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Investigation of the Energy Efficiency and Environmental Impact of Central Tire Inflation Systems for Commercial Vehicles Focusing on Agriculture and Forestry

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Abstract

Based on existing research studies, it is known that the adjustment of tire inflation pressures shows evident improvements in the operating performance of agriculture and forestry vehicles, especially when used in challenging off-road conditions. Often encountered by abruptly varying road surface qualities, these vehicles require systems that allow the continuous adjustment of the tire inflation pressures to be able to sustain a high level of operational efficiency as regards to energy efficiency and environmental impact.

In this work, a central tire inflation system (CTIS) designed to allow on-the-go adjustment of the tire inflation pressures was studied. The primary focus of this study was emphasized on tractors used in the agriculture industry as well as logging trucks used in transportation operations of the forestry industry. The content of this thesis was divided into an initial introduction of the origin of CTIS and its available variations, gradually proceeding to analyze various tire inflation pressure-related concepts affected by the system usage. Based on the comprehensive literature analyses presented in this work, the average savings in fuel consumption for agricultural tractors was 8.9% when CTIS was implemented. For logging trucks, the improvements in fuel economy resulted in more moderate fuel consumption savings of 0.5 to 1.7% due to the limited working range of approximately 6 to 7% where the use of CTIS proved beneficial. However, under the influence of extreme weather effects, the use of CTIS highlighted in the extension of the timber harvesting seasons which alone shows considerable monetary benefits to the operators of the forestry industry.

Though the benefits of CTIS have already been proven, the widespread adoption of the system is yet to happen. Based on the industry-specific case studies presented in this work, the reason is that often the initial acquisition costs directed to the vehicle owner are not justified by the system's short-term benefits. Secondly, as investigated in a brief market study, the availability of the system hinders the widespread use of CTIS as currently there is only one original equipment manufacturer (OEM) offering CTIS as a factory-new installment in their production of agricultural tractors.

Based on the results, CTIS is a solution with proven benefits and a high level of technological maturity. To increase the market penetration of the system, the number of OEMs collaborating with the CTIS suppliers should be increased. Additionally, to overcome consumer hesitance in the system acquisition, cost-sharing models should be implemented within agricultural subsidies as well as between the benefitting parties such as the operators of the forestry industry.

Keywords CTIS, tire inflation pressure, tractor, truck, fuel consumption, environmental impact

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Tekijä Tomi Juselius

Työn nimi Tutkimus rengaspaineiden säätöjärjestelmien vaikutuksesta maa- ja metsätalouden hyötyajoneuvojen energiatehokkuuteen ja ympäristövaikutuksiin

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Tiivistelmä

Olemassa olevien tutkimusten perusteella tiedetään, että rengaspaineiden säätö osoittaa ilmeisiä parannuksia maa- ja metsätalouden ajoneuvojen toimintatehokkuuteen, erityisesti kun ajoneuvoja käytetään haastavissa maasto-olosuhteissa. Äkillisesti vaihtelevien tienpintojen laatujen vuoksi nämä ajoneuvot vaativat järjestelmiä, jotka sallivat jatkuvan rengaspaineiden säätämismahdollisuuden ylläpitääkseen korkeatasoisen toimintatehokkuuden suhteessa energiatehokkuuteen ja ympäristövaikutuksiin.

Tässä diplomityössä tutkittiin rengaspaineiden säätöjärjestelmää (CTI), joka mahdollistaa rengaspaineiden ajonaikaisen säädön. Tutkimuksen pääpainoa korostettiin maataloudessa käytettävien traktoreiden sekä metsäteollisuuden kuljetukseen liittyvien puutavara-autojen yhteydessä. Tämän diplomityön sisältö jaoteltiin CTI-järjestelmän alkuperän ja järjestelmästä olemassa olevien erilaisten variaatioiden alustavaan esittelyyn, josta vähitellen edettiin analysoimaan useita rengaspaineiseen liittyviä käsitteitä joihin CTI-järjestelmä toiminnallaan vaikuttaa. Perustuen diplomityössä esitettyihin laajoihin kirjallisuustutkimusanalyyseihin, keskiarvolliset polttoainekulutussäästöt maataloustraktoreissa olivat 8,9 %, kun CTI-järjestelmää käytettiin. Puutavara-autoilla maltillisemmat polttoainetaloudellisuuden 0,5–1,7 % parannukset johtuivat rajallisesta noin 6–7 % käyttöalueesta, jossa CTI-järjestelmän käyttö osoittautui hyödylliseksi. Kuitenkin, äärimmäisten sääolosuhteiden vaikutuksen alaisena CTI-järjestelmän käytön hyödyt korostuivat puunkorjuukausien pidentymisellä, joka yksinomaan osoittaa merkittäviä rahallisia hyötyjä puutavarateollisuuden toimijoille.

Vaikka CTI-järjestelmän hyödyt ovat jo osoitettu, järjestelmän laajamittaista käyttöönottoa ei ole vielä tapahtunut. Perustuen diplomityössä esitettyihin toimialakohtaisiin tapaustutkimuksiin syynä on usein se, että järjestelmästä aiheutuvat alustavat hankintakustannukset ajoneuvon omistajalle eivät usein ole perusteltu järjestelmän lyhytaikaisilla hyödyillä. Toiseksi, kuten tutkittu työn lyhyessä markkinatutkimuksessa, järjestelmän saatavuus rajoittaa laajamittaista käyttöönottoa, koska tällä hetkellä vain yksi alkuperäinen laitevalmistaja (OEM) tarjoaa CTI-järjestelmää tehdasasennuksena uusien maataloustraktoreiden tuotannossa.

Perustuen tuloksiin, CTI-järjestelmä on ratkaisu, jolla on todennetut hyödyt ja korkeatasoinen teknologinen kypsyys. Järjestelmän markkinaosuuden lisäämiseksi yhteistyötä tekevien OEM-valmistajien määrää CTI-järjestelmien toimittajien kanssa olisi lisättävä. Lisäksi, jotta kuluttajien epäröintiä järjestelmän hankinnan suhteen saataisiin poistettua, kustannusten jakamismalleja täytyisi panna täytäntöön maataloustukiin sekä hyötyvien osapuolien kuten metsäteollisuuden toimijoiden välille.

Avainsanat CTIS, rengaspaine, traktori, kuorma-auto, polttoaineen kulutus, ympäristövaikutus

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Abbreviations

CO_2	Carbon Dioxide
CTIS	Central Tire Inflation System
ECU	Electronic Control Unit
FKM	Fluorocarbon rubber
GHG	Greenhouse Gas
ICE	Internal Combustion Engine
NBR	Nitrile rubber
OEM	Original Equipment Manufacturer
PCU	Pneumatic Control Unit
PTFE	Polytetrafluoroethylene
TPCS	Tire Pressure Control System
WBV	Whole-Body Vibration

Units

CO_2e	Carbon Dioxide equivalent
MPa	Megapascal
Mtoe	Million tons of oil equivalent

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1 Introduction

Climate change has been identified as a result of excessive anthropogenic greenhouse gas (GHG) emissions since the mid-20th century. As none of the individual sectors of the economy is solely responsible for such an outcome, the seriousness of the subject calls for the combined efforts of all branches to reduce the level of GHG emissions. By mitigating the environmental footprint, a healthier planet and living environment can be preserved for future generations.

During 2019, 24% of the total GHG emissions worldwide came from transportation, of which the share of road transport was nearly three quarters (IEA, 2020). Without classifying the types of transport, the unifying factor in the vast majority is that they are all operated on wheels with tires forming the only contact surface to the ground. Through this contact surface, the tractive forces generated by an engine as fuel is combusted are transformed into energy propelling the vehicle. (Soltani, Goodarzi, Shojaeefard & Saeedi, 2015)

Tires and their relevant rolling resistance characteristics have a noticeable effect on the fuel consumption of vehicles equipped with internal combustion engines (ICEs). The higher the value of rolling resistance, the higher the fuel consumption which then exacerbates the amount of harmful GHG emissions, such as carbon dioxide (CO_2), that are released into the atmosphere. (Gent & Walter, 2006, p. 214)

The rolling resistance of tires is a combination of mechanical energy losses due to aerodynamic drag, friction between the tire tread, road as well as the wheel, and structural deformations within the tire carcass. In the case of friction and structural deformations, the level of tire inflation pressure has a noticeable significance in the magnitude of these losses (Soltani et al., 2015). With proper tire inflation pressure, the size of the tire-ground surface contact area is optimal for the maximum coefficient of friction to provide sufficient traction. Simultaneously, with sufficient vertical stiffness, the tire shape is sustained, and unnecessary deformations of the tire structure are prevented. (Gent & Walter, 2006, p. 477; 524)

However, in the industries of agriculture and forestry, the definition of proper tire inflation pressure reconfigures. The daily operations of the industry-related vehicles, such as tractors and trucks, are often carried out on a partial requirement to operate in challenging off-road conditions. In such conditions, which are highly affected by weather and for other reasons beyond human control, there are no predetermined tire inflation pressure settings to face the ever-changing road surface conditions, where the tire-ground interaction may fluctuate abruptly and can be of high uncertainty. (Brown, & Sessions, 1999; Adams, Reid, Hummel, Zhang & Hoeft, 2004; Hoy, Rohrer, Liska, Luck, Isom & Keshwani, 2014, p. 19)

To face the ever-changing road surface conditions with the most optimal tire inflation pressures, the capability of being able to carry out on-the-go adjustments would be required. This, however, would not be possible without proper on-board equipment. For the effortless adjustment of tire inflation pressures, a separate system known as the central tire inflation system (CTIS)[1] has been developed. By having this system installed in the vehicle, the

[1] In certain literature sources systems with identical working principle are referred as tire pressure control systems (TPCS). For consistency, the abbreviation CTIS will be used henceforth.

operator is then capable of adjusting the tire inflation pressures without needing to exit the vehicle. When lowering the tire inflation pressures, vehicle mobility and drawbar-pull can be significantly improved in the challenging off-road conditions. (Kaczmarek, 1984)

Lowering the tire inflation pressures increases the size of the tire-ground surface contact area, which in conditions of off-road lowers the amount of rolling resistance and improves traction due to reduced tire-soil interaction. Positively affecting the parameters that hinder the vehicle's operational efficiency corresponds to lowered fuel consumption, which decreases the impacts the vehicle causes to its surrounding environment through a reduction in the amount of GHG emissions. Besides the direct operational efficiency improvements of the vehicle, several indirect benefits are to be perceived as well. In agriculture, less tire-soil interaction reduces soil compaction which sustains ideal crop growth conditions to increase the annual yields. In forestry, the less rutting the tires cause to distant forest roads, the longer the timber harvesting seasons and the lower the annual maintenance requirements are. For the benefit of both of the industries, considerable improvements are perceived in the ride quality, driving comfort, and tire wear when suitable tire inflation pressures are being set. (Adams et al., 2004; Granlund, 2006; Rieppo, 2006; Tigges, 2015; Brokmeier, 2017)

Though the benefits of CTIS were first introduced during World War II, the system has yet to reach its full potential in applications that have already been proven to be benefitted by it (Kaczmarek, 1984; Adams et al., 2004; Ghaffariyan, 2017). Therefore, as one of the principal goals of this thesis, the aim is to investigate and evaluate the current and future perspectives of CTIS.

1.1 Research Objective

The research objective of this thesis consists of three major sections. In the first section, a comprehensive literature overview is formed for a broader understanding of the subject. The first part of the first section reviews the primary concepts of CTIS by presenting the operation principle, main components, and possible variations at the system level.

Following the introduction of CTIS, the second part discusses the tire inflation pressure and what are the benefits to be achieved when adjustments can be performed accordingly. This part focuses on the tire inflation pressure concepts that are relevant for the industries of agriculture and forestry, where CTIS have gained noticeable recognition for decades (Hassan, 1983, as cited in Adams et al., 2004; Pletts, 2006, as cited in Ghaffariyan, 2017). Based on the presented concepts, the potential benefits in terms of increased energy efficiency and reduced environmental impacts are illustrated through case studies. In this part, the economic perspectives arising from the acquisition of CTIS, individually for both of the study-related industries, are considered as well.

In the second section, a brief market review of CTIS is formed. In this section, the leading suppliers of CTIS are identified, their targeted applications are recognized, and their market areas are reviewed. Further to the suppliers of complete systems, suppliers focused on supplying the main components of CTIS are investigated. The focus on the component suppliers is on the variations and availability of different CTIS sealing solutions. In addition to the supplier overview, this part of the study will also investigate if any original equipment manufacturer (OEM) uses of CTIS currently exists.

In the third and final section of this thesis, the concluding remarks are presented and the future perspectives of CTIS are discussed. Regarding the future perspectives of CTIS, a short survey of other types of application uses is carried out as the benefits of CTIS are not necessarily limited only to the study-related industries of agriculture and forestry. The screenings for other potential application uses are performed with intentions to increase the market penetration of CTIS.

1.2 Motivation

The foreground initiative, and thus the motivation for this research study came from the thesis commissioner Trelleborg AB – a world leader in engineered polymer solutions that seal, damp, and protect critical applications in a variety of demanding environments. The thesis supports the launch of the company's newly developed CTIS for agricultural applications. The system at hand has been developed jointly by Trelleborg Wheel Systems and Dana Incorporated. (Trelleborg, 2019)

The contributions the vehicles within the industries of agriculture and forestry cause to the environment and the global GHG emissions are well recognized (Rieppo, 2006; Bradley, 2009; Volk, Denker & Rose, 2011). However, even though the positive benefits CTIS have to the operational efficiency and various other parameters of these vehicles have already been proven, the widespread adoption of CTIS is yet to happen (Kaczmarek, 1984; Greenfield, 1992; Adams et al., 2004; Granlund, 2006; Munro & MacCulloch, 2008; Oksanen & Rytkönen, 2009; Tigges, 2015; Brokmeier, 2017; Ghaffariyan, 2017). Therefore, the generalized motivation of this thesis is to structure an overview of CTIS and its benefits, and thus raise awareness of the system's existence.

Followed by the points outlined above, as the ultimate motivation of this thesis, the work that is to be carried out throughout this project simultaneously functions as the finalizer to the author's studies at Aalto University.

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2 Central Tire Inflation System

CTIS is a system that allows the operator of the vehicle to adjust the level of tire inflation pressures without stopping or exiting the vehicle as a way to improve the vehicle's performance on varying road surface conditions (Kaczmarek, 1984; Greenfield, 1992).

In this chapter, the brief history of CTIS is discussed and the operation principle of the system including its different variations and implementations is presented.

2.1 Brief History of Central Tire Inflation Systems

The history of CTIS dates back to times of World War II when such systems were first installed and experimented with military vehicles of the United States and the former Soviet Union. The aim of the system at that time was to improve vehicle navigation through rough terrain by reducing the ground contact pressure, increase traction, and the overall quality of the ride. (Kaczmarek, 1984; Greenfield, 1992)

After World War II, the Eastern Bloc countries, including the former Soviet Union as well as the Warsaw Pact countries, continued to emphasize the benefits and use CTIS on all types of wheeled military vehicles. In the United States, the system regained its popularity at the beginning of the 1980s, when the durability and the benefits of the system were better recognized, studied, and proven ready for wider deployment (Adams, 2002, as cited in Ghaffariyan, 2017). (Kaczmarek, 1984)

For the use of agricultural applications, CTIS has been a subject of discussion ever since one of the first studies related to its benefits was carried out in the United States in 1983. A significant accelerator for the widespread adoption of CTIS was the technical improvements in tire technologies. Bias-ply tire design was predominantly used in agricultural applications until the more efficient radial-ply tire designs became more popular at the beginning of the 1980s. (Adams et al., 2004)

In bias-ply tires, the body ply cords are laid at an angle substantially less than 90° to the centerline of the tire tread. The cords extend from bead to bead alongside the tire tread, resulting in erratic tread motion when the tire is operated. Opposingly, in radial tires, the body ply cords are laid at a nominal 90° angle to the tread centerline. In addition to the cords forming the tire body, diagonal belts are laid in the direction of the tread for increased strength and stability of the tire structure. (Gent & Walter, 2006, p. 3–4) (Figure 1)

The major benefit of the radial-ply tire design when comparing to the bias-ply variant is how the tire structure reacts to lower tire inflation pressures. When the tire inflation pressure of a radial tire is lowered, the flex on the tire sidewall is not transmitted to the tire tread, and therefore, the size of the tire-ground surface contact area increases only in the longitudinal direction. With such an effect on the tire-ground surface contact area, the rut depth on soft grounds shallow with the width of the track remaining largely unaffected. The benefit of these effects is realized in the field as a significantly reduced rolling resistance and improved traction due to improved grip area of the tire tread. (Adams et al., 2004; Bradley, 2009, p. 6)

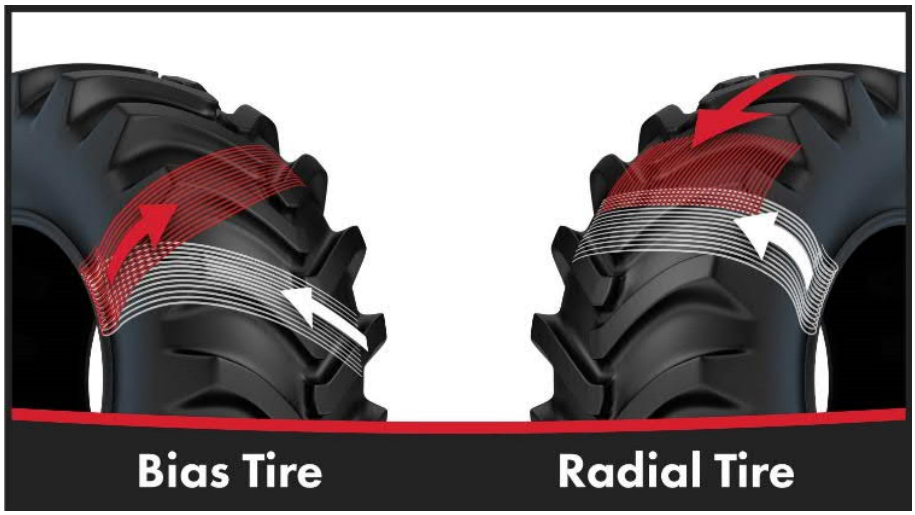

Figure 1: Bias and radial ply tires for agriculture applications (NTS Tire Supply Team, 2019).

With just the replacement of bias-ply with radial ply tires, the improvements in fuel efficiency due to reduced wheel slippage and improved traction were recorded in the range of 6 to 14% (Brodbeck, 2004, as cited in Hoy et al., 2014, p. 18).

In conjunction with radial ply tires, the advantages of lower tire inflation pressures were quickly noticed when the vehicles were operated in the field. Lowered rolling resistance, increased traction, and less soil compaction made the economic aspects of CTIS an even more appealing solution for the use of consumer markets (Adams et al., 2004).

For the use of the forestry industry and especially logging trucks, the investigations for the benefits of adjusted tire inflation pressures using CTIS were first started in the early 1980s at the instigation of the United States Forest Service. From the United States, the CTIS were first recognized, researched, and implemented in Canada, New Zealand, and Australia in the late 1980s. In Northern Europe, CTIS were first initiated by Sweden at the beginning of the 1990s. (Brokmeier, 2017) In Finland, the first logging truck that had a CTIS installed was introduced and tested in 2008 (Oksanen & Rytkönen, 2009).

Several studies related to the use of CTIS in connection with logging trucks confirmed the benefits reported from the previous military experiences. Adjustable tire inflation pressures presented promising results on gravel and soil surfaced forest road conditions due to improved traversing capabilities, reduced road damage, and extended timber harvesting seasons. (Granlund, 2006; Brokmeier, 2017)

The foremost CTIS solutions from the World War II-era were based on a single-line configuration, meaning that they were continuously pressurized to sustain the set level of tire inflation pressure. The major downside of these single-line systems was their fragility, low level of reliability, and maintenance requirements in short service intervals. The components that wore in these single-line systems were the rotary seals used to seal the connection between the rotor and stator elements of the wheel valve assembly (Schmitz, 2000). In the single-line systems, the rotary seals endured only 100 hours of active operation, deeming the solutions of that time unsuitable and uneconomic for the use of commercial vehicles. (Tigges, 2015)

Since the need for adjusting the tire inflation pressures in agricultural and forestry vehicles were not continuous, it was realized that changes in the system had to be done. Simply redesigning the system to be pressurized only when the tires are being inflated lengthened the operational lifetime of the rotary seals in the system tremendously. The redesigned CTIS were then based on a dual-line system in which a secondary air line was added to control the wheel valve to open the main air line only when tire inflation pressure adjustments were needed. (Tigges, 2015; Brokmeier, 2017)

However, to reduce the amount of damage sensitive components even further, the use of modern technological improvements introduced electronically controllable valves, which in the latest CTIS have replaced the need for the secondary air line. Nowadays, the invention of the dual-line system has been made obsolete, as the state-of-the-art systems are now based on a single-line system where the controlling of the air flow within the main air line is handled via electronically controllable valves. (Corneli, 2020)

2.2 Operation Principle of Central Tire Inflation Systems

In this subchapter, the operation principle of a CTIS is briefly introduced. The presentation is constructed to illustrate the prime functionalities of the system so that the details would be applicable regardless of the possible differences in other types of configurations and in the target applications the system is most typically installed in. The functionality is presented through the main components of the system.

