Tielking and Roberts 1987*).

As can be observed in Figure 5, the centre and intermediate ribs of a radial tire experience more "fore-aft" motion than the edge ribs and the reverse is true for transverse stresses. The result is a gyratory motion that increases as tire inflation decreases. Douglas et al. (2003) postulate that this gyratory motion may explain why tires with reduced inflation pressures have a beneficial effect on unpaved roads–compacting the surface and smoothing existing ruts. The paper cautions that the increased gyratory motion at low tire inflations may promote aggregate plucking on chip sealed roads; however, there is no evidence to support this in the literature from operational tests or controlled field trials.

Travel speed and tire inflation oppositely influence pavement strains and the rutting they causes in thin pavements. The longer a spot in the pavement is stressed, the more time it has to be plastically deformed (rutted). Thus, pavement rutting is inversely proportional to travel speed. Generally speaking, lower tire inflations reduce the pavement stresses under the tire by more uniformly distributing vertical loading and by lengthening the contact area. Since rutting is related to the time-based integral of the strain exposure, however, the benefits of reduced tire pressure will be somewhat decreased by the longer strain exposure caused by the longer footprint (Gillespie et al. 1992).

A recent Texas A&M University–commissioned study realistically modelled the impact of over- and under-inflated truck tires on thick and thin asphalt pavements and found decreased pavement fatigue (bottom-up) cracking and rutting could be expected with reduced tire pressures (Wang and Machemehl 2006). The study made a number of important conclusions regarding crack orientation, wheel configuration, and tire load and pavement thickness when the average tire inflation pressure was decreased from 130 psi to 70 psi (896 kPa to 483 kPa):

- Transverse cracking damage index dropped by about 67% and longitudinal cracking damage index dropped by about 50% (Figure 6). Because radial tire footprints elongate but don't get significantly wider when deflated, transverse cracking was more strongly influenced than longitudinal cracking.
- Steering single tires generated larger transverse strains than longitudinal strains; the reverse was true for dual-tire single axle and tandem axle configurations because of the overlapping influences of their multiple tires.
- For both the thick and thin asphalt pavements, the transverse cracking damage was much greater than the longitudinal cracking damage at higher pressures, primarily because single and tandem axles with dual tires far outnumbered single-tired steering axles. As inflations neared 70 psi, the difference in cracking damage grew smaller because the impact of the dual tires decreased rapidly.
- The effect of tire pressure on tensile strains at the bottom of the asphaltic (A/C) layer was also dependent on tire load. At a high tire load the tire pressure effect was more significant and, therefore, decreases in tire pressure had more benefit at high tire loads than at low tire loads.
- Thick pavement showed less bottom-up (fatigue) cracking damage than thin pavement. This suggests that the thickness of the asphalt concrete layer plays an important role in the control of pavement fatigue cracking, especially in the control of longitudinal cracking.
- Mean pavement rut depth decreased by about 40%, and was comparable for both thick and thin pavements. Vertical subgrade strains and, hence, subgrade rutting were not significantly influenced by tire inflation. Rutting, however, was likely the cumulative plastic deformation of each of the pavement layers.

Drakos et al. (2001) note that asphalt pavement rutting in the wheel paths is due to either consolidation or instability. The first type is the result of excessive consolidation along the wheel paths due to reduction of air voids in the asphalt mat or permanent deformation of the base or subgrade. Rutting can also result, however, from instability of the asphalt mix, typically in the top 50 mm of the asphalt mat.

Wang and Al-Qadi (2008) reported higher shear stresses in the top 100 mm of perpetual hot mix asphalts (HMA) than tensile stresses at the bottom of the HMA. The authors believe that near-surface cracking caused by shear is more critical than tensile strain at the bottom of HMA for perpetual pavements. The authors also noted that tire pressure mainly influences the top 50 mm of HMA perpetual pavements.

Wang and Al-Qadi (2008) also evaluated the influence on pavements of a pressure differential in a dual tire assembly. Pressure imbalance is a common problem with dual tire assemblies on over-the-road transport trucks.[5] The study compared longitudinal strains measured under a moving dual-tired assembly in which one tire was kept at 760 kPa and the other's inflation varied from 210 to 760 kPa. The tests were performed on three pavement sections of 152, 254 and 429 mm HMA placed on 300 mm of lime-stabilized subgrade. Longitudinal strain under the control tire was greater than the other by up to 70%. The increase in average longitudinal strain due to tire pressure imbalance was as much as 40%, depending on the level of pressure differential, pavement structure, and axle loading (Figure 6).

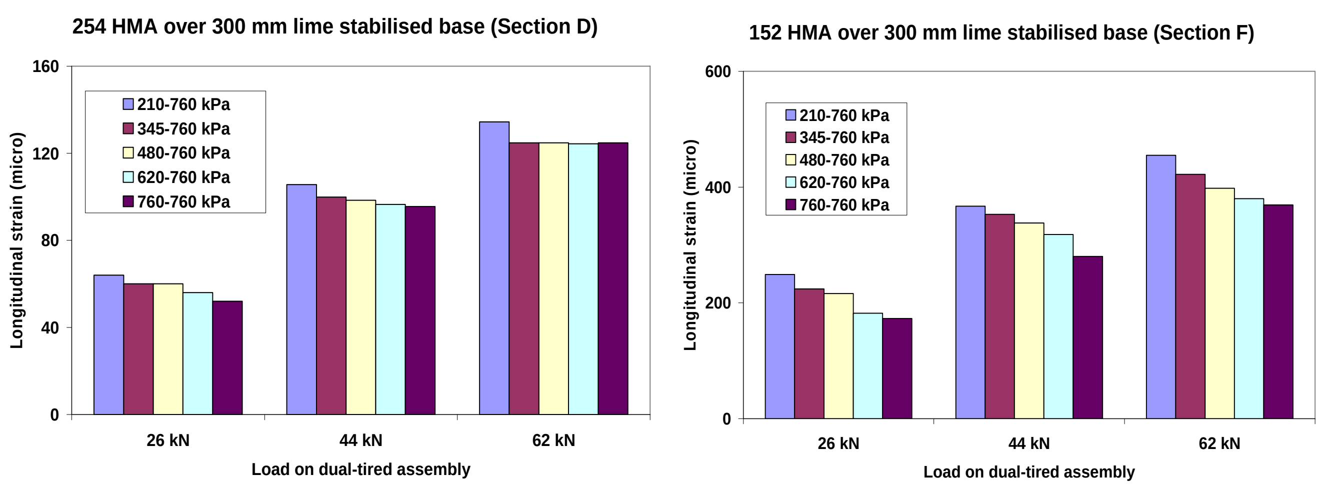

Figure 6. Influence of dual tire pressure imbalance and load on longitudinal strain measured under the HMA mat in two full-depth flexible pavements (*Wang and Al-Qadi 2008*).

An earlier Texas A&M University study (Roberts et al. 1986) also predicted the influence of elevated tire pressures on pavement damage. The authors noted that rut depth was less for locations with lower seasonal temperatures regardless of tire pressure, and that the thicker surfaces were more sensitive to increases in seasonal temperature than the thinner ones (Figure 7).

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5 A recent USDOT study reports approximately 20% of all tractor dual tire assemblies have tires that differ in pressure by more than 5 psi, and 25% of all trailer dual assemblies have tires that differ in pressure by more than 5 psi (http://www.fmcsa.dot.gov/facts-research/research-technology/tech/tire-pressure-sensors.htm).

