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Impacts of Central Tire Inflation Systems application on forest transportation – Review

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Abstract

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Central Tire Inflation Systems (CTIS) have been introduced to forestry transportation in the last 30 years to the point the forest industry is one of the biggest users of the technology (Pletts 2006). The benefits of operating with this CTIS technology mentioned in the literature include: (*i*) reduced road surfacing and/or base course requirements, (*ii*) reduced road maintenance, (*iii*) reduced driver fatigue and medical complaints, (*iv*) lower vehicle operation costs, (*v*) increased vehicle mobility, (*vi*) extended haul seasons (Bradley 1995). This paper presents a literature review of previous international studies on the impacts of CTIS. This document can assist the forest industry and research users to gain basic information on this transportation technology.

Keywords: timber transportation; road maintenance; transportation cost; vehicle mobility; fuel consumption; safety

Pletts (2006) described a brief history of the Central Tire Inflation System (CTIS) which goes back to World War II when this type of technology was developed to improve the mobility of transport on poor roads in the Soviet Union and Warsaw Pact countries (Kaczmarek 1984). From the early 1980's most of the military tactical vehicles produced in the USA were equipped with CTIS to improve the overall vehicle mobility (Adams 2002). Pletts (2006) indicated that the South African sugar cane industry identified CTIS as a technology that could improve vehicle performance and reduce the transport costs but he emphasized that nowadays the largest application of CTIS is in the forest industry. Bradley (2009) indicated that road impacts by CTIS were investigated by forestry related organizations (such as United States Forest Service, Skogforsk, Forest Engineering Research Institute of Canada (FERIC) – currently called FPinnovations), however this type of technology has attracted interest in highway and urban applications. CTIS has also been applied in Australia for the last 20 years as one of the CTIS contactors has supplied it to the transport industry in Eden, Bunbury, Kalgoorlie and Mount Gambier. Operational experiences have indicated that this technology has positive impacts on reducing the transport cost, improving the safety and reducing negative impacts on the road surfaces (Cline 2016).

The United States Department of Agriculture (USDA) Forest Service started studying the impact of low tire pressure on their forest road network in 1983 (Altunel, De Hoop 1998). One of the technologies to assist this was CTIS. A CTIS is an onboard, electromechanical system that permits the operator to vary a vehicle's tire pressure from the cab while driving. CTIS generally comprises five component assemblies including an air-compressor unit (auxiliary utility or brake system compressor), air control valves, air lines, rotary union hardware to transmit air into and out of rotating wheels, and a computerized control interface/panel for selection of appropriate tire pressures with respect to vehicle weight, road surface type and speed of travel. If the air brake compressor system is used, air priority valves are included to protect the brake system's integrity, by allowing for tire inflation only when the brake pressure is above a safe level. The truck speed is managed relative to the tire pressure and load, to prevent damage, and there is an override if design speed limit warnings are ignored (Owende et al. 2001). Bradley (2009) described the configuration of the tire pressure control systems and stated that air for inflation and deflations 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. Bradley (2009) described two types of suppliers of this technology. The Dana Spicer Road ranger features entirely internal drive axle plumbing while the International TIREBOSS has externally routed drive tire air supply lines. Steering axle tires on North American trucks are not typically equipped with this technology because their loading is relatively heavy and constant and this limits the opportunity for pressure variation if the truck is equipped with conventional tires (Bradley 2009).

Figure 1 illustrates a CTIS at the wheel (Lynch Hummer 2006). The electronic control unit tells the pneumatic control unit to check current pressure and either inflate or deflate the tire to the pressure

