The effect of new tyre type, tyre pressure and axle configurations of heavy trucks on asphalt pavement lifetime

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ABSTRACT

There has been an increasing trend in the transportation industries of the Nordic countries over the last decade towards a move to longer and heavier trucks and heavier axle configurations. In Finland in 2013 the allowable total weights and dimensions of heavy trucks were raised from 60 tonnes to 76 tonnes. In Sweden the maximum total weight of trucks will rise to 74 tonnes and in Norway 60 tonnes trucks will be permitted on main roads. In order to assess this trend in Finland the Finnish Transport Agency established a "Weights and Dimensions" project to determine the present condition of the Finnish road network and estimate the effect of new heavier trucks on road loading resistance and lifetime.

Outside the Nordic countries other countries will also face the effects of rapidly increasing numbers of super single tyres and higher tyre pressures over the next few years, even those where the total truck weights or axle weights are not being raised. To assess this the ROADEX Network partners commissioned a prestudy project on "The effect of axle and tyre configurations on pavement durability". The aim of the prestudy was to produce a general information package on the effects of different truck options, axle configurations, tyre types and tyre pressure options on pavement structures. This included modelling stresses and strains within the pavement and performing calculations of residual pavement lifetimes for typical pavement structures used in the ROADEX Network area

The paper will present the key results of the two projects mentioned above and present some recommendations how pavement management policy should be changed to meet the future challenges.

Keywords: Bearing capacity, Fatigue Cracking, Freeze-Thaw, Permanent Deformation, Stiffness

1. INTRODUCTION

Total weights of trucks have been slowly growing in Finland with the result that they are now much higher compared to standard truck weights in other EU countries. The maximum total weights of trucks in Finland can now be 76 tonnes, and the maximum height can be 4.4 metres. The maximum allowed axle loads on the trucks have also been increased; e.g. the maximum total load for a triple bogie axle on a truck can now be 27 tonnes instead of the earlier 24 tonnes. The maximum total load of the triple bogie axle on a trailer however still remains at 24 tonnes. Extensive discussions on the new rules resulted in the further new rule that requires 2/3 of the trailer loading on the road surface to be applied through dual tyres. In addition to these new rules, Finland also started a five year pilot program where up to 110 tonnes road trains can be used in main road transports between predefined terminals.

However, Finland is not the only country allowing the use of heavier truck combinations. Sweden has tested 90 tonnes “En Trave Till” (one stack more) timber trucks in timber transportation between terminals. Heavier trucks are also being used in mine transports. Sweden is also currently discussing a new rule allowing 74 tonnes trucks on the Swedish road network. Also in Norway 60 tonnes trucks will be permitted on main roads.

Outside the Nordic countries other countries will also face the effects of rapidly increasing numbers of super single tyres and higher tyre pressures over the next few years, even those countries where the total truck weights or axle weights are not being raised.

With the above background, a lack of know-how based scientific research results on the effect of heavy traffic on pavement structures was identified in Finland and in Sweden. Totally opposite opinions exist on the true effect of different truck weights, axle configurations and tyre types on the lifetimes of old road structures in cold climate areas.

The problem in producing such information is that current models are not totally applicable to the existing northern European road networks, where the most important factors affecting the lifetime of pavements are the permanent deformations taking place in the base course layer during frost thaw periods. During such frost thaw periods the use of super single tyres and heavier axle weights on thin pavements causes the base course stress level to easily rise above 70 % of the material’s breaking strength. Exceeding this limit usually means very rapid pavement rutting (Figure 1). It has been estimated that in cold climate areas 80-90 % of the pavement damages take place during winter, and especially the spring thaw.

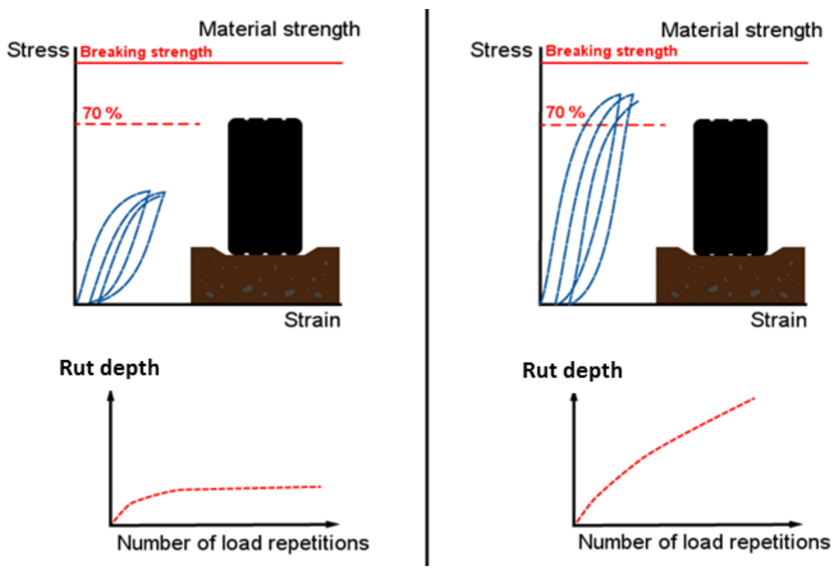

Figure 1: The effect of stress level on deformations taking place in the road structure. The diagram on the left presents the case where the stress level is well below 70% of the material strength and the structure follows linear-elastic behaviour. On the right side shows the case where the 70 % limit is exceeded and the pavement rutting under heavy traffic loading is continuous.