Figure 2 presents a CTIS configuration installed on a tractor, indicating its main components. The main components are the operator control panel, electronic control unit (ECU), pneumatic control unit (PCU), pneumatic system, and the wheel valves.

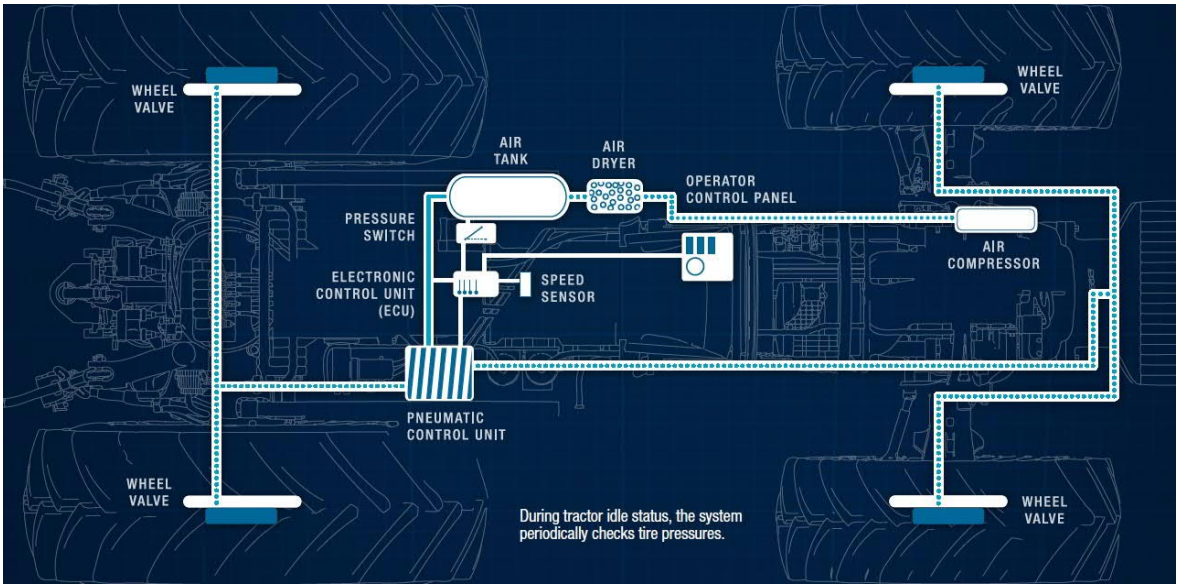

Figure 2: Setup of primary CTIS components in a tractor (Spicer, 2020).

Variations in the wheel valve constructions are discussed further in chapter 2.3 when other types of CTIS are presented. In Figure 3, a closer inspection of an internal CTIS manifold

including the wheel valve configuration is presented. The illustration shows the components required to control the tire inflation pressures on each wheel. The mechatronic control unit is a proportional device to the PCU which regulates the inflation and deflation procedures of the tire pressures. The functionality of the PCU is discussed further in chapter 2.2.2.

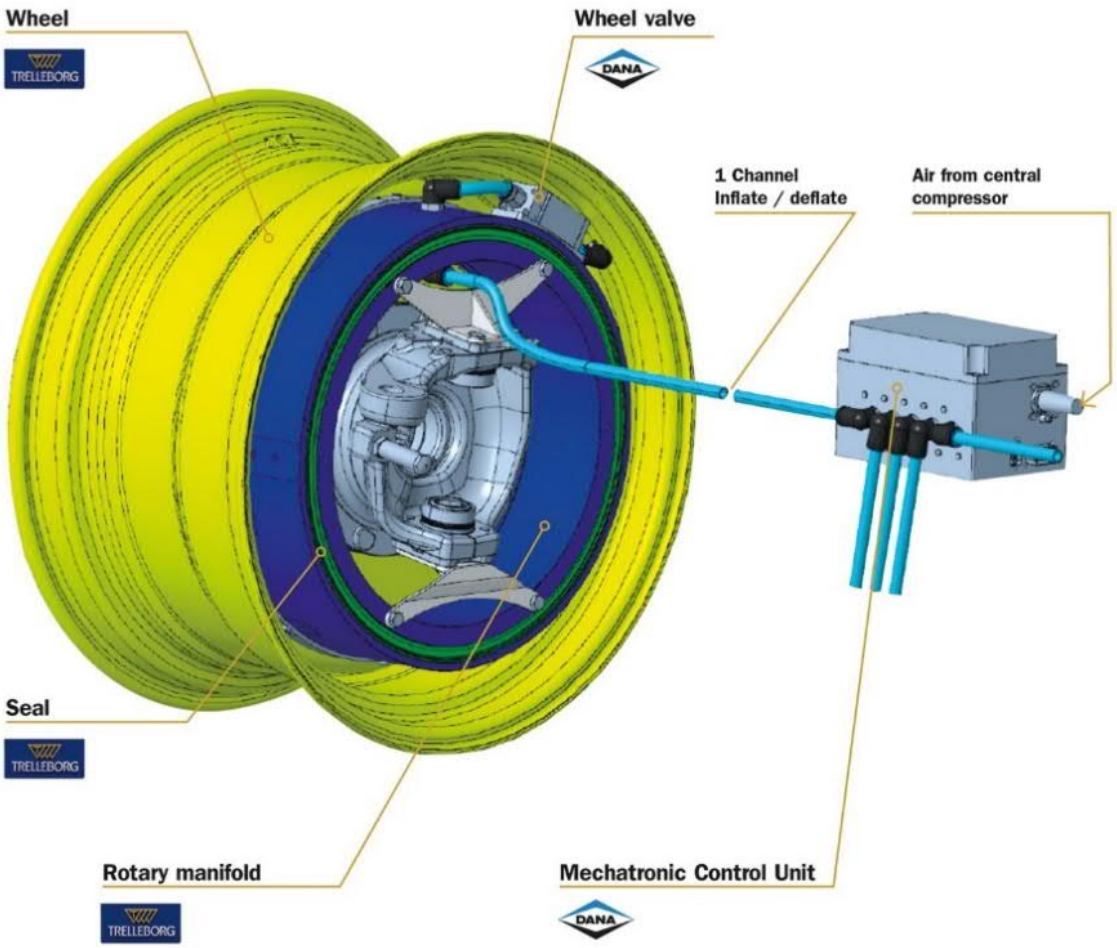

Figure 3: Internal CTIS manifold and wheel valve construction (Trelleborg, 2019).

2.2.1 Operator Control Panel

In CTIS, the operator control panel is the user interface that permits the tire inflation pressure adjustment requests from the operator seat. The control panels by their design vary between the different CTIS configurations. The differences can be perceived in the amount of visible data and the level of control the operator has. However, the basic operating principle is the same, which is to monitor and control the inflation and deflation procedures of tire pressures.

In the advanced state-of-the-art operator control panels, the operator is capable of individually monitoring the tire inflation pressures of each tire, select from pre-made tire inflation pressure settings, and even set the system on automatic mode. Under pre-determined settings, the automatic mode senses and performs the adjustments without actions required from the operator (Trelleborg, 2019) (Figure 4).

Figure 4: State-of-the-art operator control panel (Trelleborg, 2019).

If the CTIS is equipped with the capability of an automatic mode, the system has to be configured with a separate software to receive pressure recommendations. The configuration settings typically consist of basic information of the application in use, such as vehicle power, front and rear weights, and the vehicle's wheelbase. If applicable, mounted equipment must also be defined for precise tire inflation pressure recommendations. The configuration programs can be used without compatible CTIS to receive recommended tire inflation pressures, but without the availability of CTIS, the tire inflation pressures must be set manually. (Trelleborg, n.d.b)

After the system has been successfully configured, the recommended tire inflation pressures can be activated to apply automatically by confirming the settings on the operator control panel. In Figure 4, the "Adjust Tire Pressure" setting in the bottom right-hand corner of the control panel activates the automatic mode after the system configuration has been successfully carried out (Trelleborg, 2019) (Figure 4).

2.2.2 Electronic and Pneumatic Control Units

From the settings applied on the operator control panel, an adjustment request to the ECU is forwarded. The ECU receives and processes the request and checks that all of the requirements for the adjustment of the tire inflation pressures are met. The requirements are for example that the system is functional, no errors in the system have been diagnosed, and that a sufficient amount of air pressure is available in the pneumatic system to perform the requested adjustment of the tire inflation pressures. (TPC International, 2020b)

The requirement of sufficient air pressure is of especial importance in vehicles equipped with pneumatic braking systems, as enough pressure for the safe operation of the braking system must always be prioritized. The vehicles which have pneumatic braking systems are, but are not limited to, modern agricultural tractors intended to tow trailers and other equipment, and trucks often used in timber transportation operations. In agricultural tractors, even if the tractor's main brakes were to be implemented as hydraulic, the braking of the trailer implement is typically controlled via a pneumatic braking system (Kamiński & Czaban, 2012). (Brokmeier, 2017; Ghaffariyan, 2017; TPC International, 2020b)

After the ECU with the strict parameters has confirmed that the level of pressure available from the compressor and the air tank is as required for the safe operation of the pneumatic braking system, the request is then translated to the PCU (Figure 2). (Brokmeier, 2017; Ghaffariyan, 2017)

State-of-the-art CTIS solutions are often equipped with continuous monitoring capabilities of the tire inflation pressures. In case pressure leaks from any of the tires are detected, the ECU will automatically request the adjustment of the tire inflation pressures from the PCU to correct the deviations. (Ghaffariyan, 2017; Trelleborg, 2019)

2.2.3 Pneumatic System

The air which the CTIS uses to inflate the tires is generated by an air compressor that supplies the air through an air drier to the air tank for storage (Figure 2). For vehicles equipped with pneumatic braking systems, the air system is shared between the operation of brakes and CTIS under applied prerequisites presented in the previous subsection (Brokmeier, 2017; TPC International, 2020b).

From the PCU the distribution of the pressurized air is regulated along air lines connected to the stator element of the rotary manifold attached to the center of each individually regulated wheel on both front and rear axles (Figure 2). On the wheel hub, the inflation and deflation of the tire pressures are regulated by a wheel valve. The inflation of the tire pressures is through a final connection through the rim of the wheel, whereas deflation occurs right at the wheel valve. In Figure 3, the wheel valve is located on the rotor element of the rotary manifold. (Trelleborg, 2019) Depending on the CTIS configuration at issue, variations in the wheel valves are possible. Different wheel valve constructions are presented in chapter 2.3.

2.2.4 Sealing Solutions

The main seals used to prevent the pressurized air from leaking out of the system during operation, are rotary seals specifically designed for the use of CTIS. Illustrated in Figure 5, a state-of-the-art rotary seal design for the use of CTIS is presented.

The seals used in CTIS are often manufactured from a combination of materials. The main sealing element is the seal lip manufactured of polytetrafluoroethylene (PTFE) supported by an elastomer jacket. The elastomer jacket by its springback properties allows the sealing lip to generate a uniform sealing performance. The PTFE and elastomer jacket are combined with a metallic encasing which forms the structure of the seal. (Trelleborg, 2017)

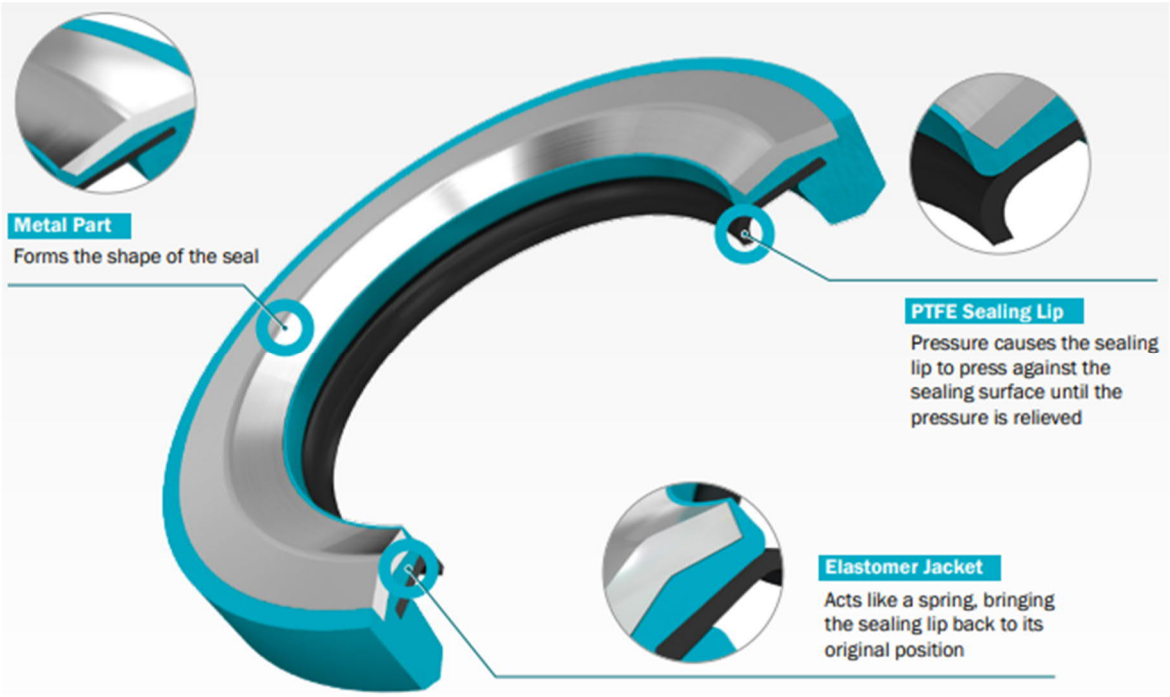

Figure 5: State-of-the-art rotary seal for the use of CTIS (Trelleborg, 2017).

The principal idea of CTIS sealing solutions is that a pair of seals are fixed on the opposing ends of the rotary connection. The connection between the stator and rotor elements of the rotary manifold must be sealed for the pressurized air to be able to reach the rotating tire (Figure 6). (Trelleborg, 2019)

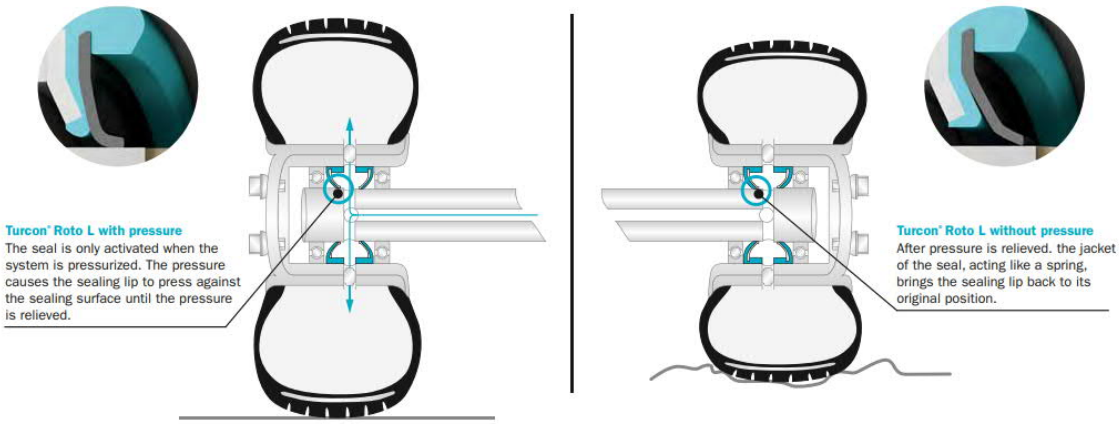

Figure 6: The operation principle of a state-of-the-art CTIS rotary seal (Trelleborg, 2020).

The implementations of the sealing solutions used vary as the different CTIS structures are being compared. The different sealing solutions available for CTIS are discussed further in chapters 2.3 and 5.2.

2.3 Types of Central Tire Inflation Systems

The operation principle of CTIS, as broadly described in chapter 2.2, shows consistency in all modern CTIS solutions available. Certain variations are possible due to minor differences in the system configurations. The different types of CTIS are often classified as external and internal systems due to major structural differences and configurations as presented in the following subchapters (FTL Technology, 2020).

Due to the availability of tailored solutions, it is impossible to list all of the possible variations of CTIS. Therefore, the aim of this subchapter is to illustrate the two main structures from which all of the main variations can be derived from.

2.3.1 External Systems

The external configuration of CTIS is the most common structure. This is due to limitations in the availability of OEM-ready, integrated CTIS solutions discussed further in chapter 5.3. The external CTIS configurations are often recognizable from the air lines drawn on the outer side of the vehicle chassis to the wheel valve located on the outer side of the wheel hub. (Figure 7)

Figure 7: External CTIS installed in an agricultural tractor (TractAir, 2020).

The key advantage of external CTIS configurations is that the system is retrofittable to virtually any type or class of a vehicle. In Figure 8, an external CTIS retrofitted to a truck is illustrated. In the illustration, the main components presented during chapter 2.2 are visualized. (FTL Technology, 2020)

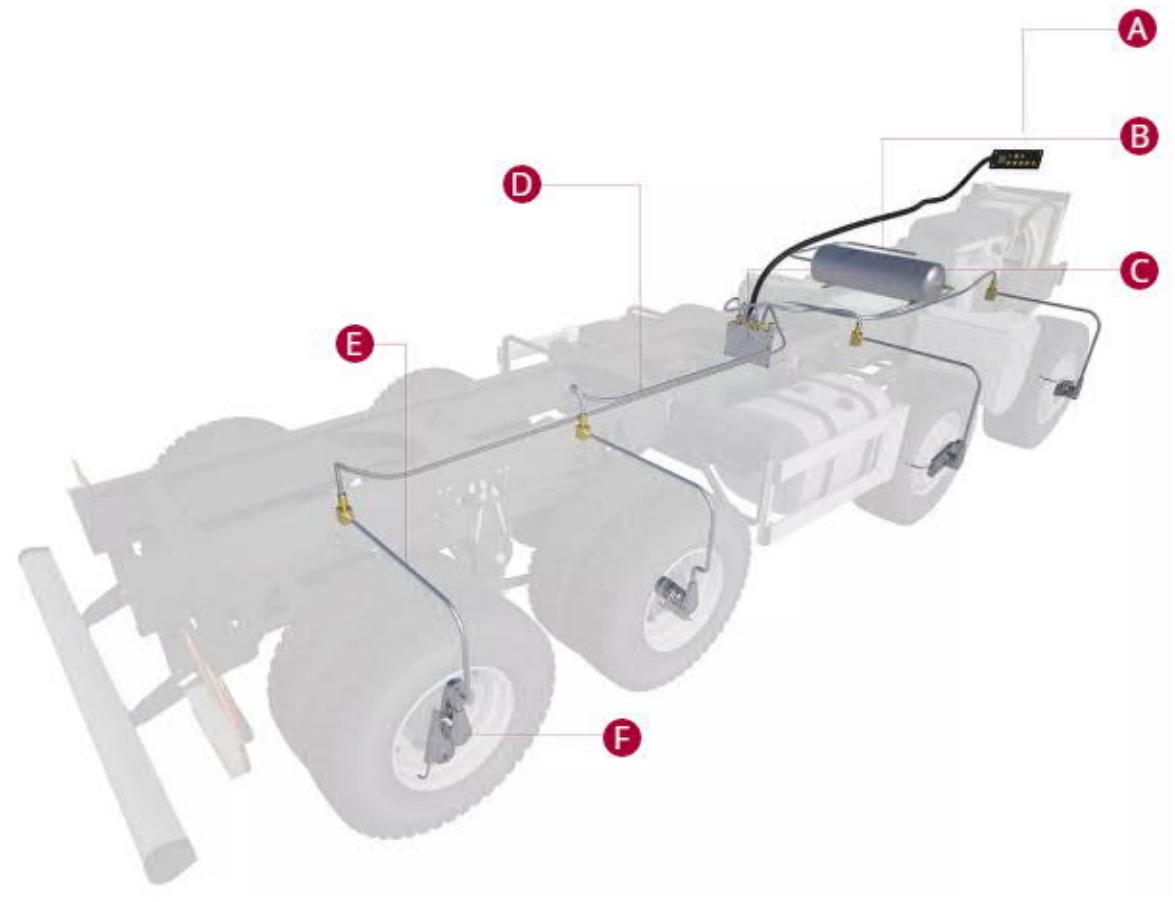

Figure 8: External CTIS in a truck (FTL Technology, 2020).

In alphabetical order, the components are the operator control panel, air tank, ECU and PCU, air lines along with the vehicle chassis, air line connections to each wheel, and the rotary wheel valve.

As mentioned in chapter 2.2.3, there are variations in the air distribution systems, especially in the design and construction of the wheel valve. In the CTIS configuration presented in Figure 8, the wheel valve itself contains the rotary connection.

Since there is no separate manifold in Figure 8 as presented in Figure 3, the wheel valve contains the stator element connected to the air line, and the rotor element attached to the wheel hub. From the rotor element, the final connection which regulates the tire inflation pressures is through the wheel rim. Since the rotary connection is included within the wheel valve, the rotary seals are also included within the construction of the wheel valve.

Various external CTIS configurations and designs exist. Figure 9 presents a comparable external CTIS configuration to the system illustrated in Figure 8. Certain differences can be detected between the two presented configurations mainly in the way the systems are constructed within the vehicle structure. However, based on the operation principle, the functionality between the systems remains unchanged.