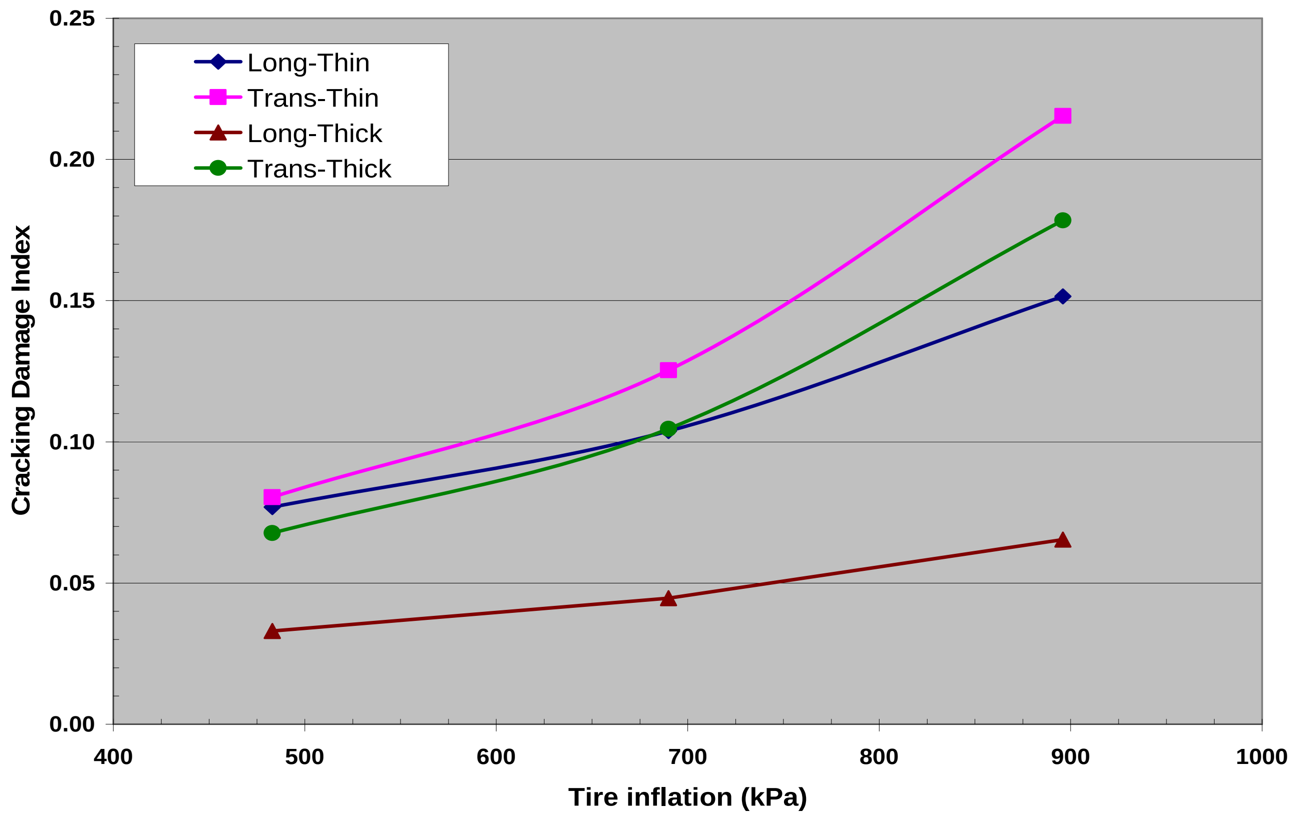

Figure 7. Influence of tire inflation on longitudinal and transverse cracking strains in thin and thick pavements (*Wang and Machemehl 2006*).

Researchers at Université Laval's test track measured the impact of reduced pressures on strains in 100-mm-thick and 200-mm-thick pavements under both springtime and summertime conditions[6]. Measurements were gathered in the spring for the vehicles travelling on smooth pavement and also after traversing an obstacle approximately 5 cm high. Preliminary results for the loaded urban transit bus indicate that lowering inflations of its dual tire assemblies reduced the average peak horizontal strains measured at the bottom of the asphalt mat under both spring and summer conditions (Table 2).

6 Grellet, D.; Fachon, J.; Doré, G. *Étude de l'impact des Systèmes de contrôle de gonflement des pneus (CTI) sur l'interaction véhicule-route (Study of the impact of TPCS on pavement impacts).* University of Laval, Pavement engineering research group. November 2008 draft report GCT-2008-11. 75 pp.

Table 2. Average peak horizontal strain reduction at 30 km/h measured at the bottom of the asphalt mat in response to lowering a loaded transit bus' dual-tire assemblies from 100 to 75 psi

	200 mm-thick A/C pavement	100 mm-thick A/C pavement
Spring conditions	8.3%	2.4%
Summer conditions	5.0%	8.0%

Preliminary results for a legally loaded log-hauling truck indicate that lowering the inflation pressure of the trailer's dual tire assemblies from 100 to 55 psi also generated substantial reductions in strain at the bottom of the asphalt mat (Table 3). Results have been expressed as averages of the combined transverse and longitudinal horizontal strain.

Table 3. Average peak horizontal strain reduction at 30 km/h measured at the bottom of the asphalt mat in response to deflating 8 tonne-axle, dual-tire assemblies from 100 to 55 psi

	100 mm-thick A/C pavement	50 mm-thick A/C pavement
Spring conditions	6.8%	14.5%
Summer conditions	7.1%	6.5%

Dynamic pavement loading

The dynamic loading of highway pavement has now been recognized as a significant factor in pavement design; the vertical axle load of a heavy vehicle is not steady but varies because the road is not even. Dynamic axle loadings of ±20% of static levels are commonly generated by the heavy vehicle's suspension response to road surface perturbations. The main movements of a heavy vehicle are the "body bounce", specific frequency usually between 1.5 and 3 Hz and "axle hop" (wheel hop), specific frequency about 10 Hz. Body bounce dominates on paved roads whereas wheel hop can be significant under rough road conditions in which traction is limited. Given the same travel speed, a vehicle will duplicate the magnitude and spacing of dynamic loadings again and again. Most pavement–vehicle interaction models have failed to account for the spatial repeatability of dynamic loadings on the road (Huhtala 1995).

A 1987 NATC trial with low- and high-tire-pressure log trucks concluded that lowering tire inflation pressures significantly reduces the shock and vibration experienced at all axle positions. Accelerometers mounted on the test trucks found that lower tire pressures lessened the impact energy felt by the truck by 5/6^{ths} on smooth pavement (NATC 1987). Some truck components had impact reductions of two to ten times. The rougher ride of the high-tire-pressure truck caused it to have maintenance and repair costs eight times higher than the low-pressure-truck (Ad Hoc Tire Inflation Applications Team 1988).

NATC's researchers believe that tire pressure can have a far more significant impact on truck damping than a truck's suspension system.[7] There is a significant improvement in damping ability of a typical highway truck tire below approximately 50–60 psi (345–414 kPa) and above 15–18% sidewall deflection.

In light of the observed changes in tire damping, wheel hop frequency, and tire stiffness with variable inflation pressures, it is likely that they are important factors in reducing road damage. Both operational trials and structured tests have found that lowering tire pressures reduces the damaging impact of trucks on roads, especially on rough roads.

Research into the influence of dynamic tire forces on pavement damage, using conventional tire inflation pressures, has found that these forces can greatly exceed the average force under a static tire, which is commonly used for pavement design. Cebon (1993) predicts that dynamic tire wheel loads are likely to have a much greater influence on pavement fatigue life than moving static (i.e., average) tire loadings because road condition is governed by damage at the worst (95th percentile) locations rather than some average value for the entire road surface. Given typical conditions, fatigue cracking at the worst locations is predicted to be 2–14 times greater than that due to moving static loads (the highest damage rates were for poorly performing suspensions, such as walking-beam and pivoted-spring tandem suspensions). Theoretical rutting damage was found to be much less sensitive to dynamic loads.

As discussed, reducing tire pressures increases the damping ability of tires, effectively changing the natural frequencies of a vehicle and reducing the dynamic tire forces transmitted to the pavement. These changes are likely to reduce damage to previously damaged sections in two ways. First, frequency changes are expected to disrupt the spatial repeatability of axle loads generated by a truck, and thus reduce the concentration of pavement damage. Second, the reduction in dynamic forces is expected to slow the spread of cracking from damaged sections. It is expected that full scale, long term testing of thick, highway A/C pavements would find significant benefits from the use of variable tire pressures, especially where the pavement is already damaged and vehicles must slow down. Lessening of pavement damage is likely to be even more dramatic with the use of variable tire inflation pressures if the vehicle has a stiff walking-beam or pivoted-spring tandem suspension.

[7] Tom Moore, VTP Program Leader, USDA Forest Service-SDTDC. Personal communication, March 1996.