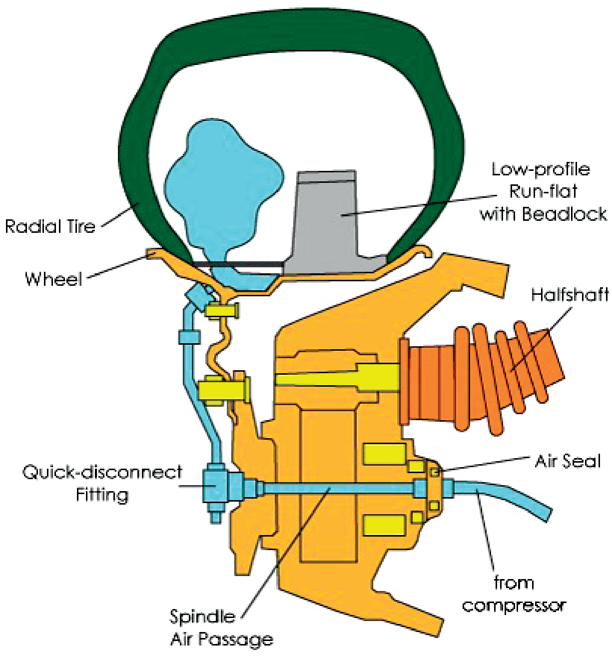

Fig. 1. Central Tire Inflation System at the wheel (Lynch Hummer 2006)

selected by the driver. If the system determines that inflation is needed, it first checks to make sure that brake pressure reserves are where they should be; if they are, it applies a slight pressure to the wheel valve to allow inflation. If the tires are overinflated, the system applies a slight vacuum to the wheel valve. When the pneumatic control unit reads that the appropriate pressure is reached, the valve closes. In this illustration, there is a pathway that the air travels for inflation or deflation once it gets to the wheel. The tubing runs from the vehicle's air compressor through the wheel hub and then to the tire valve. The "quick disconnect fitting" allows the tire to be separated from the CTIS system for removal or servicing (http://auto.howstuffworks.com/self-inflating-tire2.htm).

There are two main manufacturers of the CTIS: U.S.-based Dana Corporation and France-based Syegon. Dana Corporation has two versions, the CTIS for military use (developed by PSI) and the Tire Pressure Control System (TPCS) for commercial, heavy machinery use (http://auto.howstuffworks.com/self-inflating-tire2.htm). There is another small manufacturer called Air CTI which is based in Australia (Victoria) and it has served the customers in Australia and New Zealand.

The reported benefits of operating with lower tire pressures include: reduced road surfacing and/or base course requirements; reduced road maintenance, reduced driver fatigue and medical complaints, lower vehicle operation costs because of less vibration-related vehicle operating costs because of less vibration-related vehicle damage and fewer tire repairs, increased vehicle mobility and extended haul seasons (USDA Forest Service 1993; Bradley 1995). This paper presents the review of previous international studies conducted to investigate the impacts of CTIS in forestry applications. The paper has created a compiled document which can assist the forest industry and research users to gain basic information on this transportation technology.

IMPACTS OF CTIS

Road surface and truck mobility. A vehicle's recommended tire inflation pressure may vary by 656 kPa in a single trip; reduced pressures (i.e., less than 483 kPa) are recommended for slower speeds and gravel/dirt roads. Most of the Canadian forestry trucks use a cold inflation pressure of approximately 689.5 kPa (normal highway tire pressures). Vehicles lacking CTIS typically operate at a single high inflation pressure that may result in fuel savings but also causes reduction of tire life, traction and ride quality and increases road damage (Bradley 1995).

The USDA Forest Service started researching on CTIS with a study on road damage and set up field trials in Idaho and Washington (Taylor 1987, 1988) and other studies in Alabama (Ashmore, Sirois 1987). Based on the results, road damage decreased and vehicle performance improved under adverse conditions.

On unpaved roads heavy truck traffic is one of the major causes of road sedimentation (Foltz 1994). USDA Forest Service tested CTIS and it was found that reducing tire pressure from normal highway pressures to CTIS pressures could reduce sedimentation up to 38% (Foltz, Burroughs 1991). Moore and Sowa (1997) also mentioned that USDA Forest Service trials confirmed that reducing tire pressures in light- and heavy-haul vehicles by 40 to 60% (340 to 420 kPa) of standard highway pressures significantly reduced rutting and erosion of gravel- and native-surfaced roads. Tests conducted by Sturos et al. (1995) on log trucks showed that reduced tire inflation pressures reduced the average load measured in rolling resistance tests on loose sand roads by 45% and increased traction. A three-year study of sedimentation in Oregon (USA) demonstrated using a single constant reduced tire pressure resulted in sedimentation reduction of 45% on average. By varying the tire pressure using CTIS sediment yield was reduced by 80% on average (Bradley 1995).

