Aalto-yliopisto
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Determining the Road Wear Limits in the Type Approval of Studded Tires

Master's Thesis

Thesis submitted in partial fulfilment of the requirements for the degree of Master of Science in Technology.

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Diplomityön tiivistelmä

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Tiivistelmä

Nastarenkaat ovat yleisimmin käytetty talvirengastyyppi suomalaisissa henkilöautoissa, ja ne ovat laajalti käytössä myös muissa Pohjoismaissa sekä esimerkiksi Venäjällä. Nastarenkaita käytetään talvikuukausina parantamaan renkaiden pito-ominaisuuksia liukkaissa olosuhteissa, erityisellä jäisellä tienpinnalla. Nastarenkaat aiheuttavat kuitenkin tien päällysteen kulumista, mikä johtaa teiden urautumiseen ja tiheämpään uusintapäällystystarpeeseen. Teiden urautuminen lisää myös vesiliirtoriskiä. Nastarenkaista johtuva tienkuluminen lisää myös katupölyn ja pienhiukkasten muodostumista, jotka saattavat aiheuttaa hengitystieongelmia kaupunkialueilla erityisesti keväisin. Tämän lisäksi nastarenkaat kuluttavat myös tiemerkintöjä, millä on sekä taloudellisia että liikenneturvallisuutta vaarantavia vaikutuksia.

Nastarenkaista johtuvaa tien kulumista pyritään rajoittamaan määrittelemällä niiden sallittu vuosittainen käyttöaika, sekä asettamalla vaatimuksia niiden tietyille teknisille ominaisuuksille. Perinteisesti rajoitukset ovat koskeneet nastojen mittoja, nastamäärää ja niiden asettelua renkaan pintakuviossa. Nastarenkaiden tien kuluttavuutta mittaavalla yliajokokeella voidaan kuitenkin hyväksyä vapaammin suunniteltu nastarengas, kunhan sen tien kuluttavuus on viranomaisen määrittelemällä tasolla. Yliajokokeen kulumisrajoja tiukennettiin viimeksi vuonna 2013, jonka jälkeen myös koemenetelmän luotettavuuden parantamiseksi on tehty useita muutoksia.

Traficomissa on valmisteilla määräyshanke nastarenkaiden tyyppihyväksynnän osalta. Tämä diplomityö on tilattu kyseisen määräyshankkeen valmistelun tueksi. Diplomityön tavoitteena oli tutkia, onko yliajokokeen kulumisrajoja tarpeen muuttaa ja mitkä olisivat muutoksen mahdolliset vaikutukset.

Diplomityössä tehtyjen havaintojen ja tulosten perusteella annettiin ehdotukset tien kulutuksen raja-arvojen asettamiseksi. Tässä tekstissä esitettyjä ehdotuksia voidaan hyödyntää nastarenkaisiin liittyvän määräyshankkeen suunnittelussa.

Eräänä pitkäaikaisena haasteena yliajokokeessa on ollut vähäinen kuluma suhteessa testikivien painoon, mikä voi lisätä virheiden mahdollisuutta. Työssä tultiin siihen tulokseen, että yliajokokeen raja-arvoja ei voida laskea lisäämättä kokeen aikana tapahtuvaa absoluuttista kulumaa.

Avainsanat nastarengas, kitkarengas, talvirengas, liukuesteet, tyyppihyväksyntä, yliajokoe

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Abstract of master's thesis

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Abstract

Studded tires are the most commonly used winter tire type on Finnish passenger vehicles. Studded tires are also widely used in other Nordic countries and e.g. Russia. They are used to increase the safety properties of the tires, especially on icy road conditions during the winter months. However, studded tires cause road wear, which leads to grooving of the roads and results in more frequent resurfacing of the pavement. Furthermore, they also generate road dust and particle emissions, which may increase respiratory diseases in urban areas during springtime. Studded tires also cause wear on road markings, that has both economical and traffic safety related issues.

The use and technical properties of studded tires is regulated in order to reduce their effect on road wear. The use of studded tires in traffic is limited to the winter months. Traditionally the technical regulations have been concerning about the stud dimensions, their location on the tire thread and the stud amount. The studded tire properties can be more freely designed, if their effect on road wear is measured in a so-called over-run test. The over-run test method including the road wear limits are defined by Traficom. The road wear limits in the over-run test were tightened in 2013. Several improvements on the accuracy and reliability of the test have been implemented since then.

Traficom is preparing a new decree on the type approval of studded tires. This thesis is ordered by Traficom to provide research as a background in the preparation of the new decree. The objective of the thesis was to investigate if it is purposeful to change the current road wear limits and to analyse the consequence of those possible changes.

Suggestions on designating the road wear limits in the over-run test were given based on the observations and results achieved in the thesis. The results presented in this thesis may be utilized in the preparation of the new decree on studded tires.

One long-term issue with the over-run test has been the relatively low mass loss compared to the test specimen's weight. This potentially increases the errors in the test method. One result in the thesis was that the limit values in the over-run test can not be further tightened without increasing the absolute wear during the test.

Keywords studded tire, studless tire, non-studded tire, winter tire, anti-slip device, type approval, over-run test

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Vantaa 09.04.2019

Hannu Mustonen

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Abbreviations

3PMSF	The Alpine symbol, three-peak-mountain with snowflake
4WD	Four wheel drive
ABS	Anti-lock braking system
ESC	Electronic Stability Control system
ETRMA	European Tyre & Rubber Manufacturers' Association
ETRTO	European Tyre and Rim Technical Organisation
FHWA	Federal Highway Administration (United States)
FTA	Finnish Transport Agency
FWD	Front wheel drive
LVM	Ministry of Transport and Communications
RWD	Rear wheel drive
STRO	Scandinavian Tire & Rim Organization
Traficom	Finnish Transport and Communications Agency
UNECE	United Nations Economic Commission for Europe
VTT Oy	Technical Research Centre of Finland Ltd.

1 Introduction

1.1 Background

Winter tires are compulsory in Finland on passenger cars (M1) and vans (N1) during the winter months from December to February. The majority of the winter tires are studded, but studless tires are also available. Studded tires cause road wear, which grooves the road surface and create particle emissions. To restrict the road wear caused by studded tires, a type approval is required. The authority that regulates the type approval of studded tires is The Finnish Transport and Communications Agency (Traficom).

Traficom is preparing a new regulation regarding the technical requirements and testing procedure of studded tires. Currently, there are two options for carrying out the approval for studded tires. First, to follow the requirements for stud properties (e.g. protrusion) and the amount of studs per rolling circumference meter as set in the Ministry of Transportations Act Regarding the Studs of Vehicle Tires (20.5.2003/408) paragraph 2. Other possibility is to apply for type approval, where the tire manufacturer is required to test the road wear properties of the tire. The most commonly used test for this purpose is the so-called over-run test, which is developed to measure the wear of test stones, that are demonstrated to be in correlation to actual road wear. The over-run test has been widely utilized in the 2010's and the requirements regarding the test procedure have been kept relatively unchanged since then.

1.2 Research problem

The results of the over-run test have proven to become more reliable and consistent and therefore it could be possible to update the contents of the current type approval method. The over-run test method was standardized as a Finnish national standard in 2018, but the standard does not include the road wear limit values or other specific requirements, but is merely a standardized test description of the procedure. To validate and determine the contents and requirements set with the new regulation in sight, research is needed from various topics, such as how to designate the road wear limits. The current limits are based mainly on empirical research data from the over-run tests conducted by VTT and Timo Unhola from 1990's to early 2000's.

The limit values should be determined in a way that the road wear caused by studded tires could be further reduced without significantly impacting their safety properties. In addition, it should be analyzed if the new data and information provided by the over-run task force, test facilities and other involved parties after the previous researches contain insights that should be taken into consideration. In the topic of studded tire testing, some long-term discussion has been focused on e.g. these questions and aspects:

- What is the correlation between the road wear in the over-run test and the actual road wear?
- Is lowering the road wear limits possible without affecting the safety properties (mostly ice performance)?
- If the road wear limit in the over-run test method is decreased by e.g. 10%, does it correlate to 10% lower road wear on the public roads?

1.3 Objectives

The main objective of the thesis is to provide supportive research for the upcoming regulation. The thesis will focus on developing and improving the test arrangements and analyzing the acquired data and information in a way that the road wear limits can be correctly chosen. In order to designate the values with justification, a correlation between the wear in the test and actual road wear should be proven. The limits should not affect the safety performance or the lifespan of the tires.

As stated earlier, the focus will be in analyzing the road wear limits. However, also other factors relevant to the research topic need to be taken into consideration and are worthwhile investigating in this thesis. In order to understand the topic at hand, it is feasible to study what type of winter tires are on the markets and in the traffic and where the trend of winter tire markets is heading. What type of winter tires (studded or studless) are being sold currently and have the trends changed? How have the technical properties of the tires changed? Additionally, it is relevant to study the recent trends in vehicle and traffic related developments.

The new regulation will include the technical requirements, test method description and limit values for road wear of studded tires. The objective of the regulation is to decrease road wear while causing minimal effect on the properties of the studded tires. The suggestions this thesis proposes will be conducted and verified by using the data acquired from the key stakeholders and from the previous researches. Those suggestions will be used to provide an analysis, which will act as a support when defining the limits to reduce road wear in the new regulation.

1.4 Goal & scope

The first part of this thesis is a literature study that investigates the background of studded tires and their use in Finland and globally. Furthermore, the legislatory measures concerning studded tires is introduced, especially the implementation and use of the over-run test. After that, the development of the vehicles on Finnish roads, traffic performance in Finland and future trends are evaluated. Later parts of the thesis concentrate on the evolution and evaluation of the over-run test: what changes have been done and what changes should be implemented in the future.

Because the focus of the thesis is on the road wear limits, it is justifiable to evaluate the correlation between the road wear in the type approval test compared to the road wear in real-life situation. However, this requires applicable data considering the amount of road wear on Finnish roads. Possible sources for this type of data could be e.g. the road register, administrated by the Finnish Transport Infrastructure Agency.

The over-run test is primarily used for the testing of studded tires intended for passenger cars and vans. Therefore, it is not feasible to study the requirements and use of studded tires in heavy vehicles in this thesis.

The particulate emissions related to the use of winter tires is a topic that concerns many public and private authorities. However, the over-run test method is not used for evaluating the particle emissions of the studded tires and therefore only brief analysis of studded tire related particles emissions is provided in this thesis.

This thesis will provide an overview of the situation at the time of writing. There are no special funds for experimental test campaigns, so the new, experimental data presented here is what has been created by other means during this research.

2 Background

2.1 Stakeholders

Finnish Transport and Communications Agency (Traficom)

This thesis is ordered by the Finnish Transport and Communications Agency (Traficom) and is related to an ongoing work towards a new decree on tire studs. The current decree was last amended in 2009. Traficom is part of the sector that the Finnish Ministry of Transport and Communications (LVM) administrates. Traficom is responsible for the licences, registrations and approval matters related to transportation and communications. Transportation vise, Traficom is the authority for the controlling and regulating the traffic system in Finland. Its task is to promote traffic safety and to reduce traffic related emissions. Traficom was formed in 2019 as a merger between the Finnish Communications Regulatory Authority, the Finnish Transport Safety Agency (Trafi) and parts of the Finnish Transport Agency.

Traficom's current organization is divided into 5 main branches: National Cyber Security Centre, Spectrum Management, Transport System and Markets, Means of Transport and Transport Operators. Each branch has their own branch manager, whose responsibility is to assist and lead the units within the branch and report to administration considering the performance of those units.

Type approval is a national or international procedure to verify a vehicle or a vehicle component to meet their requirements. Requirements are based on national acts or international legislation, such as EU directives, UNECE regulations or decrees. Traficom is the official type approval authority in Finland and therefore mainly serves Finnish and Nordic customers. However, Traficom also works in co-operation with other type approval authorities around Europe and other countries and participates in maintaining and developing of vehicular regulations.

The Decree of the Ministry of Transport and Communications on Tyre Studs 408/2003 allowed the use of a road wear test in the type approval of studded tire. The over-run test has been widely used in type approval testing in the 2010's. The wear limits in the over-run test were updated in 2013 and many improvements have been introduced since then to enhance the repeatability and reliability of the test. An over-run task force consisting of recognized experts was created to identify and correct the weak points in the test and to make the test arrangement more uniform and comparable. Furthermore, the over-run test method has been accepted as a national standard by the Finnish Standards Association SFS in 2018. As the test method has been harmonized and the test has been proven suitable for studded tire wear testing, Traficom has decided it is suitable to re-examine the requirements and limit values of the test.

Recognized experts

Recognized experts are companies which perform testing, measurement and inspections for type approval purposes. They are validated and audited by Traficom and their operation is regulated by EU or national level legislation. Currently, there are six companies responsible for performing the over-run test for studded tires:

- BD Testing Ltd.

- Goodyear Innovation Center Luxemburg
- Nokian Tyres PLC, Testing Laboratory
- Test World Ltd.
- Tikka Spikes Ltd.
- Turvanasta Ltd.

The over-run task force is comprised of these companies. The objective of the task force is to recognize and correct the systematic errors in the test. The task force reports its findings to Traficom. The final report was finished in 2018.

Tire and stud manufacturers

More than often, there are products of two different companies in a studded tire. The tire itself is designed and manufactured by the tire company, but the studs may come from a company that specified is stud design and manufacturing. Some tire companies have own designs for studs and only outsource the stud manufacturing. It is rare that a whole tire-stud combination is designed and manufactured in-house.

Before the current legislation, the shape and dimensions of the studs were strictly regulated and a type approval for a stud design had to be applied. Thus, every tire manufacturer used very similar stud designs. These studs were called universal studs and are still being manufactured, especially to tires which are not approved using the over-run test method. Applying the over-run test method for a tire approval, the stud design and shape can be chosen more liberally. Currently, most tire manufacturers prefer using a stud that is designed for their specific tire-stud configuration. A single tire can also have two or more different types of studs.

Many stud manufacturers are also certified recognized experts and carry out over-run tests and can therefore provide the tire manufacturer complete service regarding studded tires. However, tire manufacturers typically perform the installation of the studs to the tire by themselves or by using a specific studding service.

2.2 Winter tire use and definition

Winter tires are widely used in areas where the temperatures reach below freezing, such as Europe, Russia, China and North America. Winter tire as a term is often loosely defined. Typically, an M+S (mud and snow) marking has been used to indicate that the material and tread of the tire is designed to work on mud and snow. In many countries, the M+S marking is used as the legal definition of a winter tire. However, the M+S does not measure the performance capabilities in mud and snow, but is only a manufacturer´s declaration. In 2012, the three-peak-mountain with snowflake (3PMSF) symbol was included in the Regulation No. 117 of the Economic Commission for Europe of the United Nations (UNECE). The 3PMSF symbol can only be used, if the tire meets the performance criteria on snow as set in the regulation.

In this thesis however, the term winter tires is used for a so-called Nordic winter tyres (both studded and studless), which are typically used in the Scandinavia, Russia and Canada. Nordic winter tires are specifically engineered for snowy and icy conditions and operate well in freezing temperatures. These types of winter tires can be divided in to two categories: studded tires and studless: (Tuononen & Sainio, 2013)

- Studded tires have metallic inserts that extrude from the tire tread (stud protrusion)
- Studless tires are designed to provide good traction on snow and ice without studs. The rubber compound of the tires is typically soft even in cold temperatures. Contact pattern of the studless tires consist of lamellae, which enhances the grip on snowy and icy roads. Central European studless tires have better wet grip properties, whereas the Nordic studless tires perform better on ice and snow. The Nordic studless tires typically have a lower speed rating than the Central European studless tires. However, the speed ratings of Nordic studless tires have increased and the division between Nordic and Central European studless tires has become more difficult to point out.

In Finland, the studded tires are the most popular winter tire option. Around 85% of all winter tires on passenger cars are studded tires, which is one of the highest percentages in the world. (IF, 2018) The obvious benefit of the studded tires is their grip on ice, especially near the temperature of 0°C, due to the temperature dependent hardness of the ice (Rantonen et. al. 2012). Studded tires also reduce the polishing of the roads as the studs roughen the smooth surface of the icy road.

However, the abrasive effect of the studded tires also causes road wear and therefore there are restrictions regarding their use. In Finland, studded tires are allowed to use between November 1st to March 30th or the next Monday after the Easter Monday, later one being the determinative. If the road conditions so require, studded tires can be used longer. Winter tires are compulsory from December to February.

Some countries where studded tires were previously used have started to ban their use completely or at least in specific areas, where they cause most problems. Germany and Japan has banned the use of studded tires completely. Norway has banned their use in several cities to reduce PM_{10} particle emissions. Sweden has placed bans on some specific roads in its largest cities.

2.3 The use of studded tires

Commercially manufactured studded tires gained success in the 1960's in Finland. Concurrently, the first highways were built and the majority of roads gained asphalt pavement. Therefore, the impact on pavement wear caused by studded tires caused concern. The first restrictions limiting the use of studded tires to winter months were set in place in 1970, followed by regulations regarding the properties of studded tires in 1974 . The regulation was based on studies conducted in the 1970's and contained restrictions on amount of studs per tire and on stud force & protrusion. (Unhola, 1995)

Winter tires are mandatory in the Nordics due to the weather conditions, as the temperature goes below 0 °C in the winter months. Due to the freezing temperatures, road surfaces can become icy and covered with snow. Statistically, the winters have been milder in Finland in the recent years (Finnish Road Administration, 2009). The increasing temperatures means that the temperature goes below less often in the southern parts of the country. For the central and northern parts, it means more "around 0 °C" temperatures, overall increasing the slippery driving conditions. Furthermore, the road surfaces more often stay clear from snow and ice, which could increase the road wear caused by studded tires.

The market for studded tires is relatively small considering the total amount of tires sold globally. However, Finland and the Nordics in general constitute for a significant amount of studded tire markets and are therefore considered important for the tire manufacturers. Additionally, because Finland has a long lasting history in the research and legislation regarding studded tires, the industry and other countries follow the Finnish legislation closely and it plays a significant role in the research and development of studded tires. The studded tire type-approvals granted in Finland are principally recognized in Sweden and Norway as well. Therefore, the influence of Finnish legislation and the jurisdiction of the type approval authority (Traficom) reaches further than national level. Thus, the stakeholders (countries and manufacturers) are trying to contribute towards the harmonization of the legislation.

The concerns considering the use of studded tires can be divided to two separate issues: pavement wear and particle emissions. The pavement wear is larger issue on highways where speeds are high but the areas near the highway is scarcely populated. Pavement wear leads to the need for resurfacing of the road that causes expenses. Additionally, the grooves created on the road may increase risk of aquaplaning. On the other hand, the particle emissions are bigger issue in cities and urban areas, where the particles developed by the worn pavement may cause health issues as the dust is gathered on highly populated areas.