In addition, lifetime of pavement is determined by the condition of the weakest 10 % of the road length. So, in the future these weakest sections will play an important role when considering the maintenance costs and the risks caused by heavy traffic on the road network.

Even though the proposed increases in total truck weights in Sweden and Finland will not affect all EU countries, the new road condition problems caused by the new generations of heavy trucks will not be able to be avoided. For instance, the loading pattern of trucks on the pavement will be changing in the short term. The use of super single tyres in heavy trucks is rapidly increasing everywhere and this will mean higher stress levels on the upper part of pavements and shorter lifetimes. This will bring particular issues on those roads where the pavement thickness is less than 200 mm.

Another new challenge for pavement fatigue will be the new truck "autonomous steering systems" as recently introduced by many truck manufacturers. The operational benefits to the haulage industry of these systems are clear and most likely these systems will soon be widely used in Europe. However, the negative thing on the pavement point of view will be that the heavy trucks will be driving on the road in the future "like a train" with every wheel passing on exactly the same place. This will mean less tyre wander and the potential for up to 6 times higher rutting in pavements, as Figure 2 shows.

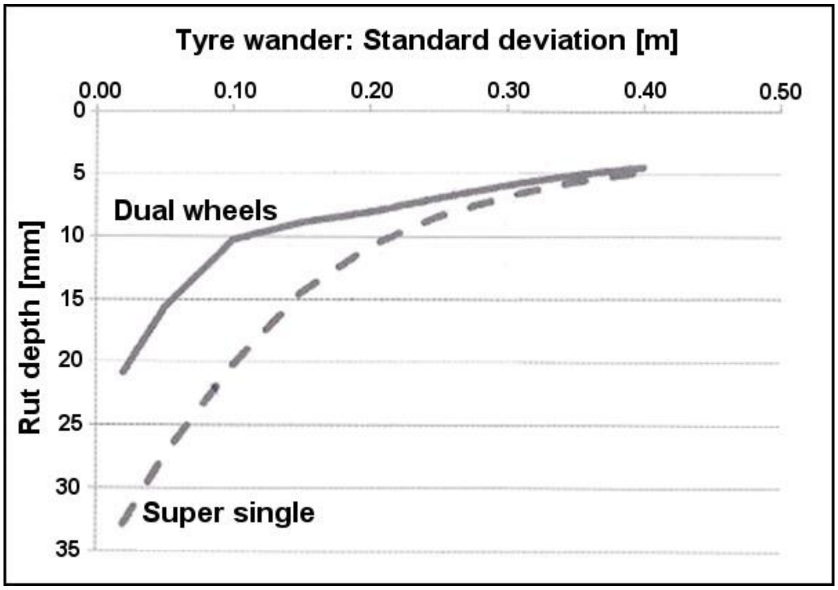

Figure 2: Effect of tyre wander on pavement rutting (Said 2013)

This paper summarizes the key results of two projects. One is the "Massat & Mitat" (Weights & Dimensions) project for the Finnish Transport Agency, the goal of which was to determine the present condition of the Finnish road network and estimate the effect of new heavier trucks on road loading resistance and lifetime. The other is the pre-study project "The effect of axle and tyre configurations on pavement durability" ordered by the ROADEX Network partners. The aim of the pre-study was to produce a general information package on the effects of different truck options, axle configurations, tyre types and tyre pressure options on pavement structures. This also included modelling stresses and strains within the pavement and performing calculations of residual pavement lifetimes for typical pavement structures used in the ROADEX Network area. The paper will also present some recommendations how pavement management policy should be changed to meet the future challenges.

2. ROADS DAMAGE MECHANISMS AND RUTTING MODES

The fatigue and damage mechanisms of a road can be classified into five main categories based on their origin [2]:
1. The fatigue of the pavement and unbound structural layers under repeated loading. This normally requires millions of heavy axle load repetitions on a new road.
2. Permanent deformations in the structural layers of the road. These permanent deformations could take place even after few heavy truck passes. The majority of these permanent deformation damages take place in spring during the frost thaw period.
3. Damages related to frost and insufficient drainage. These problems are often the reason for the problems in the previous category. Frost cracks can be formed in winter when the road structure is frozen.
4. Geotechnical problems. The most typical example of geotechnical problems is settlement.
5. Design and construction errors, such as problems with culvert bumps, damages due to transition wedge problems and reflection cracks on widened roads.

When discussing the effects of heavy trucks on road condition it is important to be familiar with the rutting modes related to permanent deformation which were developed within the ROADEX project. Mode 0 rutting takes place due to the compaction of the road structure. Mode 1 rutting happens in granular structural materials, or in the pavement near to the pavement surface. Mode 2 is the rutting that takes place at the road structure – subgrade interface. Mode 3 rutting, otherwise known as pavement abrasion, takes place due to tyre wear on the pavement of a paved road, or the wearing course of a gravel road. Figure 3 gives a diagrammatic summary of these four rutting classifications. Mode 3 is the only mode that is not related to permanent deformations caused by heavy vehicles. The main reason for Mode 3 rutting in the Nordic Countries is the abrasion caused by studded tyres.