Reduced tire pressure and pavement performance

Pavement trafficking trials

The US Army Corps of Engineers published empirical rutting relations for asphalt pavements, gravel-surfaced roads and un-surfaced roads based upon regressions of data from a large number of test pavements, roads, and airfields (Barber et al. 1978). The rut depth equation for 2-layer asphalt pavements was based on 233 data points and had a correlation coefficient r^2 of 0.77. These equations are important because they are representative of a wide variety of road structures and tires, and because they are the only published empirical relations for which tire pressure, axle configuration, and axle load are specific variables. Figure 8 illustrates the predicted influence of tire pressure on rut-based equivalency factor (i.e., ESALs) in three types of roads. Rutting in 2-layer pavements is predicted to be relatively insensitive to inflation pressure as compared with rutting in weaker structures, such as gravel-surfaced or un-surfaced roads. Despite this, even with the modest gains in rutting predicted with reduced tire pressures (e.g., 6.6%) this may still result in sizeable economic gains from longer pavement life.

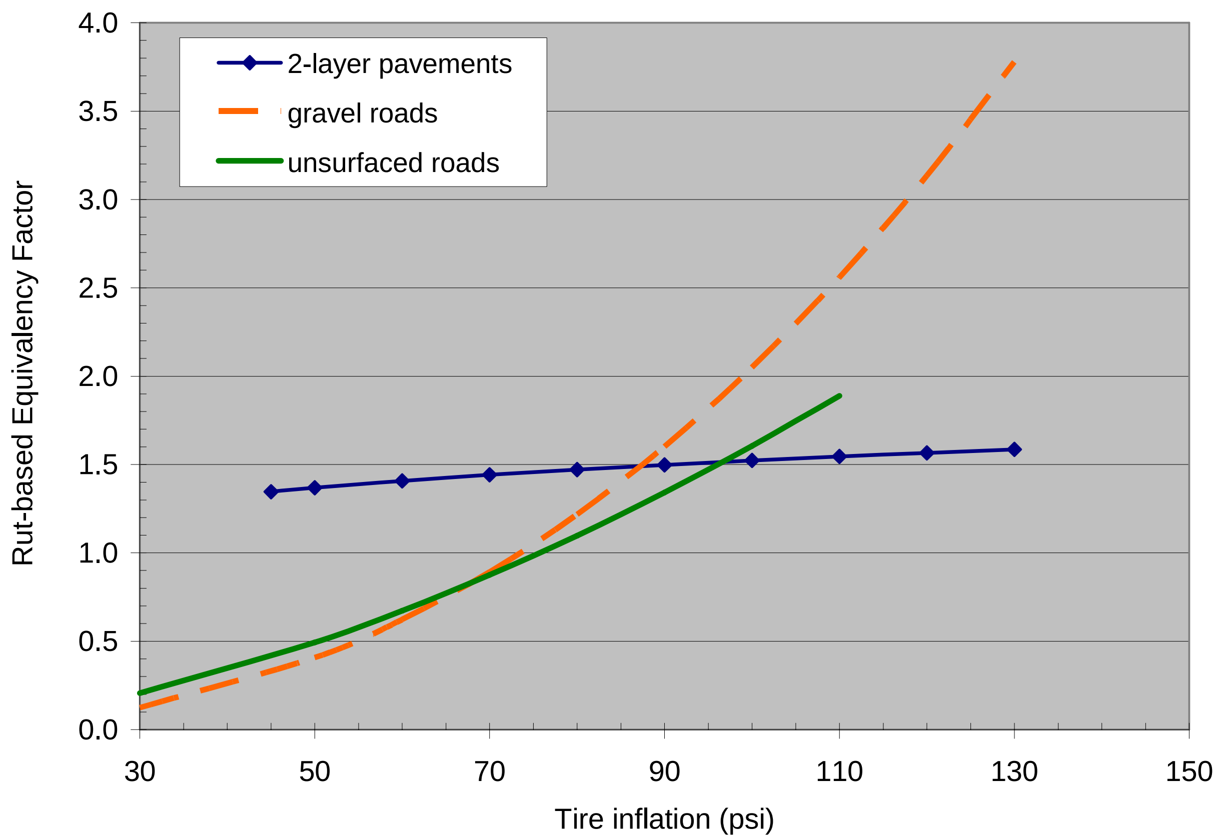

Figure 8. Predicted influence of tire pressure on rutting in three types of road structure caused by a 9-tonne dual-tired single axle (*Barber et al. 1978*).

In 1986, NATC conducted an evaluation of surface damage to A/C pavement, chip seal pavement, and gravel-surfaced sections caused by heavy truck traffic using variable tire inflation pressures. Two loaded log trucks, one with normal highway tire inflation (sidewall deflections of 10–12%) and one with lowered tire inflations (sidewall deflections of 20–22%) were driven side-by-side in parallel lanes around an AASHO-type closed-loop test circuit. The track included two A/C pavement sections (51-mm-thick hot mix over 102-mm-thick aggregate base) and two double penetration chip seal sections (over 150-mm-thick aggregate base). Trafficking of the test track was conducted first under dry subgrade conditions and then trafficked until failure under saturated subgrade conditions. NATC reported that the test lane dedicated to the low-tire-pressure truck showed little cracking and no rutting (wheel track depression) whereas the high-tire-pressure lane showed considerable cracking and some rutting after 3205 loaded and 3200 empty passes with a dry subgrade. None of the lanes required repair or maintenance after the loaded and empty truck phases, although the high-tire-pressure lane in the chip sealed sections was rutted and cracked. The next test phase was to saturate the roadbed by flooding the ditches and then traffic the road to failure. On all paved sections, the low-tire-pressure truck was able to accomplish 100% more passes than the high-tire-pressure truck before rutting and/or pothole failure, except on section 11 (50-mm-thick A/C) where it ran 33% more passes before potholing failure. The lowered tire pressures provided significantly longer pavement life than the higher tire pressures. Longitudinal crack propagation in the high-tire-pressure lane preceded all structural failures of the double penetration chip seal and the 51-mm A/C pavement, and allowed accurate prediction of impending failure. In the low-tire-pressure lane, there was only lateral crack propagation (Nevada Automotive Test Center 1987).

At the end of the testing, after 4180 vehicle kilometres in each lane, the road maintenance requirements were significantly lower in the low-tire-pressure lane (Table 4). Reducing tire pressure resulted in reduced road surfacing and maintenance costs.

Table 4. Material and labour requirements to repair roads after 4180 km of testing (*Nevada Automotive Test Center 1987*)

High-tire-pressure lane	Low-tire-pressure lane
approximately 7 m^3 of Class B Type II aggregate	none
approximately 204 m^2 of double penetration chip seal	approximately 7 m^2 of double penetration chip seal
approximately 167 m^2 of 50 mm A/C lift	approximately 3 m^2 of 50 mm A/C lift
approximately 106,000 L of water to restore grade and compaction in rutted areas	approximately 30 280 L of water to restore grade and compaction in rutted areas
14 h of grading and 14 h of watering	6 h of grading and 4 h of watering

In 1989, the US Army Corps of Engineers Waterways Experiment Station conducted a trial to evaluate the impact of reduced tire inflations on road surface deterioration and pavement thickness requirements. Loaded trucks at either low- or high-tire-pressure trafficked a two-lane closed loop test track constructed with a variety of low volume road structures. The asphalt pavements varied in both the thickness of mat and aggregate base (Table 5).

Table 5. A/C pavement test sections used in inflation pressure trial (*Grau 1993*)

Section	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Surface thickness (cm)	50	50	50	100	100	100	100	150	125
Base course thickness (cm)	100	150	200	0	200	150	100	0	0

Researchers concluded that:

- The failures or distresses in the high-tire-pressure lane of the A/C sections with surface thickness 100 mm thickness or less were more pronounced than those sections in the low-tire-pressure lane.
- When failures occurred in both lanes of the same A/C section, the ratio of low-tire-pressure to high-tire-pressure truck passes to initial failure ranged from 1.5:1 to 21:1 (Grau 1993).

Although researchers noted some differences in the levels of damage between thick asphalt sections subjected to low and high tire pressure traffic, the results were not conclusive and therefore not reported.[8]

Army researchers, using multi-depth deflectometers at sections 10 and 12, measured decreases in surface deflection and vertical compressive strain in both the A/C pavement base and the subgrade in response to lowering truck tire pressures from 100 to 40 psi (689 to 276 kPa) and to increasing travel speeds from 8 to 32 km/h (5 to 20 mph) (Figure 9) (Smith 1993). The results indicate that reduced tire pressures were effective for pavement sections with low granular base equivalency (GBE) (i.e., on sections with GBE values between 240 and 310) and that travel speed had more influence on subgrade strain than did tire pressure for the conditions tested.