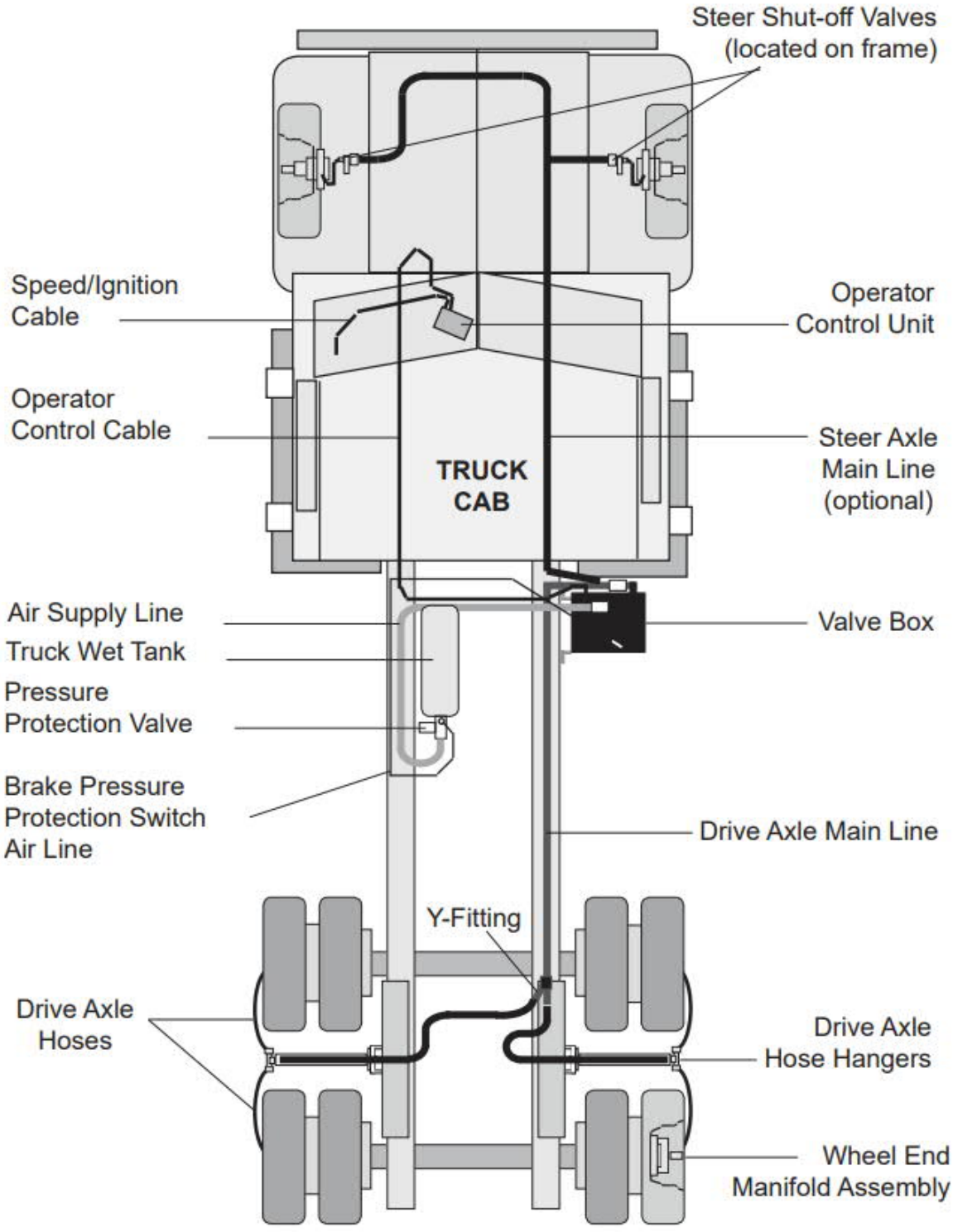

Figure 9: External CTIS in a truck (TPC International, 2020b).

Another example of external CTIS is presented in Figure 10. In this configuration, the same components apply, in a comparable construction which operates similarly as the above configurations (Figure 8 & Figure 9). The most notable difference in this configuration is the detachable hose packets, which allow the deactivation of CTIS when the adjustment of the tire inflation pressures is not required.

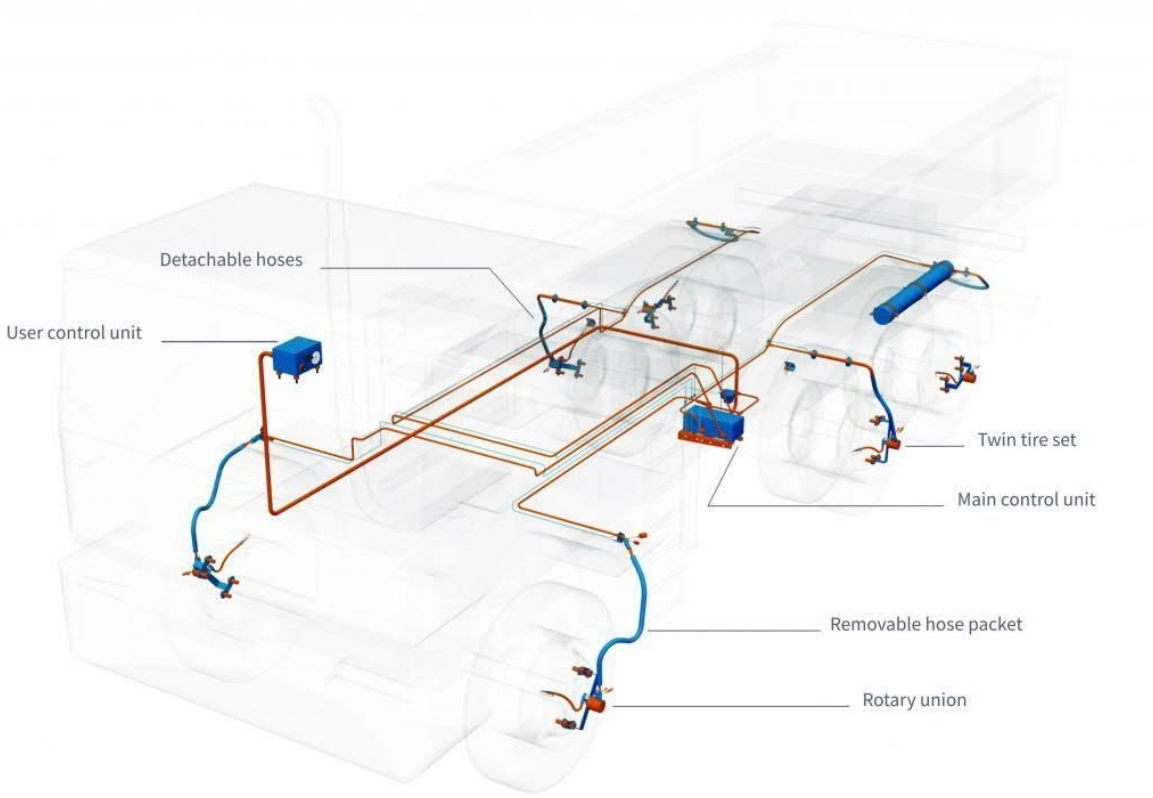

Figure 10: External CTIS in a truck with detachable hose packets (Ti.systems, 2017).

In conclusion, external CTIS configurations are a functioning solution with a high level of technological maturity (Bradley, 2009, p. 3). With the system being fully retrofittable to virtually any type of a vehicle requiring tire inflation pressure adjustments, external CTIS can be considered as a technology with a low level of technical requirements.

As the disadvantage of the external CTIS configuration, the components that protrude outside the vehicle chassis must be mentioned. These components include the air lines and wheel valves. Since these components are out in the open to encounter any direct impacts, they are highly susceptible to external damages. (FTL Technology, 2020)

Certain configurations allow the protruding components to be removed when they are not in use (Figure 10). However, it must be noted that when the system is deactivated, the CTIS cannot be used. This presents a contradictory problem since the occurrence of external damage increases substantially in the off-road conditions where the requirement for adjusted tire inflation pressures typically arises.

2.3.2 Internal Systems

The internal CTIS configurations consider all of the integrated solutions within the chassis of the vehicle with only a few or zero externally visible parts (FTL Technology, 2020). In 2019, a concept tractor including a fully integrated state-of-the-art CTIS was presented (Tyrepress, 2019) (Figure 11).

Figure 11: Internal CTIS installed in an agricultural tractor concept (Tyrepress, 2019).

The benefit of internal CTIS configuration is that there are no protruding components outside the vehicle chassis susceptible to external damages. In principle, the way the system operates is unchanged to the external variation.

From the consumer perspective, the major difference between the external and internal CTIS is that the latter is not a practical retrofit solution. Therefore, the acquisition of the system must typically be decided simultaneously with the purchase of the vehicle.

Considering the purpose of this thesis, this creates a contemporary solution for the wider implementation of CTIS. If the systems were to be implemented within the vehicle from the very first deployment, the vehicle operator (or the vehicle owner) would become accustomed to and in using the system, and thus the need to decide on additional investments later on would be removed.

Compared to the external variances, the internal configurations of CTIS are more of a permanent solution in the vehicle typically offered as an OEM solution with limited availability in the aftermarket as discussed in chapter 5.3.

In Figure 12, an internal CTIS integrated into a truck is illustrated. The illustration includes the main components in a configuration that resembles the exemplary operation principle presented in chapter 2.2. (FTL Technology, 2020)

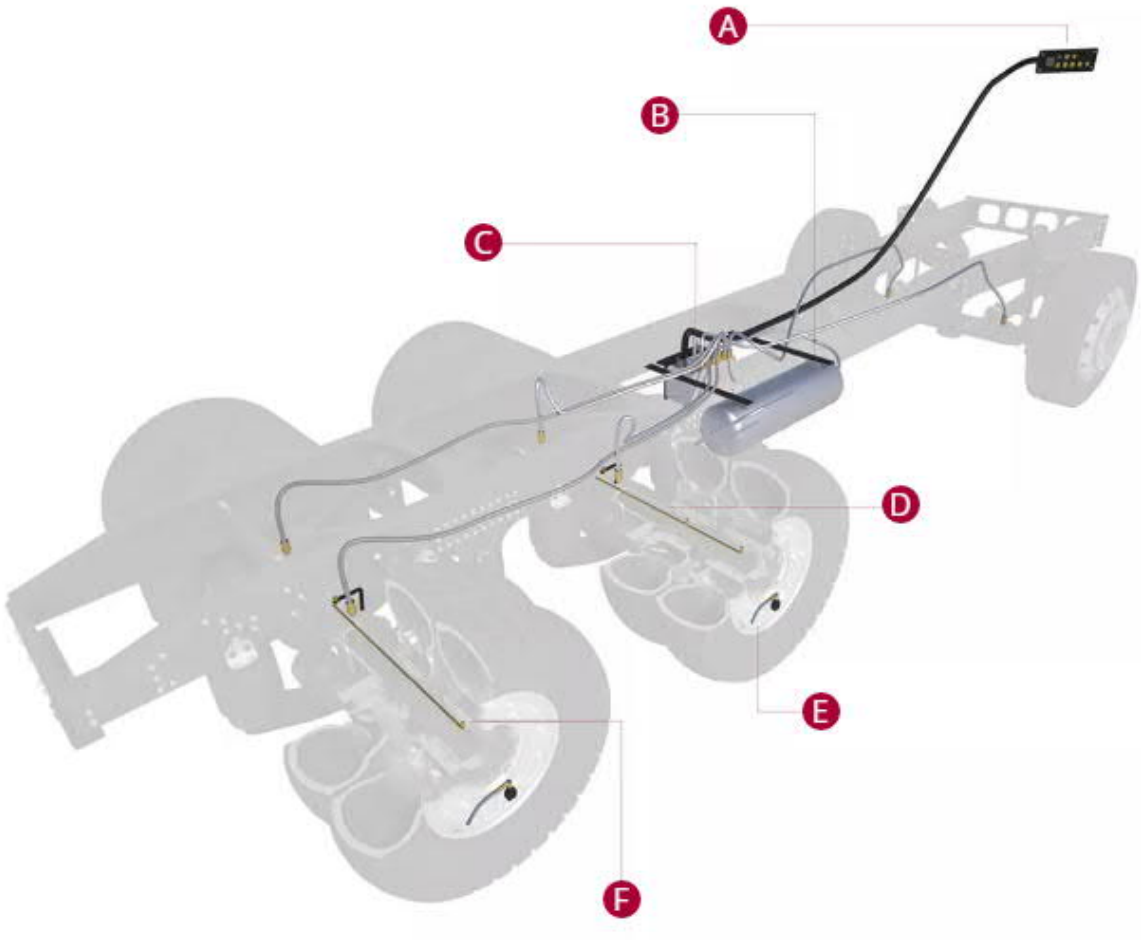

Figure 12. Internal CTIS in a truck (FTL Technology, 2020).

The components listed in alphabetical order are the operator control panel, air tank, ECU and PCU, air lines along with the vehicle chassis, air passages through the drilled pathways in the rear axles, rotary manifold, and the wheel valve connection on each wheel assembly.

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3 Tire Inflation Pressure

The characteristics of a tire are important in a variety of features affecting the behavior of a vehicle. Since tire forms the only contact surface between the vehicle and the road surface, the tire characteristics are crucial for handling, accelerating, and braking performance, as well as the dynamic behavior of the vehicle.

As one of the most important characteristics of a tire, affecting nearly all areas of its operation, is the vertical stiffness of the tire. The vertical stiffness of a tire is a combination of size, construction, and inflation pressure. However, tire inflation pressure with an effect of approximately 80% is by far the most important parameter. (Soltani et al., 2015)

In this chapter, the concepts affected by tire inflation pressure are presented. The presented concepts are based on the study-related industries of agriculture and forestry where the typical operational conditions set an exceptional demand for tire inflation pressures to be adjusted accordingly to the varying operating conditions.

3.1 Concepts Affected by the Tire Inflation Pressure

The dynamic behavior of a tire includes a variety of performance-related concepts. The majority of these concepts consider the forces that affect the amount of energy that must be inputted to perform the required activities. With appropriate adjustments of the tire inflation pressure forces such as rolling resistance and traction can be altered according to the surrounding operating conditions. With improvements in rolling resistance and traction, significant improvements in the vehicle's fuel consumption can be perceived. Additionally, with optimal tire behavior concepts such as the comfort and quality of the ride can be improved and the lifetime of the tire tread can be lengthened. (Soltani et al., 2015)

3.1.1 Weight Force

Weight force, wheel or axle load defines the amount of pressure the weight of the vehicle directs through the tire-ground surface contact area. For the studied industries of agriculture and forestry, weight force is one of the key concepts affecting the vehicle's mobility, and thus the ability to perform the designed operations.

The connection between weight force and adjusted tire inflation pressures can be demonstrated through a tractor tire. By implementing lower tire inflation pressures, the size of the tire-ground surface contact area increases. With an increased size of the tire-ground surface contact area, the weight of the tractor is distributed on a larger section of the tire tread (Figure 13).

As the weight force of the tractor is distributed on a larger tire-ground surface contact area, the peak pressure levels directed onto the soil surface are lowered. Lowering the amount of weight force reduces a significant amount of stress directed through the tires to the surface of the soil. (Tigges, 2015; Yap, 1988, as cited in Ghaffariyan, 2017)

Figure 13: Comparison of tire-ground surface contact area with low and high tire inflation pressures respectively from left to right (AGCO Fendt, 2020).

In the context of an agricultural tractor, the tire inflation pressures should be lowered when the vehicle is transferred to operate in the field. Reduced weight force decreases the depth of the tracks formed on to the soft soil as the tractor is operated. By implementing a larger tire-ground surface contact area the tires float on top of the soil surface, generating significantly shallower tracks. The shallower the tracks are, the less resistance the soil causes to the operation of the vehicle. The less resistance on the wheels, the smoother the tires roll resulting in lowered tire-soil interaction. Reduced interaction sustains the condition of the soil structure which projects in greater crop growth. (Figure 14)

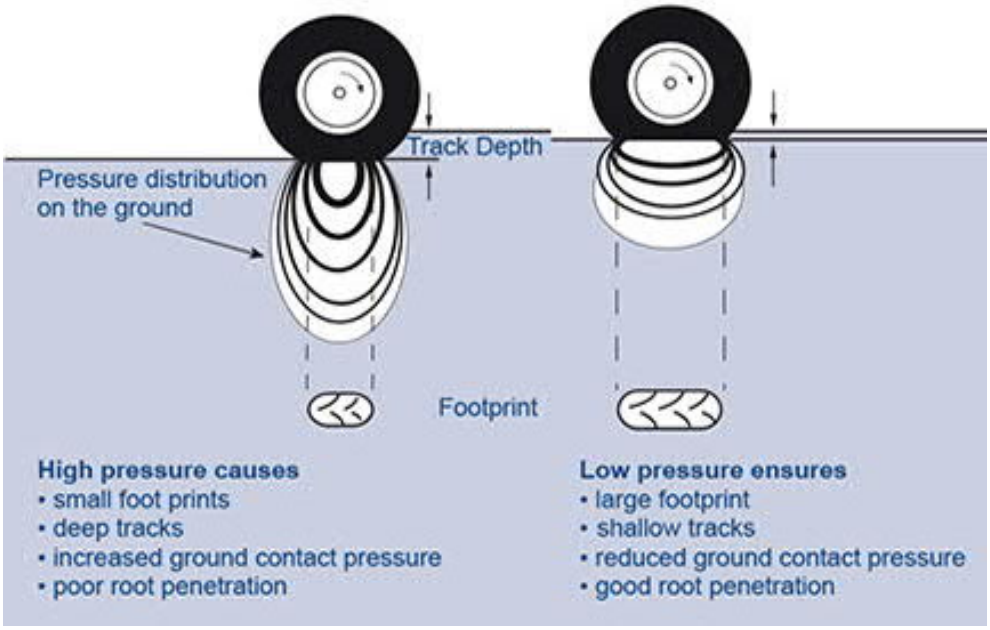

Figure 14: Effects of tire inflation pressure on the ground surface (PTG, n.d.).

For the applications of forestry, such as logging trucks, the effect of weight force applies similarly as in the agricultural setting. By lowering the level of tire inflation pressures the size of the tire-ground surface contact area can be increased to better distribute the weight of the truck to reduce the stress caused to forest roads (Figure 15).

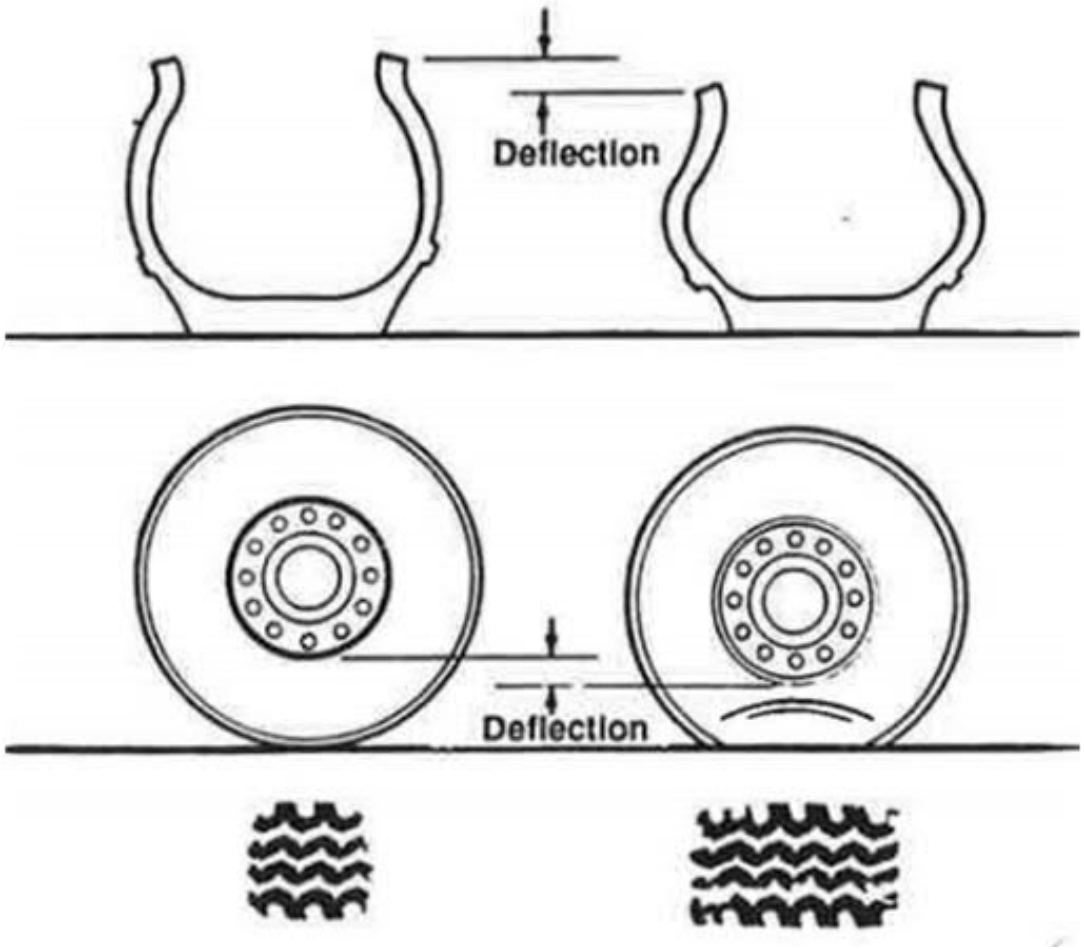

Figure 15: Effect of tire inflation pressure on deflection and size of the tire-ground surface contact area (Simonson, 1993).