The practice of optimising (reducing) pressures of tires on heavy trucks to minimise damage to lower standard roads has become common in Canada where CTIS and TPCS are proven technologies (Bradley 2003). Two trials conducted in Saskatchewan (Canada) indicated that lower tire pressure causes less deep ruts than the standard highway-pressure lane where road surface deflections were, on average, 11% less in the reduced- pressure lane compared to standard highway pressure (Bradley 2003). Optimizing tire pressures theoretically reduced the damage potential of the loaded test trucks by 61%. A trial on Alberta-Pacific's standard temporary access roads showed that over the length of the trial (250 loaded truck passes), the use of optimized tire pressures resulted in 19 and 100% less grading maintenance for the lift and compacted lift sections, respectively, compared to the equivalent sections trafficked with high tire pressures (Bradley 2001).

Another project in north-western Saskatchewan evaluated the use of reduced tire pressures and tridem drive tractors to improve vehicle mobility in soft sand conditions. Its results indicated that increasing the ground contact area of the steer tire by using a wider tire at reduced inflation pressures could improve the flotation to decrease the steer tire ploughing. Reducing the tire pressures for tandem drive tractor provided a noticeable improvement in traction. Despite 8,000 kg more Gross Combination Weight, the tridem drive tractor configuration with low tire pressures demonstrated the best mobility while manoeuvring and required the least assistance (Jokai, Webb 2001). Bulley and Blair (2001) developed a model to help increasing the gradeability of logging trucks [their simulation was based on studies conducted by Sessions et al. (1986) and Goldsack (1988)] using reduced tire pressure on the drive tires in British Colombia (Canada). Drive tire pressures were lowered from 690 to 410 kPa and no incremental tire pressures were applied to the trucks while they attempted to climb the adverse grade. By decreasing the tire pressure, the average length of the tire footprint increased from 28 to 38 cm. The trucks with reduced pressures on their drive tires immediately benefited from the increased tire footprint and were able to climb the hill unassisted, while trucks operating at normal, high tire pressure (690 kPa) needed an assist vehicle for every load. Clark (1993) mentioned that using reduced inflation tires would increase the resistance to punctures and tread face damage. When tire inflation is reduced, the peak drive axle torque would decrease, which can reduce the risk of drive line failures (Simonson 1993). Reducing the tire pressure also reduces the unit stress on the road surface, which can lead to more tire traction and less wheel slip and less road damage (Simonson 1993). The reduced wheel slip results in improving traction from 17 to 19% under different surface conditions and axle loads (Ashmore, Sirois 1987; Sturos et al. 1995). Tire loading impacts on the shoulder region contact pressures but inflation pressure impacts on the centre-region contact pressures. When inflation pressure is reduced, the vertical pressures can be distributed more uniformly under the tire contact area and therefore peak values are decreased (Yap 1988). Another study by USDA Forest Service in Idaho showed that CTIS could increase the number of operating days as vehicle traction and flotation were enhanced. When wet road conditions reduced traction to the point where operations were unable to continue, the use of CTISs enabled operations to continue due to the increase in traction that is achievable when using CTIS (Powell, Brunette 1991).