[8] Tom Moore, VTP Program Leader, USDA Forest Service-SDTDC. Personal communication, March 1996.

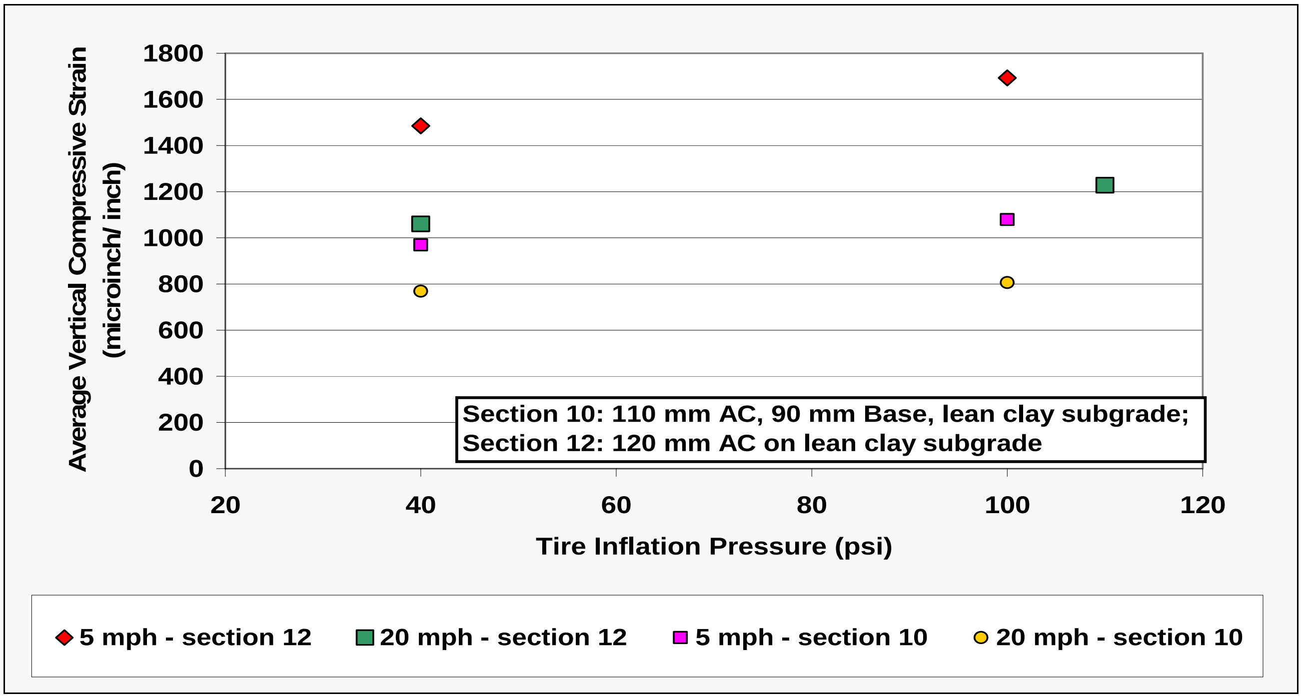

Figure 9. Influence of tire inflation pressure and speed on vertical strain measured in a lean clay subgrade under two road structures (*data from Table 11 in Smith [1993]*).

Subsequent predictions of the impact of the modest strain decreases with tire pressure, however, indicated very significant improvements in pavement service life (Figure 10). Thin pavement service life tends to be governed by fatigue cracking and subgrade rutting, and these are strongly influenced by horizontal tensile strain at the bottom of the asphalt mat and vertical compressive strain at the top of the subgrade, respectively. Test pavement life was computed using the subgrade strain values obtained from the multi-depth deflectometer data. These estimates showed large increases in pavement life from 690 to 276 kPa tires (100 psi to 40 psi tires). The data in Figure 9 also showed a decrease in measured strain as speed increased, which was due to the decrease in duration of load.

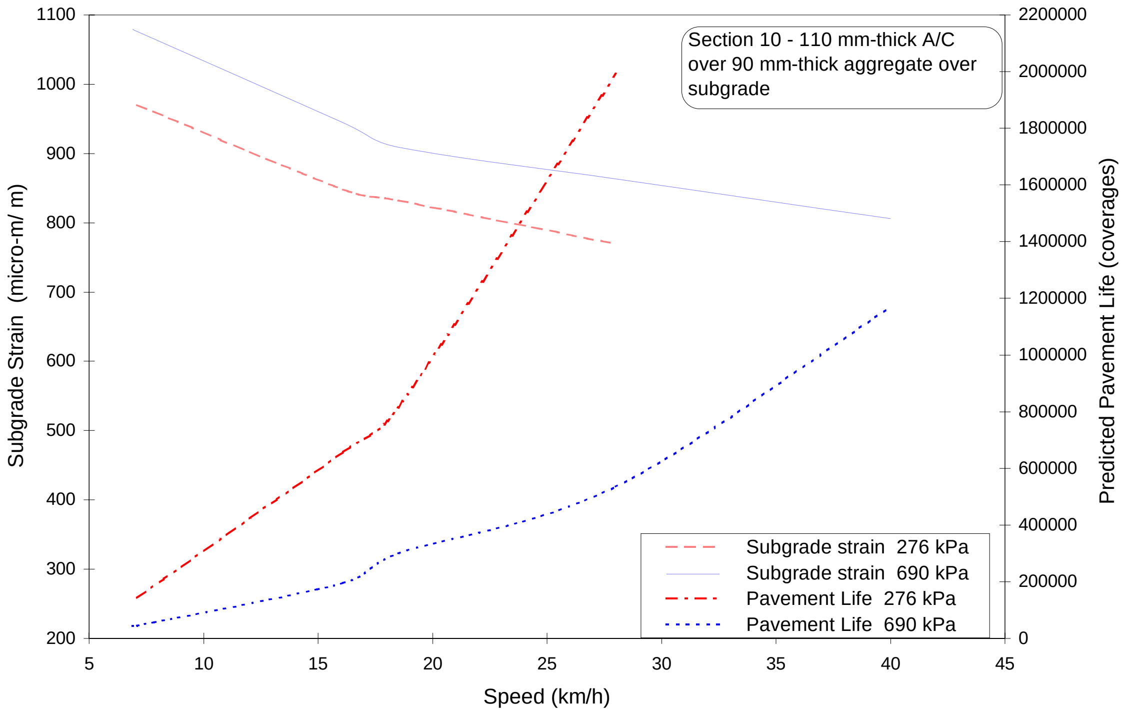

Figure 10. Relationship of speed to subgrade strain and predicted pavement life (*based on subgrade strain data from Table 12, in Smith (1993)*).

The effects of vehicle speed and tire pressure on the response of A/C pavements is significant. Chatti et al. (1996) found that increasing truck speed from a creeping motion to 64 km/h (40 mph) reduced measured peak longitudinal strain in an A/C pavement by approximately 30% to 40% but the effect on transverse strain was more variable and less pronounced. Decreasing tire pressures from 90 to 30 psi reduced measured longitudinal strain at the bottom of the A/C mat by 20% to 40% depending on speed, but the reduction of strains at the surface of the A/C mat was much less significant. At faster operating speeds, loaded tires require higher inflation pressures and this will decrease the potential benefit from reducing tire pressures. The opposite also holds—slowing the truck will allow the use of lower tire pressures but this will also decrease the potential benefit from faster speed.

Chatti et al. (1996) suggest two practical applications from these findings:

- Unless the pavement is rough, vehicle speeds should not be restricted unnecessarily, especially for thaw-weakened pavements.
- Lower tire pressures may partially offset pavement fatigue cracking damage incurred from normal truck axle loads, especially during spring-weakened conditions.