The gravel or soil-based forest roads can be prone to track formation similarly to agricultural fields. Therefore, by being able to adjust the tire inflation pressures the possibility of causing unwanted road damage can be avoided and the traversing capabilities of the truck can be improved. (Simonson, 1993)

On the unpaved forest roads, heavy truck traffic is one of the main causes of road surface erosion promoting sedimentation[2]. Sedimentation of the road surface occurs when the vehicle increasingly stresses and wears the road surface. With appropriate tire inflation pressure adjustments, the weight force of the truck can be decreased and the effects of road surface sedimentation can be reduced by up to 45% (Foltz, 1994). (Bilby et al., 1989, as cited in Foltz, 1994)

[2] Sedimentation defines the dislodging of substance from the road surface which is considered pollutive and harmful for nearby water bodies (Akbarimehr & Naghdi, 2012).

3.1.2 Soil Compaction

Soil compaction is one of the major environmental and economic issues concerning modern agricultural operations. Soil compaction as a concept influences the yield levels the fields are able to provide. Lowered yield levels correlate directly to the viability of the farming operations, as the farm output is the source of the livelihood of the farming industry.

As a concept, soil compaction is directly related to the effects of weight force caused by external influences. As one of the primary causes of soil compaction is the continuous bypasses of heavy agricultural machinery used to effectively cultivate and process the field. (Gharibkhani, Mardani & Vesali, 2012)

Increased soil compaction decreases the pore space and causes physical degradation of the soil structure. A high level of soil compaction negatively affects the spread of nutrients, root penetration, and thus the growth of the crops. Severe degradation cumulates to the bottom layers of the soil structure, resulting in irreversible damage. (Elaoud & Chehaibi, 2011; Gharibkhani et al., 2012)

To decrease the effects of soil compaction, the effects of external weight force influencers must be minimized. As discussed in chapter 3.1.1, the effect of weight force caused by tractors can be reduced by increasing the size of the tire-ground surface contact area. Thus, when the tractor is transferred from paved roads to operate in the field, the tire inflation pressures should be adjusted to be as low as permissible to reduce the effects of soil compaction (Elaoud & Chehaibi, 2011).

As an indicator of soil compaction, a value of soil penetration resistance is measured. This value is measured with a penetrometer that is pushed into the soil at a constant speed. Soil resistance to penetration is a complex function of parameters that characterize the state of the measured area. It takes into consideration the cohesion and compaction of the soil and the frictional values involved. Soil penetration resistance is measured in units of pressure. (Elaoud & Chehaibi, 2011; Gharibkhani et al., 2012)

In the tests carried out by Elaoud & Chehaibi (2011), the soil's resistance to penetration was measured at three soil depths of 5, 10, and 15 centimeters with three individual tire inflation pressure settings of 1.2 (T1), 2,0 (T2) and 3.0 (T3) bars. With the varying tire inflation pressure settings, the weight force of the passing tractor was simulated and its effects on the soil structure at different depths were measured. The used tractor was Kubota L3430 with an informed gross weight of 1200 kilograms.

The measurements of the soil's resistance to penetration were taken on three occasions: initial state, after the first pass, and after the second pass. Both of the passes after the initial measurement were carried out with the same predetermined tire inflation pressure setting, on the same track, and in the same field as the following test phases.

Figure 16 presents the results of the soil's resistance to penetration using the lowest tire inflation pressure of 1.2 bars (T1). With this setup, the increase in the respective soil resistance to penetration after the first pass was increased by 55.56%, 61.61%, and 29.48% at the respective depths of 5, 10, and 15 centimeters when compared to the initial state.

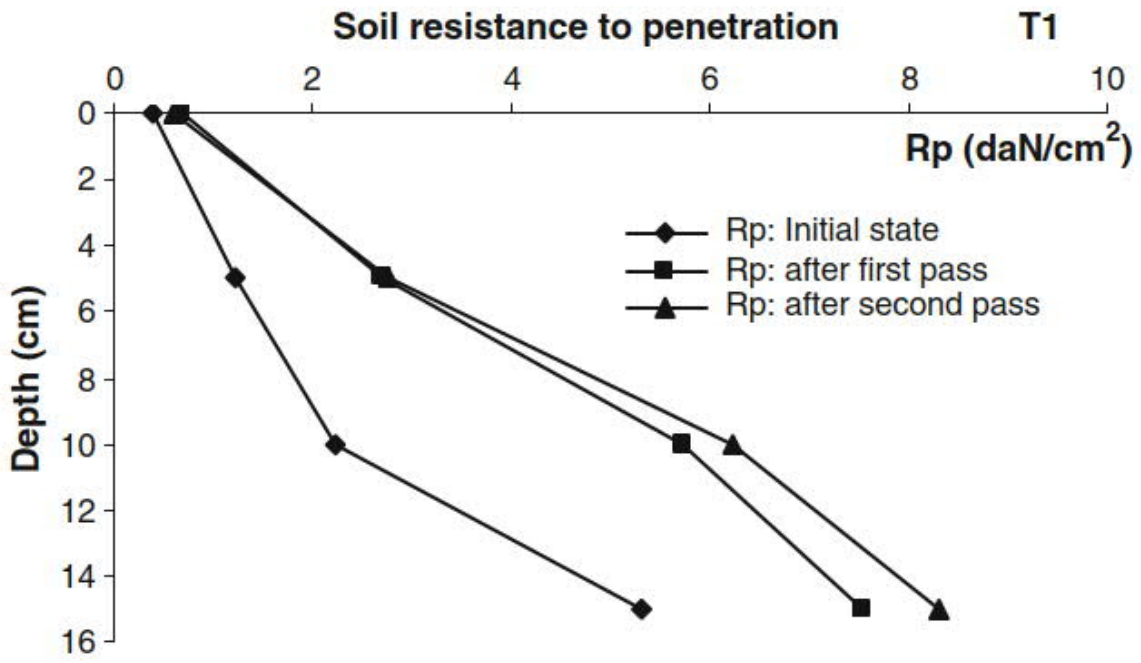

Figure 16: Values of soil resistance to penetration with a tire inflation pressure of 1.2 bars (Elaoud & Chehaibi, 2011).

Figure 17 presents the test results of the soil's resistance to penetration using a tire inflation pressure of 2.0 bars (T2). With this setup, the increase in the respective soil resistance to penetration after the first pass was increased by 56.23%, 63.96%, and 30.41% at respective depths of 5, 10, and 15 centimeters when compared to the initial state.

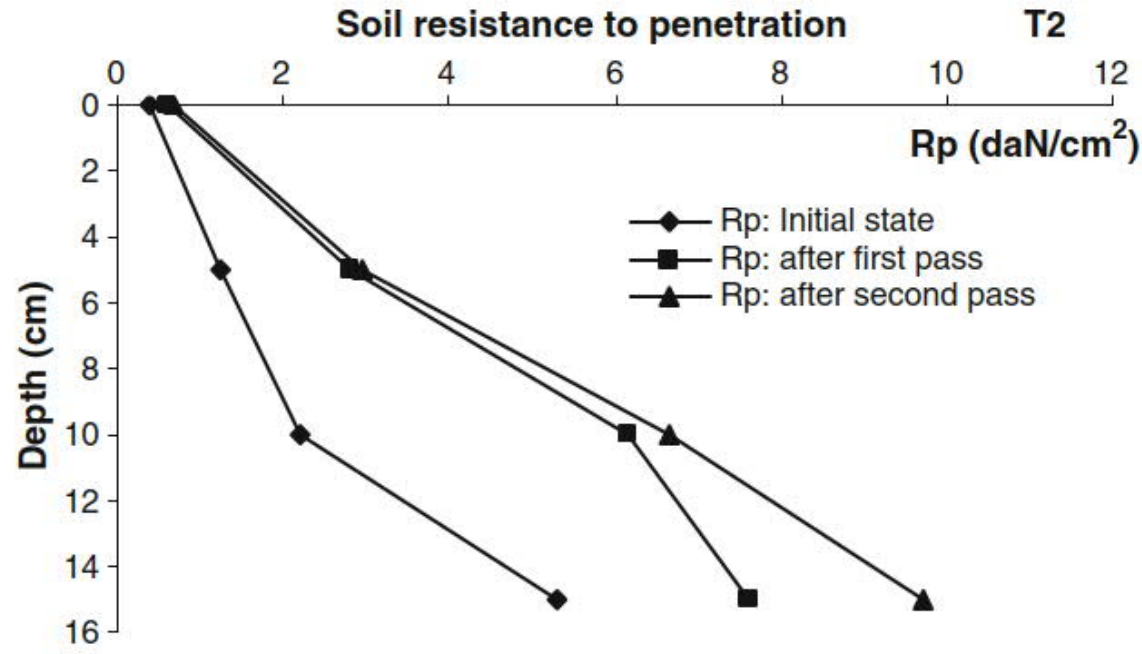

Figure 17: Values of soil resistance to penetration with a tire inflation pressure of 2.0 bars (Elaoud & Chehaibi, 2011).

Figure 18 presents the test results of the soil's resistance to penetration using the highest tire inflation pressure of 3.0 bars. With this setup, the increase in the respective soil resistance to penetration after the first pass was increased by 67.0%, 70.0%, and 43.0% at respective depths of 5, 10, and 15 centimeters when compared to the initial state.

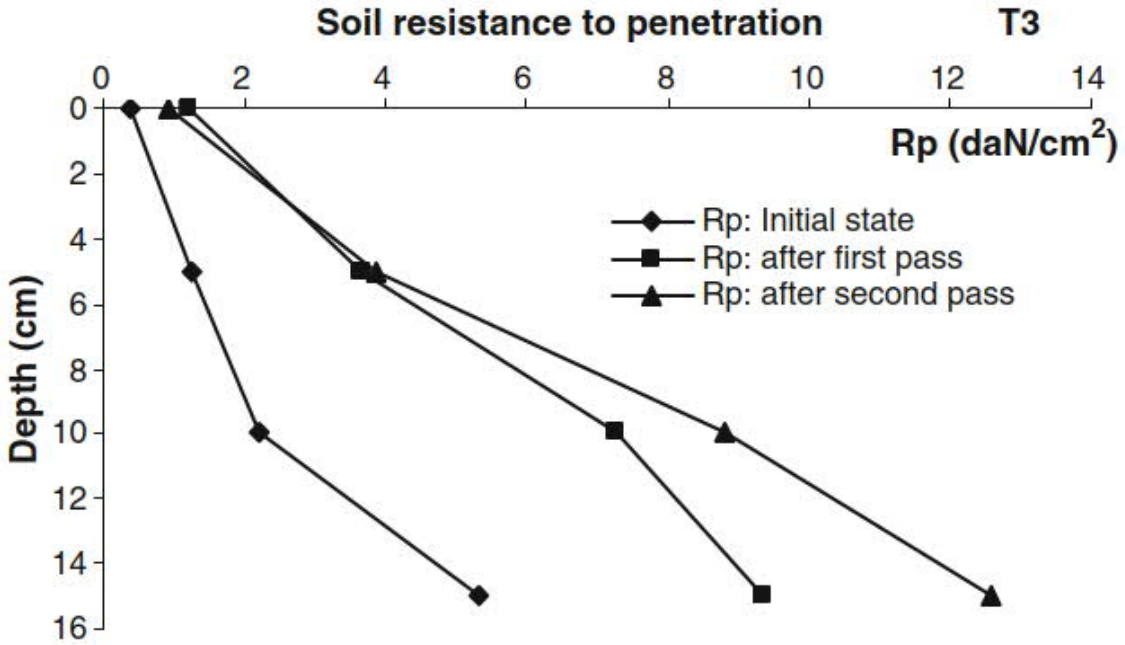

Figure 18: Values of soil resistance to penetration with a tire inflation pressure of 3.0 bars (Elaoud & Chehaibi, 2011).

When comparing the presented test results, it is shown that the value of the soil's resistance to penetration increases when the tractor is operated with higher tire inflation pressures. The results are in connection with the increased level of pressure the weight force causes through a smaller tire-ground surface contact area when higher tire inflation pressures are used.

The test results indicate that the second pass increases the soil's resistance to penetration more than the first pass. However, the first pass affects more than the second pass. Therefore, to minimize the effects of soil compaction, the lowest permissible tire inflation pressures should always be applied when transferring to operate in the field. Additionally, multiple passes over the same area should be avoided as much as possible.

With adjusted tire inflation pressures, the level of soil compaction can be reduced. Deterioration of the soil is a serious environmental issue affecting the viability of the farming operations. With the possibility of being able to control and adjust the tire inflation pressures, the damage projected to the soil structure can be reduced to maximize the farm's output. With CTIS, the required tire inflation pressure adjustments are always available.

In Figure 19, the effects of cumulative compaction and deteriorated soil are visualized. Overly compacted soil restricts the penetration of roots which in time results in stunted growth of the crops.

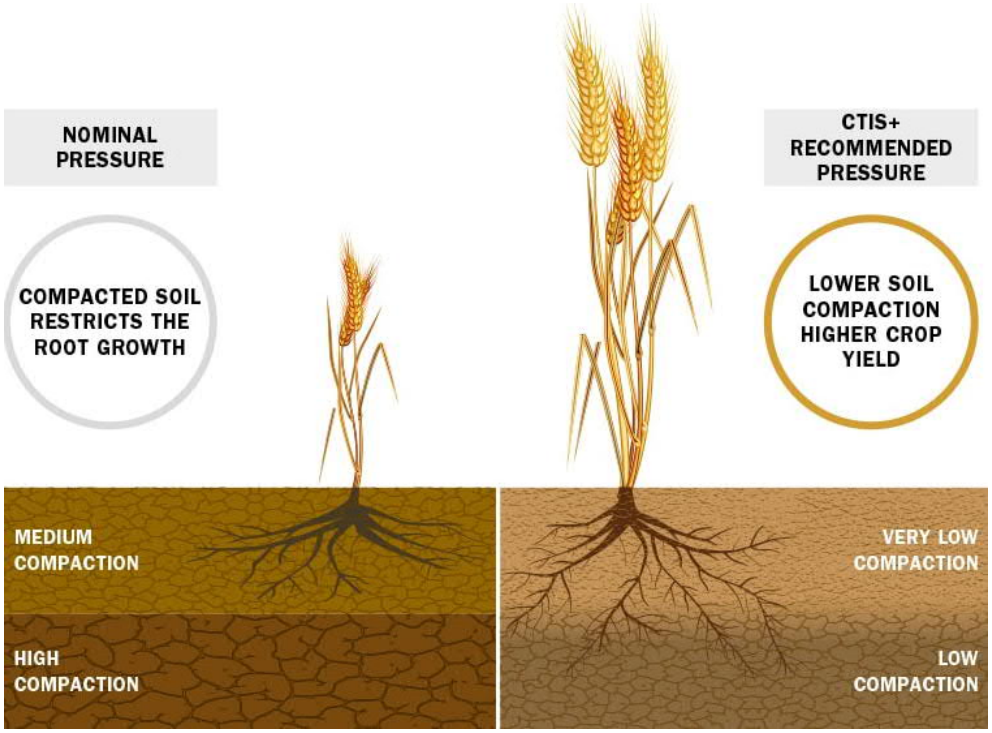

Figure 19: Soil compaction with and without adjusted tire pressures (Trelleborg, 2019).

3.1.3 Rolling Resistance

Rolling resistance describes the amount of force required to overcome the hysteretic[3] losses of a rolling tire. The larger the tire deformations are, the higher the amount of rolling resistance is. Therefore, with lower tire inflation pressures the value of rolling resistance is high because the vertical stiffness of the tire structure is reduced. Opposingly, with higher tire inflation pressure the value of rolling resistance is low because the vertical stiffness of the tire structure resisting the unnecessary deformations of the tire structure is increased. (Gent & Walter, 2006, p. 17–18)

When a vehicle is in operation, overcoming the force of rolling resistance can consume as much as 5 to 15% of the energy required to move the vehicle. However, at lower speeds, the effect can be up to 40%. For this reason, rolling resistance is one of the most detrimental effects on the vehicle's fuel economy. (Soltani et al., 2015)

When vehicles are operated in conditions of off-road, such as the field soil or unpaved forest roads, the definition of rolling resistance often reconfigures. This is due to the combination of deformations in the tire and ground structures. The softer the ground structure is, the more susceptible it is to affect the amount of rolling resistance. (Petterson & Gooch, 2020) In conditions of off-road, the higher rolling resistance poses an increased risk to lose traction. Typically, the higher the vehicle's exerted weight force is, the more significant the level of ground surface deformations are that disadvantageously affect the rolling of the tire.

[3] In the physics of tires, hysteresis defines the energy spent in the continuous deformations of the tire as it rolls across the road under the vehicle's load (Soltani et al., 2015).

The road surface deformations that indirectly contribute to the amount of rolling resistance are for example the tracks visualized in Figure 14. Therefore, with the possibility of being able to adjust the size of the tire-ground surface contact area, the severity of deformations in the ground structure can be reduced. (Gharibkhani et al., 2012)

Kurjenluoma, Alakukku & Ahokas (2009), studied the effects of tire inflation pressures recommended by the tire manufacturer for both field and road conditions in the context of an agricultural tractor. The tests were organized to simulate a situation in which one of the tire inflation pressures recommended for field or road use was applied to evaluate the effects of tire inflation pressure on the amount of rolling resistance and track depth.

In the study, both radial and bias-ply tire types were tested. As briefly discussed in chapter 2.1, the radial-ply structure shows benefits beyond the previously used bias-ply structure especially when lower tire inflation pressures are applied. Presenting the bias ply tire structures highlights the mentioned benefits for better understanding. The test tires are presented in Table 1.

Table 1: Test tire specifications with tire inflation pressures according to the manufacturer's recommendations (Kurjenluoma et al., 2009).

Tyre	1	2	3	4	5
Size	600/55R26.5	600/55R26.5	600/55R26.5	600/55–26.5	600/55–26.5
Diameter (mm)	1332	1360	1344	1348	1355
Section width (mm)	604	618	622	617	614
Carcass construction	Radial	Radial	Radial	Bias ply	Bias ply
Belt number or ply number	Textile carcass	Textile carcass	Steel wires	12	12
Load index	158D	169A8/159D	165D	169D	165A8/153/A8
Tread pattern	Versatile	Rib	Piece	Draught	Versatile
Pressure (kPa): field	120	140	100	120	120
Road	200	180	150	200	200

The experiments were carried out on the same field in a timeline of five weeks. Before each test, the field was processed to form a soil structure reasonable for further comparison. The tests were performed on soils classified as soft, tilled, and firm, each test numbered in respective numerical orders of 1, 2, and 3. The soil condition data are listed in Table 2.

Table 2: Soil conditions in the experiments (Kurjenluoma et al., 2009).[4]

Test No.	Moisture content ($m^3/100m^3$)	Cone index (MPa)			Cohesion (kPa)			Wheel load (kN)
	Mean	Mean	SD	Range	Mean	SD	Range	
1 (soft)	29	0.48	0.18	0.32–1.15	47	13	27–79	35.4
2 (tilled)	28	0.72	0.19	0.62–1.23	71	12	54–97	36.4
3 (firm)	26	1.44	0.44	1.22–2.07	155	48	86–244	35.9

[4] Cone index is a measurement of soil penetration resistance determined in standard ASAE S313.3 FEB99. In brief, the higher the value the more compact the soil is. (Kurjenluoma et al., 2009)

The test tires were mounted on a trailer towed across the field with a tractor. With a tensile load cell attached to the tractor hitch, the drawbar-pull was measured to calculate the rolling resistance of the wheel. Including the data measured of the field gradient, the data was corrected to represent only the drawbar-pull directed to the trailer. With the corrected pull force and the sum of wheel loads, the coefficient of rolling resistance was calculated separately for each test.

For the measurement of track depths, two measurement wheels were situated behind the towed trailer parallel to each other. One of the wheels was situated on the tire track and the other one measured the starting point of the soil surface right next to it.

The results of the calculated coefficients of rolling resistance and track depths are illustrated in Figure 20. Regarding the conditions of soft soil in test 1, a trend of lower rolling resistance coefficient can be seen when field pressures are used in all but tire 2. Test 2 in tilled soil indicates only minimal variations in the coefficient of rolling resistance between the tire inflation pressures. On firm soil, the results of the rolling resistance coefficient are apparent towards tire inflation pressures suggested for conditions of road use.