In countries where studded tires are being used, their use is typically regulated by either limiting their use, properties or both of these. The legislation regarding the properties for studded tires in Finland is introduced more specifically in chapter 2.5. Countries that have a climate where the temperature during the winter stays above 0°C and therefore do not have snowfall or icy road surfaces, studded tires are not necessary and are therefore typically banned.

Winter road maintenance in the Nordics

In addition to traction improving devices (studs, sometimes snow chains) fitted on tires, the road network requires special roadkeeping during winter months in countries that have snowfall. The Finnish Transport Infrastucture Agency (FTIA) and The Centres for Economic Development, Transport and the Environment (ELY Centres) have defined the winter service levels for different road according to the level of traffic they carry. On the busiest roads, the policy is to prevent slippery conditions beforehand, but in any event no later than 2–3 hours after slipperiness has been observed. Snowfall needs to be cleared within 6 hours from the rain. Slipperiness preventive measures include chemicals that keep the road surface molten (such as salt) and friction improving additives like sand. (FTIA, 2019)

2.4 Effects of the use of studded tires

2.4.1 Safety

The main benefit of studded tires is their higher grip on icy road surfaces (Rantonen, et al., 2012). For many drivers in winter conditions, this creates a feeling of security, although the road surface would be clean of ice and snow. A study of Nordström (2004 p.

23) shows, that studless tires may have twice the braking distance of studded tires in icy conditions. However, the development of studless tires has developed their ice braking properties and the difference may be smaller today. The safety benefits of studded tires are still strong among the consumers, and when a consumer is buying new tires, it is easier to choose the option that is possibly safer, or at least provides sufficient grip in all conditions i.e. is more predictable.

The safety effect of studded tires compared to studded tires is versatilely studied in Scandinavia, especially in Sweden. Elvik et al. (1999, 2013) suggests that studded tires have positive impact on traffic safety, especially due to their anti-polishing effect. When investigating the statistical safety properties of winter traffic, one must take into consideration that vehicle and tire technology has developed considerably from the 1990's. For example, a more recent statistical study of Strandroth et al., 2012) found that studded tires reduce the risk of fatal accidents. In the study, it was also found that ESC (electronic stability control) has a similar affect in winter conditions. Elvik (2015) studied the topic more thoroughly and discovered that the benefits of studded tires become less important when a car is equipped with ESC. Furthermore, Elvik also suggests that ESC system can even compensate the need of studded tires if polishing effect is not considered. The level of ESC equipped vehicles has increased significantly in the 2000's. In Norway, more than 50% of vehicle kilometers performed by cars were driven on ESC equipped vehicles in 2009, and the amount is steadily increasing (see figure 1).

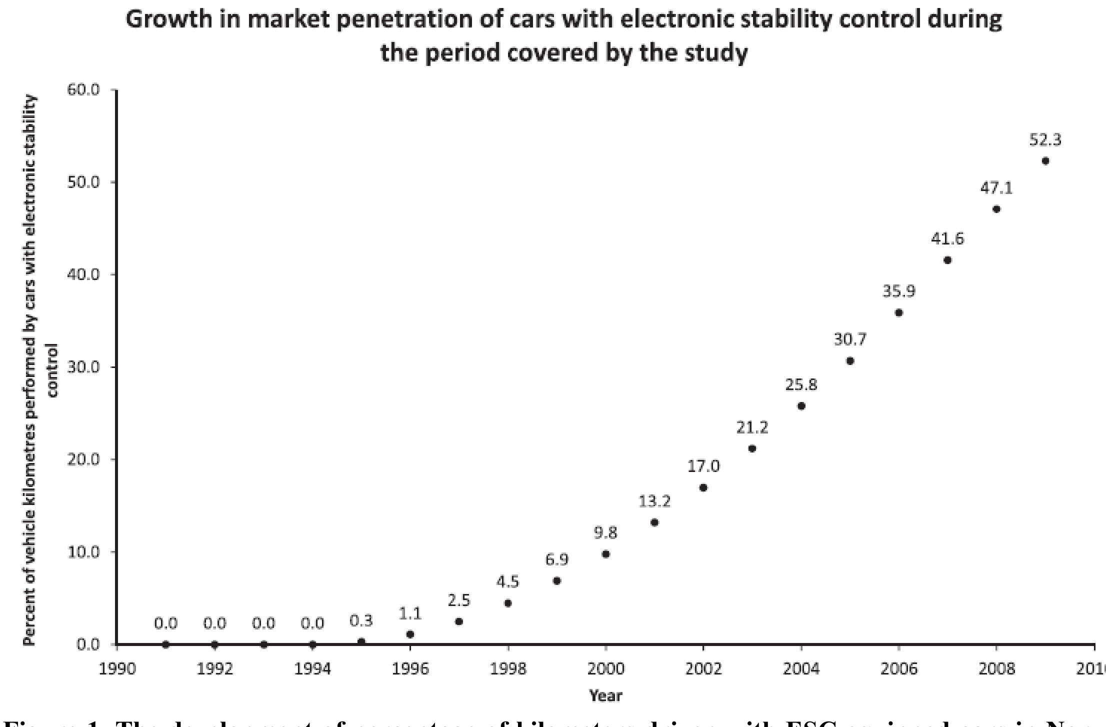

Figure 1. The development of percentage of kilometers driven with ESC equipped cars in Norway (Elvik, 2015)

Malmivuo (2012, 2016) has researched the statistics of studded vs. studless tires related accidents and the effect of decreasing the amount of studded tires in traffic. He suggests, that by doubling the percentage of studded tires in Finnish city traffic from 24 to 48 percentage, the number of personal injury related accident would rise by less than 10 cases nationwide (currently averagely 2200 cases annually). Similarly to Tuononen & Sainio (2014), Malmivuo has studied the optimal amount of studded tires in traffic. In his research, it was noted that by increasing the amount of studded tires to more than 50 percentage did not increase friction levels on snow/ice surface at 0 °C. Malmivuo notes that grooving of the surface was at its highest on the surfaces where majority of tires were studded.

The safety shell structure of cars is made to best withstand front-end collision and therefore side and rear end collisions can be more hazardous. Especially in winter traffic, these types of collisions may result from losing control of the car on a slippery surface. When traction is lost on studless tires, the driver often loses the control of the car, whereas on studded tires the driver still has some steering input (Malmivuo, 2012). An ESC system's main task is to keep the vehicle heading to the direction the driver wants it to go i.e. minimize the loss of control. Fundamentally, that is similar effect studded tires on icy surface. Therefore it can be argued that the as the amount of cars equipped with ESC increases, the need for studded tires becomes less and less important.

As stated earlier, studded tires have both passive and active effect on traffic safety. Firstly, they directly help the cars equipped with them to have better friction on icy roads. Secondly, they have a roughening effect that prevents the ice on the surface from polishing. Anti-polishing is an important factor when investigating the traffic safety on a larger scale. Whereas Malmivuo's (2016) research suggests that polishing may occur when there are less than 50 percentage of studded tires in the traffic flow, Tuononen & Sainio (2014) suggest only 25–50 percentage is required to maintain the friction levels. Elvik (2015) takes this notion further and argues that if all cars would be equipped with ESC, only 15 percent of studded tires are required.

Many studies have researched the psychological effect of winter tire types. One hypothesis and a result has been that those drivers which are preferring studless tires, tend to drive with more anticipation and care. However, depending on the study, the results can be somewhat controversial. Elvik et al. (2011) found out that in a traffic flow with higher amount of studded tires, the mean speeds were slightly lower i.e. the reduction of studded tires slightly increases the mean speed. This is an opposite result to that of Rumar et al. (1976) which shows that drivers with studded tires feel more secure and therefore drive faster. A survey study by Kuisma and Salla (2018) shows that drivers preferring studless tires over studded tires usually drive more annually than those who drive on studded tires. Furthermore, cars equipped with studless tires were newer and had better safety equipment (ABS, ESC etc.). A general notion was made that studless tire users are typically more experienced drivers and choose studless tires over studded ones based on a more comprehensive analysis, whereas studded tires are typically chosen with only safety in mind.

The argument towards using studded tires in Finland has long been that the safety benefits overcome the issues related to studded tire use (Unhola, 2004). However, as ESC and other various safety features become more common in passenger vehicles and the ice performance of studless tires enhances, it is justifiable to re-examine the benefits of studded tires and to investigate if the amount of studded tires could be reduced. Furthermore, it could eligible to e.g. allow studded tire use on vehicles, which are not equipped with ESC.

2.4.2 Road wear

Road wear is a major issue in countries where studded tires are widely used. As the hard metal studs hit the road surface, they remove particles from it. As the road vehicle tracks are nearly identical and cars are driven in a same line, the abrasive effect of studded tires causes grooves on the road. The road wear mechanism of studded tires is discussed more in chapter 3.1. Grooves decrease the safety level of the road in various ways; the vehicle may be unstable and unpredictable while entering or exiting the groove. Additionally, water may become dammed in the grooves increasing the risk of aquaplaning and causing more ruts as the water may freeze in the holes on the surface of the pavement and remove material on the road. Grooves can also form as the weight of the vehicles are transformed through tires and the road surface deforms. According to the Finnish Transport Agency however, only small amount of deformation occurs on a new pavement (early rutting) and after that point, all the rutting is caused by abrasion of studded tires, studless tires are considered not to cause any wear. However, the early deformation creates the outset for the grooves, which the traffic flow follows. I.e. if deformation would not occur, the grooves caused by abrasion may be wider, as the usual driving line in the winter varies due to snow. The grooving does not increase the total wear, but means that the pavement needs to be resurfaced sooner.

In Finland, the increased traffic volumes and mileage causes an issue to road maintenance administrations. Furthermore, the vehicles driven on the roads have become heavier which increases both wear and deformation.

The dependency of stud weight and road wear was quickly noticed as studded tire became widely used and therefore the stud weight have been controlled by legislation. VTT Technology Research Center of Finland was one of the first ones to prove this theory by research in 1986. According to their research, the stud weight is directly proportional to road wear. Although this research is relatively old, the results are still relative today, as the study by Gültlinger et al. (2014) verifies. Stud weight is also a property, which the manufacturers are pursuing to decrease. The current stud weight limits are difficult to furthermore decrease with aluminum stud bodies, which is the most commonly used. However, some manufacturers have recently introduced e.g. rubber-bodied studs for road-use, which could potentially have significantly lower road wear. (Continental, 2018)

2.4.3 Noise emissions

Traffic related noise emissions are a large issue especially in densely populated areas such as cities and urban areas and therefore affect many people. Due to the use of studded tires in the Nordics, the pavement material needs to be more wear resistant than in countries where studded tires are prohibited. The wear resistance properties are typically achieved by selecting proper stone materials and with higher grain size. This makes the pavement rougher and therefore increases tire noise. Furthermore, the studded tires wear the bitumen quickly as well, causing the surface to become even rougher.

In addition to tire noise, aerodynamic and power-source related noises are also sources of traffic related noise. According to the city of Helsinki (2008), the tire noise is considered to be the most dominant on roads with 50–80 km/h speed limit. This is true especially in the Nordics where the road surfaces are rough. Below that, the power-source noise levels are higher, and on higher speeds the aerodynamic noise becomes dominant. However, the power-source and aerodynamic related noise levels decrease constantly, as newer vehicles noise emission limits are tightened.

Due to the higher tire related noise emissions in Finland, special noise-dampening materials and manufacturing technologies have been developed. One of these reseaches was the HILJA-project in 2003. In the research, altogether 50 test sections were built on public roads. The target was that the sound dampening road material needs to be 3 dB(A)max SPB or 4 dB(A)max CPX quitter than the reference pavement at speeds of 50–60 km/h. Several test materials fulfilled this goal, but some lacked the necessary wear properties. Few materials were both quiet and had the necessary wear-resistance properties. Due to the higher cost however, these materials have not yet been utilized on a larger scale. (Kelkka et al., 2003)

Studded tires increase the tire related noise by 8–9 dB comparing to studless tires. (FTA, 2008), which is relatively high, as the EU traffic noise threshold is 55 dB for daily exposure. In Finland, 117 200 inhabitants are exposed to that level of noise. (FTA, 2017) traffic is considered to one of the most harmful environmental stressors in Europe and therefore traffic related noise is monitored in the EU nations. On areas where noise levels are high, special building regulations are required, such as noise barriers etc.

2.4.4 Wear of road markings

Road marking are optical signs used on pavement to instruct and guide the road users. Typical uses for road markings are travel lane and crosswalk markings. They are often sprayed directly on the surface of the pavement, although in order to achieve thicker layer of paint, the pavement is sometimes grooved. Studded tires and winter road maintenance (snowplows) cause significant amount of wear on road markings, as the paint material is considerably softer than the hard metal materials used in tire studs and the blades on snowplows (Pasanen, 2012).

2.4.5 Particulate emissions and road dust

Stud impact on the road surface causes material to remove from the pavement and creates dust. The dust is spread into the air by the traffic and may be an issue on densely populated areas, such as cities. This issue is greatest during springtime, as much of the dust particles accumulated in the snow and on the street are released into the air when the streets are swept. The particulate matter (PM) in the dust is hazardous to humans according to various studies. Particulate matter is often divided to two categories depending on the particulate size. PM_{10} is for particulates, which are smaller than 10 μm in diameter, and $PM_{2.5}$ for, smaller than 2.5 μm. Both PM_{10} and $PM_{2.5}$ are small enough so they can enter the human lungs and thus can cause respiratory deceases (Caiazzo et al., 2013).

In Norway, the coastal cities are often located between the Atlantic ocean and mountain slopes where the temperature during winter often goes above and under 0°C resulting in poor driving conditions. Furthermore, the geographic location of these cities may even cause smog as the air is clogged in the valleys. Therefore, Norway has had an environmental point of view towards studded tire use since the 1990's. To limit the percentage of studded tires in cities, a fee has been charged for vehicles equipped with studded tires. Similar to Norway, some studded tire restrictions have been implemented in Sweden as well. However, the restrictions are implemented mainly in some city centers and individual streets.

2.5 Legislation on studded tires

As the commercially manufactured studded tires became available for the consumers and become more common in winter traffic, the concerns for their road wearing effect started to arise. First regulations regarding the properties of the studs quickly took place in Finland, as Finland was one of the first countries to have significant levels of studded tires in the winter traffic. When regulations are being prepared, the subject at hand needs to be investigated and researched and therefore Finland has been the pioneer in studded tire research.

2.5.1 History of studded tire road wear testing in Finland

In the early 1980´s, there was a demand for a new type of road wear test of studded tires. All the previous test tracks and laboratory equipment had limits regarding to vehicle and tire properties. VTT Technical Research Centre of Finland started to test various new methods for measuring and researching the stud-road interaction. Stud-surface contact was studied by investigating stud marks on different stone and metal plates. The stud marks ans scratches were clearly visible on the metallic plates, but due to the ductile properties, there was no material loss. On stone samples, the issue was with the brittle nature of the material that causes cracks. This problem can be solved however by selecting a more suitable stone type. (Unhola 2015)

While the road material does not consist of only stone, is stone the single most important factor affecting the road wear properties of the pavement material. (Liikennevirasto, ASTO) As the pavement is typically asphalt, would asphalt make the ideal material for testing the road wear. However, in order to achieve reliable, comparable and repeatable results, the test material needs to be consistent. Thus, a stone of certain type can be justifiable used as a test specimen material.

The over-run test became under development in 1985 in VTT Road Laboratory, as a simple test measuring the weight-loss of the material was required. The task is challenging as the amount of material removed in one stud contact is measured in micrograms (µg) and therefore several repetitions are required. It was noticed that watering the test specimen increases road wear by a factor of 1.5–3 and evens out the variance caused by test conditions.

The manufacturing of a “standard” asphalt is difficult, but moreover it is impossible to get the asphalt to same state before and after the weighing, as material is removed from the asphalt during the drying process. Kuru grey granite was chosen as the most suitable test specimen material due to its mineral composition, uniform grain structure and being one of the most homogenous stone types found in Finland. Other stone types were also tested e.g. in ASTO-project between 1987–1992, where 12 different stones and their wear against studded tires were tested on a real pavement. Kuru grey had moderate road wear properties compared to the most common stone types used in the pavements, and is not commonly used as a asphalt material in Finland. However, its homogenous mineral structure and even quality within the different mines made it suitable for testing purposes. (Unhola, 2015)

The first test setups consisted of cylindrical test specimens that were attached on a rubber plate. The cylindrical stone specimens were however inconvenient to set up to the base and would also crack easily during the test. In 1996, a new test stone specimen was introduced, that was sawed from the top. The top part of the stone is grid/crisscross shaped which forms knobs, which resemble the typical grain in an asphalt and where the minerals of the stone are evenly divided. The shape and measurements of the stone can be seen in figure 2.