Clearly, reducing tire inflation pressures reduces the impact energy imparted to the road by the vehicles. This reduces pavement damage but may not explain all of the observed improvements. Some of the improvement may relate to the size of the depression in the pavement under each tire (i.e., the size of each deflection basin). When a radial tire's inflation pressure is reduced, its contact patch lengthens. It has been theorised that a probable cause for the decrease in pavement fatigue observed with low tire pressures may be an increase in deflection basin length and thus area.[9] The increased basin length is expected to reduce the rate of strain change of the A/C and thereby reduce fatigue damage. From the previous discussion, it is clear that this effect would be most pronounced on thin pavements where fatigue is a major source of damage and elevated tire pressure has already been well established as a damaging influence.

TPCS use on thaw-weakened roads

The University of Washington's Civil Engineering Department and Weyerhaeuser Company conducted computer modelling to investigate the impact of reduced tire pressure on thaw-weakened pavement damage. They used ELSYM5, a layered elastic program, to model pavement strains in response to various axle configurations, axle loads, and tire inflation pressures. Input data included substantial field data collected locally by Mahoney during previous spring thaw periods. The number of axle loads to pavement failure by fatigue cracking and by rutting was estimated with strain-based formulas from the Asphalt Institute (Finn 1977).

Mahoney et al. (1994) concluded that, while the results were preliminary, they indicated that:

- Reducing tire pressures will reduce pavement strains and extend pavement life.
- Pavement life will be extended with respect to both fatigue and rutting failure (Tables 4 and 5).
- The improvement is larger for fatigue cracking failure than rutting failure.
- The extent of the improvement depends greatly on the pavement material properties.
- Knowing pavement section stiffness is critical to determining whether to allow heavy vehicle traffic with or without reduced tire pressures or tire load or both.
- Thinner pavements will experience more benefit from reducing tire pressures.
- The actual number of load repetitions to failure must be considered when making a decision to permit traffic on a thaw weakened road. For example, reduced inflation pressure may increase load repetitions to failure by 200%, but the actual load repetitions to failure may only be 50. Another possible scenario is that reducing tire pressure would result in a 40% increase in load repetitions to failure, but represents an increase of 50 000 load repetitions to failure.

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9 Dr. Joseph Mahoney, Department of Civil Engineering, Washington State University. Personal communication, February 1993.

The authors made the following comments regarding the implementation of TPCS as a pavement damage mitigation technology:

- Local/state highway regulations and policies need to be changed to reflect new truck technologies such as TPCS.
- Local road owning agencies need to be better able to assess the actual structural condition of thaw weakened pavements. Without such knowledge, it will be difficult to assess the potential benefit of TPCS.
- Further field and analytic studies are needed to verify the benefits of variable tire pressures on weak pavement structures.
- Ultimately, an easy-to-use decision process for the local road owning agencies will be required. This would enable a systematic, straightforward way of assessing the viability of variable tire pressure benefits.

In 1994, the USDA Forest Service contracted the US Army Corps of Engineers Cold Regions Research and Engineering Laboratory (CRREL) to conduct computer analyses to investigate the effect of varying tire pressure on damage to three types of low volume pavements during spring thaw. Field measurements for validating the modelling was gathered from monitored pavements in Oregon and Montana. The three pavement types were: a 13-mm-thick double penetration chip seal over a 200 mm-thick base course; a 64-mm-thick A/C mat over a 150-mm-thick base course; and a 100-mm-thick A/C mat over a 200-mm-thick base course.

Cumulative damage to the three pavements was simulated for one year with CRREL's mechanistic pavement design procedure developed for areas with seasonal frost. CRREL estimated pavement strains with a finite element model and a layered elastic model. Rectangular contact footprints with non-uniform vertical pressure distributions were used as inputs for the finite element modelling. The finite-element-model–estimated strains for tires at low inflations were found to be about 15% higher than if calculated using the layered elastic model with circular footprints with uniform vertical pressure distributions as inputs.

Kestler et al. (1996) reported results for thin pavement fatigue and rutting that were consistent with those of Mahoney et al. (1994) and concluded the following:

- Use of variable (manufacturer-recommended) tire pressures significantly reduces fatigue damage and rutting of thin A/C mats (i.e., less than 25 mm thick). The reduction in fatigue damage and rutting is less for pavements with thick A/C mats (i.e., 100 mm or thicker).
- For very thin A/C courses (i.e., seal coats less than 13 mm thick), cumulative rutting damage is decreased by 43% when tire pressures were reduced from 100 to 60 psi (690 to 414 kPa) (Figure 11, top).
- For very thin A/C courses, cumulative fatigue cracking damage was reduced by 78% when inflation pressures were reduced from 100 to 60 psi. Also, there was negligible fatigue damage for inflation pressures less than the threshold pressure of 60 psi (414 kPa) (Figure 11, bottom).

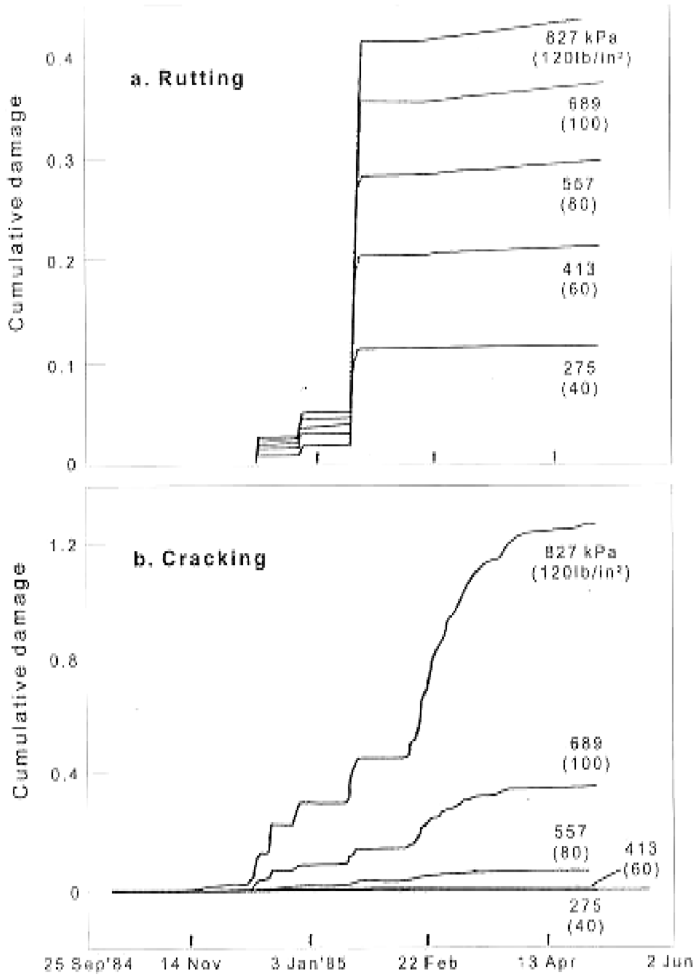

Figure 11. Predicted cumulative rutting (top) and fatigue cracking (bottom) damage in a seal coat pavement near Troy, MI, at the end of one winter and spring as a function of tire inflation pressure (*Kestler and Berg 1996*).

All Canadian provinces are subject to freezing temperatures and use seasonal load restrictions (SLR) to protect their road infrastructures. Weight restrictions frequently result in prolonged curtailments of commercial trucking and hardship for related truck-based industries and communities. In 1988, the Forest Engineering Research Institute of Canada (now the Feric Division of FPInnovations) began an investigation into the feasibility of using reduced tire pressures, in lieu of reduced axle loads, to haul on seasonally load restricted roads. As per a recommendation by Smith (1993), Feric elected to conduct its evaluation using a layered elastic model. In consultation with Dr. Joe Mahoney and Dr. Tom Christison (Road research manager, Alberta Research Council), Feric developed a layered elastic modelling approach to estimate the influence of reduced tire pressures on thaw-weakened pavements. This modelling approach was similar to that described by Mahoney et al. (1994); however, it differed in several significant ways:

- An analysis of Benkelman beam surface deflections under low pressure tires led to modelling the elongated contact areas of low pressure radial tires in ELSYM5 with multiple load circles having a total area equivalent to that of each tire's measured gross contact area.

- The strength of the subject pavement layers was estimated by varying layer strengths in the model within published ranges until the output surface deflection closely approximated actual Benkelman beam deflections measured on the subject road near the end of seasonal load restrictions (thawed and recovering condition). Road performance earlier in the SLR period was then estimated by incrementally weakening the base, subbase, and subgrade layers.
- The impact of individual axle passes were aggregated and number of truck passes to failure by fatigue cracking and rutting estimated. The lesser of the two failure mode estimates governs.