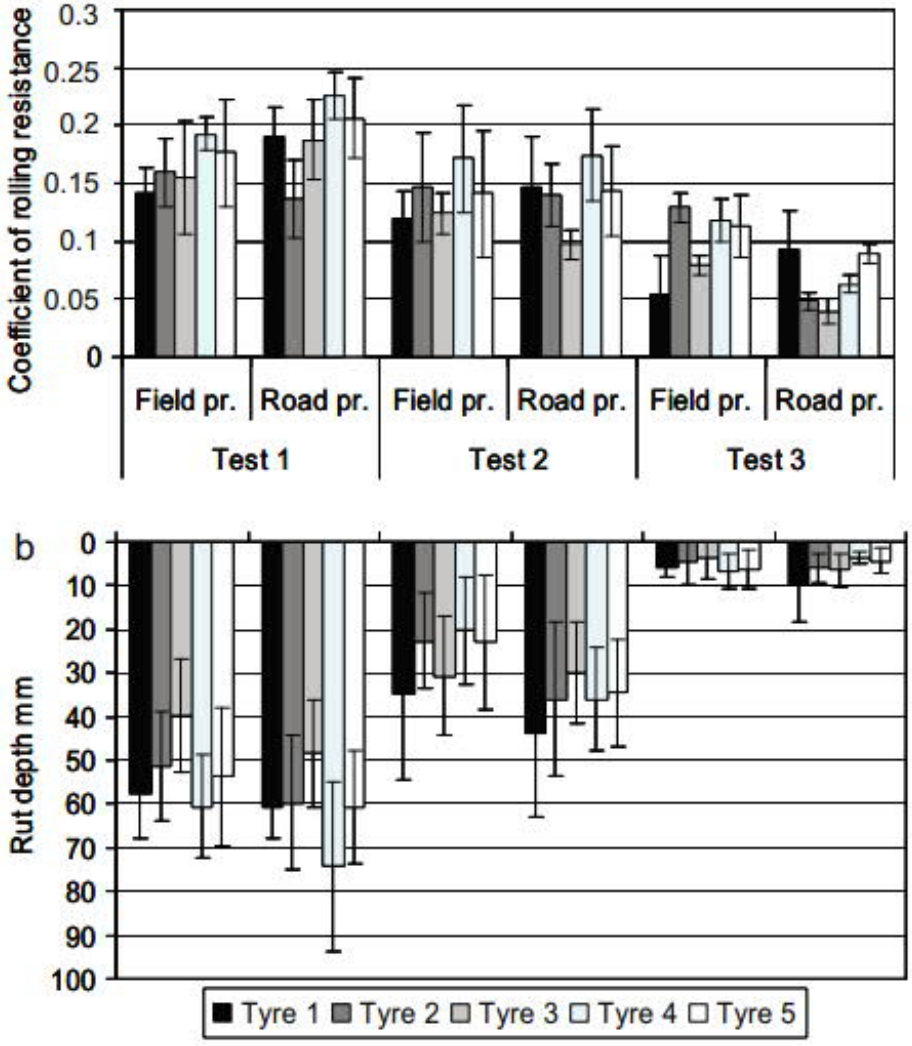

Figure 20: Coefficients of rolling resistance (a), and rut (track) depth (b) of tires with inflation pressures recommended for field and road use (Kurjenluoma et al., 2009).

The measured track depths in all of the test scenarios in relation to the applied tire inflation pressure setting show a trend of benefits towards the recommended field setting. However, the track depths begin to even out in test scenarios 2 and 3 because the soil condition hardens and thus begins to resist track formation.

Results of the study carried out by Kurjenluoma et al. (2009) indicate that it is difficult to include rolling resistance to be dependent only on the effects of tire inflation pressure. In conditions of off-road, the combination of the tire type and structure, carrying capacity of the road surface structure, and the tire inflation pressure is what forms the concept of rolling resistance. The results indicate that when the radial-ply tires were implemented the coefficient of rolling resistance was on average 20% lower than with tires of bias-ply design. Similarly, the track depths were on average 15% shallower with radial tires. However, the results display that for both of the tested tire types it is evident that with even minor tire inflation pressure adjustments the amount of rolling resistance can be decreased, especially in conditions of soft soil. Based on the results, an ideal state for the lowest amount of rolling resistance and tire inflation pressures is when the tires form as shallow tracks as possible.

To elaborate on the importance of sustaining the least amount of track formation as possible is to avoid the occurrence of a phenomenon known as the "bulldozing effect". The bulldozing effect defines a situation when the tire faces more soil than the tire tread is capable of displacing. This excess soil that the tire is unable to displace eventually begins to accumulate in front of the tire, forming a wall of soil which the tire must continuously push forward. (Volk et al., 2011) (Figure 21)

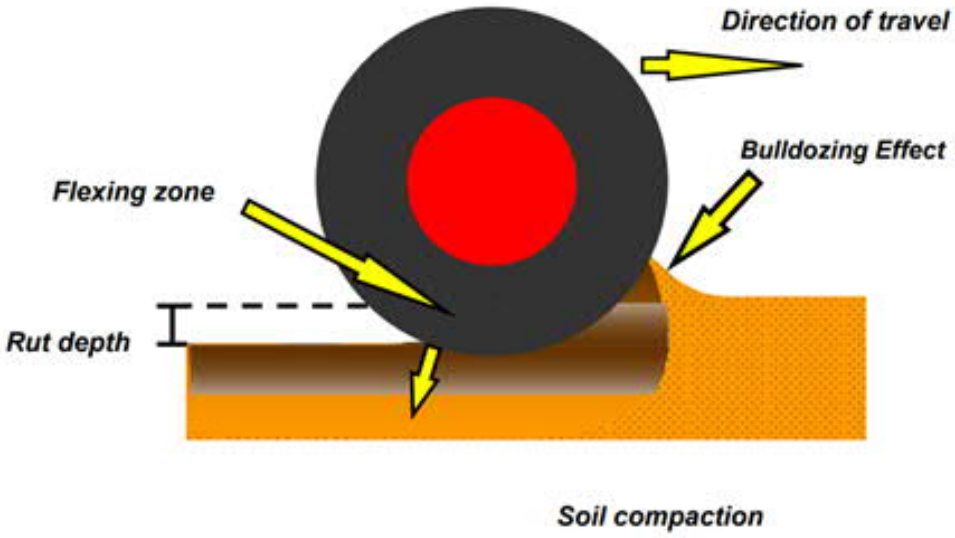

Figure 21: Track depth and the bulldozing effect (Volk et al., 2011).

In conditions of soft soil, the bulldozing effect is a major contributor to the vehicle's fuel consumption. Track depth of one centimeter promoting bulldozing effect corresponds to a constant uphill drive of approximately 1% steepness[5]. In addition to fuel consumption, the bulldozing effect is what poses an increased risk for the vehicle to lose traction and stagnate into the soft ground. (Volk et al., 2011; Ghaffariyan, 2017)

[5] The ascent of a hill is typically given in percentages that is in relation to the distance traveled.

In connection with the already defined concept of weight force, the number of forces that add up to the total amount of rolling resistance is greatly influenced by the size of the tire-ground surface contact area. When the size of the tire-ground surface contact area is larger, the tire sinks significantly less into the soft ground, minimizing the potentiality of resistive forces such as the bulldozing effect to occur.

When the forces that resist the rolling of the tires accumulate, the more adverse the effects towards the efficient operation of the vehicle are. To replace the energy lost in overcoming these forces, the more energy the ICE must produce. The more energy the ICE has to produce, the more fuel it uses. Increased fuel consumption not only exacerbates the level of GHG emissions but increases the operating costs of the vehicle as well.

Therefore, by being able to continuously monitor the tire inflation pressures with for example CTIS, the recommended tire inflation pressures can be maintained. Additionally, with CTIS the tire inflation pressures can be adjusted to suit the surrounding operating conditions if they were to vary during the designated task at hand.

3.1.4 Traction

Tire traction is the definition of force that is transmitted between the tire and road surface under all circumstances. Traction, as it is strictly associated with friction, defines the ability of the tire tread to grip onto the road surface to prevent the tires from slipping. With a minimized slip, the tires can provide higher efficiencies of controlled motion from the mechanical forces generated by the ICE. (Gent & Walter, 2006, p. 422)

The condition and quality of different road surfaces have a significant effect on the amount of traction. When a vehicle is operated on paved roads, the level of traction is very high due to the very high level of friction. Opposingly, on icy road surfaces, the level of friction is low, and thus the level of traction is also low. A similar decrease in traction can often be detected when a vehicle is operated on soft ground surfaces, such as field soil or forest roads. However, often this is not due to low friction, but due to deformations caused by increased tire-soil interaction as the road surface gives in under the weight force of the vehicle (Gharibkhani et al., 2012; Petterson & Gooch, 2020).

In the context of agriculture, tire slippage is one of the main parameters to be considered when discussing the environmental and economic aspects of the used machinery. Tire slippage, whether high or low, results in direct energy losses. On average 20 to 55% of the energy generated by tractors ICE is consumed in the tire-soil interaction. This value considers the energy spent in tire slippage, deformations directed onto the tire structure, and compaction of the soil. (Šmerda & Čupera, 2010; Janulevičius & Damanauskas, 2015; Janulevičius, Pupinis, & Juostas, 2018)

Tractors operate on maximum tractive efficiency when a reasonable level of approximately 10 to 15% tire slippage is sustained when working in the field. A certain level of tire slip is recommended to balance the tractor's tractive performance in terms of fuel consumption and drivetrain longevity. Tire slippage of significantly less than 10% results in lowered utilization of the tractive power, and thus the amount of energy per unit of performed work increases. At tire slippage of 20%, the highest tractive efficiency is typically reached.

However, it is recommended that the tire slip value would not exceed 15% in order to minimize the amount of damage caused to the soil structure due to excessive tire-soil interaction. (Battiato & Diserens, 2013, Lacour et al., 2014, Janulevičius et al., 2018, as cited in Janulevičius et al., 2018)

Based on studies related to terramechanics, there are two viable methods to control the amount of tire slip. Either by increasing the tractor's mass by adding ballasts or by increasing the size of the tire-ground surface contact area by adjusting the tire inflation pressures. (Damanauskas, Janulevičius & Pupinis, 2015)

Janulevičius et al. (2018) demonstrated the effects of tire inflation pressure on the amount of tire slippage and traction power. The tests measured the drawbar-pull of a tractor where the front driving wheels were turned off and the rear axle differential was locked. The test conditions were dry stubble with a cone index hardness of 0.4 megapascals (MPa). Referring to Table 2, the soil condition is assumed as soft (Kurjenluoma et al., 2009). The tests were carried out with tire inflation pressures of 0.8, 1.2, 1.4, 1.6, 2.0, and 2.4 bars. The tire inflation pressures were set identically for both front and rear axles.

Indicated by the results presented in Figure 22, with adjusted tire inflation pressures the amount of tire slippage and tractive power can be controlled. In conditions of soft soil, the best performance in terms of tractive force was reached when the lowest tire inflation pressure of 0.8 bars was used.

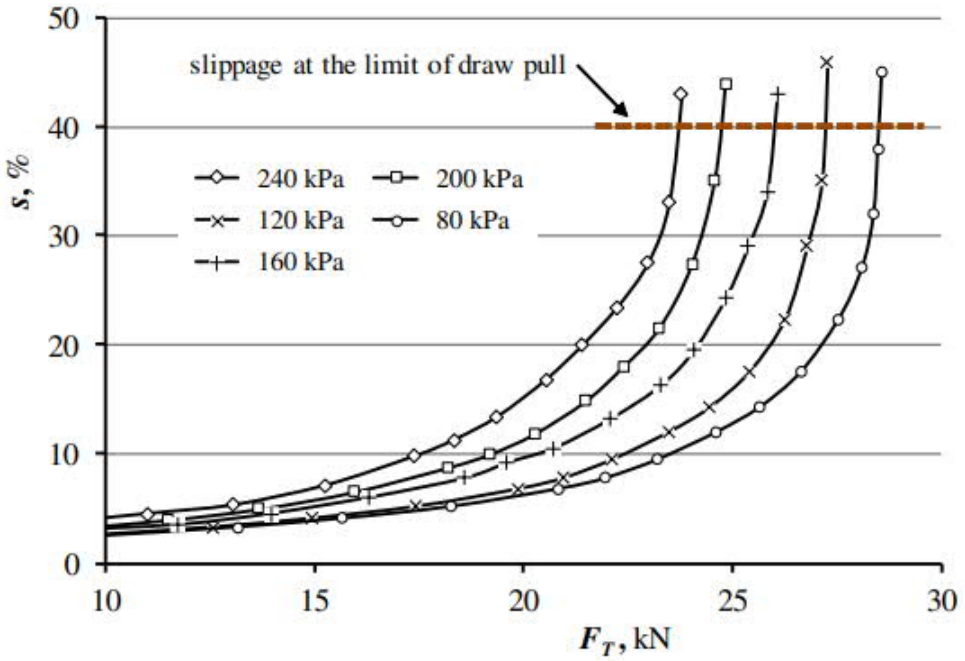

Figure 22: Dependence of the amount of tire slippage on traction power and tire inflation pressure (Janulevičius et al., 2018).

An additional benefit of using lower tire inflation pressures is that the stiffness of the tire structure reduces, improving the flexing capabilities of the tire body. Increased flexing capabilities promote a better self-cleaning ability of the tire tread to unclog the sticky soil

that has been stuck between the tire lugs[6]. Tires that continuously have their lugs unclogged maintain their ability of biting onto the soil surface resulting in an increased grip and thus reduced tire slippage. (Tigges, 2015)

Regarding the industry of forestry, logging trucks achieve comparable benefits in terms of improved traction when tire inflation pressures are lowered. Logging trucks in their timber transportation cycles face a variety of different types and conditions of road and forest road surfaces. The ability to adjust the tire inflation pressures brings a significant advantage in terms of continually being able to sustain an appropriate level of traction which affects the truck's operational efficiency and capabilities to perform in the ever-changing road conditions.

In the tests carried out by Brokmeier (2017), the effects of adjusted tire inflation pressures were studied on a logging truck driven on two separate test track conditions to simulate potential forest road conditions. The condition of test track 1 simulated a soil-based forest road classified to be in a good condition. Test track 2 simulated a much more challenging forest road condition, where an additional layer of loose sand was applied on top of the base soil. The thickness of the sand layer varied between 35 to 50 centimeters.

An articulated vehicle was used in the tests. Scania R420 6x4 was used as the truck unit and it was equipped with a loading crane and a full-length two-axle trailer. The tested tire inflation pressures were selected individually for each of the vehicle's axles based on analyzes showing the influence of tire load and the tire inflation pressure on the tire distortion, tire-ground surface contact area, and distribution of weight. The tire inflation pressures which were tested are visible in Table 3.

Table 3: Applied tire inflation pressure settings for the axles of the test vehicle (Brokmeier, 2017).

Tire pressure setting	Steer axle [kPa]	Drive axles [kPa]	Trailer axles [kPa]
Standard highway tire pressure	850	750	850
Public road unloaded	550	400	400
Forest road loaded	650	450	550
Forest road unloaded	400	300	350

The effects of tire inflation pressures were compared by analyzing the mean value of the traction coefficient, separately calculated for 10 different slip levels between 10 to 100%. The traction coefficient, as it is the quotient of the vehicle's traction and weight force, allowed the comparison between loaded and unloaded trucks.

The use of adjusted tire inflation pressures in the conditions of test track 1 showed similar improvements in the amount of increased traction coefficient across all levels of tire slippage. In the more challenging conditions of test track 2, the use of adjusted tire inflation pressures presented significant traction coefficient improvements up until the tire slip values exceeded 50%. After 50% the benefits of improved traction were lost in increasing amounts on tire-soil interaction.

[6] Tire lugs are the definition of the raised portion of the tire tread.

On average, the results indicated a positive effect on adjusted tire inflation pressures in both of the test track conditions. In the conditions of test track 1, an average increase of 14.5% and 16.7% in the traction coefficients were reported respectively for unloaded and loaded trucks when lower tire inflation pressures were used. Comparable benefits were reported in the more challenging conditions of test track 2. In the conditions of test track 2, where the test results were shown only for the loaded vehicle, an average increase of 23.3% was perceived in the traction coefficient when lower tire inflation pressures were used.

The concept of tractive efficiency is the sum of the maximized use of tractive devices and control of the drive wheel slippage. The presented studies show benefits in terms of improved traction when only the tire inflation pressures are adjusted. With proper attention paid to the tractive efficiency, significant savings in fuel consumption may be achieved. (Moitzi et al., 2013; Eto et al., 2018, as cited in Janulevičius et al., 2018)

3.1.5 Fuel Consumption

Decreased fuel consumption is one of the primary concepts, that in the core of increasing the level of operational efficiency, can be achieved with properly adjusted tire inflation pressures. The forces such as rolling resistance and tire slippage due to reduced traction have a demonstrated effect on increasing the fuel consumption of agricultural tractors as well as logging trucks.

In the context of agricultural tractors, the bulldozing effect, as presented in chapter 3.1.3, significantly increases the tractor's fuel consumption as the track depth increases. The increments in the track depth affect the amount of wasted energy in the continuous deformations of the ground structure simultaneously as the resistivity of the bulldozing effect increases. Increments of one centimeter in the track depth in conditions of soft soil corresponds to increased fuel consumption of as much as 10%. (Volk et al., 2011)

Serrano (2008) studied the effects of adjusted tire inflation pressures on the tractive performance of a tractor pulling a disc harrow. The tested tire inflation pressures were 1.0 bars in front tires and 0.7 bars in rear tires, and 1.4 and 1.9 bars in both front and the rear tires.

The results of the study showed, that even in ground conditions of good traction where the amount of tire slippage was within the accepted ranges of 7 to 15%, the use of adjusted tire inflation pressures proved beneficial. When the lowest tire inflation pressures were used, an increase of 3 to 5% was demonstrated in the tractor's working capacity. Simultaneously, the results indicated that with lower tire inflation pressures the fuel consumption of the tractor reduced by 10 to 25% per processed field hectare.

Hoy et al. (2014) reported average fuel savings of up to 8% on a four-wheel-drive tractor operated in field conditions with recommended tire inflation pressures rather than with overinflated tires. Similar benefits were reported in conditions of paved road, where fuel savings of up to 11.4% were reached when higher tire inflation pressures were used rather than using tire inflation pressures more suitable for field conditions (Udompetaikul et al., 2011, as cited in Hoy et al., 2014, p. 19)

Damanauskas et al. (2015) studied and compared the effects of ballast and tire inflation pressures on the fuel consumption of a tractor operating at a recommended tire slippage range of below 15% during tillage work. The tractor used in the tests was a four-wheel-drive Ford 8340 SLE tractor with an operating weight of 4 936 kilograms and an engine power of 82.3 kilowatts. The tested soil condition was a leveled, smooth-texture, loamy wheat-stubble after crops were harvested. Reported soil hardness was 1.14 ± 0.09 MPa, indicating a firmer soil structure (Table 2) (Kurjenluoma et al., 2009).

The studied variables were ballasts of 520, 360, 200, and 0 kilograms, and tire inflation pressures of 2.4, 1.9, 1.5, and 1.0 bars applied in both front and rear tires of the tractor. The tests were performed with all possible combinations of the aforementioned variables. The results were formed based on 16 different combinations of ballasts and tire inflation pressures to illustrate the effects on tire slippage and fuel consumption per hour (Figure 23), and per processed field hectare (Figure 24).

Figure 23 indicates that with tire inflation pressures of 1.0 bar without any additional ballast, the hourly fuel consumption was lowest at approximately 15.9 liters per hour. Compared to tire inflation pressures of 2.4 bars, again without any additional ballast, the fuel consumption was approximately 16.3 liters per hour. Between these two settings, the difference in hourly fuel consumption was roughly 2.5%. However, in addition to benefits concerning fuel consumption, adjusted tire inflation pressures showed significant improvement in the amount of tire slippage. Between tire pressures of 1.0, when the amount of tire slip was 8.8%, and 2.4 bars, when the amount of tire slip was 13.5%, the difference in the amount of tire slip was approximately 35%.

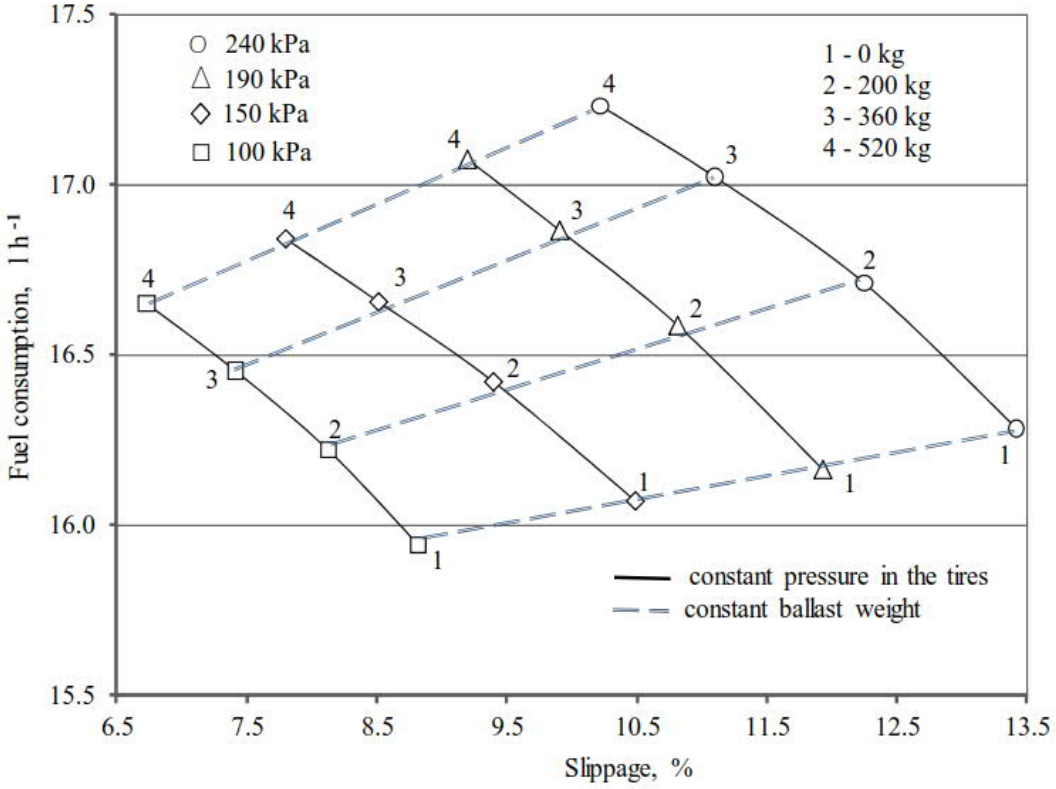

Figure 23: Fuel consumption per hour in relation to tire slippage depending on tire inflation pressure and ballast variables (Damanauskas et al., 2015).