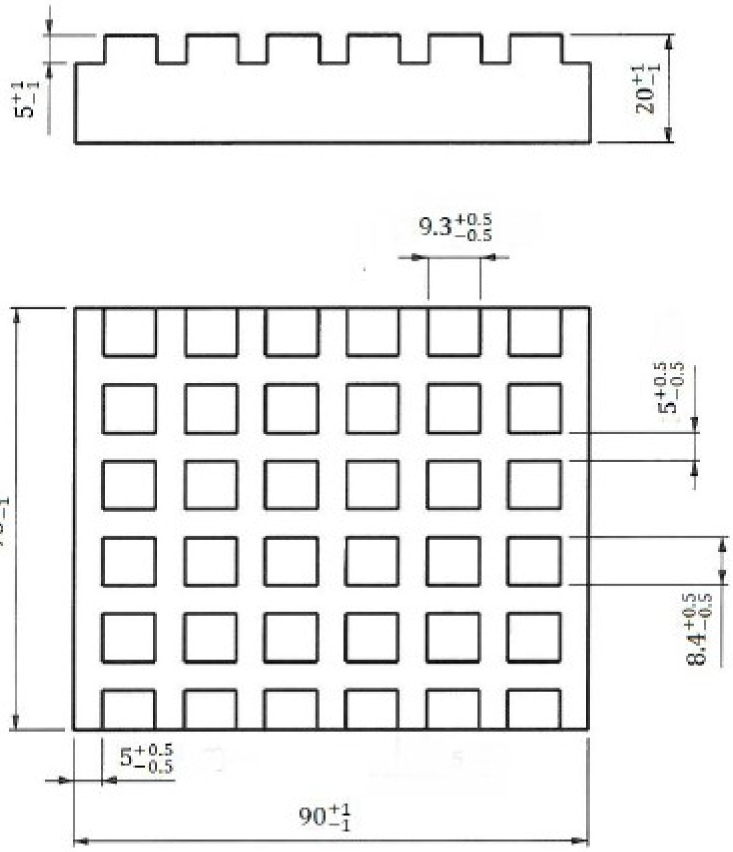

Figure 2. Test stone shape and measurements (Trafi, 2013)

2.5.2 History of regulatory measures for studded tires

The over-run test method was developed originally for research and development purposes. As the winter tire technology improved greatly in the 1990-2000's and the passenger car tire width and profile changed concurrently, the tire industry and authorities began to investigate methods to improve the legislation of studded tires. To reduce road wear and ecological impact of studded tire use, the systematic development of legislation regarding studded tire properties began in Finland in the 1980's. At first, only the stud amount, protrusion and impact force was limited. The extensive research in the 1980's lead to the conclusion that stud weight and driving speed had a major impact on road wear and the stud weight limits were introduced. The limit values were tightened on every few years and by the early 2000´s the maximum allowed stud weight had dropped from 2.0 grams to 1.1 grams resulting to 45 percent less road wear. (Unhola, 2004)

Between 2006–2008 the need for revising the type approval regulations of studded tires were studied as a cooperation between The Technical Research Centre of Finland (VTT), The Ministry for Transport and Communications (LVM) and Finnish Vehicle Administration (AKE, later Trafi and Traficom). The main goal of the study was to investigate how the vehicle and tire development and increased traffic volumes effected the type approval requirements for studded tires. The secondary goal was to reduce road wear without compromising traffic safety. The study proposed three modifications to the regulation:

- The maximum amount of studs per tire should not be tied on the diameter of the rim, but the rolling circumference of the tire
- The rule of not allowing studs on the 1/3 centermost part of the tire should be deleted
- Any kind of studded tire should be possible to approve for road use, if it can be proven that that tire does not cause more road wear than a tire approved according to the regulations

The second proposal was due to the reason that at the time it was required that no studs should be placed on the centermost 1/3 of the tire tread (so-called 1/3 rule). This was based on research conducted in the 1970´s on a test track. The study showed that the centermost studs have higher impact force than those placed on the sides of the tread and would therefore cause more road wear. By the 1990's the tire size, especially the profile had changed considerably to that of the 1970´s and the validity of 1/3 rule was questioned. A series of over-run tests were conducted in 2008 in order to determine if the 1/3 rule was necessary. The results suggested that actually the centermost studs had the smallest road wear and it was suggested that the 1/3 rule should be renounced. (Unhola, 2008)

The third proposal was suggested to provide the tire manufacturers more research and development possibilities, as the earlier relatively strict stud regulations limited stud and stud-tire combination possibilities considerably. The study proposed that the over-run test should be used in order to verify that the specific tire does not cause more road wear than a tire approved according to the regulations.

2.5.3 Over-run test method & legislation

The regulations for type approval and regulations for studded tires are set in the Decree of the Ministry of Transport and Communications on Tyre Studs 408/2003, last amended 466/2009.

In subsection 1 of the section 3 of the decree states that the studs used in the studded tire should be of an approved type and that the approval is granted by the Finnish Transport and Communications Agency, Traficom. Subsection 2 determines the preconditions for the type approval, which are that protrusion shall be no more than 1.2 mm while a maximum static stud force is 120 N. Weight of the stud designed for a passenger car should not be more than 1.1 grams. In subsection 3, it is stated that Traficom may approve any kind of studded tire "provided that such a tire does not wear the road surface more than a studded tire complying with the regulations laid down in section 2 as well as section 3, subsections 1 and 2 of this decree."

The road wear of such a tire is verified in the over-run test method. The test method is verified and monitored by Traficom, but the tests are conducted by the recognized experts. Purpose of the over-run test is to measure the road wear of a real studded tire in a real-life type of an environment. Vehicle specifications and the test conditions are defined loosely, as the test is conducted in an ambient environment o, real car(s). The test provides a wear result in grams after driving over 15 test stone specimens 200 times resulting 400 tire over runs. Speed during the impact is 100 km/h on a passenger car and 80 km/h on a van and lightweight truck. Test stone assembly on the test track is shown in figure 3.

Figure 3. The standardized way of setting the test stones. The 15 test stone samples placed on the metal test frame that is bolted onto the test track. The rubber bars on the sides with the red markings help the test driver to hit the frame.

Simplified over-run test method according to Traficom approved regulation is as follows:

1. Selecting the test stones to be used in the test (total of 20, 15 for over runs, 5 for reference) and checking that their measurements are within tolerance. Each test sample is individually numbered.
2. Cleaning the test stone specimen with a plastic brush applying tap water. Excess water is removed using compressed air.
3. Drying the samples in an oven at 110 °C for a total time of 72 hours
4. Cooling the samples 120 minutes in chamber where humidity must be less than 10 %
5. Weighing of the samples on a scale with and accuracy of 0.001 g

6. Installing the samples on a metal frame with rubber separators. The height difference of the stones is compensated with shim plates. Test samples are tightened to the frame to keep them in place during the test.
7. Preparing the test tires and vehicle. The stud protrusion is measured before and after the test from 20 consecutive studs of every tire. The car must be loaded and weighed accordingly. Tires must be installed on standard rims specified by ETRTO.
8. Preparing the test track; installing the metal frame with the test samples on its place in the track and maintaining a comprised 100–150 l/h water flow over the test samples. Five reference stones are kept underwater during the test and kept near the test location.
9. Driving over the test samples 200 times. Driving is done from both directions. Accelerations shall be smooth. Atmospheric temperature during the test must be 2–25 °C during the test. The test driver is changed during halfway of the test.
10. Test samples are packed and phases 2–5 repeated.
11. The road wear result (g) is calculated taking the average of the total wear of the stones in a single row.
12. Reference correction
13. Limit values in the over test based on the load rate of the tire:
    - 0.9g (<600kg)
    - 1.1g (600–800kg)
    - 1.4g (>800kg)
    - 1.8g (C)

The over-run test method was accepted as a national standard by the Finnish Standards Association SFS in 2018 by the name “Road wear test of studded tyres” SFS 7503:2018:en. The standard describes the testing method similarly to the above listed description, but it does not include any reference values for e.g. road wear.

3 Research on road wear caused by studded tires

3.1 The road wear mechanism of studded tires

Tire-road contact is a challenging research topic due to multiple reasons. Firstly, the grip between the tire and the road surface is based on friction, which is not yet solidly understood as a physical phenomenon. Secondly, the tire impact on road surface is a challenging contact to monitor visually as both tire and pavement materials are non-transparent. Furthermore, the pavement material is typically rough and uneven and the tire material soft, so the tire presses into the pavement. Due to these reasons, even the true contact area in the tire-road contact is challenging to estimate, which makes the tire related friction calculations difficult.

The tire industry is global and currently a very large industry and business, therefore it is also a topic of extensive research. However, studded tires only counts for a small portion of that business and its market is confined to only few countries. Due to that reason and the reason mentioned before, there are only few large-scale studies related to studded tires, and much of the information is based on few known and recognized models.

Lampinen (1993) did extensive research for VTT in the 1990's on pavement rutting caused by studded tires. He studied the stud-road impact on test tracks and observed that the impact can be divided to four stages:

1. Dynamic first impact
2. Dynamic stud force
3. Adhesion
4. Snap-out during exit of the stud

The impact force is based on kinetic energy, which is transformed from the stud to the pavement material. Kinetic energy formula is:

$$E = \frac{1}{2} \cdot m \cdot v^2 \qquad (1)$$

where m is the mass of the stud and v is the horizontal velocity of the stud as it impacts the surface of the pavement.

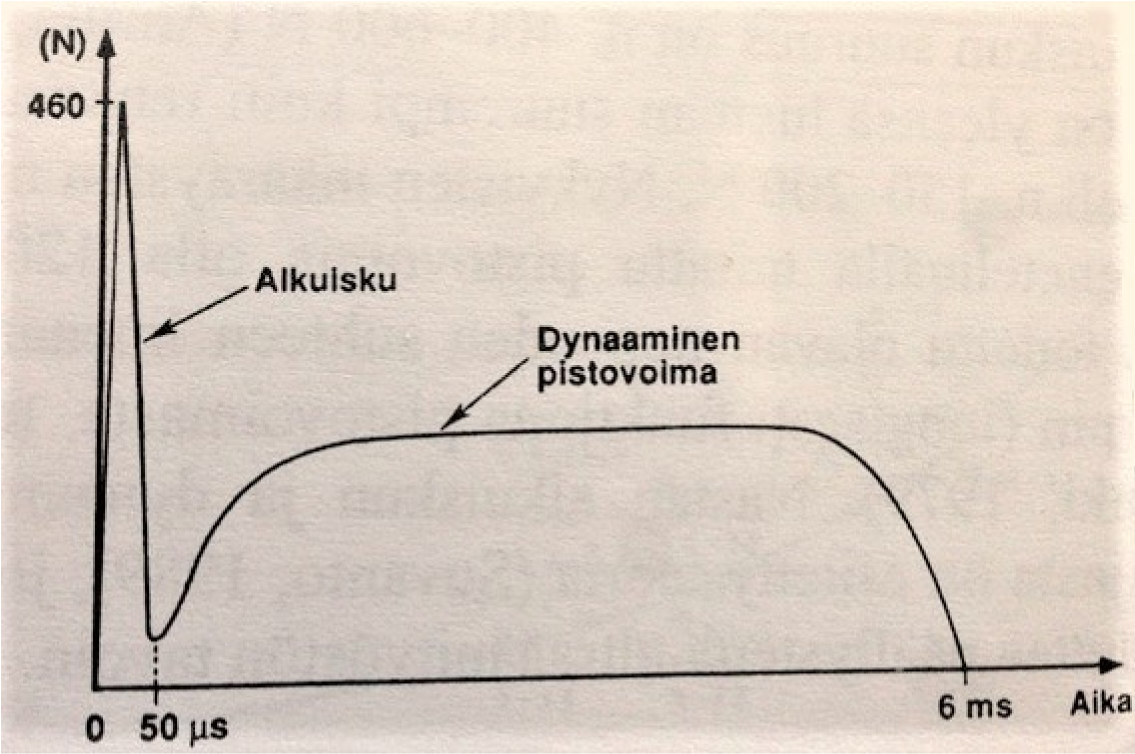

Figure 4. The dynamic impact force as a function of time. The peak before 50 µs is the first impact. After that the dynamic stud force remains constant until the contact ends. (Lampinen. 1993)

As seen on the figure 4, the impact force reaches near zero N at the end of the impact. After the impact the force transform to dynamic stud force and remains constant until the stud is removed from the surface.

According to Lampinen, the adhesion stage is section of the wearing process where the stud's horizontal movement on the pavement surface causes the surface to crack and results in minor material loss. The duration of the adhesion depends on geometry between the tire and road surface as well as the slip related changes in the state of motion (e.g. braking, acceleration, turning). During braking, the wear can be up to 2.8-times higher than during steady driving, due to the longer duration of the adhesion.

The snap-out at the end of the impact results from the discharge of the forces between the stud and the road surface as the stud comes apart from the pavement. The effect of the snap-out is considered irrelevant considering the total road wear during the process. (Lampinen, 1993)

Lampinen's studies are based on the tire and stud technology if the 1990's after which especially the tire profile and width have changed resulting in significant changed in the tire contact area shape and size. Therefore, the results are not entirely comparable to the studded tires of today. However, the study shows that the process of the stud impact is occurs in multiple stages, which is still relevant result today.

Gültlinger et al. (2014) conducted similar research to Lampinen in Karlsruhe Institute of Technology, and also identified the multi-stage process of the impact. However, compared to Lampinen´s four stages they distinguished six different sections as seen in figure 5. According to them, there are three main phases: impact, contact and snap-out. Contact can be divided into four individual stages. Similarly to Unhola, they suggest the contact is the most important stage regarding the road wear.

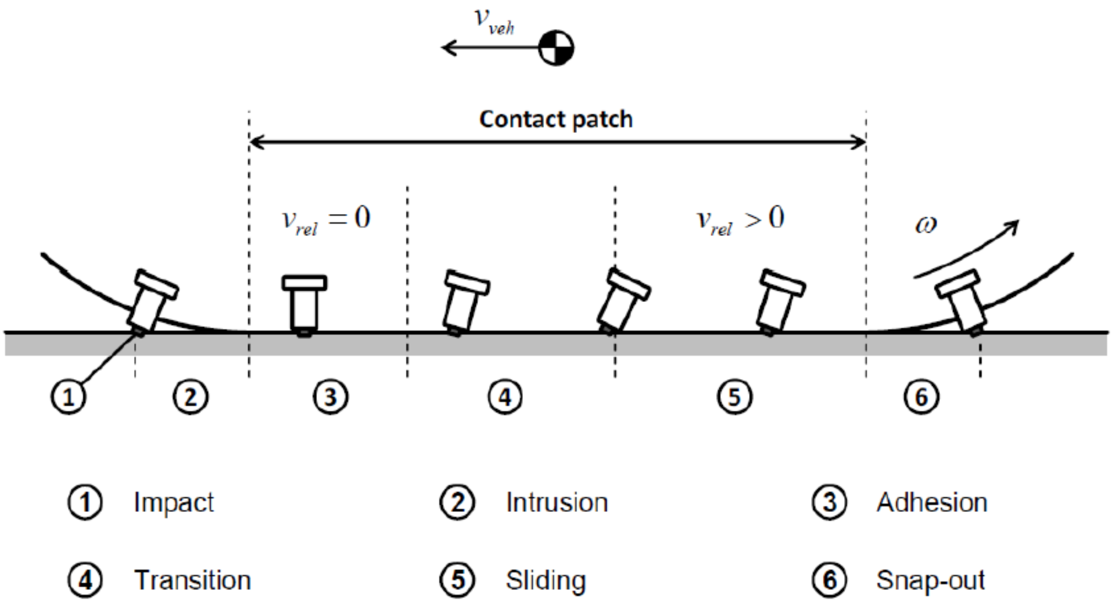

Figure 5. The six stages of the stud-road impact according (Gültlinger, 2014)

3.2 Tire related factors

Unhola (2004) has studied how the different tire properties effect the road wear caused by studded tires. He noticed that especially the tire profile had a significant impact; the wear decreases 10% when the profile is 0.1 lower. This is due to the fact that a tire with smaller profile has relatively stiffer sidewall and the length of the contact phase is shorter and the studs cause less adhesion. Figure 6 shows how the tire contact area varies within two different tire profiles.

Figure 6. The effect of different tire profiles on the shape and size of the contact area. (Unhola, 2004)

Whereas lowering the tire profile stiffens the sidewall of the tire and decreases road wear, Unhola (2004) noticed that increasing tire pressure (which also stiffens the tire) increases road wear. In his research, the increasing pressure from 220 to 230 kPa increased wear by 3.6 %. Increasing the tire pressure decreases the contact area, which results in higher surface pressure, thus the vertical forces between the pavement and the stud are higher. The over-run task force (2018) also studied the effect on tire pressure and discovered that increasing the pressure from 200 kPa to 250 kPa caused 20 % increase in road wear. They also noted that lower tire pressure increases the rolling resistance and thus the tire temperature, further decreasing the stud force.

3.3 Vehicle related factors

Unhola (2004) studied the effect of vehicle weight to road wear. The test was conducted using the same type of vehicle with 2 masses, unladen (1230 kg) and loaded (1644 kg) while driving at 80 km/h. Tire pressure was not changed. The result was that the wear increases in the similar percentage as the vehicle mass is increased; 1200 to 1300 kg mass increase resulted in 11% higher wear.

The effect of vehicle speed to road wear has been studied in various research (Unhola, 1997 & 2004, Kupiainen et al. 2003, Heikkinen, 2012) and even though the studies suggests that higher speed equals higher wear, the results are not unambiguous. Unhola suggests that the wear rate increases drastically above 100 km/h due to the increased impact force and is at its minimum between 50–80 km/h. Kupiainen et al. suggest that the road wear increases linearly as a function of speed. Heikkinen studied the road wear at urban speeds and observed that studded tires have insignificant effect on road wear at speeds below 60 km/h. The over-run task force (2018) also studied the influence of speed to road wear by using speeds of 50 km/h and 100 km/h in an over-run test. While the results show that the wear on the test stones at 50 km/h was lower, the effect is not linear. Similar to Unhola, it was observed that at high speeds, the impact of the stud is dominating factor. Thus, it could be possible that the behavior of the road wear may be different in urban and highway speeds.

As the over-run test is conducted on a normal passenger vehicle, the propulsion system / drivetrain of the vehicle may have an impact. Currently, all types of drivetrain options are allowed to be used in the test (4WD, FWD & RWD). The over-run test description recommends maintaining driving speed while driving over the test stones and therefore small amount of force is applied to the driving wheels during the tire impact on the test stones. The over-run task force studied the effect of drivetrain on road wear using a 4WD vehicle, which could be converted easily to either FWD or RWD propulsion as well. The highest wear resulted with FWD configuration, as seen in figure 7.

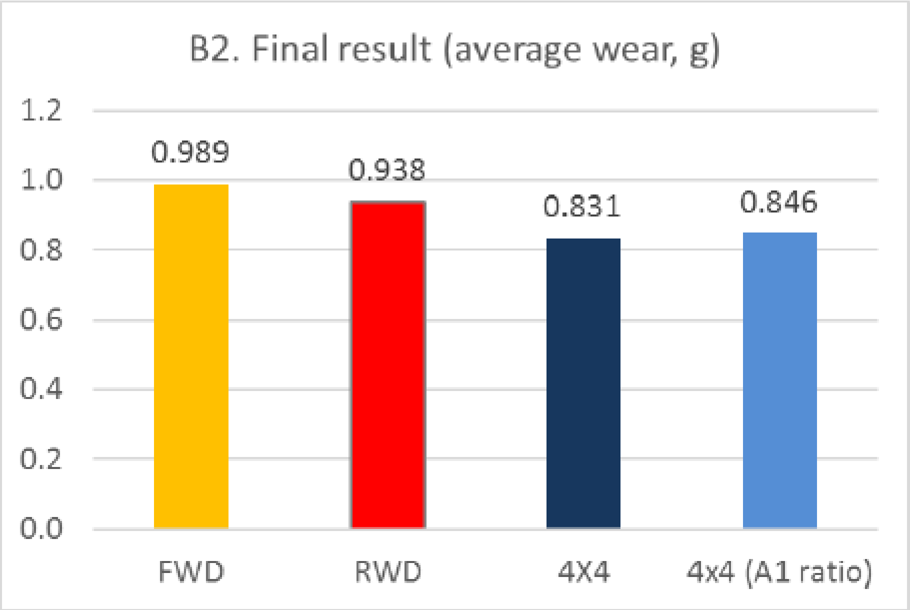

Figure 7. Road wear during over-run test on different drivetrain configurations. Task Force (2018)

3.4 Stud related factors

3.4.1 Stud mass

The impact of stud weight on road wear was first proven in VTT Technology Research Centre Finland in 1986 using an earlier version of the over-run test with cylindrical test stones. During that time, the typical stud weighed 2.3 grams. Four different weight studs were used in the test, heaviest being 4 g and lightest 1 g. Study shows that test stone material wear was 53–64 % smaller on 1 g studs compared to the typical 2.3 g studs. Results of the tests were used to set the maximum weight limit for the studs in the 1990´s. (VTT, 1986)

Kupiainen et al. (2011) researched how stud weight and the amount of studs affected PM10 emissions. The change in PM10 emissions was regarded as a change in the road wear, as no other dust sources should exist during the test other than the pavement. Test was conducted on a test track using NUUSKIJA vehicle, which analyzes the air from behind of its tires. Testing speed was 70–90 km/h. Two different studded tires were used: A tire with 110 studs weighing 1.1 g each and a tire with 55 studs weighing 2.2 g each. Results showed that two lightweight studs (1.1 g) caused less emissions than one heavier (2.2 g) stud. However, doubling the stud weight did not equal two times higher emissions.