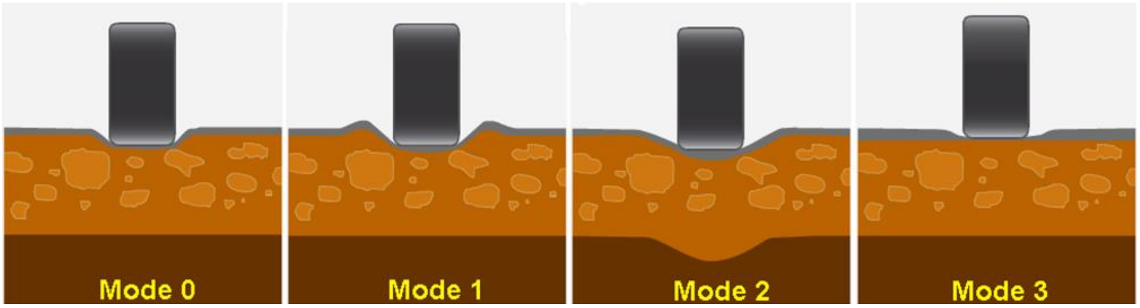

Figure 3: The ROADEX rutting classification

3. FACTORS AFFECTING THE LOAD BEARING CAPACITY OF ROADS

3.1 General

The load bearing capacity and lifetime of the pavement structure of road network is the sum of many factors and the factors can be classified as follows [2]:
1. Structural condition
2. Functional condition
3. Road width, geometry and optical guidance
4. Heavy vehicles that are using the road
5. Traffic volume
6. Climate conditions
7. Load restrictions

The effects of these factors on the condition of paved roads will be discussed in the following sections.

3.2 Total Weights and Number of Axles

It is often stated that increasing the total weight of heavy vehicles does not have effect on road damages if and when the number of axles is also increased. This is however false. The number of axles does matter. There are three factors that reduce pavement lifetime if the number of axles is increased.
First of all the increased number of axles on the same vehicle can cause the pore water pressure in the road structure to rise, especially in the spring during the frost thaw and after freeze-thaw cycles. Figure 4 gives an example from Koskenkylä Percostation from Finland, where two trucks are driving close to each other over the same spot, and the rise in the subbase layer pore water pressure can be seen immediately. Because of the increased pore pressure the stiffness of the unbound structural materials is decreased. Under several consecutive heavy loading repetitions this leads to increased deformations and rutting speed, and in the worst case rapid plastic deformation.

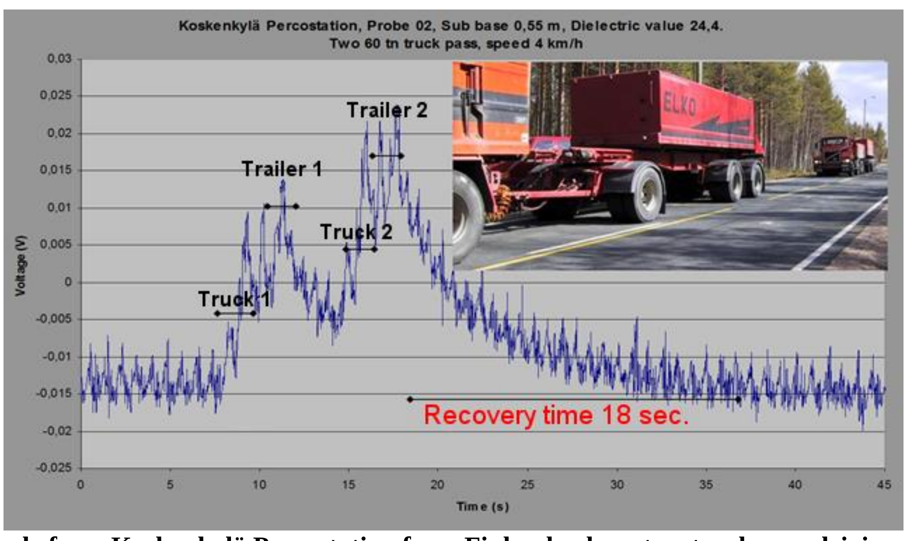

Figure 4: An example from Koskenkylä Percostation from Finland, where two trucks are driving close to each other. Due to the several consecutive axles, the structure does not have a long enough time to recover and this leads the pore water pressure to rise higher and higher.

Secondly, weak subgrades do not behave in a fully elastic fashion and because of this, with a long vehicle combination, any deflections / deformations do not have enough time to recover before the next consecutive axle load is on the same spot. This reloading raises the pore water pressure in the subgrade and weakens it, which further leads to increased deformations and rutting speed. Figure 5 shows a calculation example made by the authors of the effects of two different heavy truck options. On the basis of the cumulative subgrade displacement evaluation, the 76 tonnes truck (with 9 axles) is approximately on 40 % higher displacement level than the traditional 60 tonnes truck (with 7 axles).