The model is used to estimate the number of passes to the governing road failure mode that the subject truck can make before the road will fail for each of the strength conditions evaluated. Each strength condition is identified by an estimated surface deflection that would result with a standard deflection test (e.g., Benkelman beam or Falling Weight Deflectometer). The baseline road life is taken to be the number of passes to failure by a legally loaded, conventional truck under strength conditions at the end of the SLR period. The subject truck configuration is more road-friendly than the conventional truck because it has TPCS-reduced tire pressures, multiple axle groupings, larger steering tires, etc. The reduction in strains resulting from the road-friendly measures typically results in the subject truck being able to begin hauling at a much weaker condition than at the end of the SLR period—with no decrease in estimated pavement life (Figure 12).

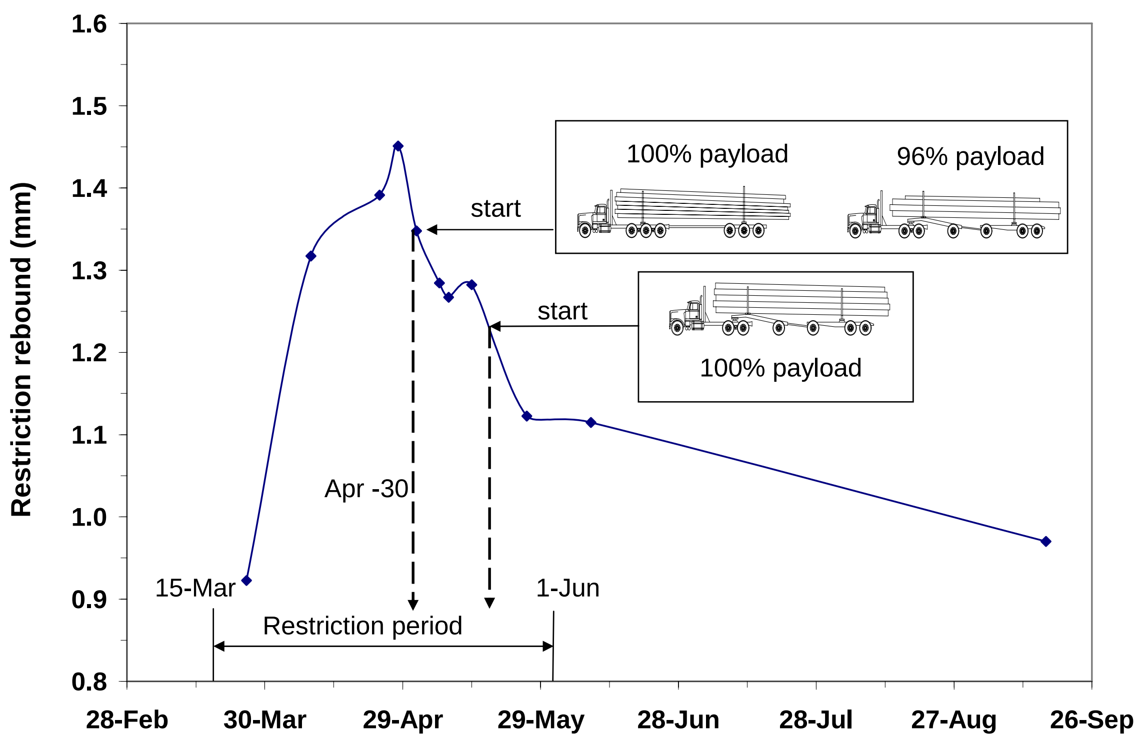

Figure 12. Schedule for resuming hauling with BC test truck configurations using reduced tire pressures (*Bradley and Mercier 2006*).

Feric, and later FPInnovations-Feric Division, conducted twelve operational trials to validate the results of its modelling on a variety of low volume road structures, including a chip sealed road, cold mix A/C pavements, surface-treated roads, and both thin and thick hot mix A/C pavements (Blair 2001; Bradley 2005; Bradley and Mercier 2006; Bradley and Mercier 2008, Mabood and Tighe 2008). In each of these trials, detailed pre- and post-trial surface damage assessments were conducted to evaluate the effectiveness of reduced inflation pressures at mitigating surface damage. The following is a summary of the results of this work:

- The modelling approach was successfully adapted to each of the SLR road structures and truck configurations encountered.
- Good correlations can be developed between FWD and PFWD peak deflection measurements. The more economic PFWD can be used to monitor road recovery and indicate when the road has reached a modelled target deflection for haul resumption (Mabood and Tighe 2008).
- Significant economic and operational benefits accrued to the forest companies, trucking companies, and communities involved.
- Damage to the test roads by test traffic was negligible in eleven of the tests and, in the twelfth, the small amount of damage that did occur did not exceed normally anticipated springtime levels (Bradley and Mercier 2006).
- Hauling with full payloads and reduced inflation pressures has typically been able to start 3-4 weeks prior to the end of the SLR period. Strength testing of some of the test roads identified candidates for the postponing of SLR onset due to frozen conditions or elimination of SLR due to strong performance.

In response to favourable test results, the British Columbia Ministry of Transportation (BCMOT) introduced a TPCS SLR hauling initiative in 2004 (Bradley 2005). The BCMOT reports that there have been no road damage issues or compliance problems with the trucks participating in the program.

Participating truckers are required to install hardware on their trucks that allows the gathering of trip data while on the SLR roads and automatic downloading of this data for display on a compliance website. This innovation permits the BCMOT to ensure compliance on 100% of the truck loads, as well as creates a body of instrumented trucks that can potentially participate in other technology initiatives.

In 2006, Skogforsk concluded a 3-year-long research program with TPCS-equipped log trucks and thaw-weakened roads (Granlund 2006). Following this the Swedish government implemented a program to exempt TPCS-equipped trucks while travelling on seasonally or on permanently load restricted roads (where the restriction is not due to a bridge limitation). A cooperative research program by northern European countries is continuing to examine TPCS opportunities and support the implementation of TPCS SLR programs.[10]

An initiative similar to that in BC is currently being developed by the Ontario Ministry of Transportation, industry and FPInnovations. FPInnovations trials aimed at supporting the development of TPCS initiatives also are in progress in Manitoba and Nova Scotia. Under Saskatchewan's Transportation Partnership Agreements, if participating trucks have TPCS, the usual incremental road damage fees for hauling full loads on 10-month Primary Highways during their 2-month-long SLR are waived.

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[10] More information can be found at http://www.roadex.org

Policy implications

There is sufficient evidence to conclude that implementation of TPCS technology on vocational trucks would benefit urban and suburban pavements through reduced pavement maintenance and prolonged pavement life. Where roads are constructed to lower standards or have problematic subgrade conditions that generate increased maintenance requirements, the savings would be greater. TPCS will also help reduce pavement strain levels in urban roads caused by slow-moving heavy trucks and buses.

Depending on application, however, there are numerous other benefits of implementing TPCS. Examples from past and present applications give some indication of the variety of potential opportunities:

- Improve fuel efficiency of transport trucks (Carme 2006).
- Allow larger payloads of trucks operating under special permit agreements (NRCAN 2008) and trucks operating under TPCS SLR haul programs (Bradley 2005; Granlund 2006).
- Improve traction and mobility of emergency response vehicles (e.g., airport crash fire rescue trucks and high mobility fire trucks [Bassel and Raybould 1992]).
- Reduce damage to thaw-weakened roads by non-load-restricted vehicles (e.g., road maintenance and construction vehicles, school buses, dairy trucks, and garbage trucks).
- Improve ride characteristics of public transport (Rakheja and Wang 2006), ambulances, and vehicles with sensitive instrumentation or fragile payloads. Improving the ride of buses may also reduce vibration levels in buildings and bridges located along public transit routes.
- Improve truck safety by balancing and maintaining tire pressures, reducing the incidence of tire punctures, and optimising traction and braking under all loading conditions (Clark 1993; Bradley 1993; Smith 1994).
- Reduce road and vehicle impacts in government road maintenance and construction operations and on routes subjected to concentrated industrial hauls.[11]
- Oilfield vacuum trucks used for spraying well drilling fluids on agriculture fields are subject to restrictive transport regulations because of the damage that their heavy lugged flotation tires cause to thin, rural pavements. Many have converted to TPCS and conventional tires to eliminate the logistical difficulties and expense of the flotation tires, with no increase in rutting or soil compaction on the fields (Bradley 2002).
- Use of TPCS on concrete trucks improves off-road traction and mobility, and reduces rutting. Use of TPCS on Demix's concrete trucks in Québec (Figure 1) has resulted in improved access to rural locations, reduced site maintenance requirements, fewer incidents of truck extraction, and greatly improved ride when travelling unloaded. Many Florida-based concrete companies have needed all-wheel-drive concrete trucks to negotiate sandy work sites; however, many have now found that 4x6 units with TPCS provide comparable mobility at less cost.