Various other studies (VTT, 1987, VTT, 1989 and Gültlinger, 2014) however, suggest that the doubling the stud mass equals double amount of road wear. Furthermore, the VTT studies suggest that the increase of stud mass increases road wear proportionally. Whereas the VTT studies were conducted on the cylindrical test stone specimens, Gültlinger et al. researched the stud mass / road wear correlation using similar test stones that are used in the over-run test today. Although more than 20 years apart and using different test samples, the results were similar: doubling the stud mass increases the road wear by almost double as seen in figure 8.

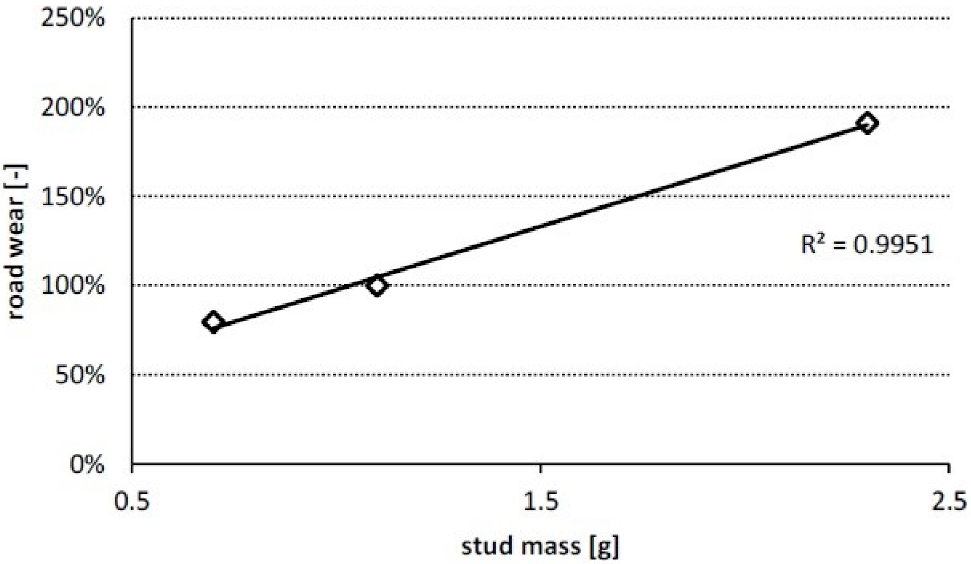

Figure 8. Road wear increases in linear motion to stud mass (Gültlinger, 2014)

3.4.2 Stud protrusion

The effect of stud protrusion has also been studied extensively. Lampinen (1993) suggests that stud protrusion is related to static stud force and the speed of stud impact. He claims that the higher the stud protrusion, the higher the vertical force from stud impact, as the angle between the tread of the tire and the pavement is larger. Results of his studies can be seen in figure 9.

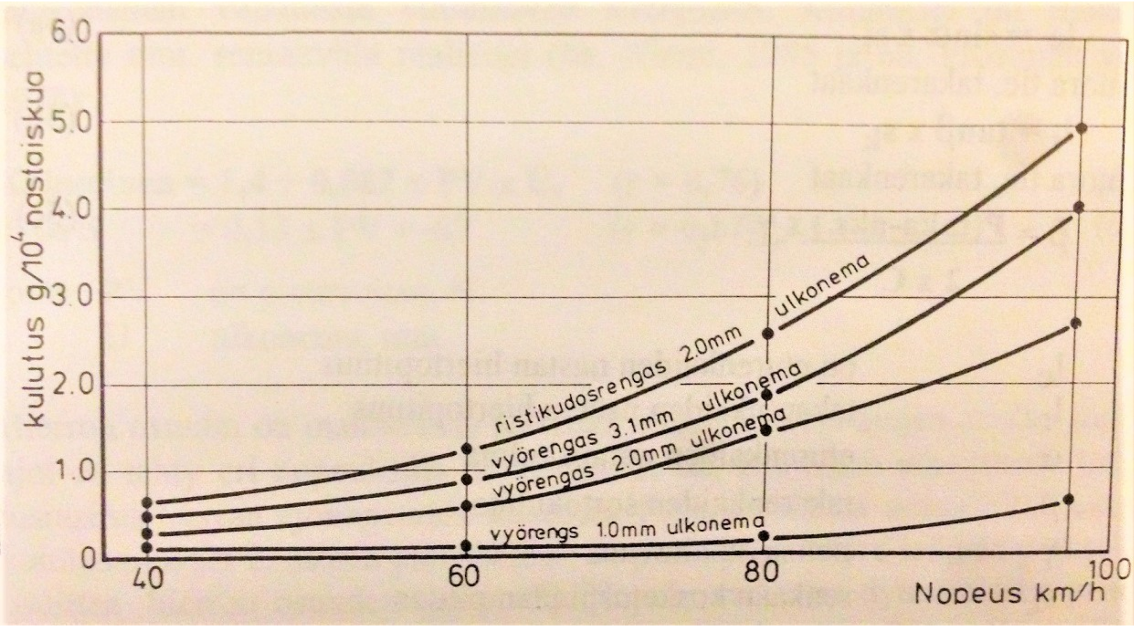

Figure 9. Road wear as a function of speed on different stud protrusions. The upmost curve is a crossply tire others are radials. (Lampinen, 1993)

Unhola (1995 & 1997) also studied the effect and correlation of stud protrusion and stud force. He suggests that the increase of stud protrusion slightly increases road wear, but not in a linear manner. Furthermore, the earlier study showed only 5–9 % increase in road wear when protrusion was increased from 1 mm to 1.5 mm, when in the later study the increase was up to 40 %. The stud taskforce (2018) also comes to the same conclusion that the stud protrusion has a non-linear effect on road wear. One possible scenario to the non-linear effect on road wear could be that as the stud protrusion becomes high enough, the stud force decreases as the stud collapses easier.

3.4.3 Stud force

The stud force was one of the first technical properties of a studded tire that was regulated. The decree on tire studs 408/2003 (last amendment 466/2009) says the maximum allowed stud force for a passenger car tire is 120 N. No maximum limit is set if the tire is type approved with the over-run test method. The study of Kossi and Raatikainen (2019) indicates that the road wear increases in a linear motion to the stud force, as seen in figure 10. One observation made during the research was that the stud force and the amount of studs were inverse on the tires used in the test. The tires with large amount of studs had small stud force and vice versa.

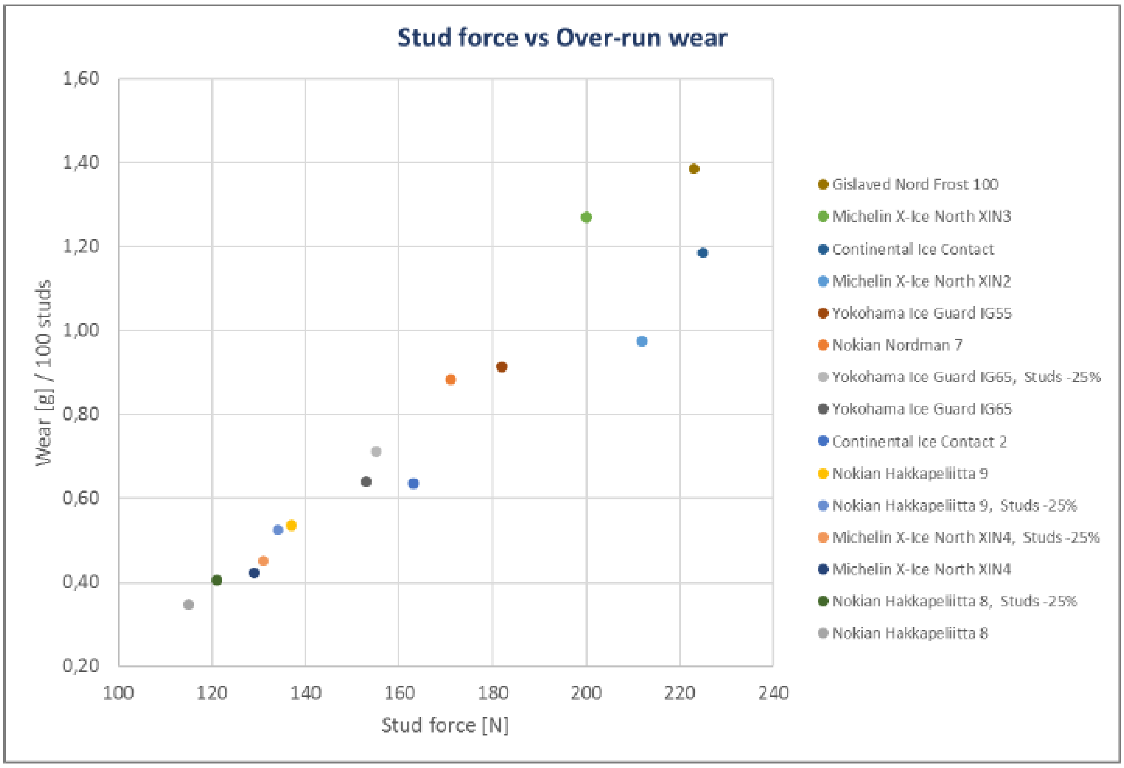

Figure 10. The effect of stud force on road wear (Kossi & Raatikainen, 2019)

3.4.4 Various other factors

Kupiainen et al., (2011) also studied how the stud amount effects road wear. They used 3 different type of tires in their test: non-studded, half-studded (55 studs), and fully studded (110 studs). Result was that on 40 km/h speed the fully studded tire increased wear by a factor of 1.68 and in speeds 70–90 km/h, the wear was 2.79 higher. The research of Gustafsson et al. (2015) and Gültlinger et al. (2014) also shows that increasing stud amount significantly increases road wear.

During the over-run test, the test stones are watered, as the wear caused by studded tires is said to be 1.5–3 times higher on wet pavement (Unhola, 2015). The official test description advices to use water flow of 100–150 l/h, which is very loose definition. However, this is considered to be sufficient to keep the whole test frame wet, but not to have too thick layer of water on it. Having the test stones totally submerged could lead to pressure shocks from tires (Syvänen, 2016).

3.5 Various road wear testing methods

Using the over-run test method as a type approval test for studded tires has made the test probably the most used testing method for measuring the road wear of studded tires. However, many other methods also exist.

3.5.1 Tests in laboratory conditions

Whereas the over-run test method is conducted outdoors and is therefore sort of a field test, some laboratory-based test methods are used as well. In Karlsruhe Institute of Technology (KIT), a large inner drum is used for multipurpose tire testing (see figure 11). As the over-run test method has become more commonly known especially due to its type approval purposes, has KIT started to utilize its drum bench for road wear testing of studded tires as well. The test equipment consists of a drum (1) with a diameter of 3.8 meters and of a hydraulically controlled wheel hub and tire combination (2, 3). The motion of the test wheel can be adjusted and the load is variable. In addition, the wheel can be aligned as in a real car to achieve specific camber and caster angles. The hub measures forces and moments in three directions. The drum is rotated by an electric motor, which is mated to a 16 speed gearbox. The drum can be spun at speeds that correlated to 200 km/h driving speed. The pavement material (4) on the inside surface of the drum can be selected freely and is changeable.

When the test rig is used for researching road wear of studded tire, a test stone samples (5) similar to over-run test can be placed into the pavement. However, only six test stone samples are used (3 per row). Therefore, the absolute road wear is slightly different, as the row wear measured in the over-run test is calculated from 5 test stones. Furthermore, unlike in the Finnish test setup, the stone samples are not dried in an oven at any point, but the mass loss is measured from wet stones (Task force, 2018). The test equipment is placed in a temperature-controlled room in laboratory conditions. The temperature can be set as low as -15 °C allowing the test to be conducted on ice and snow surfaces as well. Additionally, the test frame can be kept dry or watered and the water layer thickness can be altered.

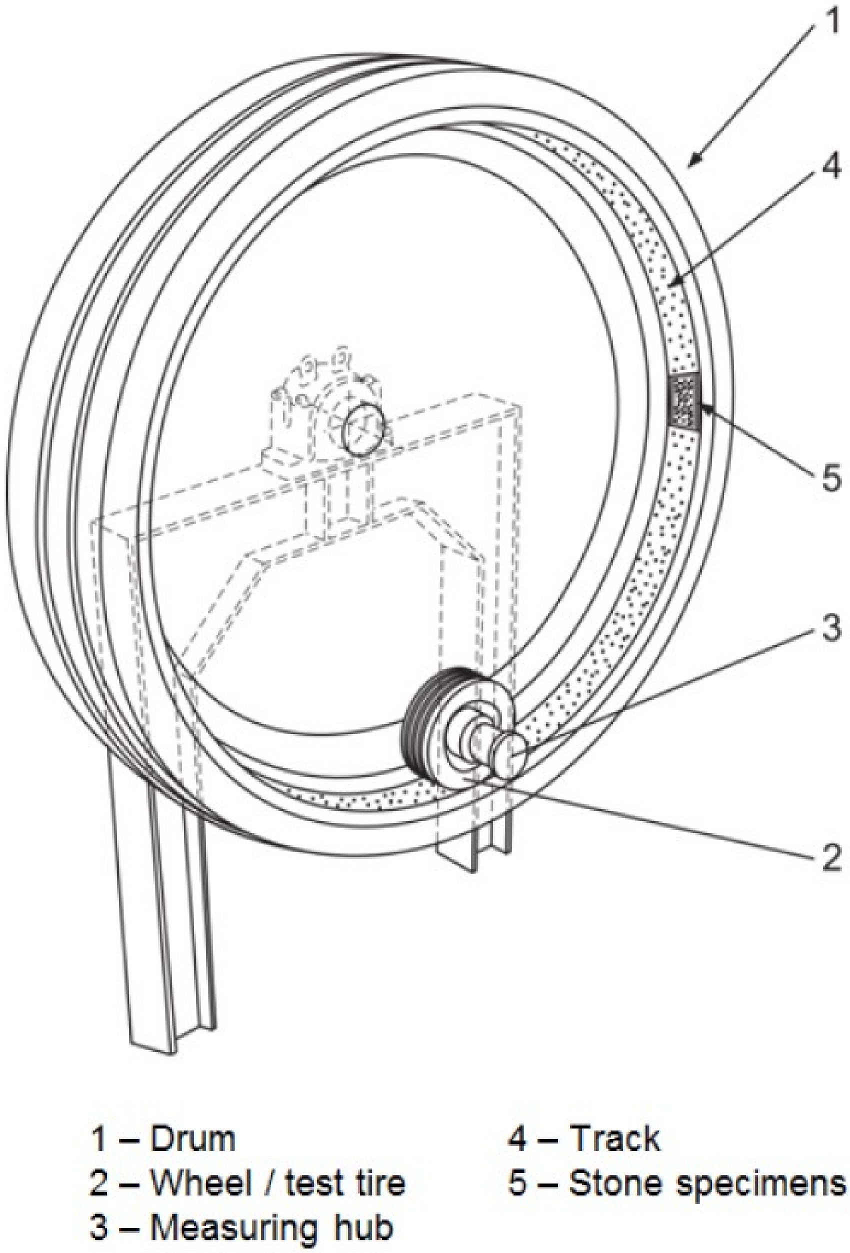

Figure 11. The test equipment used in Karlsruhe Institute of Technology (KIT, 2014)

The Swedish National Road and Transport Research Institute (VTI) has constructed a horizontal, carousel-shaped test track (See figure 12). In the machine, four tires are driven on a round test track. Similarly to KIT test setup, the tire loads and angles can be adjusted. However, due to the vertical structure and round shape of the test track, a lot of turn-slip motion occurs which limits the comparability of the results to over-run test. Furthermore, the maximum driving speed in the machine is 70 km/h, which is 30 km/h less than the testing speed for passenger car tires in the over-run test. The advantage of the setup is however that the distance travelled during the test is significantly lower than that compared to the over-run test with same amount of tire over-runs. Therefore, the carousel is suitable for testing higher number of over-runs or creating results faster. (VTI, 2016)

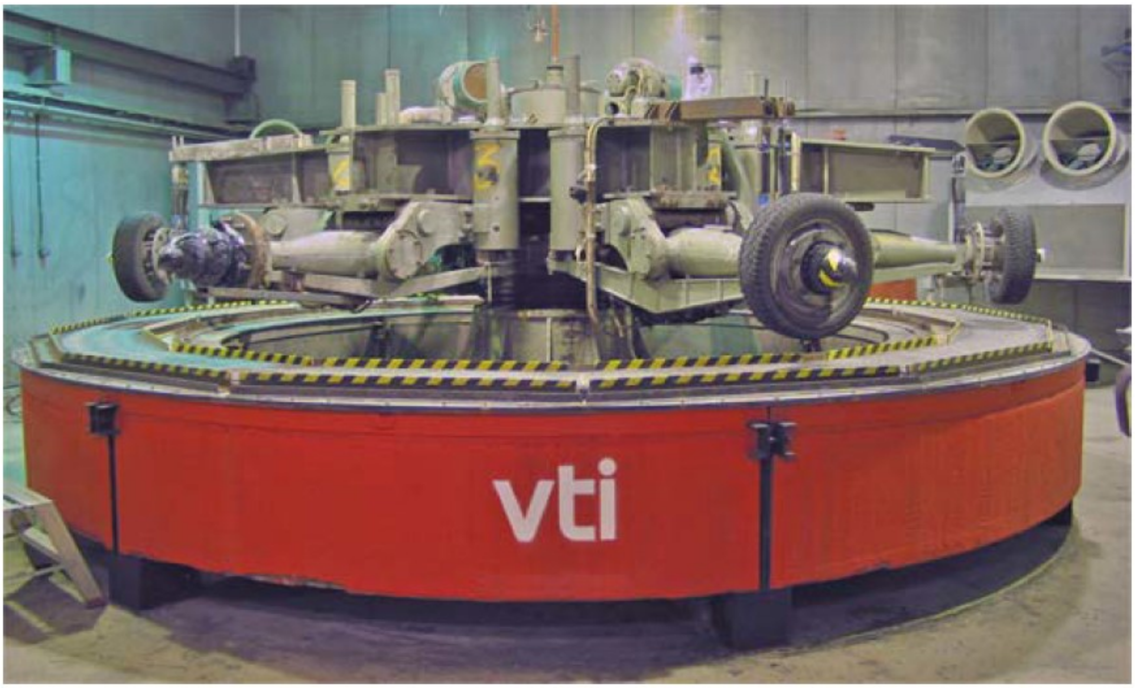

Figure 12. VTI's carousel-shaped tire testing eguipment (VTI, 2009)

In Russia, similar test to the over-run test is used for type approval purposes. The test method is standardized in 2018 by GOST and is thus applied in many countries of Commonwealth of Independent States (CIS). The standard has some different technical differences, but the principles remain the same. Even Kuru Grey granite is used as test stone material. (GOST 34342-2017)

3.6 Brief analysis on road wear in Finland

Throughout the time that studded tires have been used in the traffic, the issue of their effect on road wear has been discussed. In Finland, the safety benefits of studded tires have been seen to overcome the issue of road wear and other problems related to their use e.g. dust and PM_{10} generation. However, the effect of these issues have been reduced by various regulations and improving the pavements road wear properties.