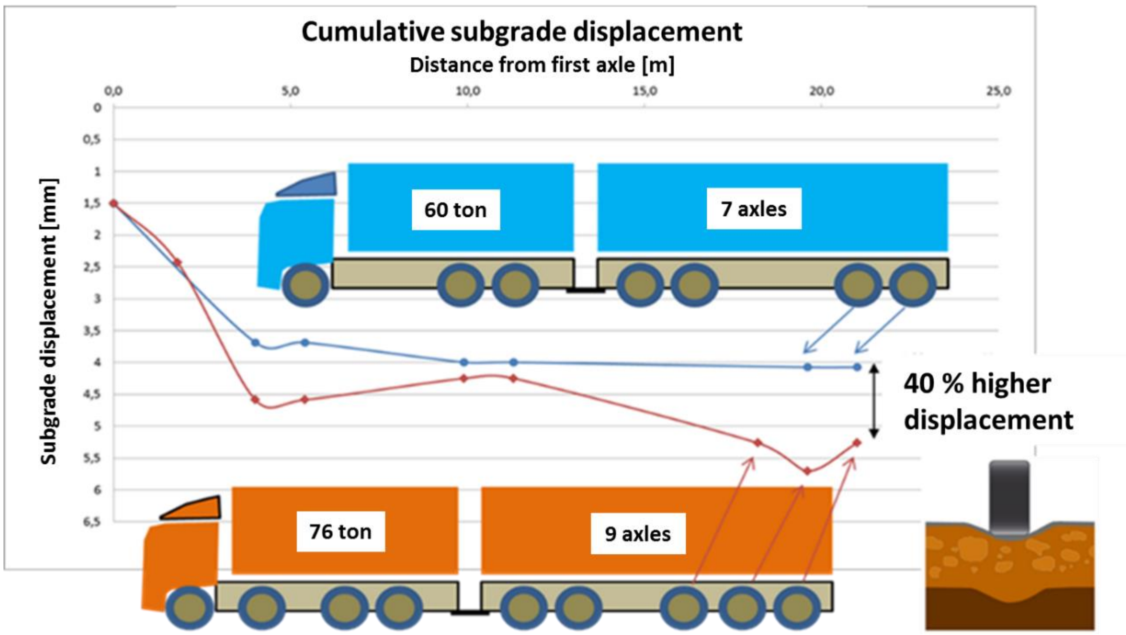

Figure 5: The cumulative displacement of a weak subgrade (modulus 10 MPa) calculated for two truck options. The horizontal axis presents the distance from the first axle of the truck. Zero is the first axle and the dots along the displacement curve represent the locations of the consecutive axles. The vertical axis displays the cumulative subgrade displacement calculated at one point. The maximum cumulative subgrade displacement with 76 tonnes truck (9 axles) is approximately 40 % higher than with the traditional 60 tonnes truck (7 axles).

The third important factor that is often ignored is that the increased number of axles on the same vehicle causes more and more tyres to load exactly the same wheel path, which leads to greater rutting speed (see Figure 2).

3.3 Axle Configurations and Axle Weights

Different axle configurations cover the variation of axles on heavy trucks and the suspension of those axles. Previous section discussed the significance of the distance between consecutive axles and how it had an effect on the load bearing capacity of the road. This inter axle distance has been studied by theoretical calculations in the ROADEX project, and the results indicate that after 1.6 metres increasing the distance does not have a significant effect. Typically the minimum distance required is 1.3 metres. The distance between combination axle groups should be at least 3 metres. A distance greater than 3 metres did not have a major effect on the elastic response, only on recovery times.

Axle weights have a great effect on the damage risk of a road. For instance in the new Finnish regulations the most critical dimensioning element is the triple bogie with maximum total weight of 27 tonnes. At least two axles of this triple bogie are required to be equipped with a dual tyre assembly. It has to be taken into account that the weight of the two (driving) axles with dual tyres is usually much greater than the weight of the third axle equipped with super singles. However, calculations performed by the authors in the "Weights & Dimensions" project indicate that even one axle with super single tyres has a dominant effect.

Figure 6 presents a comparison made by the authors of the effect of different single axle weights, tyre types and tyre pressures on the lifetime of a pavement. It can be observed from the figure that in this case the estimated pavement lifetime with a 10 tonnes axle weight is about 25 - 35 % shorter than the lifetime compared to 8 tonnes axle weight.

It can also be noted that the pavement lifetime with 1000 kPa tyre pressures can be only half of the lifetime compared to 800 kPa tyre pressures. The effect of tyre type is even greater than the effect of tyre pressure however. With same axle weight the estimated lifetime with dual tyres is in this example calculation more than twice the lifetime obtained with super single tyres.