Figure 24 presents the previous results in relation to fuel consumption and tire slippage per processed field hectare. With tire inflation pressures of 1.0 bar without any additional ballast, the fuel consumption per processed field hectare was 11.4 liters. Opposingly, with tire inflation pressures of 2.4 bars, again without any additional ballast, the fuel consumption per processed field hectare was 12.0 liters. Indicated by the results, the difference in fuel consumption per processed field hectare was approximately 5% when adjusted tire inflation pressures were used.

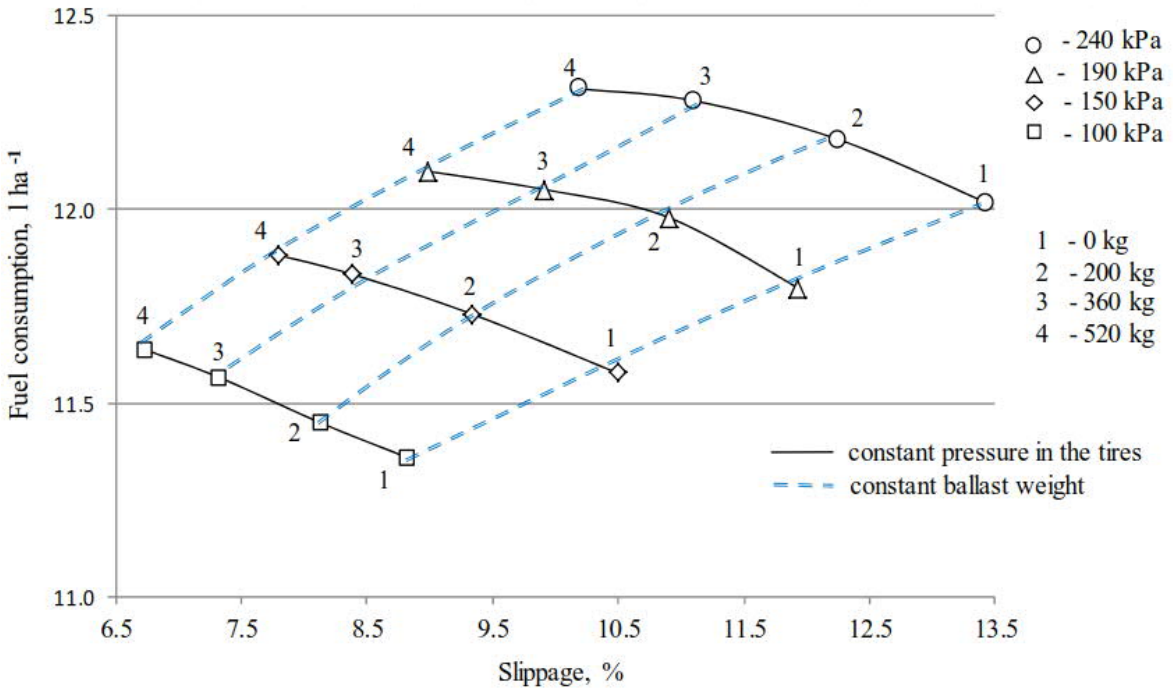

Figure 24: Fuel consumption per processed field hectare in relation to tire slippage depending on tire inflation pressure and ballast variables (Damanauskas et al., 2015)

To conclude the results carried out by Damanauskas et al., 2015, adjusting the tire inflation pressures show improvements towards fuel consumption and tire slippage. Though similar results can be achieved with proper ballasting of the vehicle, the achieved results were better in both of the measured scenarios when adjusted tire inflation pressures were implemented.

For logging trucks periodically used on varying forest road conditions, improvements in fuel economy can be achieved when lower tire inflation pressures are used. Based on the tests carried out by Brokmeier (2017) as presented in chapter 3.1.4, the savings in fuel consumption, when the truck was operated with lowered tire inflation pressures on test track 1, a soil-based forest road classified to be in a good condition, were on average 0.5% for the unloaded truck and 1.7% for the loaded truck. In the conditions of test track 2, a more challenging forest road condition, where an additional layer of loose sand was applied on top of the base soil, the savings in fuel consumption were on average 23.1% for the unloaded vehicle and 18.1% for the loaded vehicle.

In the case of logging trucks, the above examples show some improvements in fuel economy when the truck is operated in conditions of off-road and the tire inflation pressures are adjusted. However, the effect is similar when the vehicle is directed back to paved roads.

The use of higher tire inflation pressures in conditions of paved roads is recommended, as every 0.7 bars below the most suitable tire inflation pressure on average results in a 1% increase in fuel consumption (Goodyear, 2003, as cited in Brokmeier, 2017).

Since fuel consumption and the number of harmful emissions released into the atmosphere are directly interrelated, improvements in fuel economy reduce the amount of emitted GHG emissions. The studies presented above show that significant reductions in terms of fuel consumption can be reached in both agriculture and forestry applications when adjusted tire inflation pressures are implemented accordingly.

3.1.6 Operator Comfort and Safety

Heavy work machinery, such as tractors and trucks, expose their operators to general vibrations. The effects are highlighted in conditions of off-road where the road irregularities demonstrate the major source of vibrations directed on to the vehicle (Soltani et al., 2015). Being exposed to long-term low-frequency whole-body vibrations (WBV) can cause serious physical damage to the operator ranging from chronic back pain to damages in the nervous systems. (Młyńczak, Celiński & Burdzik, 2015)

The effects that these WBVs cause on human health are evaluated within the standard ISO 2631-1:1997. Based on this standard, comprehensive studies have been carried out to identify the effects in several different vehicle types such as agricultural machinery and a variety of different transportation vehicles including logging trucks. (Smith & Leggat, 2005, as cited in Zhao & Schindler, 2014)

The overall harmfulness of WBVs varies in terms of the direction the effects are directed to the operator of the vehicle. The vibrations in the standard are measured in three directions perpendicular to each other in order to accurately evaluate the effects of WBVs (Figure 25). (Oksanen & Rytkönen, 2009)

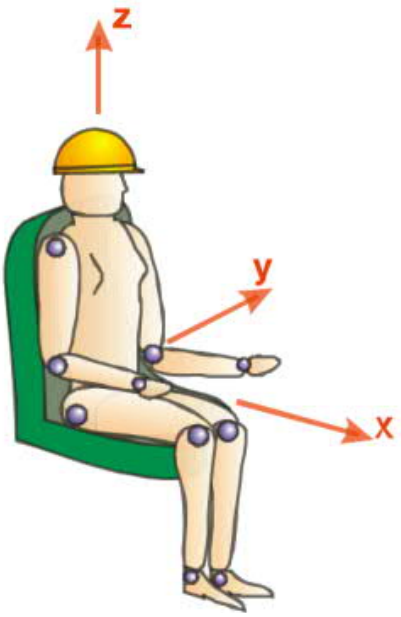

Figure 25: Directions of WBV measurement and evaluation (Oksanen & Rytkönen, 2009).

Agricultural machines are on top of a list of vehicle classes which through their operational conditions are susceptible to sudden accelerations transmitting high levels of WBVs to the vehicle operator (Horton & Crolla, 1984, as cited in Adams et al., 2004).

Adams et al. (2004) studied the effects of adjusted tire inflation pressures on a tractor operating on three different road conditions representing a variety of surface profiles a tractor would typically be operated on. The first road type represented a degraded secondary road formed on Belgium blocks. The second and third road types represented typical field conditions of respectively roughening quality. The test tractor was CaseIH 8950 equipped with detachable secondary tires next to the main tires for both front and rear axles to double the size of the tire-ground surface contact area. The experiments were run on both of the available options of single and dual tire settings. The tested tire inflation pressures P1, P2, and P3 are illustrated in Table 4.

Table 4: Applied tire inflation pressure settings in the experiments (Adams et al., 2004).

Tire inflation pressure level (kPa)	Singles		Duals	
	Front	Rear	Front	Rear
CTIS (P1)	62	69	62	21
Proper (P2)	83	103	83	41
Overinflated (P3)	103	138	103	62

Video analysis of the results indicated that in certain coarser parts of the course when the vehicle was operated on higher tire inflation pressures, the wheels lost contact with the road surface. Loss of contact indicates that the tire deflections are not enough to dampen the road surface irregularities due to the high vertical stiffness of the tire structure. Such behavior results in sudden accelerations and impacts to the vehicle chassis which are also transmitted to the vehicle operator.

Results of the study indicated that with reduced tire inflation pressures the tire deflections were greater which consequently led to improved ride quality. Based on the evaluations carried out as instructed in the ISO 2631-1:1997 standard, the improvement in the ride quality was 99% when the lowest tire inflation pressures were applied using CTIS. When the vehicle was not in resonance the improvements in the ride quality were 177%. The use of the detachable dual tires for both front and rear axles increased the ride quality by 10% for both of the non-resonating and resonating drive scenarios.

In the tests described in chapter 3.1.4, Brokmeier (2017) studied the effects of adjusted tire inflation pressures on the ride quality of logging trucks operated on simulated forest conditions. The tests were carried out as instructed in the ISO 2631-1:1997 standard. The test results were reported in each direction perpendicular to the vehicle's operator for both unloaded and loaded operation scenarios (Figure 25).

The results indicated a positive trend in the achieved benefits when adjusted tire inflation pressures were applied. When the vehicle was unloaded and operated on test track 1, a soil-based forest road classified to be in a good condition, the average reduction in vibrations in the direction of the X-axis was 13.9%, in the direction of the Y-axis 2.4%, and in the direction of the Z-axis 6.2%. A rerun of the tests on test track 1 with a loaded vehicle resulted

in lower reductions in the number of vibrations. When the vehicle was loaded, the average reduction in the number of vibration, in the direction of the X-axis was 2.6%, in the direction of the Y-axis 0.9%, and the direction of the Z-axis 3.1%.

The results when the vehicle was unloaded and operated on test track 2, a more challenging forest road condition, where an additional layer of loose sand was applied on top of the base soil, showed comparable reductions in the number of vibrations. The average reduction in vibrations in the direction of the X-axis was 12.7%, in the direction of the Y-axis −1.1%, and the direction of the Z-axis 3.4%. With a loaded vehicle, the average reduction in the number of vibrations in the direction of the X-axis was 2.3%, in the direction of the Y-axis 1.9%, and the direction of the Z-axis 4.5%.

The measured acceleration values were highest in the Y-direction. The presented test results indicate that the Y-direction was the most difficult direction to dampen the shocks to reduce the number of vibrations. In the test scenario of test track 2 with an unloaded vehicle, the benefit of adjusted tire inflation pressures in the Y-direction was negative. This can be the cause of disproportionally low vertical stiffness of the tire, promoting an increased amount of vibrations due to the elastic motion of the tire structure which transmits to the vehicle operator. However, in the other tests and measured directions, the benefit of adjusted tire inflation pressures is always positive towards a reduced amount of WBVs.

The results of the study conducted by Brokmeier (2017) are comparable to the results reported in a test based on the ISO 2631-1:1997 standard on five different categories of Swedish roads with adjusted tire inflation pressures. Noticeable improvements in the driving comfort were reported and the measured values in the difference of vibration levels ranged from 4 to 14% on the seat of the operator. The results were highlighted in conditions of unloaded, high-speed travel on unpaved forest roads. When the vehicle was loaded the most significant improvements in the number of vibrations were visualized during low-speed travel. (Granlund, 2004, as cited in Bradley, 2009, p. 10)

With adjusted tire inflation pressures, a reduction in the number of vibrations is not only to increase the comfort of the vehicle operator. With fewer vibrations directed to the vehicle chassis the fewer impacts are directed to the vehicle's components, promoting reduced wear in the suspension components as well as longevity of the damage sensitive components (Tigges, 2015; Brokmeier, 2017; Armstrong, 2008, as cited in Ghaffariyan 2017).

According to tests carried out by Nevada Automotive Test Center, a reduction in the number of impacts caused an 87% decrease in component breakdowns which lowered the repair costs by 83% (Altunel & de Hoop, 1998, as cited in Rieppo, 2006). In the majority of such vehicle breakdowns, the repair costs can be very expensive, especially if the damage to the vehicle occurs when it is situated in distant or hard-to-reach locations. Additionally, if the vehicle were to break and bog down in far-away locations, it would also pose a safety risk for the operator as getting the necessary help would not be available immediately (Armstrong, 2008, as cited in Ghaffariyan 2017).

Oksanen & Rytkönen (2009) studied the effects of adjusted tire inflation pressures on logging trucks operated on four different categories of Finnish roads. As the outcome of the study was that tire inflation pressures should always be adjusted accordingly to the surrounding operation conditions to reduce the number of vibrations.

3.1.7 Tire Wear

Tire wear occurs when the tire tread and ground surface contact area slide against each other under the influence of friction. Friction as a dissipative process results in the generation of heat which through abrasion causes the transfer of material, or in other words wear, in both of the contact bodies. (Gent & Walter, 2006, p. 534)

The wearing of tires is highly affected by the level of tire inflation pressure. The effect of tire inflation pressure on the vertical stiffness of the tire affects the size of the tire-ground surface contact area which then correlates to the amount of friction. In addition to friction, excessively high or low tire inflation pressure promotes uneven wear of the tire tread due to inappropriate tire form.

In agricultural vehicles, approximately 90% of the tire wear takes place when the vehicles are operated in conditions of paved roads when for example travelling on public roads. This is due to the hardness and inflexibility of pavement compared to the softer ground surface conditions on a typical field site. The downside of paved road surfaces is that the pavement allows only minimal if any bending under the vehicle's weight, and therefore, the tire receives unnecessary amounts of flex. This flex when directed through the tire-ground surface contact area causes excessive amounts of abrasion and friction of the tire tread, which in agricultural tires puts an excessive strain on the tire lugs (Figure 26). (Tigges, 2015)

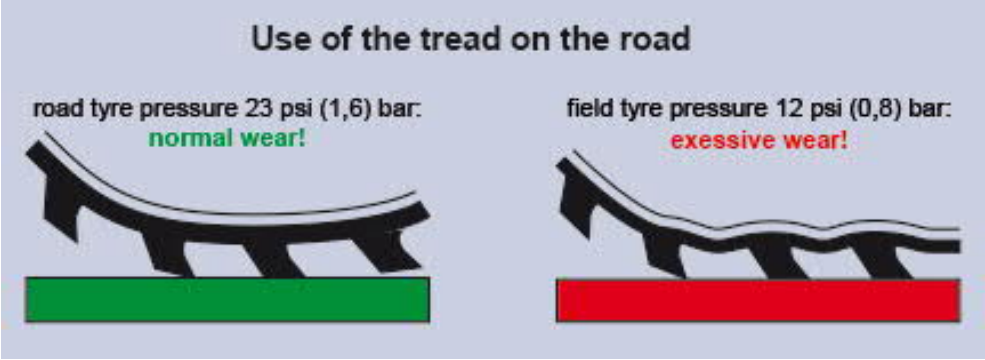

Figure 26: Use of the tread on the road (PTG, n.d.).

To minimize tire wear when the tractor is directed on to paved roads, the highest permissible tire inflation pressure should be applied. Increasing the tire's vertical stiffness reduces the amount of flex in the tire structure and the size of the tire-ground surface contact area. Increasing the tire inflation pressure results in a lowered abrasion effect of the tire lugs which can reduce tire wear by up to 30%. (Tigges, 2015)

In the case of trucks, such as the ones used in the industry of forestry, optimal tire wear is typically achieved when the tire tread has a uniform contact on the road surface under all operating conditions. Uniform contact of the tire tread results in an even distribution of the vehicle's weight across the tire-ground surface contact area. Any deviation from the recommended tire inflation pressure typically results in uneven wear of the tire tread and consequently a reduction in the lifetime of the tire. (Munro & MacCulloch, 2008, p. 13) (Figure 27)

Figure 27: Illustration of the effects of tire inflation pressure on tire shape and contact area (Munro & MacCulloch, 2008, p. 13).

When tires are operated below the recommended tire inflation pressure, the center of the tire tread puckers upwards which results in weight distributive contact, and thus tire wear only at tire edges and shoulders. Opposingly, when tires are operated above the recommended tire inflation pressure, the center of the tire tread puckers outwards which results in weight distributive contact, and thus rapid wear at the center of the tire tread. (Gent & Walter, 2006, p. 26; Munro & MacCulloch, 2008, p. 13)

Overinflation, due to a reduction in the size of the tire-ground surface contact area, reduces the amount of traction the vehicle has. The decreased size of the tire-ground surface contact area poses an increased risk for the vehicle to undergo hydroplaning[7] when the vehicle is operated at higher travelling speeds. Therefore, in addition to tire wear, the overall safety of the vehicle operator can be sustained by maintaining recommended tire inflation pressures. (Gent & Walter, 2006, p. 657)

Due to the aforementioned reasons, maintaining tire inflation pressures as recommended by the tire and vehicle manufacturers typically delivers a satisfactory performance in terms of tire wear and dynamic behavior. However, in the context of logging trucks periodically operated in conditions of off-road it is difficult to rely on such tire inflation pressure recommendations and estimations.

As presented in the previous subchapters, logging trucks benefit from adjusted tire inflation pressures when they are directed off of paved roads to forest roads often composed of gravel or soil. The achieved benefits can be highlighted further when comparing freestanding unloaded trucks travelling to the loading site and loaded trucks when they are returning to paved highways.

Figure 28 illustrates an unloaded and loaded truck tire. Supposing that the tire inflation pressure remains unchanged between the loading process, the deflection gap indicates how much the tire structure gives in under the increased weight of the vehicle. In terms of tire wear, the presented deflections can be described so that the freestanding situation would illustrate tire form of tire inflation pressures recommended for road use, and the loaded situation would illustrate tire form of tire inflation pressures recommended for off-road use.

[7] Phenomena of losing traction due to tires raising on top a waterbed as they confront more water than the tire treads are capable of displacing (Gent & Walter, 2006, p. 3).

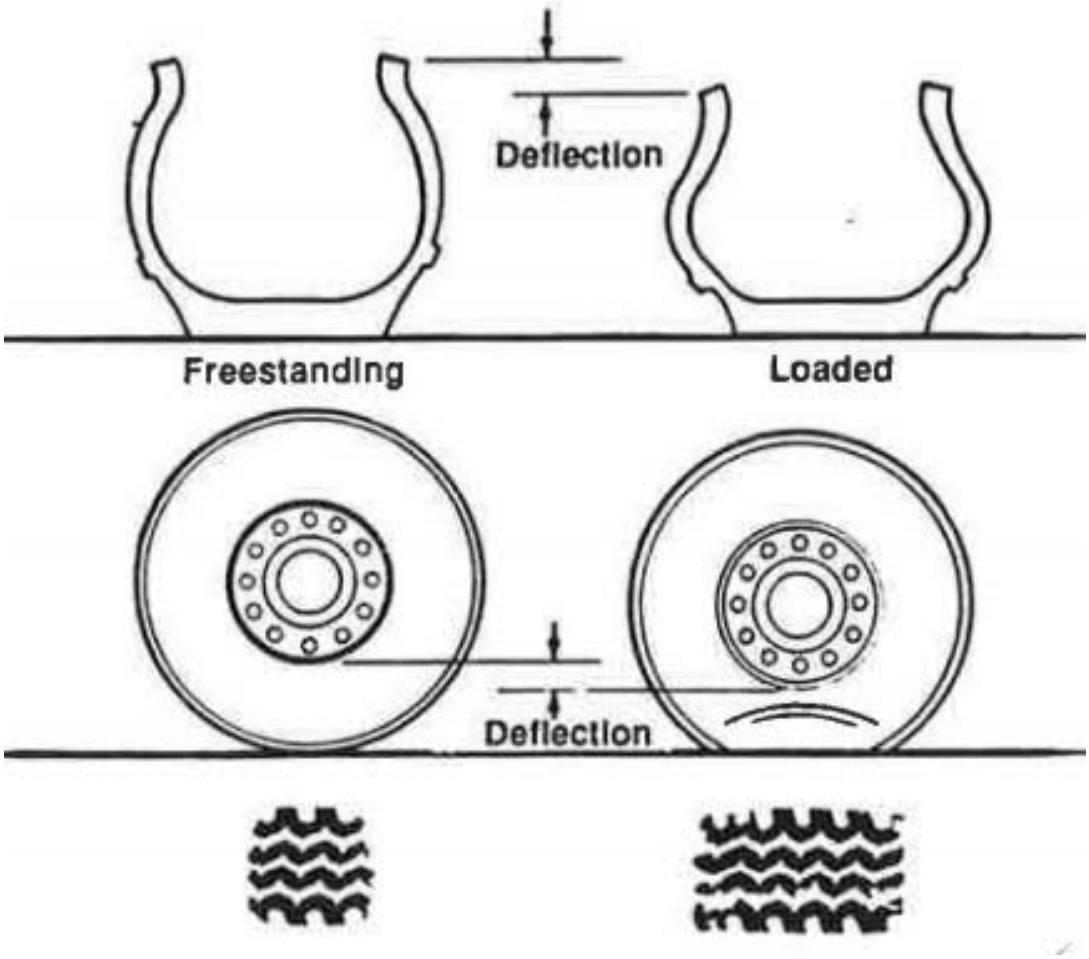

Figure 28: Effect of load and tire inflation pressure on deflection and size of the tire-ground surface contact area (Simonson, 1993).