Yle, the Finnish public broadcasting company published an article "Studs are grooving the pavement on a record pace" in 2016, stating that the level of grooving on high traffic volume roads has increased. According to the article, the grooving between 2008–2011 was 2 mm per year and was increased to 2.5 mm per year in 2011–2015. The grooving rates are shown in figure 13. The article refers to the over-run test as "exceptional procedure" in the decree on tire studs. According to it, tires approved by over-run test have become general in the traffic since 2011. However, the first type approval where the stud-tire combination was tested using over-run test method was granted already in 2006 for Nokian Hakkapeliitta 5 (Traficom). Notable is however, that there was an increase in the number of new studded tire type approvals granted in 2012: whereas 9 new stud and stud/tire combination type approvals were granted between 2000–2011, the number was 15 in 2012 alone (Traficom).

The article also notes that the amount of studs per tire has increased after the over-run test was began to implement as a type approval test. However, the stud amount on tires type approved using over-run test before 2013 was not significantly different from tires fitted with universal studs (limit 50 studs per rolling circumference meter). The first tire with considerably different amount of studs was Nokian Hakkapeliitta 8, which has 96 studs per rolling circumference meter (total of 190 studs per tire) in size 205/55 R16 (Traficom). Hakkapeliitta 8 was introduced in 2013.

Figure 13 shows a relatively significant increase in annual grooving depth in 2011–2012, after which the rate has remained higher than previous years. The increase cannot be solidly pointed on studded tires, as no major difference has occurred in the legislation or tire properties during that period of time. Additionally, the lifespan of a tire is several years, so a new tire model will probably not count for major percentage of the whole amount of studded tires in the traffic. As studded tires do cause road wear, they are potentially related to the increased grooving, but the changes in studded tire properties would be seen on a much longer period, as it takes years before all tires on the road are renewed.

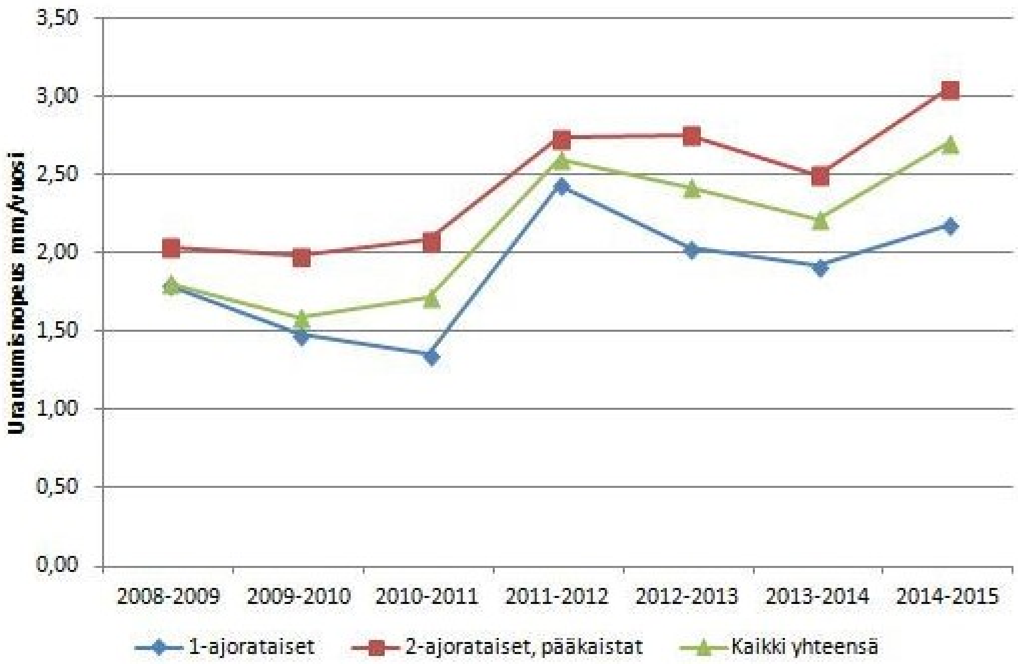

Figure 13. Amount of pavement grooving on high traffic volume roads in Finland 2008–2015. (FTA, 2016)

4 Various viewpoints regarding restrictions on studded tires

The use of studded tires is permitted due to the reason that the safety benefits are seen to overcome the issues they cause. Whereas the safety benefits are unambiguous (better ice performance), the issues are complex and challenging to attest. None of the issues discussed in this paper can be exclusively limited to studded tire use, but are typically caused by several factors, typically related to winter road maintenance. The defense and accusations regarding studded tires depend on the individual interests of the stakeholder. Therefore, the public discussion regarding studded tire restrictions lacks consensus. This section briefly introduces the stakeholders related to studded tires and evaluates their agenda on the subject of studded tire use.

List of key stakeholders:

- Tire manufacturers
- Stud manufacturers
- Cities
- Government officials (agencies)
- Public and private road administrations

Tire manufacturers often operate on a global market. As studded tires are used in few countries, the sale of studded tires is relatively small compared to total passenger car tires sold annually. Most manufacturers also produce various types of studless tires, which competes on the same customer base. Therefore, it could be argued that even if studded tires were to be banned, the manufacturers would already have a substitute product to offer. However, some manufacturers have specialized in winter tire technologies and studded tires constitutes for an important part of their business. For example, winter tires counted for 67% of total sales for Nokian Tyres in 2016 (Nokian Tyres, 2016).

Whereas tire manufacturers hypothetically have a substitute product for studded tires (studless tires), the business of stud manufacturers is dependent on studded tire markets. Therefore, it is in their interest to promote studded tire use in a sustainable way. Requirements on road wear test and restrictions on stud properties and stud amount compels the stud manufacturers to develop their products and to innovate new solutions that are potentially less harmful to the pavement and the environment.

In essence, the road wear caused by studded tires is a two-sided issue. In cities, the biggest concern is the material that is removed from the pavement causing dust and PM_{10} particles and therefore causing health issues, whereas on the highways and sparsely populated areas the grooving and rutting is the main issue, mainly due to the need of renewing the pavement. Additionally, as mentioned in section 3.2, it is possible that the road wear behavior may be different at highway speeds.

The air pollutant levels in the Helsinki metropolitan area occasionally exceed the threshold values and therefore the air quality is being regulated by an environmental law. The air quality is particularly poor during spring due to road dust. The city of Helsinki has investigated the possibilities to reduce the use of studded tires in order to increase the air quality. (The City of Helsinki, 2013)

The renewed Finnish Road Traffic Act 729/2018 will come into effect in 2020. Amongst other additions, the new act entails a traffic sign, which indicates an area where driving on studded tires is prohibited (see figure 14). Similar signs have already been used in Sweden. So far it is not certain where the sign will be applied, but it gives e.g. the cities an opportunity to limit the studded tire use on individual streets or areas where the air quality and/or road wear is an issue.

Figure 14. Traffic sign prohibiting the use of studded tires introduced in the new Finnish Road Traffic Act 729/2018.

The Ministry of Transport and Communications (LVM) has the jurisdiction to set decrees regarding traffic in Finland. Traficom, part of LVM's administration, complies with the decrees and is authorized to provide more detailed decrees based on them. One of Traficom's responsibilities is to improve transportation safety and to reduce traffic related emissions. Traficom actively participates and follows the research and discussion of various road safety topics, such as studded tires. Studded tires improve safety on icy surfaces. However, the grooving and rutting of the road causes increased risk of aquaplaning and loss of control. Therefore, it is also a benefit for Traficom to limit the road wear caused bt studded tires in order to improve traffic safety.

The Finnish Transport Infrastructure Agency (FTIA, previously Finnish Transport Agency) is responsible for the maintenance of the state-owned road network and systems in Finland. FTIA's annual budget for road network in 2017 was 1042.2 million Euros, which counts for more than 60 percent of their total annual budget. (FTIA, 2017) FTIA has noticed, that the grooving rate and surface rut development has been increasing (Malmivuo, 2017). Reducing the road maintenance costs would therefore allow more effective allocation of FTIA's annual budget.

5 Changes in tire, traffic & vehicle properties and markets in Finland

5.1 Motorization in Finland

Passenger cars gained success in Finland during the 1950´s. Concurrently, the Finnish road network was also largely reconstructed and the first highways were built. Before, the majority of the cars were in cities and in southern parts of the country and the road pavement was mostly gravel. Where in the year 1950 there were total of 26 814 passenger vehicles in Finland, the number was already almost seven folded by 1960 with 183 409 vehicles. By 1965 there was one vehicle per 10 capita in Finland. For reference, the same ratio was achieved in the United States already in the year 1923 (FHWA). After the 1960´s, the number of passenger cars in Finland has increased steadily, and by the end of 2017 there were total of 3 422 792 vehicles registered in Finland. 2 720 663 of those vehicles were in traffic use. As can be seen on figure 15, the increase paused shortly in the early 1990´s, presumably due to the economic depression in Finland during that time. (Statistic Finland, 2018)

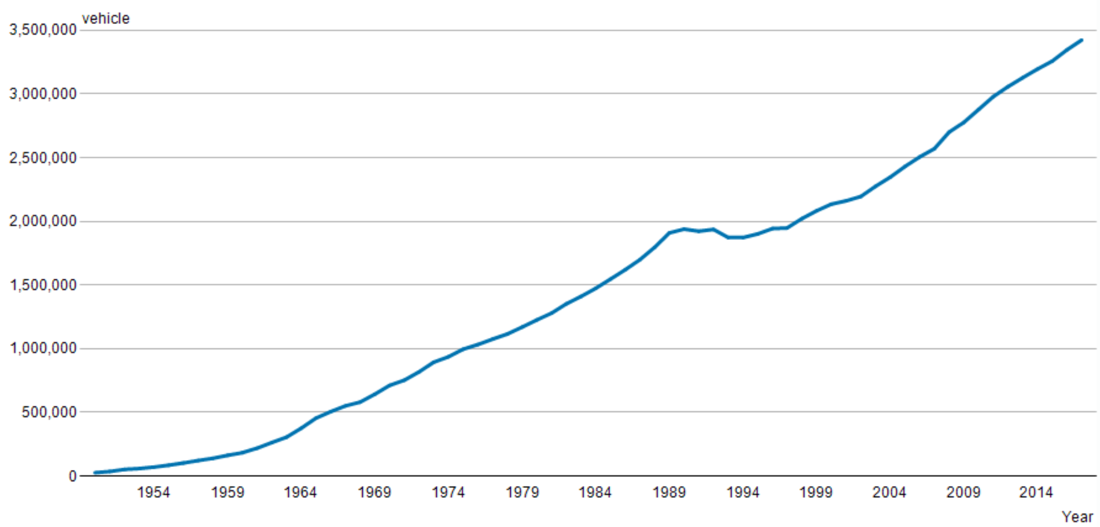

Figure 15. The amount of passenger vehicles (M1) registered in Finland from 1950 to present. (Statistic Finland, 2019)

The road wear caused by studded tires has been a topic of discussion since the studded tires became publicly available. However, first studies on the effect of stud properties on pavement were made in the late 1980's and diverse research on the stud-road impact mechanism started in the 1990´s. The first technical legislative measures were also introduced then, which led to use of lightweight studs (mostly aluminum-bodied), compared to the steel ones used previously (Unhola, 2008). The total amount of vehicles and the total distance driven on vehicles per year has increased significantly in Finland in the last 30 years. Furthermore, the traffic is concentrated on a smaller area, as urbanization increases. Additionally, the vehicle properties (e.g. mass, dimensions, power) and tire dimensions (profile, diameter, width) have changed simultaneously. During this time, the regulations for studded tires and stud properties has been changed twice. To compensate the changes in vehicle & tire properties and traffic performance it may be justifiable to revise the requirements more frequently.

5.2 Traffic, population & environment related changes

Finland is a scarcely populated country, but the level of urbanization is increasing and more and more population is moving towards larger cities in the southern parts of the country. The Finland's center of population moves towards south at a pace of 1 kilometer per year (Yle, 2016). Typically, the population moves from municipalities to the largest cities that already have a relatively high traffic performance (See figure 16). The intercity highways especially in the southern Finland are also heavily trafficked, as are the ring roads of the largest cities. The increasing population and urbanization also increases the transportation of goods, not just passenger traffic. In conclusion, the traffic performance concentrates on a smaller area every year, further worsening the existing traffic levels of those areas.

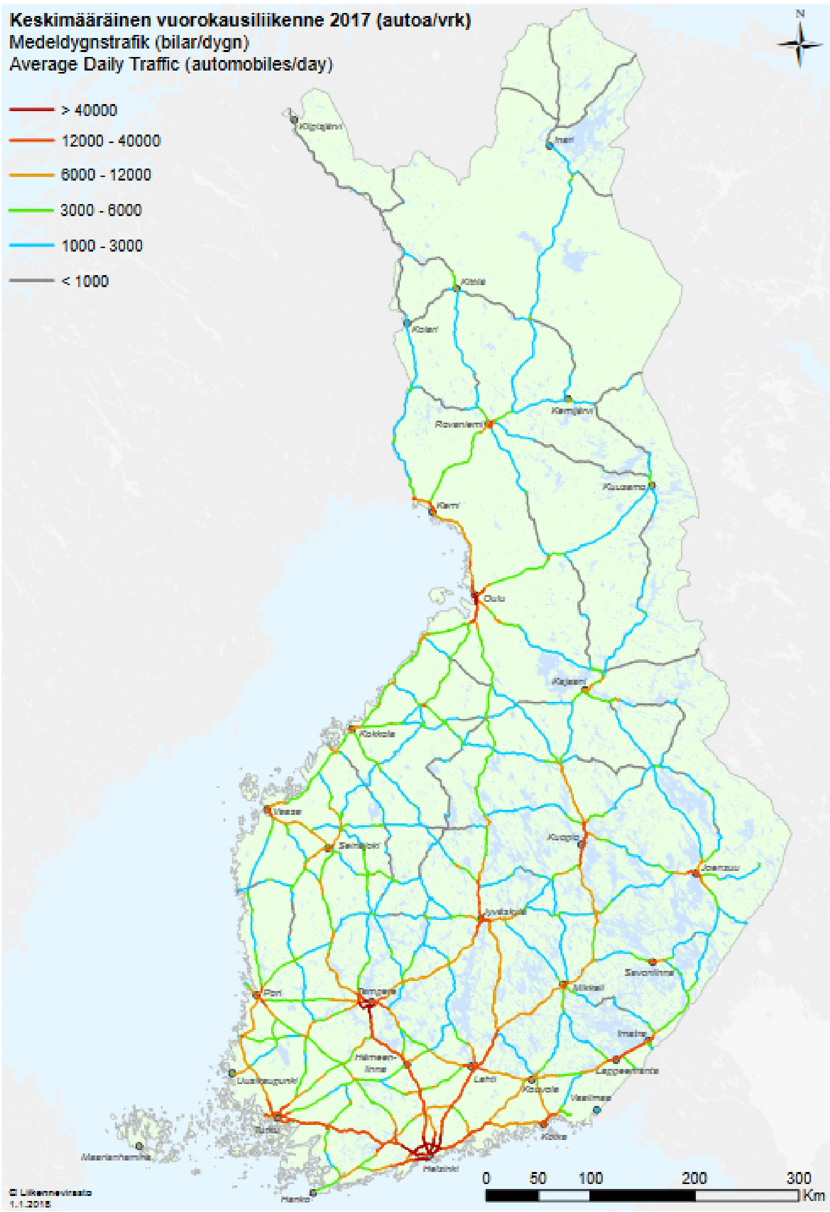

Figure 16. Intensity of average daily traffic is focused on cities, the intercity highways and city ring roads (FTA, 2017)

In the cities, the most discussed problem related to studded tire use is dust generation. Cities have specific threshold values for e.g. breathable particles PM_{10} and $PM_{2.5}$ concentrations. In Helsinki, the total number of threshold crossings is on acceptable level, but the daily threshold values are often exceeded. (Malkki et al., 2018) This is an issue especially during springtime when the road dust problem is at its worst as the roads are snow-free and dry. Additionally, vehicles cause exhaust and noise emissions and take up relatively much space, which is an issue especially in the cities. The city of Helsinki is trying to limit these issues with converting streets to light traffic and public transportation only (Helsinki, 2013) and by creating urban boulevards on most of the incoming highways (Sarjamo, 2017). The renewed Finnish Road Traffic Act in 2020 will give the road keepers e.g. the cities a possibility to limit studded tire usage on specific streets or areas. Therefore, it is possible that studded tire use will be regulated in Finnish cities in the future.

Traffic performance is used to express the total mileage driven on vehicles in a year. Figure 17 shows the development of traffic performance on Finnish highways since the 1980´s. Except for a small decrease in the early 1990's, the traffic performance has increased steadily. From 1983 to 2017, the number has almost doubled from 19818 to 38229 million vehicle-kilometers per year. Thus, not only is the traffic concentrating on smaller parts of the country, but also more and more kilometers are driven on those areas annually.