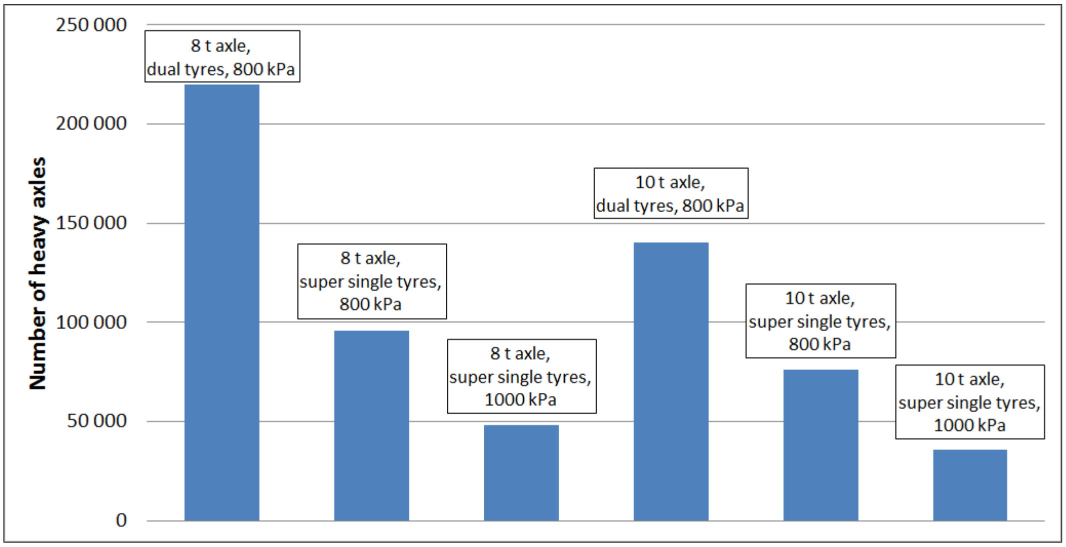

Figure 6: The effect of a single axle load, tyre type and tyre pressure on pavement lifetime (number of heavy axle passes) in the normal (summer) conditions. The critical factor is the strain at the pavement bottom.

3.4 Tyre Types

Tyre type, and especially tyre width, has a great effect on the road stresses. The effect is greatest on pavement fatigue and on Mode 1 rutting. The stresses induced by single tyres are significantly higher than the stresses induced by dual tyres. During the last ten years super single tyres have rapidly become very common, the most common width being 385 mm. According to the results of EU's COST 334 study the effect of narrow single tyres on pavement rutting is the greater the thinner is the pavement. With thin, less than 100 mm, pavements typical for many northern European countries the rutting speed can be 8-18 times higher with super single tyres than with dual tyres (Figure 7). The "Tyre Configuration Factor" value, presented in Figure 7, tells how many times higher the rutting speed is with other tyre types compared to wide dual tyres that have TCF value of 1.

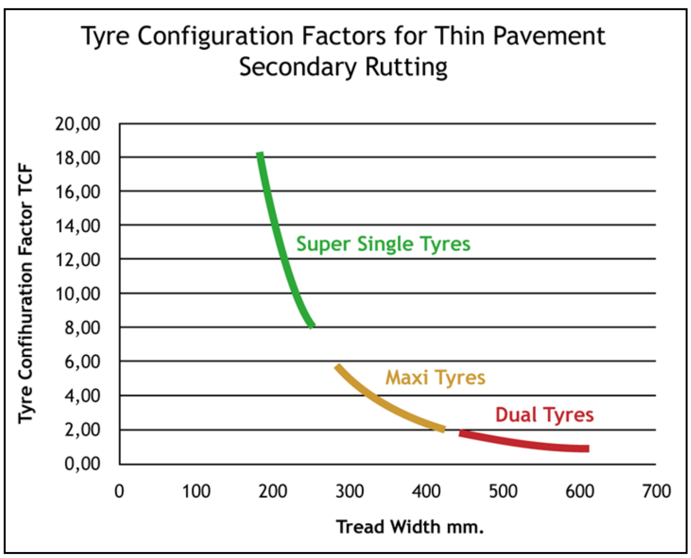

Figure 7: The effect of narrow single tyres on pavement rutting is the greater the thinner the pavement. With thin pavements the rutting speed can be 8-18 times higher with super single tyres than with dual tyres. (Figure modified from Colin Mackenzie 2012)

The dramatic effect of tyre type on road stresses was also verified by field measurements performed in two locations in Finland. For instance the results of the tests on the Vesilahti road [4], presented in Figure 8, show that super single tyre types 385/65R22.5 and 425/65R22.5 with 8 and 10 tonnes axle loads are the most risky when considering the structural condition of the road. The 425/65R22.5 super single tyre with a 10 tonnes axle load had a 3.9 times worse loading effect compared to the standard axle (a 10 tonnes axle with dual tyres). With the lighter 8 tonnes axle load, the 425 tyre effect was still 1.7 times worse compared to the standard axle. The other tested super single tyre, 385/65R22.5, with a 10 tonnes axle load was 3 times worse, and even with a lighter 8 tonnes axle load 2.9 times compared to the standard axle. According to the project calculations the loading effect of a wide base tyre (455) with a 10 tonnes axle load was 1.8 times worse than the standard axle. The same factor with a wide (maxi) 495 tyre was 1.2. It should be also noticed that the loading effect of the front tyre of the truck, 385/55R22.5 with a 7.4 tonnes axle, was 2 times greater when compared to standard axle.