Regardless of the vehicle load, these settings can be simulated with CTIS. Aiming for less deflection of the tire structure in conditions of paved road conforms to a more uniform tire form which results in an even wear of the tire tread. Increased deflection in conditions of off-road dampen vibrations, smoothen the ride for the vehicle operator and permit passing of stony surfaces without damaging the tire tread. For logging trucks, with proper use of CTIS adjusted tire inflation pressures, the lifetime of tires can be extended by as much as 15% (Sturos et al., 1995, as cited in Rieppo, 2006).

4 Analysis for the Study-Related Industries

In this chapter, the applications and operational conditions from the industries of agriculture and forestry, that in the core of this study indicate demand for systems that allow the effortless control of the tire inflation pressures, are briefly presented.

For both of the study-related industries, a case study investigating the benefits in terms of energy efficiency and environmental impact is executed when CTIS would be implemented. In addition to the direct and indirect benefits, the following case studies will discuss the related economic perspectives arising from the acquisition and use of CTIS.

4.1 Agriculture

In a typical agricultural setting, tractors are arguably the most multifunctional farm equipment used to carry out versatile work tasks. As one of the most fundamental tasks, tractors perform drawbar work including tasks such as tilling, fertilizing, and other tasks related to cultivation operations in the field. Outside the field, tractors may be used to transport all kinds of goods which often imposes a requirement to operate on public roads that are often paved. (Janulevičius et al., 2018) (Figure 29)

Figure 29: Tractor performing tillage (AGCO Fendt, 2020).

Characteristically, the working environment of a tractor sets an exceptional requirement to continuously work under rough and varying driving conditions. In conditions of the field, the roughness of the ride is often the cause of the spacing between the plantation rows influenced further by the condition of the specific soil structure. (Adams et al., 2004)

Tire inflation pressures for agricultural tires vary and usually the recommended level depends on the concepts presented throughout chapter 3.1, such as the specific application, designated use, pulled equipment, axle loads, tire types, and the road surface conditions. Therefore, it is impossible to give accurate values for proper tire inflation pressures. However, the range of minimum and maximum tire inflation pressures for tractors is typically in the range of 1 to 4 bars (Trelleborg, n.d.a). In specific conditions, such as when the soil is extremely wet, the most efficient tire inflation pressure can be as low as 0.4 bar to minimize the effects of soil compaction (Kurjenluoma et al., 2009).

Based on the research studies presented in chapter 3.1, it is obvious that agricultural tractors perceive considerable improvements in terms of fuel consumption when adjusted tire inflation pressures are implemented. Additionally, a variety of other parameters are also affected, such as the amount of WBVs and tire lifetime.

In the case of fuel consumption, the presented studies are not as such comparable to each other due to variations in the timing of the studies, tested equipment, conditions, and measurement equipment used. Nonetheless, the presented situations understandably reflect reality due to comparable variables such as the different implementations of farming equipment and variations in the operational conditions.

In the studies reported by Serrano (2008), Hoy et al. (2014), and Damanauskas et al. (2015), the improvements in fuel consumption were on average 8.9% when adjusted tire inflation pressures were used. The results included versatile driving conditions on both field and paved road surface conditions.

Improvements in Energy Efficiency and Reduced Environmental Impact

In 2017, the energy consumption of the agricultural sector in the area of the European Union (EU) (excluding Germany due to data unavailability) was 24.3 million tons of oil equivalent (Mtoe) (Eurostat, 2019). Of this value, the share of oil and petroleum-derived products was 53%, resulting in an energy share of 12.9 Mtoe (Eurostat, 2019).

The majority of modern agricultural tractors use diesel fuel (Hoy et al., 2014, p. 6). Since one cubic meter of diesel fuel corresponds to 9.8×10^{-7} Mtoe, the total amount of diesel fuel can be calculated (Eurostat, 2018). Extrapolating the aforementioned 12.9 Mtoe to assume that all of the oil and petroleum-derived products were to be combusted as diesel fuel in tractors performing cultivation operations, a total of 13,163,265 cubic meters of diesel fuel, which translates to approximately 13.2 billion liters, would be combusted.

With average fuel consumption savings of up to 8.9% when adjusted tire inflation pressures are used, as much as 1.2 billion liters of diesel fuel could be saved annually. On average, diesel fuel releases approximately 2.7 kilograms of carbon dioxide equivalent (CO_2e) GHG emissions for every liter of fuel combusted. Consequently, the presented amount of saved diesel fuel indicates reductions of as much as 3.24 megatons of CO_2e GHG emissions per annum when CTIS would be used in all agricultural tractors located and operational within the area of EU (excluding Germany due to data unavailability).

During 2017, the total GHG emissions of the EU were 4 483 megatons of CO_2e (EEA, 2019). Calculating the possible 3.24 megatons of CO_2e GHG emission reductions shows a 0.072% reduction in the whole region of the EU. The presented reduction value considers only the direct improvements in the energy efficiency of the tractors used through improved fuel economy, and thus the indirect benefits, such as reduced soil compaction, are not taken into consideration.

To provide more significant CO_2e GHG emission reductions, the effects perceived in reduced soil compaction providing increased yields, and thus a decrease in a variety of other emitting sources than farm machinery should be noted. However, as stated by Tigges (2015), the availability of studies with serious approaches to the benefits of less soil compaction

associated with units of emissions reduced per improvement in yields is very limited. This was confirmed by the author of this thesis, and therefore, the benefits in terms of lowered soil compaction can only be mentioned as based on the study presented in chapter 3.1.2 carried out by Elaoud & Chehaibi (2011).

Despite the difficulty of accurately estimating the benefits of reduced soil compaction, the observed results would most likely be unique to each cultivation activity. The uniqueness would thus require prolonged investigations to receive comparable and trustworthy data. As this is not possible within this thesis, the effect of reduced soil compaction cannot be considered within the aforementioned GHG emission reductions and in the further economic evaluations.

Economic Perspectives

In agriculture, the economic benefits of CTIS and adjusted tire inflation pressures are related to reductions in operating costs, such as reduced fuel consumption and prolonged lifetime of the tires. To provide a somewhat accurate example of the economic data, boundaries for the studied implement must be set. In order to provide accurate quantification of the economic benefits of CTIS to the tractor owner, the following parameters of engine power, annual operational hours, fuel consumption, fuel cost, tire types, and tire costs must be defined. The average 8.9% savings in fuel consumption as presented above is used in this economic evaluation when CTIS is in use.

Vesterinen (2019) studied the decisive factors influencing customer behavior when purchase decisions were under contemplation in conditions of when the acquisition of a new tractor implement was of topicality. The data was acquired through a structured questionnaire published by a well-known Finnish professional magazine. Based on the responses, the most common values for the exemplary case study can be selected.

The results of the study showed that the most common engine power selected was between 175 to 199 horsepower's and the annual operational hours were between 500 to 1000 hours. In this economic evaluation, the tractor utilization is presumed at its maximum. Therefore, it is assumed that the tractor is performing mobile work for 1000 hours each annum.

Estimation of the average fuel consumption for this described tractor would have been needed. However, as Vesterinen (2019) also stated, fuel consumption is a difficult value to predict as it varies according to operating conditions. Therefore, the fuel consumption was derived from the values reported by Damanauskas et al. (2015) with the assumption that the tractor in this exemplary scenario is of newer technology, and therefore, is likely to be a more energy-efficient construction allowing a higher power output due to lower specific fuel consumption. For the use of this case, the hourly fuel consumption is estimated at 16.0 liters without tire inflation pressure adjustments.

The price of diesel fuel is assumed at 1.2€ per liter. This price refers to the typical cost of diesel fuel in Finland during the writing process of this thesis. Generally, tractors are allowed to use fuel oil, which is diesel fuel with lighter taxation, but only if the vehicle is used to carry out work-related directly to agriculture or forestry (Traficom, 2019). The use of conventional diesel fuel is assumed due to the thesis's claim that tractors are periodically operated on public roads.

The tires were assumed to be the same as in the study by Damanauskas et al. (2015). Reported tire sizes on the front axle were 440/65 R24 and on the rear axle 18.4 R38. According to Gripen Wheels (2020), the cost of an individual tire of the selected size is approximately 900€ and 1100€ respectively for front and rear axles. Therefore, the total cost of the tires is 4000€. It is approximated that without tire inflation pressure adjustments, the lifetime of the tires is 5 years or 5000 operational hours.

With the required parameters, an estimation of the economic benefits of CTIS implementation can be calculated. Using the following equation, the annual fuel costs without the use of adjusted tire inflation pressures can be calculated:

$$c_{afc} = t_{aoh} * l_{hfc} * c_{cpl} \quad (1)$$

where c_{afc} – annual fuel cost (€), t_{aoh} – annual operational hours (h), l_{hfc} – hourly fuel consumption (l/h), and c_{cpl} – cost per liter of fuel (€/l).

To identify the annual fuel cost savings when adjusted tire inflation pressures are set using CTIS, the following equation can be used:

$$s_{afcs} = c_{afc} * r_{fcr_{CTIS}} \quad (2)$$

where s_{afcs} – annual fuel cost savings (€), and $r_{fcr_{CTIS}}$ – fuel consumption reductions with CTIS (%).

As stated in chapter 3.1.7, with properly adjusted tire inflation pressures the lifetime of an agricultural tire can be extended by 30%. Since it was assumed that a set of agricultural tires last 5 years or 5000 hours of operational usage, the following equation can be used to consider indirect annual tire cost savings:

$$s_{atcs} = \frac{c_{act} * r_{twr_{CTIS}}}{5} \quad (3)$$

where s_{atcs} – annual tire cost savings (€), c_{act} – the acquisition cost of tires (€), and $r_{twr_{CTIS}}$ – tire wear reduction (%) when adjusted tire inflation pressures are implemented with CTIS.

Indicated by the results from equations 2 and 3, the combined direct operating cost savings from lowered fuel consumption and prolonged tire lifetime to the tractor owner would be in the range of approximately 1,948.8€ each year.

To assess the viability of the monetary savings, the costs induced by the acquisition of the CTIS must be defined. Volk et al. (2011), approximated the cost of a simplified CTIS to be approximately 2,500€, while Crummett (2015) estimated that the cost of a fully retrofitted CTIS is in the range of 10,000€ to 17,000€. Variations in the system costs may be explained with differences between the system suppliers, and system constructions as illustrated during chapter 2.3.

Comparing the monetary benefits to the cost of CTIS, the system's payback time for the tractor owner varies from approximately 1.3 to 8.7 years. Lips (2017) estimated that the

operational and technical working lifetime of a tractor is 10,000 hours or, as indicated by the annual operation hours of this exemplary case study, 10 years. To assess the monetary benefits arising from the acquisition of CTIS, the following equation can be used:

$$s_{tfs} = s_{cacs} * (t_{lt} - t_{pbt}) \quad (4)$$

where s_{tfs} – total financial savings (€), s_{cacs} – combined annual cost savings (€), t_{lt} – operational and technical working lifetime (a), and t_{pbt} – the payback time of the CTIS.

Thus, the financial savings for the tractor owner arising from the use of CTIS would be between 2,533.44€ to 16,954.56€ after the acquisition cost of CTIS would have been compensated.

Case Study Conclusions

The case study highlighted the potential GHG emission reductions and constructed an evaluation of the economic perspectives related to the acquisition and use of CTIS in agricultural tractors. Although the benefits of CTIS have been verified, ultimately the tractor owner is responsible for the decision whether the system would be implemented.

Jantke, Hartmann, Rasche, Blanz & Schneider (2020) evaluated the attitudes of farmers towards means to reduce the amount of agricultural GHG emissions in all of the farm-related operations. The data for the study was collected through a structured questionnaire from farmers operating in Germany.

The results of the study indicated, that 64.2% of the respondents agree with the fact that reducing GHG emissions is important. However, 79.9% of the respondents would attempt to reduce the amount of GHG emissions only if the acquisition costs of such emission reductive systems would be compensated. (Jantke et al., 2020)

Although in the long-term the use of CTIS shows monetary benefits for the tractor owner, an initial investment must be made. Therefore, to set emissions reductive systems like CTIS for wider implementation, appropriate policy instruments, such as subsidies, should be placed (Jantke et al., 2020). Also, to increase awareness and recognition towards CTIS, comprehensive information programs should be launched as the existence of CTIS is often known only by the well-informed and qualified farm owners (Volk et al., 2011).

Considering the tractor manufacturer's contributions in the wider implementation of CTIS, if the use of internal CTIS would be recognized on all factory-new constructions, the need to consider the acquisition of CTIS later on would be removed. Thus, the benefits of CTIS could be achieved in a wider perspective.

4.2 Forestry

In the industry of forestry, logging trucks are used to collect and transport timber from locations commonly situated in distant areas that require traversing through remote sections of forest roads. These trucks, that for the majority of their operational time are driven on paved roads, are typically equipped with tires that lack any specific tread patterns which

would make them more efficient in these off-road driving conditions (Watkins, 1991). Due to tractive limitations, in order for the trucks to be able to carry out their designed tasks as effectively as possible, the gravel or soil-based forest roads have to be in good condition so that accidents can be prevented, traversing is safe, and the risk of stagnation is minimized (Greenfield, 1992). (Figure 30)

Figure 30: Logging truck collecting timber (TRT, n.d.).

The recommended tire inflation pressure of a logging truck is usually set by the main operational condition, that is, to operate on paved roads. In such conditions, the recommended tire inflation pressures are often the permissible maximum visible on the tire sidewall, typically in the range of 8 bars (Bradley, 2009, p. 3).

In conditions of off-road, the definition of recommended tire inflation pressure alters based on the concepts presented throughout chapter 3.1, such as vehicle load, speed, and road surface conditions. Amlin & Bradley (1992) categorized the variances in suggested tire inflation pressure levels on four distinct segments of the timber transportation cycle, which are: unloaded, on-highway and high-speed travel (1), unloaded, off-highway and low-speed travel (2), loaded, off-highway and low-speed travel (3), and loaded, on-highway and high-speed travel (4). During these distinctive transportation segments, the recommended tire inflation pressure varies between 1.7 to 8 bars in order to adjust the vehicle's operational performance in relation to the surrounding operating conditions (Bradley, 2009, p. 3).

For logging trucks, emphasizing reduced fuel consumption is more difficult as it was for the agricultural setting. Even though in chapter 3.1.5 the study by Brokmeier (2017) indicate fuel consumption reductions in off-road conditions, it must be acknowledged that only a portion of the total travelling distance is performed on the challenging conditions of unpaved forest roads. Based on estimations by Granlund (2006), only 6 to 7% of the total travelling distance is typically carried out on forest roads. Because the remaining majority of travel is carried out on paved roads, the truck's fuel consumption is largely unaffected by the benefits of CTIS, as on those conditions unadjusted and higher tire inflation pressures are often recommended (Watkins, 1991).

Forest roads are often characterized by their susceptibility to major environmental impacts due to distant locations, design standards, construction methods, and maintenance levels (Brown & Sessions, 1999). In areas that are susceptible to weather extremities, significant variances in the road surface conditions may be visualized. Such varying of the road surface qualities imposes a challenge to the operation of logging trucks, and the industry of forestry as a whole due to disruption in the steadiness of the timber supply chain. (Rieppo, 2006)

In the Northern Hemisphere, seasonal changes promoting thaw, especially during springtime when the snowbanks and the ground frost melts, causes the saturation of the forest road structures (Roadex, n.d.). Similar effects may be visualized after high-intensity rainfalls during autumn and more broadly for example in the tropical parts of the world (Brown & Sessions, 1999). The excess of water, further affected by the absence of proper drainage systems, increases the wetness of the forest roads, reducing the structural integrity. Reduction in the structural integrity increases the tendency of the forest roads to deform under the heavy weight force of the logging trucks consequently reducing the carrying capacity of the road surface. In order to avoid rutting and significant damage on the forest roads, traversing of logging trucks may be inhibited for long periods of time. (Watkins, 1991; Granlund, 2006; Rieppo, 2006) Figure 31 illustrates the onset of road surface rutting caused by timber transportation operations during spring thaw.

Figure 31: Onset of track formation on the forest road surface (Roadex, n.d.).

Controversy in the actual benefits of CTIS regarding truck's fuel consumption has been discussed by certain studies. Watkins (1991) stated that fuel consumption was largely unchanged, and Granlund (2006) indicated an increase of 3.6% in the fuel consumption of loaded trucks operating on CTIS adjusted tire inflation pressures. However, in the case of

both of these studies, the benefits of CTIS were realized in the reduction of the exerted stresses the logging trucks caused onto the unpaved forest road surfaces. Reduced level of peak pressure directed on to the road surface improves the level of payload the trucks are able to transport within full transportation cycles. Thus, with improved payloads, the number of roundtrips required will decrease which then reduces the total fuel consumption of the transportation operations. (Granlund, 2006)

Improvements in Energy Efficiency and Reduced Environmental Impact

Bergkvist, Löfgren & Löfroth (2007) stated that in Sweden, the fuel consumption of logging trucks decreased from 5.4 to 3.7 liters per cubic meter of transported wood between 1985 to 2005. A significant impact during that time was the change in legislation in 1995 which increased the permissible total weight of the truck from 43 to 60 tons.

In 2013, Finland pioneered and amended the legislation to allow the maximum total weight of truck and trailer combinations to 76 tons. Bergkvist et al. (2007) estimated, that by increasing the total weight of logging trucks to as much as 80 tons, the number of trucks required would be lower, and therefore, the amount of GHG emissions could be reduced. With increased payloads, up to 20% reductions in GHG emissions could be achieved due to reductions in the number of roundtrips required. Furthermore, ongoing field tests in Finland are studying the feasibility of high capacity transport trucks, where the permissible maximum of the total weight has been increased to 104 tons. (Keränen & Malinen, 2019)

It is evident, that a substantial level of improvement in fuel economy in the industry of forestry is due to developments in harvesting techniques and more efficient ICEs. However, with the use of additional technologies such as CTIS, improvements in the efficiency of timber transportation operations have already been demonstrated. Improvements in mobility lead to lengthened timber harvesting seasons during the effects of rain and spring thaw in countries such as Sweden, Finland, and Canada (Granlund, 2006; Bergkvist et al., 2007). Though the efficiency improvements of CTIS are not related to substantial fuel consumption or environmental impact reductions per each logging truck, the indirect benefits to the industry of forestry are considerable (Granlund, 2006). (Rieppo, 2006)

Economic Perspectives

In the industry of forestry, the weakening of forest roads is taken seriously each year as significant disruptions in the timber supply chain may cause the shutdown of industrial productions. As a preventive measure, it is typical that the industry operators increase the level of stocks in order to secure production. However, a major downside of overstocking is that it increases the costs that arise from extra handling and protection of the additional stock. In addition to the increased costs, the deterioration of quality, and the amount of capital tied up in the increased stocks must be considered. (Granlund, 2004, Mäkelä & Pennanen, 2005, as cited in Rieppo, 2006)

Although preventive measures are taken into action, the effects of abundant rainfall in autumn and spring thaw are difficult to precisely anticipate in advance, and therefore, considerable monetary losses for the industry of forestry are being placed each year. For example for the forestry industry of Finland, an excess of approximately 100 million euros of extra costs is caused (Mäkelä & Pennanen, 2005, as cited in Rieppo, 2006). The largest

portion of these costs is related to increased forestry operations between the aforementioned seasons so that enough wood can be stocked to cover the shutdown periods when the disruptions in the timber supply chain are initiated. With CTIS, the improved mobility permits the operations to continue as normal for longer periods, reducing the need for additional investments in overstocking. Considering the additional benefits of CTIS, part of these extra costs is related to the maintenance of the rutted forest roads which can be prevented further with reduced tire inflation pressures. According to the United States Forest Service, when CTIS is used, the maintenance costs of forest roads can be reduced by 62% (Menzies, 2006, as cited in Rieppo, 2006).