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[11] Brown, M.; Carpentier, A.; Davies, T.; Pragg, R.; Wall, T. 1997. *Central Tire Inflation (CTI)/ Constant Reduced Pressure (CRP) Initiative. Appendices to the Final Report.* Unpublished Saskatchewan Highways and Transportation internal report. June 1997.

Existing TPCS incentive programs require monitoring of trip data. This leverages enforcement activities, provides data for other transportation-related programs, and creates a model for regulators to encourage the adoption of other new road-friendly technologies. The TPCS SLR program in British Columbia requires applicants to collect and report road strength measurements during the SLR period. Aside from program uses, this strength data may be valuable for highway inventory systems, maintenance prioritization, and research.

Although the TPCS SLR hauling program was developed with the intention of providing provinces with an alternative to seasonally load restricting roads, it also has the potential to have a major impact on road life if TPCS use were extended into other periods of vulnerability, such as late spring or during mid-winter thaws or extended wet weather caused by climate change. Public-private partnerships or "caretaker agreements" for dedicated industrial haul routes would have less risk and lower construction and/or maintenance costs if trucks reduced impacts with TPCS.

The development and implementation of new applications for TPCS technology could be linked to current funding initiatives for research on energy efficiency and infrastructure improvement, for both domestic and international markets. Research into lessening impacts of widebase single tires or conventional steering tires with TPCS could have far reaching benefits for reducing pavement rutting and longitudinal cracking. Research into the development of new TPCS applications should consider both public benefits (e.g., longer infrastructure life) and a comprehensive evaluation of economic benefits to the truck owner (with or without a special initiative).

Implementation of TPCS by government must be done in a considered manner, especially given current economic pressures. Implementation of TPCS by Saskatchewan, British Columbia, and Sweden has been successful because the economic advantages to trucking firms were immediate and well understood. Implementation of CTIS/TPCS by the U.S. Forest Service was not successful—largely because contractual relationships with timber harvesters prevented the U.S. Forest Service from directly sharing road maintenance savings with the subcontracted trucking firms who had to buy the CTIS/TPCS. In general, when trucking firms have been pressured into purchasing CTIS/TPCS, resistance has developed and implementation has not been successful. Conversely, well-publicized programs with clear economic incentive have encouraged rapid uptake, especially when it represents a competitive advantage to participants. Current TPCS initiatives have been successful, in part, because of the active self-policing by participants and the minimal additional compliance efforts required. Tire pressure is not currently included in provincial truck safety inspection procedures; however, it should be added for roadside inspections of TPCS program trucks.

Conclusions

TPCS are a proven, mature technology used in a variety of vocational truck applications since 1991 across Canada. This technology allows vehicle operators to monitor and reduce tire pressures to an optimal level for their speed and tire loading. Optimised (reduced) tire pressures have been found to comprehensively enhance truck and tire performance, and lessen vehicle impacts to pavements. Implementation of policies to promote the use of TPCS technology would benefit urban and suburban pavements through reduced maintenance and prolonged life, and would increase industry competitiveness. Research with modelling and field trials of reduced tire inflation supports this conclusion and promotes a wide range of application opportunities. Canadian regulators are well positioned to take advantage of the high degree of domestic expertise with this technology to more widely implement it in urban trucking and transit applications.

TPCS is well suited to use on concentrated industrial hauls (e.g., on routes to agriculture processing plants and on routes to construction sites). Where roads are constructed to lower standards or have problematic subgrade conditions that generate increased maintenance requirements, the savings would be greater. Implementation of TPCS on essential service vehicles using SLR routes (e.g., garbage, dairy, school buses, gravel trucks, and petroleum delivery vehicles) is also likely to be a successful policy direction. Successful experience in Saskatchewan indicates that TPCS would be a valuable addition to government road maintenance vehicles that operate when roads are weakened, damaged, or rough.

Saskatchewan and British Columbia have already recognized TPCS in provincial technology incentive programs that have successfully improved the competitiveness of regional truck-based industries while safeguarding the public infrastructure. In the context of these incentive programs, regulators have introduced another tool for promoting the adoption of new technologies capable of meeting government objectives such as extending infrastructure life, increasing safety, improving fuel efficiency, and promoting industry competitiveness. Any efforts to streamline the adoption of programs (such as the TPCS-SLR opportunity) across provincial jurisdictions would be welcomed by industry, and would improve competitiveness of the resource sectors. Actions by European competitors highlight the need for expediency in implementing this technology.

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References

Ad Hoc Tire Inflation Applications Team. 1988. Operation bigfoot: Technology application plan. USDA Forest Service. Technology and Development Center (SDTDC). San Dimas, CA. 54 p.

Altunel, A.O.; de Hoop, C.F. 1998. The effect of lowered tire pressure on a log truck driver's seat. Journal of Forest Engineering 9(2):41–47.

Ashmore, C.; Smith, G. 1994. Tire test program: Dynamic tire temperature evaluation. Final report for the USDA Forest Service. Nevada Automotive Test Center, Carson City, NV. September 1994.

Ashmore, C.; Sirois, D. 1987. Influences of the central tire inflation system on log truck performance and road surfaces. American Society of Agricultural Engineers, St. Joseph, MI. ASAE Technical Paper Series 87-1057. 27 p.

Barber, V.C.; Odom, E.C.; Patrick, R.W. 1978. The deterioration and reliability of pavements. US Army Engineer Waterways Experiment Station, Vicksburg, MS. Technical Report S-78-8. 155 p.

Bassel, J.; Raybould, S. 1992. Demonstration of Forest Service fire engine equipped with a central tire inflation system. USDA Forest Service, San Dimas Technology Development Center. San Dimas, CA. Report 9271 1205-SDTDC. 6 p.

Blair, C. 2001. Using road-friendly technologies to extend the haul season on thawing roads. Forest Engineering Research Institute of Canada (FERIC), Vancouver, B.C. Advantage 2(48). 12 p.

Bradley, A. 1993. Testing a central tire inflation system in western Canadian log-hauling conditions. Forest Engineering Research Institute of Canada (FERIC), Vancouver, BC. Technical Note TN-197. 11 p.

Bradley, A. 2002. A comparison of soil impacts from oilfield vacuum trucks equipped with TIREBOSS TPCS and conventional dual tires vs. flotation drive tires: Final report. Contract report for Tire Pressure Control International Ltd. Bradley Consulting, Regina, SK. 13 p.

Bradley, A. 2005. Using road-friendly technologies to carry full legal axle weights on seasonally weight-restricted pavements in British Columbia. Forest Engineering Research Institute of Canada (FERIC), Vancouver, BC. Advantage 6(30). 26 p.

Bradley, A.; Mercier, S. 2006. Exploring the potential to extend the springtime haul season on thaw-weakened pavements in Ontario. Forest Engineering Research Institute of Canada (FERIC), Pointe-Claire, QC. Internal Report. 91 p.

Bradley, A.; Mercier, S. 2006. Using road-friendly trucks to haul full axle weights on weight-restricted pavements. *In* Proceedings of 10th International Conference on Asphalt Pavements. International Society of Asphalt Pavements, White Bear Lake, MN. 10 p.

Bradley, A.H.; Mercier, S. 2008. Exploring the potential to extend the haul season in New Brunswick on thaw-weakened roads using TPCS. FPInnovations–Feric Division. Pointe Claire, QC. Contract Report CR-0379-1. January 2008. 78 p.