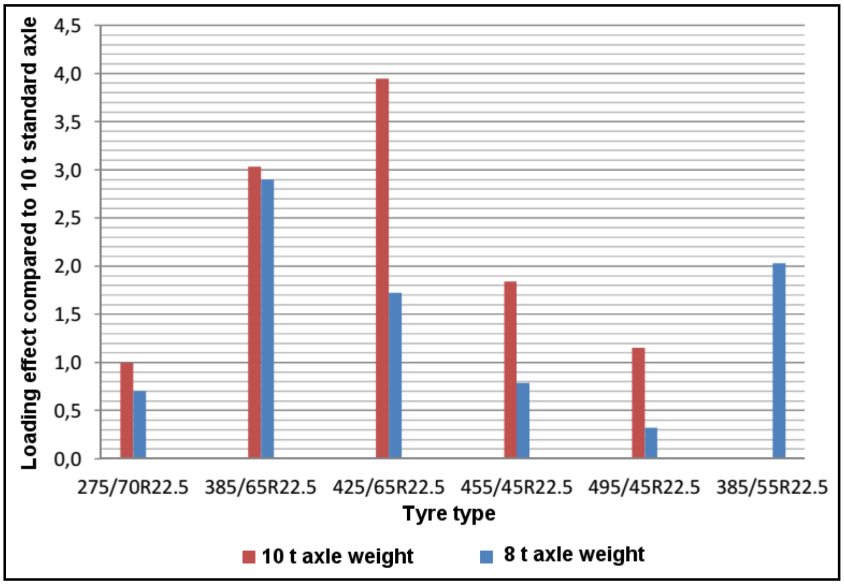

Figure 8: The loading effect of different tyre type and axle weight configurations compared to standard axle (dual tyres 275/70R22.5, axle weight 10 tonnes). The bar on the right represents the front tyre of the truck with a 7.4 tonnes axle weight.

As a result of increased use of super single tyres a new type of pavement damage, “top down cracking”, has been developed on road network. Photo series on Figure 9 presents the four different phases of top down cracking developing.

1. On the first phase, there is a very thin crack visible on the side of super single tyre wheel path. For the first 2-3 years “crack healing” takes place and the crack “glues” back by itself.
2. After a couple of years the crack has widened so much that it does not glue anymore.
3. Then another crack is formed on the other side of the super single tyre wheel path.
4. Finally the whole wheel path is totally damaged.

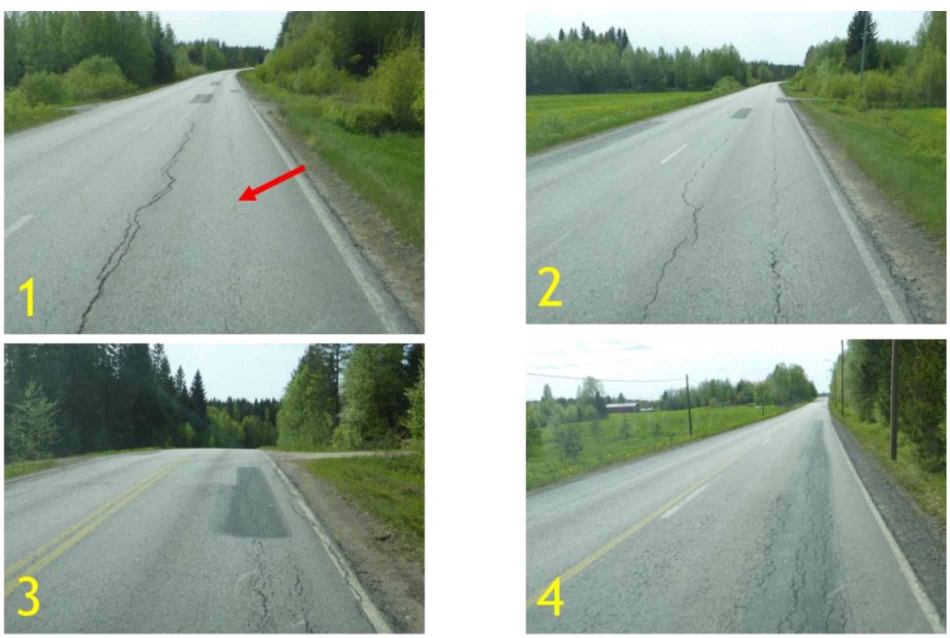

Figure 9: Photo series presenting the four different phases of top down cracking development.

3.5 Tyre Pressure

Recently there has been tendency to increase tyre pressures even higher than tyre manufacturers recommend. The main reason for this is the hardened competition in the transportation industry and the fact that higher tyre pressures reduce fuel consumption. Tests on Finnish roads in 2013 have shown that the trucks tested were using tyre pressures even higher than 1100 kPa. This is not illegal in most countries as there are no limits for maximum tyre pressures.

On the other hand there has been significant discussion in recent years on the benefits of reduced tyre pressures (CTI / TPCS) and the ROADEX project has published information on these systems in many reports (for example [8]). But now more attention should be similarly paid to overly high pressures because of their potential effect on pavement lifetime. The issue will become more critical in the future as the use of super single tyres become increasingly popular.