For the trucking businesses, the economic benefits of CTIS and adjusted tire inflation pressures are related to a decrease in operating costs, such as prolonged tire lifetime, and reduced downtime during the adverse effects caused by weather variations. When the effects of abundant rainfall or spring thaw peak on forest roads, the operation of logging trucks may be limited to certain total weights or in a worst-case scenario be halted for several weeks. (Rieppo, 2006)

In chapter 3.1.7 it was stated that with proper use of CTIS, the lifetime of the truck's tires can be extended by 15%. The cost of a single tire can be estimated to be approximately 400€ (Munro & MacCulloch, 2008, p. 15). Figure 30 shows an example of a logging truck that is equipped with a total of 32 tires on the truck and trailer units, combining to a total cost of 12,800€. Estimating that one set of tires without CTIS lasts for one year, the annual tire cost savings when CTIS is in use can be calculated using the following equation:

$$s_{atcs} = c_{act} * r_{twr_{CTIS}} \tag{5}$$

where s_{atcs} – annual tire cost savings (€), c_{act} – the acquisition cost of tires (€), and $r_{twr_{CTIS}}$ – tire wear reduction with CTIS (%).

Due to the controversy in the actual fuel and fuel cost savings, the operating cost savings are limited to the improved lifetime of the tires. Equation 5 calculates annual tire cost savings of 1,920€.

Granlund (2006) estimated that the acquisition cost of a retrofitted CTIS, when installed in both the truck and trailer units, is 20,800€. Of this acquisition and installation cost, 13,100€ is spent on the truck with the remaining 7,700€ on the trailer.

The operational lifetime of a logging truck is estimated to be approximately 5 years (Granlund, 2006; Rieppo, 2006; Munro & MacCulloch, 2008, p. 29). Thus, the additional costs arising from the acquisition of CTIS is 4,160€ each year. Deducting the yearly tire cost savings, approximately 2,240€ is to be compensated via an increase in the operational time during each annum.

The cost-effectiveness of CTIS in conditions where the system demonstrates benefits has been averaged as 1.9 to 5.7 euros per each ton of transported wood (Granlund & Löfroth, 2006, as cited in Rieppo, 2006). The variance in the demonstrated monetary benefit depends on whether the forest road has weight limitations that would prevent logging trucks from transporting full loads. To estimate the additional tons of transported payload required, the following equation can be used:

$$m_{aoh} = \frac{c_{ac_{CTIS}}}{b_{tow}} \quad (6)$$

where m_{aoh} – tons of additional payload (t), $c_{ac_{CTIS}}$ – annual cost of CTIS after the tire cost savings has been deducted (€), and b_{tow} – monetary benefit per each ton of transported wood.

The results from equation 6 indicate that to compensate for the costs arising from the acquisition of CTIS, an additional 393 to 1179 tons of wood would need to be transported outside the normal operating conditions. Estimating that the truck is limited to a total weight of 60 tons, the amount of payload is approximated to 30 tons when the weight of the truck and trailer are deducted. The number of transport cycles the logging truck must perform under adverse seasons is then in the range of 14 to 40 to cover the increased operating costs. Approximating that the exemplary truck implement operates in short to medium range operations of 100 kilometers per roundtrip and is, therefore, able to perform 2 daily roundtrips, the truck must operate an additional 7 to 20 days. Consequently, to cover the costs of CTIS, the timber harvesting season must be lengthened without interference by 1.4 to 4 workweeks. Any additional transport cycles beyond this can be considered as a direct monetary benefit to the trucking business.

Case Study Conclusions

The case study concluded that the use of CTIS has a limited effect on the amount of GHG emissions of an individual logging truck. However, the related benefits to the industry of forestry show promising results in terms of improved operating efficiency due to extended timber harvesting seasons. Year-round distribution of the transportations operations reduces the downtime of the trucking businesses and sustains the reliability of the timber supply chain. Although CTIS show benefits for the forestry industry as a whole, the acquisition costs of CTIS are often directed fully to the trucking companies (Keränen & Malinen, 2019).

Keränen & Malinen (2019) conducted an extensive survey, where Finnish trucking companies involved in forestry operations were interviewed regarding their attitudes on CTIS and its benefits. Based on the responses received, the study concluded that the initial investment, and thus the increase in the operating costs arising from the acquisition of CTIS are not covered nor justified by the achieved benefits from the perspective of the trucking businesses. A congruent opinion of the interviewees was that the operating companies of the forestry industry achieve the largest share of the realized benefits. Only one of the interviewed company representatives stated that the acquisition of CTIS ends up profitable after a four-year contract, mostly due to a reduction in the tire costs.

To reach wider acceptance in the use of CTIS, a shared cost-model between the trucking companies and the forest management should be reached. However, sharing the costs as according to the division of the benefits would require extensive cooperation programs between the interest groups. (Keränen & Malinen, 2019)

Considering that if CTIS would be implemented in all factory-new constructions, the acquisition of the system would not be of topicality later on. Nonetheless, the realization of this is unlikely as the entailed costs would still be significant considering the uniqueness of CTIS and the limited production series of logging trucks (Granlund, 2006).

5 Market Review

In this chapter, a brief market review of CTIS is executed. The primary focus of this market review is to identify some of the major suppliers of CTIS for both agriculture and forestry applications. The secondary section of this chapter aims to determine CTIS component suppliers which by the interest of the thesis commissioner are purposely delimited to focus on suppliers of the rotary seals.

5.1 Suppliers of Central Tire Inflation Systems

In this subchapter, the main suppliers of CTIS are identified, their targeted applications are recognized, and their market areas are listed.

5.1.1 Michelin

In 2017, a tire manufacturing company Michelin acquired two CTIS companies PTG and Téléflow. In succession the acquirement, Michelin became one of the largest suppliers of CTIS in the world. (Goodchild, 2018; Michelin, 2019)

The CTIS by Michelin is designed for the use of agricultural tractors in conjunction with a specific tire construction. Michelin as a tire manufacturer has developed a special tire structure which's shape and profile vary according to the level of the tire's inflation pressure (Goodchild, 2018; Michelin Agriculture, 2018).

Considering the markets, Michelin aims to achieve global availability for their CTIS (Michelin Agriculture, 2018). However, the initial availability of the system as of 2018 has been concentrated in France, Germany, Belgium, Austria, Luxembourg, Netherlands, and Switzerland (Goodchild, 2018).

5.1.2 TPC International

TPC International is a Canadian company founded in 1996. Since then, the company has developed an extensive CTIS for the use of a wide variety of different truck related applications, such as those used in the context of forestry, oil, construction, agriculture, and power utility industries. (TPC International, 2020a)

However, the most notable recognition the TPC International's CTIS has received from the forestry industry (Rieppo, 2006). Several studies investigating the benefits of CTIS, especially in connection with logging trucks, the vehicles have been equipped with CTIS developed by TPC International (Granlund, 2006; Munro & MacCulloch, 2008, p. 21; Oksanen & Rytkönen, 2009; Keränen & Malinen, 2019).

On the market, the CTIS developed by TPC International has achieved notable market penetration. According to TPC International (2020), their CTIS are operational in North America, Europe, Asia, Africa, and Australia.

5.2 Suppliers of Central Tire Inflation System Seals

This subchapter identifies certain suppliers of rotary seals used in CTIS. In addition to the suppliers, the rotary seal designs are introduced and compared to the sealing solution introduced in chapter 2.2.4.

5.2.1 Freudenberg Sealing Technologies

As a leading supplier of advanced sealing materials and products, Freudenberg Sealing Technologies focuses on variations of automotive, industrial, and alternate drivetrain applications (Freudenberg, 2020).

For the use of CTIS, Freudenberg Sealing Solutions has developed a two-component double-lip rotary seal. Figure 32 presents the cross-section of this seal. The primary lip illustrated in brown prevents the air from leaking when the tires are being inflated simultaneously reducing the pressure put on the secondary lip. The task of the secondary lip is to seal any impurities the sealing system may be vulnerable to. The primary lip is manufactured of PTFE whereas the secondary lip is manufactured to the elastomer jacket of the seal, which in this seal type may be fluorocarbon (FKM) or nitrile rubber (NBR) materials. The structural part and the spring energizing the secondary lip are manufactured of steel. (Freudenberg, 2015)

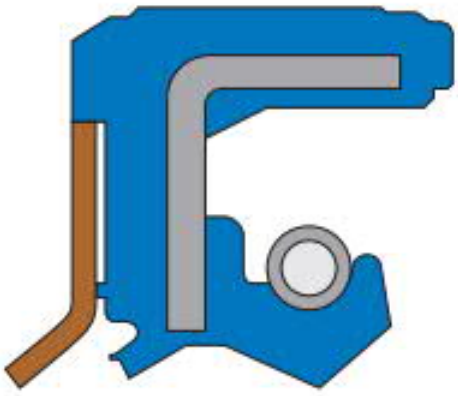

Figure 32: Cross-section of a CTIS seal developed by Freudenberg Sealing Technologies (Freudenberg, 2016).

Compared to the sealing solution presented in chapter 2.2.4, the major difference in the seal designed by Freudenberg Sealing Technologies is that the seal incorporates a secondary lip. Besides the secondary lip, the sealing performance remains largely unaffected by the pressure variations, whereas the rotary seal presented in chapter 2.2.4 activates under the increasing pressure. Being pressure-activated denotes that when the pressure increases, the increasing force presses the sealing lip tighter onto the sealed surface.

The sealing solution developed by Freudenberg Sealing Technologies is designed for the use of internal CTIS in agriculture and construction vehicles with similar operation principle as in the sealing solution presented in chapter 2.2.4. Figure 33 illustrates the setup of the sealing

solution, where a pair of seals are fixed between the rotor and stator elements of the wheel manifold. The presented air inlet supplies the pressurized air through the drilled pathways within the axles. (Freudenberg, 2016)

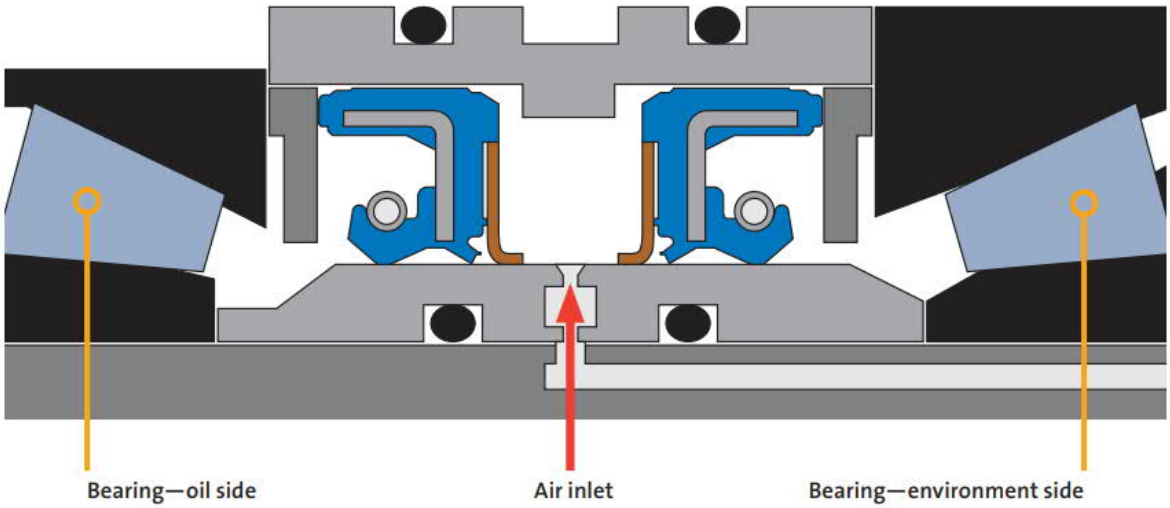

Figure 33: Illustration of the installation setup of the CTIS seals developed by Freudenberg Sealing Technologies (Freudenberg, 2016).

Operational conditions for the CTIS rotary seal developed by Freudenberg Sealing Technologies have been set to pressures of up to 8 bar and circumferential speeds of up to 10 meters per second on the sealed shaft. However, it must be considered that these values may not be reached in combination. (Freudenberg, 2015)

5.2.2 FTL Technology

FTL Technology is an engineering company specialized in providing innovative sealing solutions for a variety of key markets, such as oil and gas, chemical processing, industrial equipment, and the automotive and transportation industries. FTL Technology is based in the United Kingdom and the company operates alongside Precision Polymer Engineering and Novotema. Together these companies are part of the IDEX Sealing Solutions Group. (FTL Technology, 2020a)

For the use of CTIS, FTL Technology has developed two separate rotary seal designs. The design of these rotary seals is largely similar to the rotary seal of the supplier presented in the previous subchapter. Similarities may be visualized in the incorporation of a two-component double-lip design. In addition to the seal design, the operation principle of both of these seals remains similar. In both of the rotary seal designs, the primary lip seals the air used to inflate the tires and the secondary lip protects the seal from any external contaminants. (FTL Technology, 2020b)

Figure 34 shows the cross-section of the first rotary seal developed for the use of CTIS. The sliding surface of the primary air lip illustrated in green is manufactured of thermoplastic

that is attached to the elastomer jacket of the seal which also energizes the sealing performance of the thermoplastic lip. The secondary lip is manufactured to the elastomer jacket of the seal, which in this seal is of FKM material. The structural parts and the spring energizing the secondary lip are manufactured of steel. (FTL Technology, 2020b)

Figure 34: Cross-section of a CTIS seal developed by FTL Technology (FTL Technology, 2020b).

The cross-section of the second rotary seal developed for the use of CTIS is presented in Figure 35. In this seal, the primary air lip illustrated in green is manufactured of an individual thermoplastic element. Similarly, as in the rotary seal presented in Figure 34, the secondary lip is manufactured to the elastomer jacket of the seal, which in this seal type is also of FKM material. The structural parts and the spring energizing the secondary lip are manufactured of steel. (FTL Technology, 2020b)

Figure 35: Cross-section of a CTIS seal developed by FTL Technology (FTL Technology, 2020b).

The rotary seals designed by FTL Technology are designed for the use of military, agricultural, and forestry CTIS applications as an internal system similar to the setup presented in chapter 2.2.4. Figure 36 illustrates the pair of seals that are fixed between the rotor and stator elements of the wheel manifold where the pressurized air is also fed through the channels drilled through the axles. (FTL Technology, 2020b)

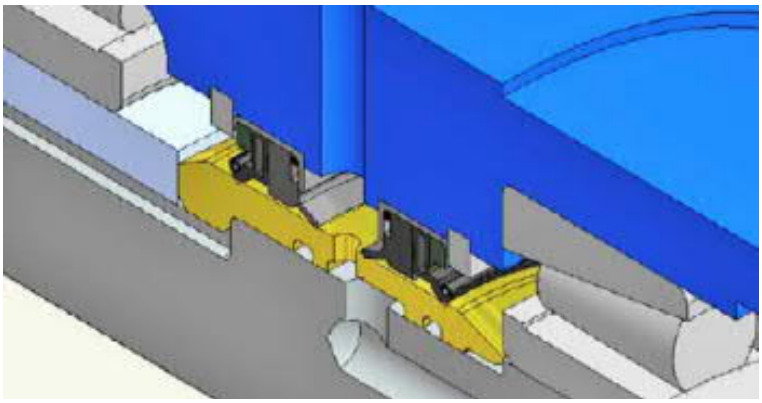

Figure 36: Illustration of the installation setup of the CTIS seals developed by FTL Technology (FTL Technology, 2020c).

For both of the rotary seals developed by FTL Technology, the operational conditions have been set to an ambient temperature range of -25°C to +160°C. Maximum pressure has been set to 10 bars on the primary air lip for both of the rotary seals. For the rotary seal presented in Figure 35, a pressure maximum of 0.5 bars has been set for the secondary lip. The maximum circumferential speed of the shaft that is to be sealed has been set to 5 meters per second for both of the rotary seal designs when the CTIS inflation or deflation processes are active. (FTL Technology, 2020b)

5.3 Original Equipment Manufacturers

During the writing process of this thesis, the only OEM offering a factory-installed CTIS in their production of agricultural tractors is AGCO Fendt (Corneli, 2020). For the industry of forestry, no manufacturers were found that would offer OEM CTIS solutions for logging trucks. However, truck manufacturers such as Scania have indicated the opportunity and approximated the potential costs arising from the installment of CTIS at the assembly line (Andersson & Granlund, 1994; Granlund & Andersson, 1998; Granlund et al., 1999, as cited in Rieppo, 2006).

The CTIS offered by AGCO Fendt was launched in 2012 (Volk et al., 2011). The solution by AGCO Fendt is an internal CTIS configuration providing substantial improvements in the energy efficiency and environmental impacts of AGCO Fendt tractors. The benefits include lower fuel consumption in the field and on the road, increased field coverage in the same amount of time, lowered soil compaction, faster traveling speeds, and ultimately decreased operating costs. (AGCO Fendt, 2020)

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6 Conclusions

In this thesis, a comprehensive overview of the CTIS, including the system's history and its different variations, was carried out. As indicated in the theoretical framework, CTIS is an auxiliary equipment that allows the adjustment of tire inflation pressures from the operator seat on virtually any type of a vehicle. As the primary focus of this study, the effects the CTIS has on the energy efficiency and environmental impact of vehicles used in connection with the industries of agriculture and forestry, such as tractors and logging trucks, were studied. In addition to the previously mentioned benefits, this study touched on several other effects the CTIS improves in the vehicle operation, such as the ride quality and wearing of the tires. Based on an extensive literature overview presented in this study, clear benefits were demonstrated when CTIS was implemented in the vehicles of the study-related industries.

For agricultural tractors, the use of CTIS showed average fuel consumption reductions of up to 8.9% in versatile operating conditions including travelling on paved roads and field work. For logging trucks, the reductions in fuel consumption were found out to be more moderate. The reason for this was that logging trucks are mostly operated on high-speeds and on paved roads for which the adjustment of the tire inflation pressures is typically not required. With only 6 to 7% of the total travelling distance of logging trucks being in conditions where CTIS proves useful, the effects on fuel consumption were measured to be in the range of 0.5 to 1.7% in conditions of a typical forest road. The fluctuation in the amount of fuel consumption reduction of logging trucks varied whether the vehicle was unloaded or loaded.

In the case of logging trucks, the importance of CTIS was highlighted in the extension of the timber harvesting seasons due to improved traversing capabilities during the effects of abundant rainfall or spring thaw affecting the forest road structure. With a more balanced timber supply chain throughout the varying seasons, the presented studies indicate that potential reductions in the amount of GHG emissions could be as high as 20%. However, in order to reach such a level of improvement, changes in the legislation would be required so that the transportation of heavier payloads would be allowed which consequently reduces the number of roundtrips required.

Even though CTIS has been studied and implemented in the vehicles of agriculture and forestry since the 1980s, the widespread adoption of the system is yet to happen. The investigations presented in this thesis concluded, that often the initial monetary investment required in the acquirement of the system is seen as too high compared to its short-term benefits to the vehicle owner. Secondly, the limitations set by the system's availability in the market make it so that the existence of CTIS is known only by the well-informed farm and trucking business owners and operators.

This thesis conducted a brief market study to study a selected range of manufacturers supplying CTIS solutions for both agriculture and forestry vehicles. In addition to the suppliers of complete systems, the suppliers of specific rotary seals used in CTIS were researched to recognize the differences in the type of sealing solutions used in a variety of CTIS. The brief investigations concluded that there are dominant suppliers for both of the study-related industries and that in terms of the rotary seals, the solutions are comparable to

each other by their fundamental operation principle. Concluded by the brief investigations of the CTIS market, it was found out that only one of the suppliers of complete systems is a tractor OEM offering CTIS as a factory-new installation.

Overall, CTIS shows promising results for both agriculture and forestry applications. However, due to the limitations in the availability of CTIS, the widespread adoption of the system currently relies heavily on the consumer willingness to search for suppliers in the aftermarket. Thus, to further increase the market penetration of CTIS, the number of OEMs collaborating with the CTIS suppliers should be increased. Increasing the number of factory-new installments would make the acquisition of the system a more streamlined process for the end-user. Additionally, to make CTIS an even more attractive solution to be used within the study-related industries, a cost-sharing model should be proposed between agricultural subsidies and the benefitting parties, such as the operators of the forestry industry.

6.1 Future Perspectives

For the increasing amount of wheeled vehicles within the industries of agriculture and forestry, CTIS shows promising results as a viable method in improving energy efficiency consequently lowering the environmental impact. As stated at the beginning of this work, the solution to climate change is not the responsibility of an individual, but rather the combination of innovative ways to reduce the emissions caused by anthropogenic actions.

Considering the future of CTIS, the benefits of its use has already been demonstrated. With existing CTIS solutions, the only remaining hurdle that restricts the wider implementation of CTIS is to affirm the system as a new norm to applications in the industries related to this study.

6.2 Identification of Other Uses and Future Work

Other uses that have been presented to CTIS throughout this work have included vehicles from the military and industries such as oil, construction, and power utility industries. As the unifying factor for these vehicles is the common requirement to be able to operate under varying ground surface circumstances and in distant locations. For this reason, the benefits presented in this study apply to these and virtually any vehicle with the requirement to operate in similar off-road conditions.

An interesting field for further study would be the use of CTIS in passenger vehicles. As studied by d'Ambrosio & Vitolo (2019), fuel consumption reductions of approximately 2% can be reached in real-world driving conditions when tire pressure managing systems such as CTIS would be implemented. Though passenger vehicles are most often driven on paved roads with pre-determined tire inflation pressures, the benefits of CTIS would be realized in the capability to perform minor adjustments while the vehicle is operated.

The need to adjust the tire inflation pressures would be the variations in weight force and temperature fluctuations in the tire bodies caused by the ambient conditions as well as the effects of friction caused by increased traveling speed. Additionally, the same rule of improved traversing capability could be seen among passenger vehicles as well.

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