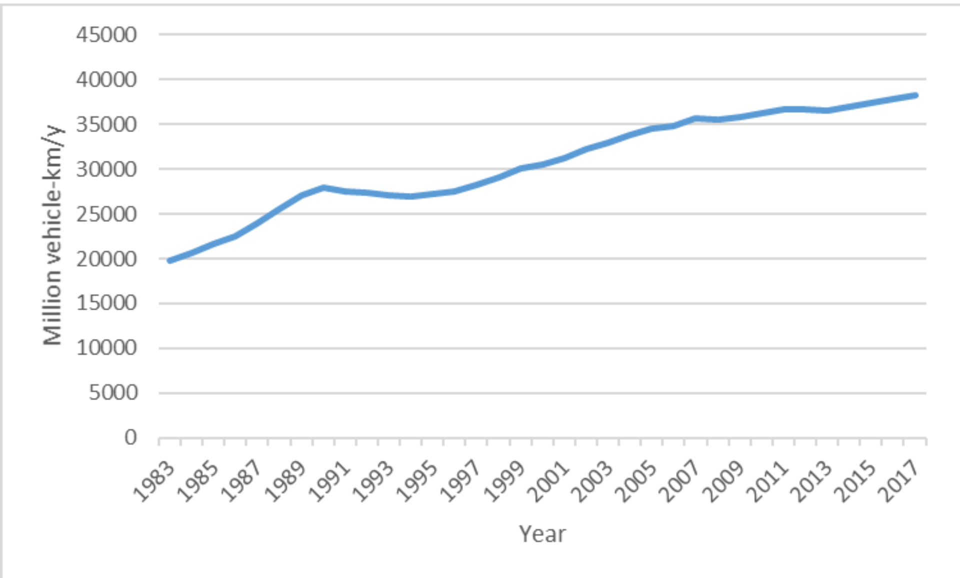

Figure 17. Evolution of traffic performance in Finland (FTA, 2018)

5.3 Vehicle related changes

The previous type approval requirements for studded tires required updating mainly due to the increase in tire load indexes in classes over and under 500 kg by multiple manufacturers. The Ministry of Transport and Communications in 2008 ordered a study on need for revisal of the restrictions concerning studded tires and their type approval. One finding of the study was that the weight of the vehicles in Finland had increased by up to 42 % when comparing vehicles in the B-segment (small cars) in little over 15 years (1989–2006). Furthermore, the study also noted, that where sedan model passenger cars had been the most popular models previously, the market trend was heading towards larger SUV's

(Sport Utility Vehicles), wagons and minivans. Due to increased masses and dimensions of the vehicles, the tires had also become wider, larger in diameter and lower in profile. All of these factors were considered to have a potentially increasing impact on road wear caused by studded tires. The results of the study was used when the decree on tire studs 408/2003 was revised a year later (amendment 466/2009).

As the above mentioned study was released over a decade ago, it is reasonable to investigate how vehicle & tire properties, their markets and traffic performance have developed since then and what is their potential impact on road wear and also safety, especially on icy surfaces.

In comparison to the previously mentioned Unhola´s result of 42 percent increase in B-segment masses from 1989–2006, according to the International Council on Clean Transportation (ICCT), the mass of the B-segment cars in Europe has increased by little over 10 % in 2001–2017. That is similar to the average growth in new car masses in EU in general (see figure 18). Only Nordic country listed in the statistics is Sweden, where the growth has been similar to EU total, thus it can be presumed the increase has been similar in Finland, too. Also noteable are the vehicle masses in Sweden, which is 13% higher than EU average. Although new lightweight material and structures are introduced on new cars, the average mass continues to rise, as vehicles are getting larger in dimensions. (ICCT, 2018)

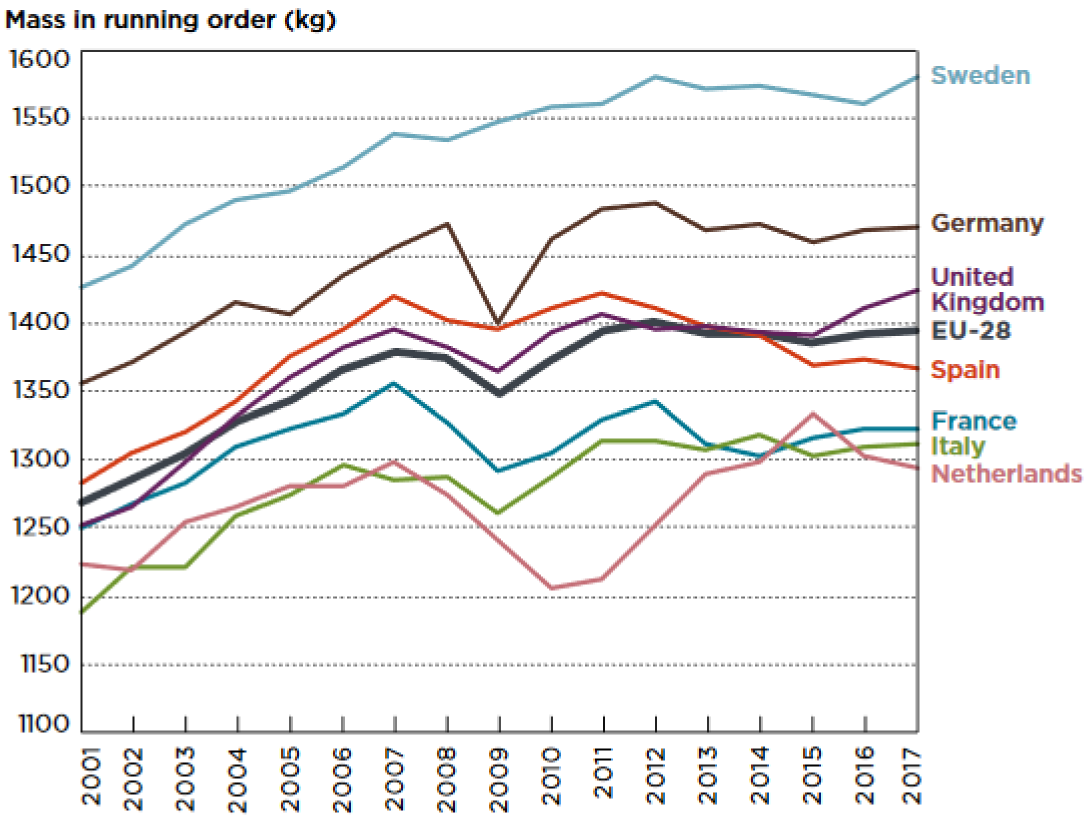

Figure 18. Vehicle masses in running order in different EU states. (ICCT, 2018)

Engine power has a potential impact on road wear as well, as potentially greater forces are applied through the driving wheels and tires and therefore the studs as well. Excess use of power also results in tire slip, which on studded tires means studs are scraping the pavement. Additionally, increased power may have an effect on stud movement in the tire, and can therefore increase the stud protrusion or result in a loose stud. As seen on figure 19, the engine power has increased by nearly 30 % since 2001. Concurrently the engine displacement has decreased by 7 %, so the power output of new engines is higher, and even smaller cars can have potentially powerful engines.

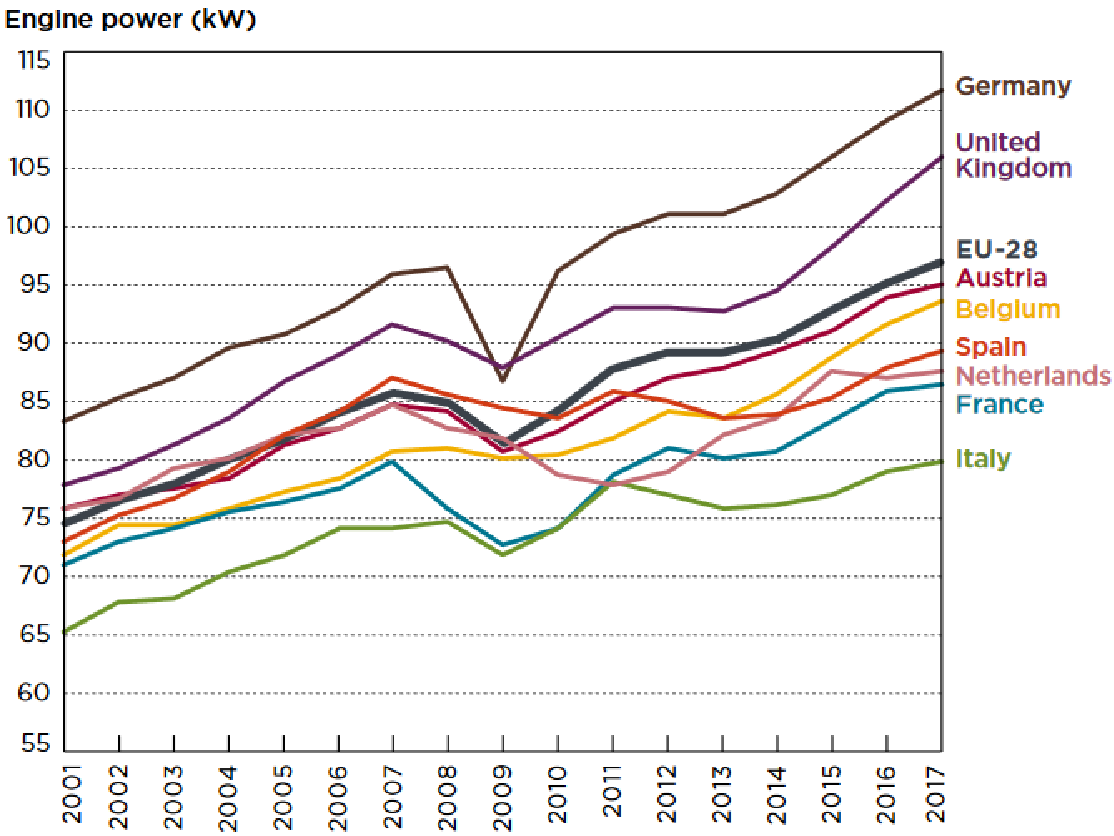

Figure 19. Increase in engine power in the EU states since 2001. (ICCT, 2018)

The vehicle segment trends have also changed considerably, even within the last 10 years. Sedan models have been typically the most sold cars in Finland, but the markets are heading towards larger vehicles, especially sports utility vehicles (SUV). In Finland, SUV was for the first time the most sold passenger vehicle in 2018, as 5540 new Nissan Qashqai's were registered (Traficom, 2019). SUV sales in the EU are more than 6 times higher than 15 years ago (see figure 20). SUV model vehicles are typically larger and considerably heavier than traditional cars and therefore have potentially larger impact on road wear when equipped with studded tires.

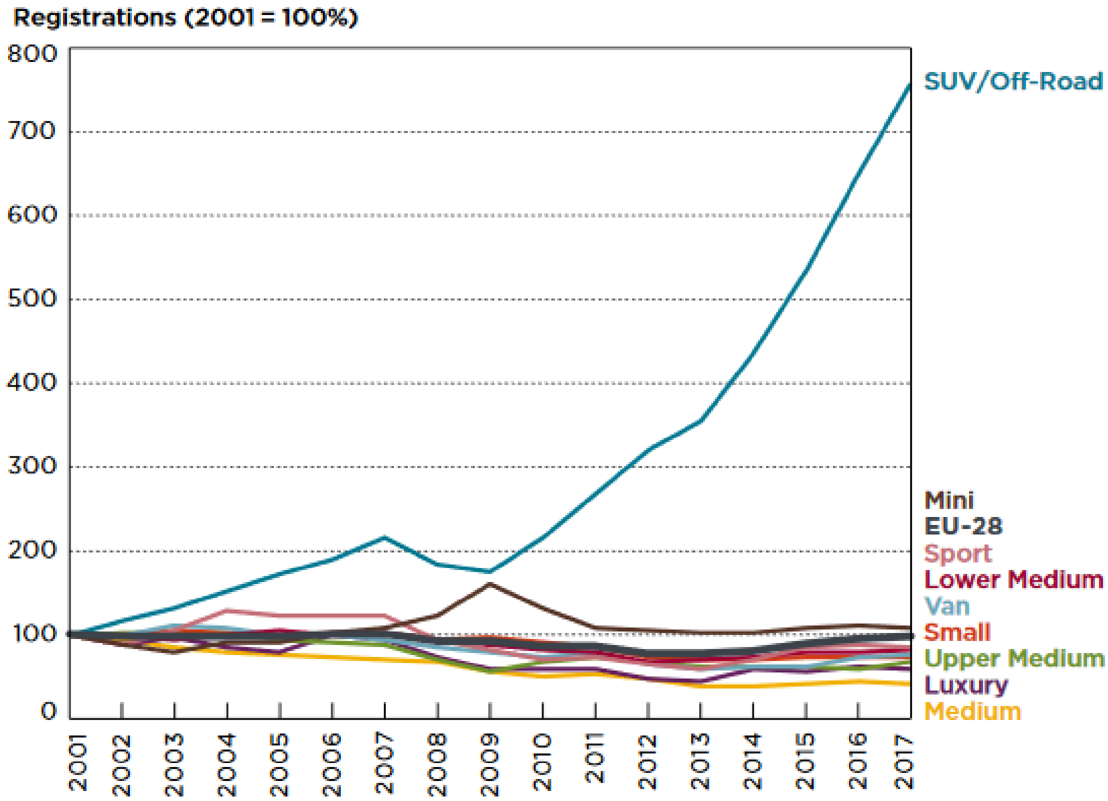

Figure 20. Passenger car registrations per segment since 2001. (ICCT, 2018)

The weight, physical size and the all-terrain properties of the SUV type vehicles also requires special purpose tires, which are often marketed as SUV tires. SUV tires are larger in diameter, wider and often have larger profile. Furthermore, SUV tires typically have higher load index as the SUV vehicles are heavier and have generally better cargo hauling properties. Higher load index tires also have higher road wear limits in the over-run test, i.e. they are allowed to cause more road wear. When the current over-run test road wear limits were originally categorized to different tire load indexes, the most popular new vehicles were different. As the trend towards SUV vehicles continues, the vehicle fleet of Finland continues to grow in weight. Therefore, it is suggested to examine if the higher load index tire wear limits need revising, or if the current categorizing needs updating.

5.4 Change in studded tire / studless tire ratio

In the Nordics, studded tires have been the most popular winter tire type since they became commonly available. The most widely used method for evaluating the proportion of drivers using studless tires and drivers using studded tires has been different sort of surveys. E.g. insurance company If has provided such surveys. In the 2018 survey by If, the result was that 86 % of all Finnish drivers have studded tires in their car. Results have small variation between different counties, for example in Uusimaa region the number is as low as 76 %, whereas in Lapland 96 % choose studded tires.

Trafi (later Traficom) has also studied the use of studded and studless tires in 2015 and 2018. The 2018 study on winter tire choosing criteria by Kuisma & Luoma was focused on Finnish individuals, who participate in car related decisions in their household. Some 1024 respondents participated in the survey. According to the study, 81 % of all respondents said they are currently driving on studded tires. In the previous study, the result was 87 %. The amount of studded tire users was the lowest (67 %) within participants living in Uusimaa region, which is the lowest amount of any comparable previous research. The study furthermore notes, that the typical studless tire user is older, more experienced driver, who drives a vehicle, which is better equipped than average. From participants under the age of 35, only 12 % used studded tires. Thus, it may be possible that young drivers feel less secure in the traffic, drive vehicles with less safety features, or choose studded tire due to their cheaper price.

Unhola has studied the percentage of studded tires in Helsinki in the traffic by analyzing the sound emissions from the tire-road impact of passenger cars and vans with so-called listening method. This is possible due to the distinctive sound that is created when a stud hits the pavement surface. Measurements have been taken on Tapaninvainiontie, which has a so-called quiet pavement material. According to Unhola, the most reliable results on this type of test arrangement are gained on this sort of pavement. The error of this measurement is said to be circa 1 percent. However, the system does not recognize badly worn studded tires. Measurement cycle is from October to April. The results of this study can be seen in figure 21. (Unhola, 2019 & Malmivuo, 2017)

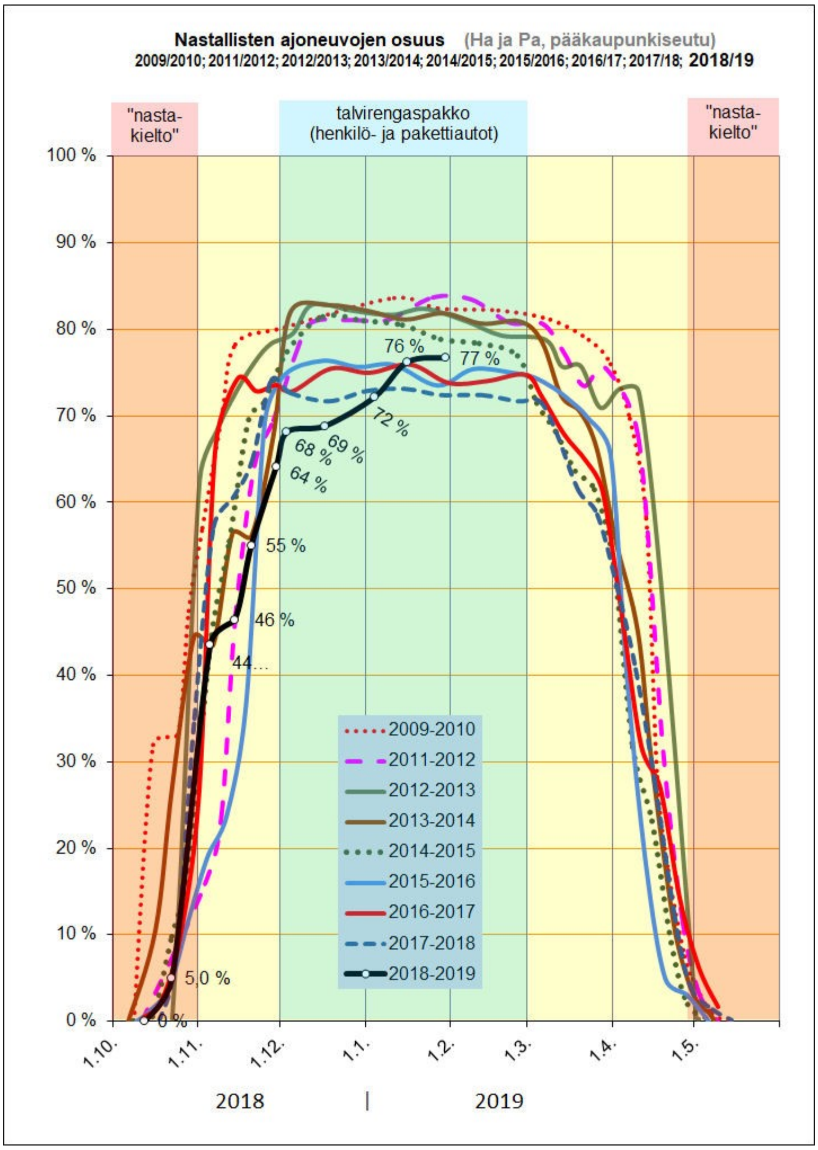

Figure 21. Percentage of studded tires in the traffic analyzed by listening method. (Unhola, 2019)

The result indicates that there has been a minor decrease in studded tire percentage from 2009 to 2018. After winter 2013–2014, the amount of studded tires has constantly been less than 80%. One limitation in the listening method is that it does not take traffic volume into account, and therefore the absolute number of studded tires may stay the same even though the percentage changes. This may be the reason for the 2018–2019 curve, which shows high increase in studded tire percentage in January 2019. This may be due to the weather conditions, as there was heavy snowfall in southern Finland in January 2019. It may be that drivers with worn studded or studless tires chose other way of transportation during that time. (Unhola, 2019)

The ratio of studded vs. studless tires was also studied in the NASTA research program by the city of Helsinki. In the study, passenger vehicles tires from vehicles parked on the streets and parking areas were observed in the winters of 2011 and 2013. The result in 2011 was that 76 % of the investigated vehicles had studded tires fitted. In 2013 the number was a little bit higher as 79 % of the vehicles were fitted with studded tires. According to the study, the percentage of vehicles with studded tires in the 90's was on average over 90 %.