The main reason for tyre pressures to be so critical on pavement lifetimes is that they have such a great effect at the pavement surface pressure, and hence on the stresses and strains in the upper parts of the pavement structure, pavement fatigue as well as Mode 1 rutting. Figure 10 presents an example by the authors of the effect of tyre pressure on the vertical stresses induced by an 8 tonnes single axle load on a typical low volume road. From the figure it can be observed that with 80 mm thick pavement and super single tyres the vertical stresses on the top part of the base course are very high. With 1000 kPa tyre pressure the critical limit of 350 kPa is clearly exceeded almost to the depth of 150 mm. Raising the tyre pressure from 800 kPa to 1000 kPa increases the vertical stress on top of the base course layer from 500 kPa up to 600 kPa. As mentioned earlier, this can reduce the estimated pavement lifetime to only half of the lifetime obtained with 800 kPa tyre pressure (see Figure 6). With lowered tyre pressures the vertical stresses are significantly lower, and this could prevent the rapid failure of the road. Due to this tyre pressure control systems are widely used on heavy vehicles in many countries on locations having spring thaw problems and weak road structures.

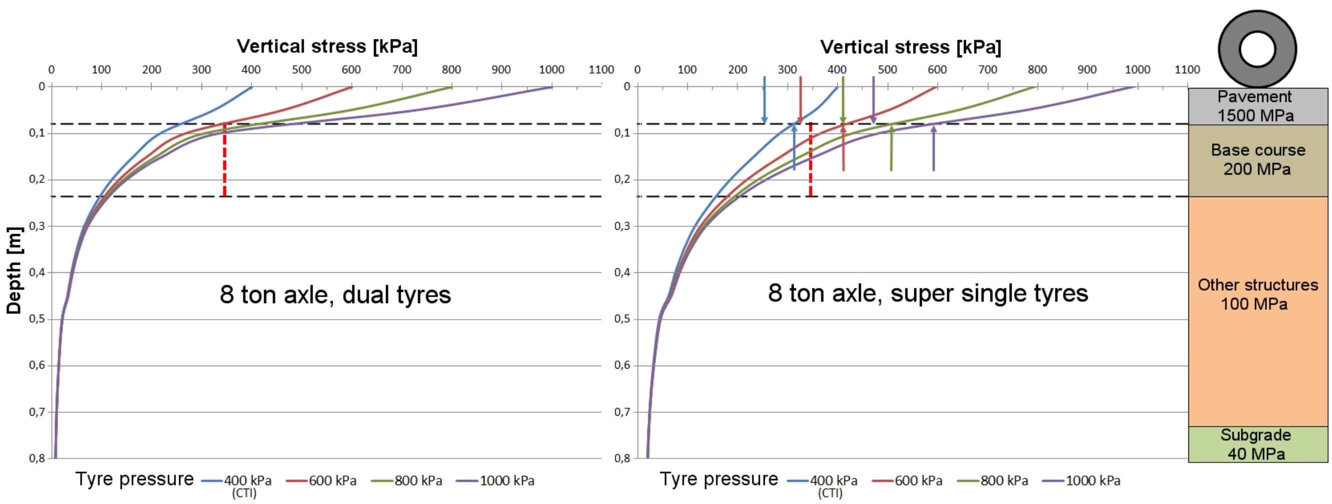

Figure 10: An example of the effect of tyre type and tyre pressure on the vertical stresses induced by an 8 tonnes single axle load on a typical low volume road. The pavement thickness is 80 mm. On the left a case with dual tyres is presented, and on the right with super single tyres. On the right the upper arrows present the stress at the bottom of pavement with different tyre pressures and with dual tyres, and the lower arrows present the corresponding values with super single tyres. The red vertical dashed line shows the stress value 350 kPa, which is often considered as critical stress limit.

3.6 Structural Condition

The most critical structural factors related to pavement fatigue or Mode 1 rutting are the pavement thickness, the total thickness of the bound layers, and the quality of the base course material. The corresponding critical factors relating to Mode 2 rutting are the total thickness and the stiffness of the whole road structure.

Research results show clearly how dramatic the effect of increase in pavement thickness is for the pavement lifetime. For example one calculation showed that with 84 mm pavement thickness, which is normal in Nordic countries, the lifetime was in summer conditions about 230,000 heavy axle passes and during the spring thaw period even less than 50,000. With a 200 mm thick pavement the corresponding lifetime would be about 11 million axles during summer and 6 million axles during the spring thaw.

If asphalt is the "weakest link" during the summer condition, during the spring thaw the most critical factors are the deformations taking place in the weakened unbound base course. Calculations showed that increasing the pavement thickness

from 100 mm to 200 mm increased the lifetime during spring thaw from less than 25 thousands of axles to almost 25 million axles.
On the other hand single axles or axle groups do not have that much effect on Mode 2 rutting. The main factors affecting Mode 2 rutting are the total weight of the vehicle combination, the number of axles and the distance between the axles. However, even though the calculations based on linear-elastic theory indicate that effect on Mode 2 rutting is not so strong; in practice it may be more significant. Indications of this were obtained during the field measurements performed in Finnish Weights & Dimensions project. The main reason for this is probably frost and thawing ice lenses.