The European Union ROADEX Project was planned for the period of 1998–2007 (Munro, MacCulloch 2008). It was a transnational roads co-operation aimed at developing ways for interactive and innovative management of low traffic volume roads throughout the cold climate regions of the Northern Periphery Area of Europe. A trial of the system of tire pressure control was set to a timber haulage vehicle at Kinbrace in northern Scotland from October 2006 to November 2007. The 2006–2007 trials of tire pressure control at Kinbrace by Forestry Commission Scotland were the first in the UK. The main conclusions from these trials included:

(*i*) Tire pressure control is a promising technology for heavy haulage vehicles with a mixture of "on" and "off" road activities;

(*ii*) Short-term benefits have been identified over the course of the 13 months trial in respect of tire life, tire management, vehicle traction, vehicle mobility and extended hauling seasons, confirming the results of similar trials in Canada and Sweden;

(*iii*) A longer period of trial is required to fully assess the system.

The experience with CTIS/TPCS in the UK has also indicated that this technology can claim up to 34% better traction in sand and 17% in mud based on the results found by FERIC (Armstrong 2008). In Ireland, CTIS was suggested for minimising the pavement wear and damage when increasing the payload of timber trucks to gain better economic returns (Martin et al. 1999). Another Irish study concluded that haulage trucks with systems for managing variable tire pressure such as CTIS can minimise distress on flexible pavements with thin asphalt surfacing layers and peat soil subgrade. This may therefore enhance the serviceability of pavements overlying peat or other soil foundations (Owende et al. 2001). The latter study also indicated that there is evidence to show an empty truck with high tire inflation pressure (770 kPa) will induce as much fatigue damage to the road pavement as a fully laden truck that is operated at low (350 kPa) tire inflation pressure (Owende et al. 2001). Stuart et al. (1987) indicated that the road life can be shortened or extended depending on the quality of the vehicle travelling, which can indicate that the road life will increase in the case of application of CTIS technology.

Fuel consumption. As a rule of thumb on hard surfaces for every 10 psi that a truck's tires are underinflated, the fuel economy is reduced by 1% (Cummins 2007). However, fuel consumption can decrease when tire pressures are reduced on soft road surfaces through reduced rolling resistance and wheel spin (Jones, Smith 1992). Nevada Automotive Test Center (1987) and Kreyns (1994) indicated that fuel consumption can be improved between 1 to 3% when trucks are equipped with reduced tire pressures on unpaved resource roads as fuel consumption is highly impacted by wheel slip and flotation when travelling on loose or soft unpaved roadways.

In a trial in Saskatchewan Bradley (2003) stated that the fuel consumption improvement through using reduced pressure of tires varied from 3 to 21% overall, but was more consistent for any given truck although the author mentioned the scope of this trial was limited to the study circumstances. Another study conducted by FPinnovations on the TPCS in Ontario indicated that in wet conditions with rain and melting snow there was no influence on highways, an average 6% improvement with empty vehicles on gravel roads, an average 14% improvement with empty vehicles on muddy roads, and an average 30% improvement with loaded vehicles on muddy roads. The tests on hard-packed snow-covered roads showed no influence for the loaded vehicles, while the tests conducted with unloaded vehicles confirm that decreasing the tire pressure deteriorates the fuel consumption when the road surface is stiff and there is no loss of traction at the wheels (Surcel 2010). Armstrong (2008) stated TPCS claims a fuel saving of 3–4% can be achieved under Scottish conditions. However Granlund (2006) reported that according to his three-year study the practical effect of CTIS on fuel consumption was negligible based on the operational trial in Sweden. However Bergkvist et al. (2007) indicated that CTIS could be one of the solutions to reduce the fuel consumption of Swedish timber trucking.

Economics and potential cost savings. Based on the study on two available systems in Western Canada (the Redline-Eltek TPCS in Alberta, and the Eaton TPCS in Ohio) the costs of TPCS that include ownership costs and operating costs (including direct costs, indirect costs and air system costs) were presented by Jokai and Bradley (2000). Purchase prices for TPCS range from 8,100 to 21,900 USD, depending on system manufacturer, number of zones controlled, and number of axles equipped. Truck utilisation impacts on TPCS operating costs. The estimated maximum ownership cost (corresponding to 1,800 annual operating hours) ranged from 1.70 to 2.72 USD$\cdot$h^{-1}, and the minimum ownership cost (corresponding to 3,600 annual operating hours) ranged from 1.11 to 2.19 USD$\cdot$h^{-1}. Total costs including the ownership and operating costs of

TPCS for these trucks ranged from 1.91 to 4.14 USD per truck engine hour (excluding costs of warranty repair and downtimes), depending on system type and manufacturer, air system capacity, truck utilization, number of zones, and number of CTIS-equipped axles (Jokai, Bradley 2000).