In conclusion, it seems that there is a slight increase in studless tire use in Finland. Studless tires are more popular in southern parts of the country and least popular in the north. The highest increase in studless tire use is in Helsinki metropolitan area.

6 Road wear limits and other upgrades in the over-run test

6.1 Current limit values in the over-run test

The over-run test method currently applied in the type approval process of a studded tires is largely based on the research conducted by Timo Unhola at VTT. The legislation including the possibility to test a road wear of a studded tire with e.g. over-run test, came in to force in 2007. The basis of the over-run test has remained virtually unchanged during the time it has been utilized as a type approval test. Only minor technical improvements and specifications have been changed. The road wear limits set in the type approval requirements by Trafi (later Traficom) are derived from the tests conducted by Unhola at VTT between 1996 to 2010. (Yliajoselvitys 2015)

As mentioned earlier, the regulation for type approval and regulations for studded tires, 408/2003 states that any kind of studded tire can be granted a type approval if "provided that such a tire does not wear the road surface more than a studded tire complying with the regulations laid down in section 2 as well as section 3, subsections 1 and 2 of this decree". At first, the over-run test was indeed used to compare tires. The tire, on which the type approval was applied, could be compared in an over-run test to a tire of the same category that met the specification set in the regulations. If the road wear result of the tire seeking the type approval was less, the type approval could be granted.

In 2010, the developers of the test came into conclusion, that there was sufficient data gathered by the over-run tests to suggest road wear limit values according to load index categories of the tires. The suggested limit values were implemented during the same year. Those values were tightened in 2013; simultaneously the amount of studs per rolling circumference was limited from 55 to 50. The original and updated values are shown in figure 22. (Unhola, 2015)

Kantavuusluokka	Mittausrenkaan koko	Rivikulumakeskiarvo
alle 600 kg	175/65R14 185/60R15 195/55R16	1,1 g (0,9 g)
600-800 kg	195/65R15 205/55R16 225/45R17	1,3 g (1,1 g)
yli 800 kg	235/65R17 255/55R18	1,7 g (1,4 g) [1)]
C-renkaat	195/70R15C 215/65R16C 225/65R16C LT225/75R16 LT265/70R17	2,2 g (1,8 g)

Figure 22. Different load indexes as used in the over-run test, the test tire sizes available in the load indexes and their corresponsive road wear limits. Limits in brackets are valid from 2013 onwards. (yliajoselvitys 2015)

The topic of this thesis is to research and investigate if the current road wear limits require revising. As stated above, the limits for studded tire road wear in the over-run test are based on tires, which fulfill the requirements of section 2 as well as section 3, subsections

1 and 2 of the decree 408/2003. It is noteworthy, that the majority of the tires in the market currently are granted type approval via over-run test. The latest approval for so-called universal stud was granted in 2013 (Traficom), which indicates that tire manufacturers are focusing their research and development on more individual stud designs and thus applying the type approval with over-run test. This means that the type of studded tires on which the limit values are based on, are not easily available on the market anymore. Therefore, the text in the decree that states “such a tire does not wear the road surface more than a studded tire complying with the regulations laid down in section…” may not be valid anymore.

6.2 Evolution of the over-run test after 2013 changes

In 2014, Trafi (later Traficom) published a study indicating that the repeatability of the test is challenging (Rajamäki, 2014). The variation in the results between the different test laboratories was too high. Trafi then requested the recognized experts to identify the problems and to improve the accuracy and reliability of the test. The recognized experts formed an over-run task force, in which they would improve the test method in co-operation. The task force consists of all recognized experts, which are accredited to conduct the over-run test.

Since it was formed in 2014, the task force has carried out three investigations in years 2015, 2016 and 2017. Final report was published in 2018. Some research acquired by the task force has been applied to the requirements of the over-run test. The first improvement suggested by the task force were the unified test report templates, including appendix with more detail, in which e.g. the quality of the studding procedure is described.

The first studies by the task force focused on improving the accuracy of the test. The tests of 2015 concerned the geometry and handling of the test stones. One issue with the test was that the protocol of stone preparation and weighing was different with each recognized expert. The task force conducted a test where each laboratory prepared the test stones to get the mass before the over-run test passes. It was noticed that one laboratory that did not use “dummy stones” in the drying oven would get different results than others. Dummy stones mean that the the drying oven is used at full capacity, fitted with test stone specimens, which are not used during the test, and therefore called dummy stones. (The over-run task force, 2018)

During the studies it was observed that not all laboratories used test stones from the same suppliers, so the impact of different suppliers was tested. Some variance between the dfferent suppliers was noted, even though the geometry between the test stones of each suppliers was identical. It was therefore agreed that every recognized expert would use test stones from a same supplier to eliminate the test stone related measurement errors. (The over-run task force, 2018)

All of the above mentioned results have been successfully implemented to the over-run test requirement in order to increase the accuracy of the test arrangement. However, the over-run task force has suggested further improvements in regard to the results proposed in their studies.

One potential problem with the different laboratories was that the test frame and therefore the test specimens, were on different level in respect to the test track. The task force conducted a round robin test on the subject and concluded that the higher the test stones, the higher the road wear (see figure 23).

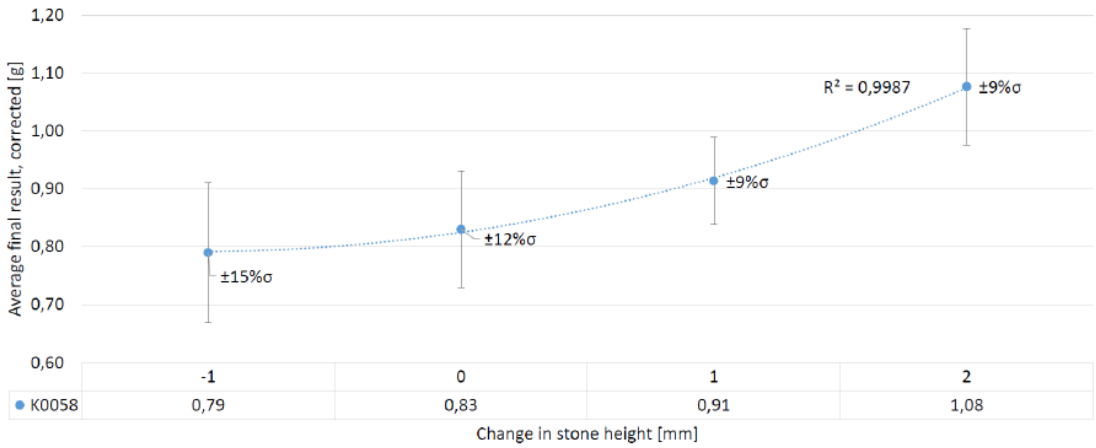

Figure 23. The effect of the height of test stones in respect to the test track (The over-run task force, 2018)

6.3 Comparable type approval tests and controversy

Exhaust emissions have been regulated in Europe since the 1992 when Euro 1 emission standard for passenger cars was introduced and added to the type approval of motor vehicles. Euro emission standards are included in the European Union directives. Euro 1 emission standard introduced exhaust emission testing for carbon monoxide (CO), hydrocarbons (HC) and nitrogen oxides (NOx). Current stage of the standard is Euro 6, which includes different emission test depending on the vehicle type and fuel. Specific maximum limit values for each emission types are set in the emission standards and the values are tightened in each emission stage. To verify that a vehicle or an engine meets the emission requirements, it is tested in various test cycles. (EEA, Directive 70/220/EEC)

Euro 3 emission (2000) introduced the New European Driving Cycle (NEDC), which is used to measure the emission levels and fuel consumption of passenger cars. The test cycle is designed to simulate typical road use of a vehicle in Europe, but is conducted typically in a test bench. NEDC test cycle was partly the reason of the emission test standard controversy, which climaxed by the Volkswagen emission scandal in 2015. It was observed, that various vehicle manufacturers had installed software in their vehicles, which recognized when the car was being tested for emissions. The car would then go in a “test mode” and optimize its emission control system for the test cycle. Thus, the vehicle would have low emissions during the test, but plausibly even exceed the limit values in real life situation. In other words, the vehicle is optimized for the test cycle, not real life application. (EPA)

Comparably to the NEDC, the over-run test, in essence is a simulation of a real driving conditions, as the test specimen are manufactured from stone and not actual pavement material. However, the test specimen used in the over-run test was originally designed to match the average grain size used on Finnish pavements and it is said that the wear in the over-run test correlates to actual pavement wear with circa 10 times higher wear rate (Unhola, 2015). However, the test specimen used in the test is standardized and the test stones used in the test need to be as identical as possible and therefore it is possible that the tire and stud properties may be designed in a way, which results in optimal wear result in the test.

The over-run task force studied how different test stone geometries effected the road wear. One long-term issue with the over-run test has been the minimal mass loss; on average circa 1 gram of mass is removed from one row (5 test stones) during 400 over-runs. The stone edges and corners have been considered to count for the largest amount of wear and therefore one focus during the study was to try different size blocks in the stones. Higher amount of blocks, the higher the total edge length and amount of corners. The different stone geometries used in the test can be seen in figure 24.

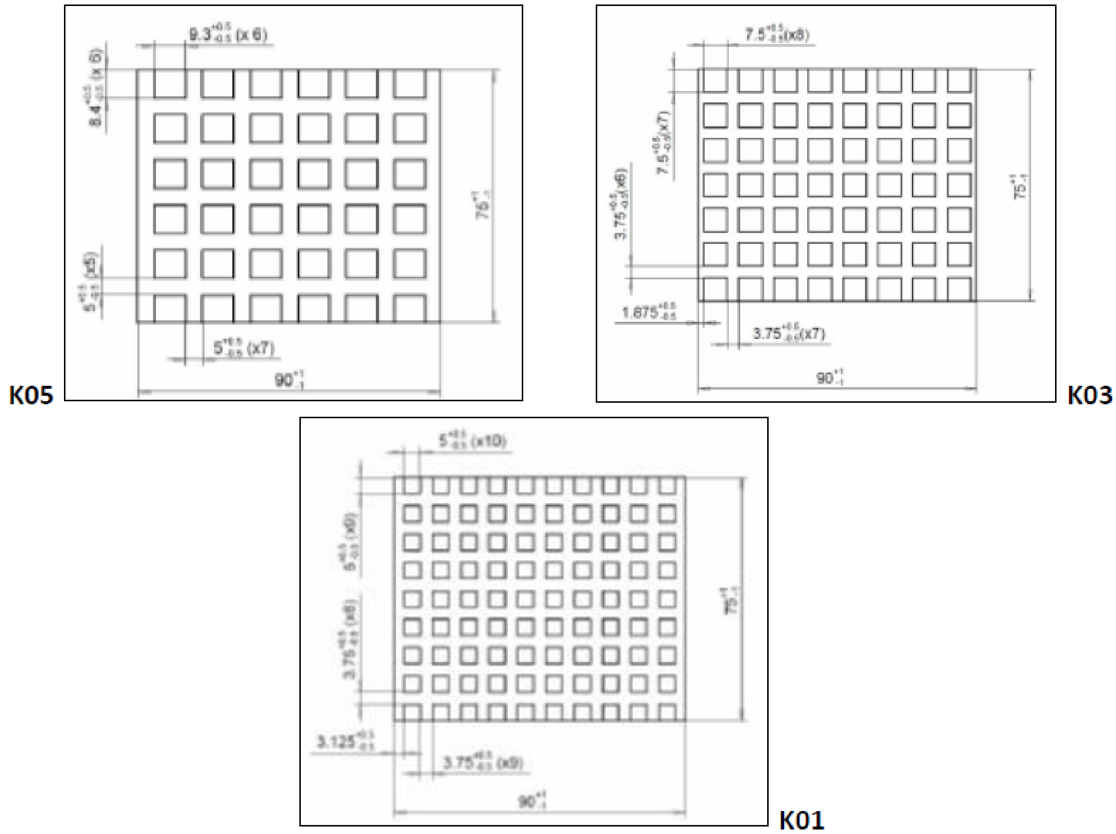

Figure 24. Different stone geometries used by the over-run task force. (Over-run task force, 2018)

The highest amount of wear resulted with the geometry K01, which has the highest total edge length and number of corners. Correspondingly, the least amount of wear occurred with the K05 geometry. According to Unhola (2015), the over-run test is expedited road wear test. The wear in the over-run test is circa 10 times higher than on a real pavement. One accelerating factor is the edge cleaving, which is obviously higher with even larger number of edges. In the study of Kossi & Raatikainen (2019), it is indicated that smaller stud diameter may be less likely to hit the edges of the test stones resulting in smaller wear during the over-run test. This will presumably not limit the number of stud-pavement impacts on a real pavement. This may lead to a direction, where the results in the over-run test may not correlate to actual pavement wear in similar manner than before. The situation could therefore be similar to the previous Euro emission standard testing: the product is optimized for the test method. Smaller test results may lead to even higher wear results in real world situation.

Due to the limitations of the NEDC which resulted in the emission scandal, the United Nations Economic Commission for Europe (UNECE) gave automotive manufacturers guidelines for a new test cycle. The result was the worldwide harmonized light vehicles test cycle (WLTP), which better represents real life driving conditions. WLTP is applied on all new cars registered in the European Union from September 2018.Similarly to the NEDC, the over-run test is only a simulation of a real driving event. Although the test is conducted outdoors and with real vehicles, the driving conditions during the test only count for a small part of the total studded tire use in traffic. Due to the similarities in the artificial nature of the NEDC and over-run test, it may be reasonable to further study the correlation of the road wear in the over-run test, or to seek possibilities in testing with real pavement material.

6.4 Increasing the over-run count

As mentioned previously, one problem with the over-run test has been the minimal mass loss of the test stones. The weight of the test stones is almost thousand times higher to that of the wear that occurs during the test (Unhola, 2015). The minimal mass loss allows for various errors to occur. Unhola studied the effect of increasing the over-run count with 200, 400, 600 and 800 vehicle overruns (400, 800, 1600 tire over-run, respectively). The result was linear increase in road wear, as seen in figure 25. As the over-run test is conducted with a real car using a human test driver, the over-run count is sensible to keep low, as even with 200 over-runs the test takes hours to complete. Due to the linear increase and already time consuming test, the over-run count was limited to 200.

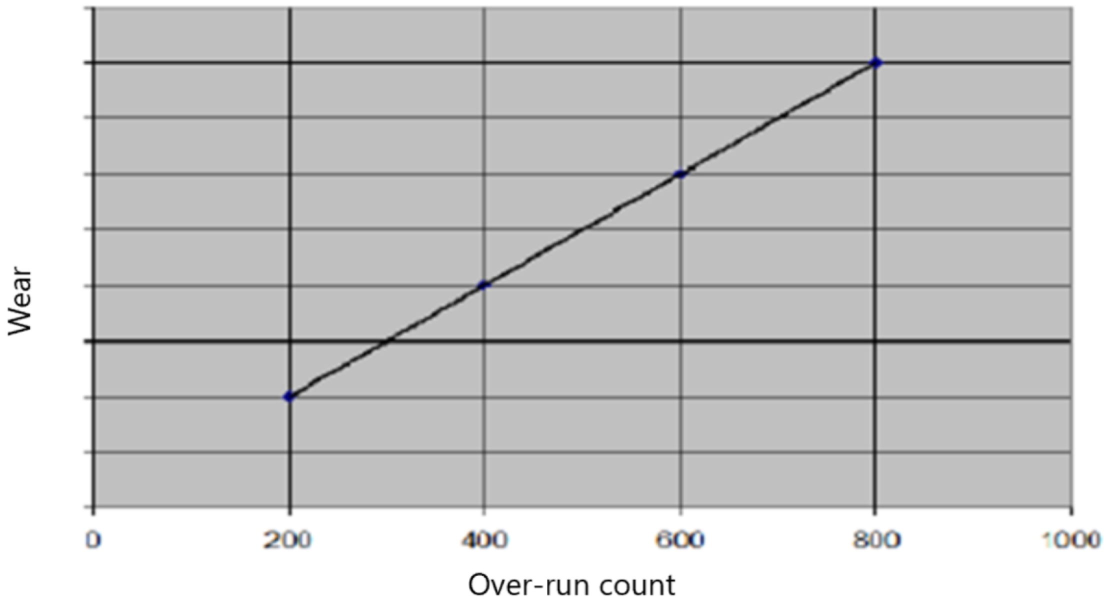

Figure 25. Effect of increasing the over-run count (Unhola, 2015)

Gültlinger (2014) did further research on over-run count with the KIT drum test equipment. The drum is suitable for testing higher amount of over-runs as the total distance travelled is far less than that in the over-run test. It is also more feasible to use the automated drum system than an actual car. The purpose of the test was to study the reproducibility of the test results so two set of test stones with variable number of over-runs was used. At 200 tire over-runs (100 vehicle over-runs, respectively), the deviation is high (see figure 26), but at higher over-run counts is averagely 3 %. After 1200 tire over-runs the wear rate begins to decline. This is due to the reason that most of the wears occurs on the edges of the sawing pattern on the test stones. As the edges become more round, the test stones are less sensitive to wear. The study suggests 800–1200 tire over-runs, to limit the possible irregularities and to stay on the linear wear area. When comparing the results made in the KIT test method to the over-run test, it should be noted that only 6 test stones are used, thus the absolute amount of road wear is smaller.

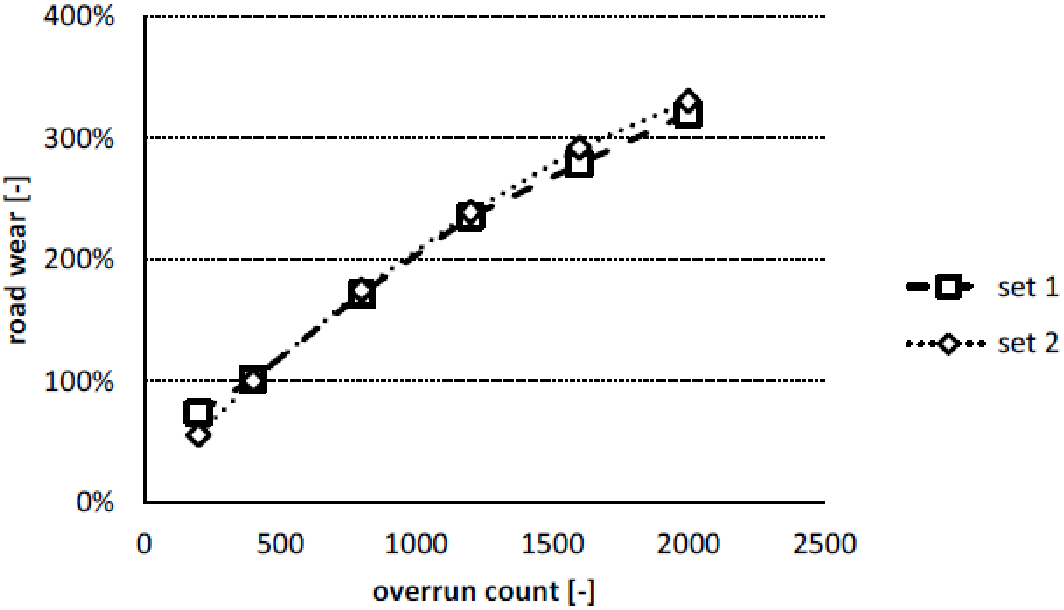

Figure 26. After 1200 tire over-runs, the road wear begins to decrease (Gültlinger, 2014)

The study of Kossi and Raatikainen (2019) suggests that the road wear limits should not be further tightened at this stage, but instead the over-run count should be increased. This may be sensible, as lowering the already relatively small wear limits may further increase errors in the test. The current amount of over-runs in the over-run test makes the test time consuming. The test drivers may become tired which can have an impact on the results. If the over-run count is further increased, the possibilities to decrease the total distance driven should be researched. The use of autonomous vehicle as a test car may also be a possibility as it would eliminate the need for a human driver.