Carme, R. 2006. Freight sustainability demonstration program project reporting-final report. Impact of tire pressure control systems on fuel consumption. Forest Engineering Research Institute of Canada (FERIC), Pointe Claire, QC. Contract Report CR0260-1. 47 p.

Cebon, D. 1993. Interaction between heavy vehicles and roads. Society of Automotive Engineers. Warrendale, PA. SP-951. 81 p.

Chatti, K.; Kim, H.; Yun, K.K.; Mahoney, J.P.; Monismith, C.L. 1996. Field investigation into effects of vehicle speed and tire pressure on asphalt concrete pavement strains. Pages 66–71 *in* Transportation Research Record 1539. Transportation Research Board, Washington, DC.

Clark, R.B.1993. Central inflation from a truck tire perspective, SAE Paper 933059. Pages 107–122 *in* Central Tire Inflation Systems Managing the Vehicle to Surface. Special Publication SP-1061. Society of Automotive Engineers, Warrendale, PA.

Cohn, A. 1991. Central tire inflation systems – increase traction without tire life penalty? Wingfoot Profiles Dec. 1991.

Douglas, R.A.; Woodward, W.D.H.; Rogers, R.J. 2003. Contact pressures and energies beneath soft tires. Pages 221-227 *in* Transportation Research Record 1819. Transportation Research Board, Washington, DC. Paper no. LVR8-1015.

Drakos, C.A.; Roque, R.; Birgisson, B. 2001. Effect of measured tire contact stress on near-surface rutting. Pages 59–69 *in* Proceedings of 80th Annual Meeting of the Transportation Research Board, Washington, DC.

Finn, F.N.; Saraf, C.; Kulkarni, R.; Nair, K.; Smith, W.; Abdullah, A.. 1977. The use of distress prediction subsystems in the design of pavement structures. Pages 3–38 *in* Proceedings of 4th International Conference on the Structural Design of Asphalt Pavements. University of Michigan, Ann Arbor, MI.

Gillespie, T.D.; Karamihas, S.M.; Cebon, D.; Sayers, M.W.; Nasim, M.A.; Hansen, W.; Ehsan, N. 1992. Effects of heavy vehicle characteristics on pavement response and performance. Ann Arbor, MI. University of Michigan Transportation Research Institute (UMTRI) Report No. UMTRI 92-2. 255 p. (Republished with the same title as NCHRP report No. 335, Transportation Research Board, National Research Council, Washington, DC. 126 p.)

Granlund, P. 2006. Five million km covered in CTI project. Skogforsk, Uppsala, Sweden. Resultat Nr. 4 2006.

Granlund, P. 2004. Lugnare korning och mindre vinrationer med CTI pa virkesfordon (Roundwood rigs with CTI – less vibration and a smoother ride). Skogforsk, Uppsala, Sweden. Resultat Nr. 22 2004.

Grau, R.W. 1993. Effects of variable tire pressure on road surfacings. Volume I: Design, construction, behaviour under traffic, and test results. US Army Corps of Engineers, Waterways Experiment Station, Vicksburg, MS. Technical Report GL-93-20 prepared for the USDA Forest Service. 152 p.

Huhtala, M. 1995. The effect of wheel loads on pavements. Pages 235–241 *in* the 4th International Symposium on Heavy Vehicle Weights and Dimensions. University of Michigan Transportation Research Institute, Ann Arbor, MI.

Kenworth Truck Company. 2006. White paper on fuel economy. Kirkland, WA. 14 p. Accessed in August 2008 at www.kenworth.com/FuelEconomyWhitePaper.pdf

Kreyns, K. 1994. Benefits and effects of central tire inflation on USDA Forest Service vehicles. Pages 31–36 *in* Special Publication SP-1061 Central Tire Inflation Systems Managing the Vehicle to Surface. Society of Automotive Engineers, Warrendale, PA. SAE Technical Paper 933032.

Légère, G.; Mercier, S. 2005. Reducing aggregate thickness on gravel roads designed for log trucks equipped with TPCS. Forest Engineering Research Institute of Canada (FERIC), Pointe-Claire, QC. Advantage 6(8). 4 p.

Leslar, D.; Fereday, A. 2008. Effect of varying tire pressure on life estimates of a 40-ft transit bus for Transport Canada. Bodycote testing group, Mississauga, ON. Report 2008-15-R1836. 17 p.

Mabood, F.; Tighe, S. 2008. Evaluating tire pressure control systems (TPCS) to improve productivity and mitigate pavement damage: Final report. University of Waterloo, Department of Civil Engineering.

Mahoney, J.P.; Sweet, B.R.; Copstead, R.L.; Keller, R.R. 1994. The potential use of central tire inflation during highway load restriction periods. Society of Automotive Engineers, Warrendale, PA. SAE Technical Paper 942245. 8 p.

Natural Resources Canada. 2008. Central tire inflation technology allows bigger payloads. FleetSmart Profiles. http://fleetsmart.nrcan.gc.ca/index.cfm?fuseaction=docs.view&id=highway-truck-north

Nevada Automotive Test Center. 1987. Central tire inflation: Final report. Carson City, NV. Prepared for the USDA Forest Service under contract 53-9JA9-6-SD647. 130 p.

PSI. 2008. Return on investment (ROI). Pressure Systems International website. Accessed August 2008. http://www.meritorhvs.com/PBCTireInflationSystem.aspx

Rakheja S.; Wang, Z. 2006. Feasibility assessment of a central tire inflation system for urban buses. Prepared for Transport Canada by CONCAVE Research Centre, Concordia University, Montreal, QC. 61 p.

Roberts, F.L.; Tielking, J.T.; Middleton, D.; Lytton, R.L.; Tseng, K. 1986. Effects of tire pressures on flexible pavements. Texas Transportation Institute, The Texas A&M University System, College Station, TX. Research Report 372-1F. 245 p.

Simonson, R. 1994. Tire deflection influence on rear-axle torque. Pages 25–30 *in* Special Publication SP-1061 Central Tire Inflation Systems Managing the Vehicle to Surface. Society of Automotive Engineers, Warrendale, PA. SAE Technical Paper 933029.

Smith, D.M. 1993. Effects of variable tire pressure on road surfacings. Volume II: analysis of test results. US Army Corps of Engineers, Waterways Experiment Station, Vicksburg, MS. Technical Report GL-93-20 prepared for the USDA Forest Service. 84 p.

Smith, G. 1994. Tire test program: Dynamic peak and slide skid on pavement and gravel surfaces at varied tire deflections. Final report for the USDA Forest Service. Nevada Automotive Test Center, Carson City, NV.

Sturos J.; Brumm D.; Lehto A. 1995. Performance of a logging truck with a central tire inflation system. USDA Forest Service, St. Paul, MN. Research Paper NC-322. 12 p.

The Tire and Rim Association, Inc. 2008. Yearbook 2008. Copley, Ohio.

The Tire and Rim Association, Inc. 2007. Engineering design information. Copley, Ohio.

Tielking, J.T.; Roberts, F.L. 1987. Tire contact pressure and its effect on pavement strain. Pages *in* Journal of Transportation Engineering, Volume 113(1):56–71. Paper No. 21193.

Wang, H.; Al-Qadi, I.L. 2008. Full-depth flexible pavement fatigue response under various tire and axle load configurations. Presentation at the 3rd International Conference on Accelerated Pavement Testing (APT'08), Madrid, Spain. Accessed January 2009 at www.cedex.es/apt2008/html/ppt/TS04/1_Full_depth_flexible_pavement_fatigue_performance.pdf)

Wang, F.; Machemehl, R. 2006. Predicting truck tire pressure effects upon pavement performance**.** Texas Transportation Institute, Texas A&M University System, College Station, TX. Report No. SWUTC/06/167864-1 prepared for Southwest Region University Transportation Center. 153 p.

Woodrooffe, J.; Divole, P. 1997. Lower tire pressures: Effects on heavy vehicle stability and control, road and tire wear. Report to Consumers' Co-operative Refineries Ltd. and Saskatchewan Highways and Transportation. Roaduser Research Report C-03-11. 33 p.

Yap, P. 1988. A comparative study of the effect of truck tire types on road contact pressures. Pages 53–59 *in* Proceedings of Society of Automotive Engineers (SAE) 1988 Truck & Bus Meeting & Exposition. SAE, Warrendale, PA. SP-765. 7 p.