Jokai and Bradley (2000) indicated that prior to implementing the CTIS, the forest companies should assess its economics. The cost of owning and operating CTIS systems on Canadian 8-axle B-train log trucks, exclusive of profit, overhead and vehicle savings, was estimated to be 2.71 USD·h^{-1} (Jokai, Bradley 2000). Application of CTIS on B-trains, as Alberta-Pacific has done, offers the greatest advantage – an increase in road grading interval of 200%. Depending on the road design, the saving on road maintenance cost (Brokmeier, Hittenbeck 2010) due to implementing optimised tire pressures varies from 33 to 70% (Bradley 2002) while in the UK's experience it was estimated that the grading of roads can be reduced by 75% (Armstrong 2008).

A three-year CTIS evaluation project for Swedish conditions in collaboration with Skogforsk confirmed that the technology costed between 25,000 to 30,000 USD to purchase and install. Average repair costs were 2 cents per kilometre (ranging from 0 to 8 cents per kilometre), and the level of technical utilization for the system was 95.5% (Granlund 2006). The corresponding average cost was about 23 cents per tonne over a five years period with an average hauling distance of 100 km in this case study.

Through the use of reduced pressure on the drive tires in British Columbia, improved gradeability allowed loaded (highway sized) logging trucks to ascend a steep grade that was otherwise negotiable only with an assist vehicle. This created an estimated savings for this scenario of 1.52 USD·m^{-3} of wood hauled (Bulley, Blair 2001). Another impact of using CTIS is increasing the number of vehicle operating hours due to enhanced vehicle traction and flotation that will result in more savings. The USDA Forest Service in Idaho, Alabama, and Alaska showed that hauling could be done under wet road conditions that would normally have been prohibitive (Ashmore, Siroi 1987; Ad Hoc Central Tire Inflation Applications Team 1988). Moore and Sowa (1997) stated that each year approximately 1,500 km of Forest Service gravel roads require resurfacing at an average cost of 9,000 USD·km^{-1} for gravel replacement. With variable tire pressure technology, the wearing action on these roads could be reduced by 10 to 25%. Therefore at least 1.3 million USD could be saved if all vehicles operating on Forest Service roads used this technology. Another trial conducted by USDA Forest Service (USDA Forest Service 1993) compared the vibration level of conventional and CTIS equipped trucks. The trucks with high inflation pressure (conventional trucks) recorded vertical energy about six times higher than CTIS equipped trucks. The conventional trucks exhibited four times the part failures and eight times greater cost of repairs than the trucks with lowered tire pressures. It is clear that the use of lowered tire pressure, under the right conditions, can reduce maintenance costs and significantly improve the comfort of the driver.

The softer tires on forest roads should reduce the vibration on the lorry, which can then increase the life of components (Armstrong 2008). FPinnovations projects have also proved that applying tire pressure management systems can increase the service life of drive tires from 27 to 90% (Carme 2006). The other substantial advantage might be reducing the vehicle speed to around 40 km·h^{-1} that might help CTIS equipped log trucks to begin hauling one-half to one day sooner after a rain without cutting deep ruts (Bradley 2001).

Some tools have also been developed to assist industry users to run a cost-benefit analysis. For example, TPC International as a Canadian supplier has developed a system called the TIREBOSS spreadsheet where the users can input vehicle type and truck configuration details to estimate the economic saving, operational benefits and extended hauling days through TPCS application. Pletts (2006) applied the Hellberg Transport Management software called HTM TransSolve 7 to run a cost-benefit analysis using a real life example. He mentioned that three segments of total transportation costs are positively affected by implementing CTIS over the five years period. Expected cost saving using CTIS included tire life (33%), fuel consumption (5%) and maintenance (10%) according to Pletts (2006).