6.5 Redefining the road wear limit categorizing

The over-run test is a result of Finnish research and is adapted to Finnish national legislation. As discussed in section 6.1, the current categorizing in the over-run test is set to 4 different classes according to the load capacities of the tire: higher load index tires are allowed a higher road wear. Finland has signed the UNECE agreement 1958 for *"Harmonized Technical United Nations Regulations for Wheeled Vehicles, Equipment and Parts which can be Fitted and/or be Used on Wheeled Vehicles and the Conditions for Reciprocal Recognition of Approvals Granted on the Basis of these United Nations Regulations"*. The agreement states, that the type approval authority shall apply the principle of worst case. Worst case principal is used to select the variant of a version, that for the purpose of testing, represents the worst case conditions for the product, e.g. a tire.

The UNECE E-regulation number 117, which is applied for tire's rolling resistance, rolling noise and wet grip, could be used as an example for adapting the worst case scenario testing to include studded tire road wear testing. For example on tire noise testing in the regulation 117, it is suggested to use a tire with the largest nominal section width and the lowest nominal aspect ratio. I.e. a tire that is expected to have the highest noise emission values. In the over-run test, the highest allowed wear is on tires with high load index. However, the tires with the highest load capabilities are not in every case the tires with the highest road wear: the wide, low profile SUV tires occasionally have lower wear results in the over-run test as their narrower, lower load index counterparts. However, tires with higher load index are presumably fitted on heavier cars, which increases the road wear. Also, the tire with the highest wear result may vary within the product family on different tire manufacturers.

The currently applied categories for the road wear limits were set over a decade ago. As the vehicle and tire technology evolves, the most commonly used tire sizes change. The load capability based studded tire regulations were changed last time due to the difficulties in finding suitable tires to fulfill test requirements for some load categories. Some tire manufacturers have notified Traficom that the current categorizing causes similar issues.

One possible option for the worst case studded tire would be to select the test tire according to the tire size which is the most widely used, as it can thereby be presumed to have the largest impact on road wear. The term most widely used is twofolded: the most sold tire may not be the tire, which counts for the most distance driven. For example, van and other commercial vehicles are typically driven more than passenger vehicles. The worst case test tire may be a tire size which is commonly used as a test tire in other tire tests as well. Thus, one suggestion for a worst case studded tire could be e.g. "A tire size, which is most widely used in the development of a tire and that has a good coverage in the existing vehicle fleet".

Other possible solution is that the recognized expert responsible for conducting the type approval test of the studded tires evaluates the size from the product family that causes most road wear. The other tires in the product family should then result in a lower wear result, which may be tested in e.g. market surveillance tests.

As suggested earlier, in order to tighten the road wear limit, it is sensible to increase the over-run count. The current load index-based categorizing requires minimum of 800 vehicle over-runs if all 4 tire sizes are tested. If the worst case scenario principle would be applied in the type approval of studded tires, it is justifiable to increase the over-run count, as the total amount of testing would not change significantly, or may even be decreased. It could be suggested that the over-run count is increased gradually in few steps e.g. 200-300–450 over-runs in 2–3 year cycles.

6.6 Other solutions against road wear

Regulating the technical properties of studded tires is carried out in order to reduce road wear. The over-run test, in essence, is a validation tool to conform a tire meets those technical properties. Therefore, it is necessary to evaluate whether it is purposeful to modify the test requirements or to effect the road wear in other means, e.g. increasing the ratio of studless tires in the traffic. Similarly to Japan, one radical solution would be banning the use of studded tires entirely. However, due to their increased safety properties especially on older vehicles, it may be reasonable to allow vehicle users the possibility to choose the tires, which they consider the safest option.

The Finnish Transport Agency (Finnish Transport Infrastructure Agency since 2019) is responsible for large parts of the Finnish road network. If there is increase in road wear, it has an impact on their annual road-keeping budget. Traficom is responsible for defining the technical regulations for studded tires and is the national type approval authority. Studded tires have some traffic safety increasing benefits when driving on icy conditions. However, the grooving and rutting of the roads creates potential safety concerns in the traffic such as increased aquaplaning and loss of stability. The road markings wear also potentially increases traffic risks. Thus, limiting the road wear caused by studded tires is in favor of both agencies' agenda and one way to support strategical tasks.

It may be suggested that the agencies, which are affected by the results of road wear caused by studded tires, should have co-operative measures in limiting the effects. One simple solution would be to inform the road users about the effects of studded tires on road wear, as it may be possible that not every road user is aware of the road wear effects of studded tires. The summer tires sold within the European Union must comply with the labeling regulation (EC) No 1222/2009 of the European Parliament and of the Council, which is used to provide information, such as economy, noise emissions and wet grip of the tires to the customer. The requirements on tire labeling are not applied to studded tires, and thus no tire labels can be found on them.

One way to inform the consumers about the impact of studded tires could be to publish the amount of road wear of a studded tire as is it is entered to the type approval documents. This would be a national labeling requirement that would be in line with the European legislation on tire labeling. Additionally, it could be considered if it possible to include studded tires in the EU regulations in order to maintain uniformity within the national and EU-wide requirements.

7 Results and discussion

The possibility to use vehicles fitted with studded tires in Finland is a privilege, as some countries where they have been previously in use have prohibited their use. The vehicle fleet in Finland is relatively old compared to the average age of vehicles in Finland. This means that the Finnish vehicles on average have less safety features (e.g. ESC) compared to other EU countries. Furthermore, being a Nordic country, the weather conditions in Finland during wintertime require the use of winter tires. As can be witnessed from the percentages of studded vs. studless tires, the largest amount of studded tires is used in Lapland, where the winter driving conditions are the harshest and last the longest. However, in the northern parts of the country, major part of the roads are covered in snow during the winter, and thus there is no stud-road contact and only small road wear. In the southern parts, the roads are snow free and often wet during winter, which leaves the road more vulnerable for studded tire wear.

In order to maintain the use of studded tires in Finland, it is reasonable to limit their effect on road wear. The over-run test is conducted on test stones manufactured from Kuru grey granite, a stone material that is not generally used in Finnish pavement manufacturing, but is considered to have moderate road wear resistance properties. The test method and the material used in the test, is not entirely comparable to actual pavement material. Therefore, it suggested that the correlation between the over-run test and actual road pavement material is validated further in relation to the latest studded tire technology.

The trends in the automotive markets in Finland are becoming favorable towards SUV type of vehicles, similarly to other markets in the European Union, where SUV sales have increased 600 % in 10 years. As discussed earlier, the vehicle weight increases road wear. Additionally, SUV type of tires are allowed higher road wear in the over-run test. Currently the most sold tire size is 205/55 R16. As the vehicle fleet moves towards SUV vehicles, the tire size moves towards larger diameter, higher load index tires. The higher load index tires have higher road wear limits. Thus, as the vehicle fleet evolves, the most popular tire size moves forward to size, which has potentially the higher impact on road wear. Additionally to the increased weight and physical size of the vehicles, traffic performance in Finland has increased and the traffic concentrates on a smaller geographical area each year as population moves towards southern parts of the country. Therefore, further increasing the issues of the already highly trafficked roads.

The over-run test is a simulated road wear test that is conducted on a purposefully made test specimen. The correlation between the test specimen and actual pavement material was studied in the 1990's, and it was observed that the wear rate in the over-run test is circa 10 times higher compared to actual pavement. However, the over-run test was originally developed to test the road wear of tires on the market during that time, i.e. not to be used as a type approval test. Currently, the over-run test is applied in the type approval of the majority of studded tires. As the test is conducted on artificial test specimens, there may be risk that the tire design is optimized in a way that the studded tire results in smaller wear during the test, but may potentially cause larger actual road wear. This hypothesis should be further researched in order to minimize the risk of unwanted consequences when requiring the use of the test method.

From a technical regulations standpoint, lowering the road wear limits in the over-run test seems like the logical thing to do, if the road wear impact of studded tires needs to be reduced. As the topic of this thesis is the limit values in the over-run test, it is furthermore the sole factor that can be adjusted. Suggestions described in this thesis, are based on the perceptions obtained during the research of this thesis. One long-term issue with the over-run test is the relatively low mass loss, that potentially increases the errors in the test method. Reducing the limit values would further increase those risks. Therefore, it is suggested that before the wear limits can be reduced, the over-run count should be increased in order to increase the absolute wear during the test. One possible solution is to gradually increase the over-run count in steps e.g. 200-300–450 over-runs in 2–3 year cycles.

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Appendices

Appendix 1. Over-run test method description. 5 pages.

Appendix 1. Over-run test method description

Over-run test method description, Appendix with more detail
Version 1.0
TRAFI/7664/05/03/1944/2014

Trafi Finnish Transport Safety Agency

Date of issue:	Date valid:	Valid until:
03/04/2014	12/05/2014	Until further notice

Statutory basis:
Paragraph 3 of Section 3 and Paragraph 2 of Section 7 of the Decree of the Ministry of Transport and Communications on Studs on Vehicle Tyres 408/2003 (latest amendment 466/2009)

Revision details:
First version 1.0

Over-run test method description, Appendix with more detail

Procedure	Method/limit value/quantity
Testing:	
Length of the test track	Sufficient, so that the vehicle accelerations do not exceed the maximum allowed value.
Shape of the test track	The test stones are overrun in both directions.
	The inclination of the test track directs excess test stone wetting water away from the test location.
Surface of the test track	Major rutting is not allowed.
Wetting of the test stones	100-150 l/h
Test stone wetting water	Tap water
Vehicle speed	Passenger car 100 km/h, +/- 2 km/h
	light-weight truck (C tyre) 80 km/h, +/- 2 km/h
	The required speed must be achieved 50 m before reaching the test stones.
Vehicle accelerations	Below 2 m/s^2
Number of test stone overruns	400 crossings by tyres.
Reference stones	Kept underwater in a container in the vicinity of the test track for the duration of one test.
	Each set of reference stones may only be used to correct the results of one test.

The placement of test stones in the frame:		
	Frame base	Must be protected from the elements when test runs are not being performed.
		Must be carefully cleaned before setting the test stones.
	The setting of test stones into the frame	3 rows, with 5 test stones in each row.
	Material between the test stones	Rubber
	Thickness of the material between the test stones	3 mm +/- 0.5 mm
	Overlapping of the test stones	The rows of test stones are overlapped/staggered at distances of 3 mm +/- 0.5 mm relative to the crossing direction.
	Material between the test stone rows	The material in contact with the test stones is rubber. There is a rigid support between the rubbers (e.g. metal) with which the test stones are secured into the frame.
	Thickness of the material between the rows of test stones	5 mm +/- 2 mm
	Tightening of the test stones into the frame	Stones are tightened so that they remain in place during the test.
	Dimensional accuracy of the test stones	The height difference between the test stones used in the same test must be 0.5 mm or less.

Test conditions:		
	Air temperature	+2… +20
		Temperature is measured in the shade prior to beginning the test.
	Road temperature	+2… +25
		Temperature is measured prior to beginning the test, at the half-way point of the test and after the test, on the track at a location where there is no spray from test stone wetting water.
	Tyre temperature	The temperatures of the test tyres are measured.
		Measurement performed from the side of the test tyre at a distance of 5 cm from the rim edge. The same, even spot is used during each measurement. The measurement is performed prior to the beginning of the test, during the test (while switching drivers) and after the test.

Test tyre:		
	Age of the test tyres	The test is carried out using new, unused tyres that have been manufactured at least two weeks prior to the beginning of the test.
		Studding must have been carried out at least 48 hours prior to the beginning of the test. The technical service does not need to monitor the studding process.
	Pressure, cold tyre	under 600kg, 2.3 bar +/- 0.1 bar
		600 to 800kg, 2.5 bar +/- 0.1 bar
		over 800kg, 2.7 bar +/- 0.1 bar
		C, 3.5 bar +/- 0.1 bar
	Even quality of the studding	Tyres cannot be accepted for testing if one or more of several conditions are fulfilled: 1) The protrusion of an individual stud on the test tyres is over +/- 30 % of the average stud protrusion of the test tyres. 2) The average stud protrusion of the test tyres is over +/- 10 % of the target stud protrusion intended by the tyre manufacturer/studder.
		With target stud protrusions of under 0.5 mm, individual stud protrusion may differ from the target value by a maximum of +/- 0.1 mm.
		If the studded tyre manufacturer/studder does not report the target stud protrusion, the test tyre will not be accepted for testing.
		20 consecutive studs are measured from both test tyres over the entire tread, beginning from a random point; in any case, this should be done using the same studs on the same tyre.
	Stud protrusion changes during over-run test procedure	The average stud protrusion of the test tyres after the test may not have changed by over +/- 25 % from the average stud protrusion of the test tyres measured prior to the over-run test. Average stud protrusion of the test tyres: ((Average stud protrusion of the test tyre on front axle + average stud protrusion of the test tyre on rear axle) / 2)
		20 consecutive studs are measured from both test tyres over the entire tread, beginning from a random point; in any case, this should be done using the same studs on the same tyre.

Test vehicle:		
	Condition	The vehicle must be in good condition
	Traction method	Free
	Transmission	Free
	Loading	For the entire vehicle, 65-75 % of the sum of the maximum loads of the test tyres
		For an individual tyre, 60-80 % of the maximum of the load index
		Less than 5 % difference between the left-hand and right-hand tyre masses
		Less than 5 % difference between the front and rear axle masses
		The masses are measured prior to the test
	Tyres not run over the test stones	Must be the same as the test tyres
	Rims	STRO or ETRTO

Measuring equipment:		
	Test stone scales	Accuracy +/- 0.001g
	Oven	Convection oven
	Oven size	There must be room for a minimum of seven plates of test and reference stones, with the different sets of stones on their own plates
	Cooling device	Desiccator / vacuum chamber / cabinet drier
	Outdoor thermometer	Accuracy +/- 1 ^{0}C
	Oven thermometer	Accuracy +/- 1 ^{0}C
	Road thermometer	Accuracy +/- 1 ^{0}C
	Tyre thermometer	Accuracy +/- 1 ^{0}C
	Tyre pressure meter	Accuracy +/- 0.1 bar
	Vehicle scales	Accuracy +/- 5 kg
	Accelerometer	Accuracy +/- 0.1 m/s^2
	Stud protrusion gauge	Accuracy +/- 0.01 mm
		The geometry of the measuring device's base must fulfil the specifications in Appendix 1.

Test and reference stones:		
	Work drawing of the test and reference stones	The test and reference stones must meet the specifications in Appendix 2.
	Number of test stones to be run over	15 pcs.
		Used for a single test only.
	Number of reference stones	5 pcs.
		Used for a single test only.
		The reference stones may not be used as run-over stones after the test.
	Test and reference stone material	Grey Kuru granite.

Processing of the test and reference stones:		
	Cleaning	Under tap water with a light application of a dishwashing brush. Use pressurised air to remove excess water.
	Cleaning water	Tap water
	Dry in a convection oven	3 days ± 2 h
		The test and reference stones are placed into the oven before and after the over-run test, always in the same places and with the same orientation.
	Cooling	120 min +/- 5 min
		Air humidity 10 % or less
		The test and reference stones are placed into the cooler in such a way that they do not touch each other.
		The test and reference stones are placed into the cooler before and after the over-run test, always in the same places and with the same orientation.
	Long-term storage	The test and reference stones are stored in a dry, warm space.
	Transportation of test and reference stones	Must be transported to the test location in a container/frame so that they are not subjected to external forces (impacts and abrasion).

Stud force measurement during the over-run test:		
	Stud force measurement	Performed before the over-run test.
	Procedure for measuring the stud force of a passenger car tyre stud	The stud force is measured in accordance with Paragraph 2 with the exclusion of items a), c) and d), and Paragraphs 3 and 4 of Section 5 of the Stud Decree 408/2003 (latest amendment 466/2009).
	Procedure for measuring the stud force of a light-weight truck tyre and a truck tyre	The stud force is measured in accordance with Paragraph 2 with the exclusion of items a) and c), and Paragraph 3 of Section 6 of the Stud Decree 408/2003 (latest amendment 466/2009). Paragraph 3 refers to the incorrect Section; the correct reference should be to Section 5.

Stud protrusion measurement during the over-run test:		
	Stud protrusion measurement	The measurement is performed prior to the stud force measurement and after the over-run test
	Number of measurements	20 consecutive studs are measured from both test tyres over the entire tread, beginning from a random point; in any case, this should be done using the same studs on the same tyre.
	The pressure force of the measuring device against the tyre	15-20 N
	Measurement result	Average stud protrusion of the test tyres. Average stud protrusion of the test tyres: ((Average stud protrusion of the test tyre on front axle + average stud protrusion of the test tyre on rear axle) / 2).

Results:		
	Result	The average wearing value (g) of the rows at a precision of two decimal places.
	Taking the reference stones into consideration	Average mass change that is used to correct individually each test stones weighing result
	Allowed reference correction	If the mass loss percentage of even a single reference stone is greater than 0.025 % compared to the original mass, the reference correction cannot be used. However, the test tyre can be approved, if the wear without reference correction is less than the defined limit value in accordance with the limit values section. Mass loss percentage: ((Reference stone mass measured prior to the test - reference stone mass measured after the test) / reference stone mass measured prior to the test) * 100.
	Confidence interval	95 % confidence that the error calculated for the row-specific wear results is less than 15 %.
	Approval	If the measurement result is at least 10 % below the limit value.
		If the results of two tests are below the limit value.
	Retesting	Required if the result is less than 10 % below the limit value.

Limit values for the wear the tyre causes:		
	Load rating class under 600 kg	0.9 g
	Load rating class 600-800 kg	1.1 g
	Load rating class over 800 kg	1.4 g
	Load rating class C	1.8 g