Safety and driver benefits. A trial conducted by Surcel (2010) in Ontario indicated that drivers using decreased tire pressures reported a noticeably smoother and safer truck ride especially when they drove on muddy roads, gravel roads and hard-packed snow-covered roads. In the UK, using TPCS could significantly reduce vibration and make driving the lorry a lot smoother and more comfortable. This could also reduce the incidence of back pain, which drivers suffer from. The improved traction also reduced the risk of bogging which represents a major safety benefit (Armstrong 2008). The drivers had a smoother ride as they reported which made them more confident, which also means less stress and lower fatigue level in this study (Armstrong 2008) and in a Swedish study reported by Granlund (2006). A Canadian study showed that the number and severity of vibration-related repairs were reduced by 30 and 26% and the ride was improved as well (Bradley 1993). Rakheja and Wang (2006) also found that TPCS resulted in constant sidewall deflections and contact area which resulted in a smoother ride. Swedish timber trucks equipped with CTIS reported lower incidents of punctured tires compared to normal trucks where the risk of bursting tires due to overheating was also reduced (Granlund 2006). Also Bergkvist et al. (2007) added that Swedish experience with CTIS showed low repair cost, improved driver environment and reduced tire wear. Rummer et al. (1990) stated that a softer ride due to reduced tire inflation improves the comfort of the driver and will also decrease the shock loading transmitted to the vehicle.

A study in Mississippi found that vibration levels were higher in the truck with high tire inflation pressure, but the differences in vibration levels between low- and high-pressure trucks were not as high as expected. Low tire pressure decreased vibration levels in driver seats from 10 to 25% and varying pavement thickness and surface types had a different effect on driver seat vibration levels. The main cause of the vibration was vertical acceleration in axles 1, 2 and 3 in both high- and low-pressure tire trucks (Altunel, De Hoop 1998). Granlund (2006) mentioned that in Swedish trials with CTIS the truck drivers indicated that this technology resulted in a smoother and more comfortable ride. To verify the drivers' feedback, the vibration in the vertical plane of one of the two trucks equipped with CTIS was read. It was most relevant to driver's comfort that it was 5 to 10% lower when CTIS was activated. The greatest improvement occurred when the vehicles were driven unladed on a substandard road and under slow speed when laden. Smith (1994) mentioned that when logging trucks applied TPCS the stopping distance when braking may be reduced on loose and dry pavement. The stopping distances were not different on wet pavements.

Application and operational practice. Based on FPinnovations' experience with CTIS in Canada, companies using these technologies should set a tire pressure policy to utilise the full benefits of the CTIS using education programs and driver self-monitoring (Bradley 2001). Driver training in proper system operation and maintenance can reduce TPCS operating costs and TPCS-related downtime. Training will help achieve driver acceptance and proper system operation. This will ensure that the full benefits of optimized tire pressures are achieved (Jokai, Bradley 2000).

Implementing CTIS/TPCS results in additional costs to transportation contractors however increasing the annual operating hours would allow the contractor to amortize the fixed truck and trailer ownership costs over more operating hours, and the resulting savings can partially (or in some cases fully) offset the ownership and operating cost of a TPCS (Jokai, Bradley 2000). Swedish experience (Granlund 2006) concluded that investment on CTIS would be profitable for the industry if an additional revenue of 5,500 USD could be achieved through longer operating hours, particularly during spring, and/or by increasing the payload on roads with low bearing capacity. Altunel and De Hoop (1998) suggested that assuming a high correlation between road conditions and axle (seat) vibration, a simulation model can be developed to estimate the optimum tire pressures at various speeds and road conditions at the real time to automate a CTIS to get optimal tire pressure. This would help optimize tire, truck, and road longevity, and driver ergonomics in addition to impacts on the fuel consumption of the vehicle.

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