3.7 Functional Condition

The magnitude of stresses and strains in a road structure can also be affected by how smooth and even the road surface is. This is due to the fact that uneven bumps can cause impact loads to the pavement due to the suspension system of trucks. Because of this the stresses and strains after a bump can be substantially higher than the normal surface and cause a faster deterioration of the pavement. Figure 11 shows an example of such case. A 120 meter long section of high rutting can be seen after a single bump on the road.

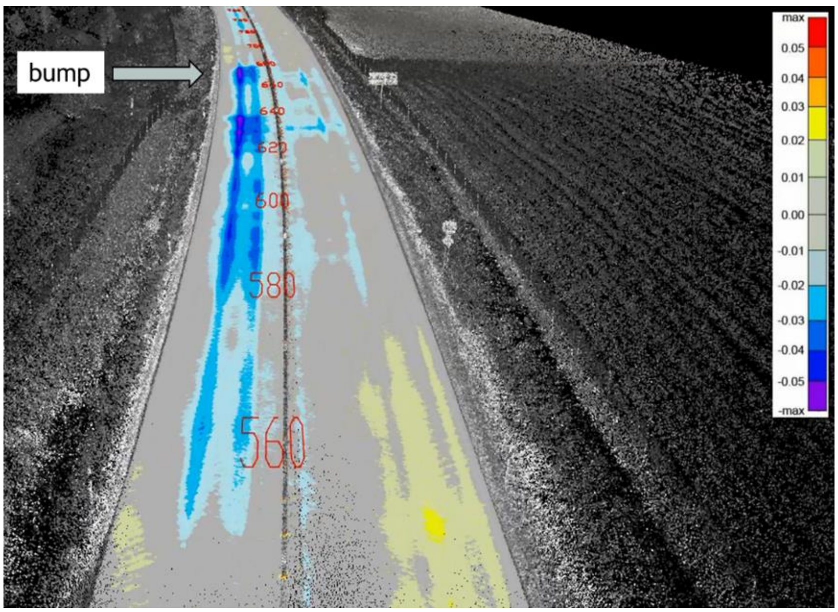

Figure 11: An example from laser scanner point cloud video from Sweden showing a long section with high rutting after a single bump on the road. The bump causes impact loads to the pavement due to the suspension system of trucks, which leads to faster deterioration of the pavement.

4. SUMMARY AND CONCLUSIONS

A statement often made is that "increasing the total weight of heavy vehicles does not have effect on road damages if the number of axles is also increased and the axle weights are not raised". This is however not true, as the increased number of axles on the same vehicle also causes the pore water pressures in road structures to rise, especially in the spring during the early frost thaw and after freeze-thaw cycles. Because of the increased pore pressure the stiffness of the unbound structural materials decreases. Under several consecutive heavy loading repetitions this can lead to increased deformations and rutting speed, and in the worst case rapid plastic deformations. Additionally, weak subgrades do not behave in a fully elastic fashion and because of this the deflections and deformations caused by a long vehicle combination do not have enough time to recover before the next consecutive axle loads the same spot. This again raises the pore water pressure and weakens the structure. Increased number of axles on the same vehicle also results in more and more tyres loading the same wheel path, which leads to greater rutting speed.
Axle weights also have a great effect on the remaining lifetime of a road. For instance with the same tyre type and tyre pressure the estimated pavement lifetime with a 10 tonnes axle can be tens of percent shorter than the lifetime obtained with a 8 tonnes axle. However, the choice of tyre type is an even more critical factor for road stresses than axle weight. The loading effect of a super single tyre can be several times higher than that of a dual tyre. Tyre type has the greatest effect on pavement fatigue and on Mode 1 rutting. According to recent studies the effect of narrow single tyres on pavement rutting is the greater the thinner the pavement. With thin, less than 100 mm, pavements the rutting speed can be 8-18 times higher with super single

tyres than with dual tyres. It can be concluded that even some increase in axle weights is less harmful for road structures if dual tyres are used, compared to current axle weights with super single tyres.

The results show that tyre pressure has also a surprisingly great effect on the stresses and strains in the upper parts of the pavement structure, pavement fatigue as well as Mode 1 rutting. For example, the pavement lifetime with 1000 kPa tyre pressure can be as little as half of the lifetime as that under 800 kPa tyre pressure. For truck owners it is very tempting to use higher tyre pressures than necessary as it is considered that this can reduce fuel consumption. This practice is not illegal because most countries do not have limits for maximum tyre pressures. There has been substantial research on the effects of reduced tyre pressures (CTI / TPCS) and their benefits are clear. Attention should now also be paid to the effects of overly high pressures. This issue will become more pressing in the future as the use of super single tyres becomes even more common. It can be recommended that decision makers should now start to consider how to their policies can be amended in order to favour the use of CTI systems, and further how the use of unnecessary high pressures could be controlled and even sanctioned, as they have a great potential to damage pavements.

Theoretical lifetime calculations undertaken clearly indicate that the new heavy duty axle and tyre configurations (especially the use of super single tyres) significantly increase the stresses and strains at the top of the pavement structure, which in turn have a great impact on lifetime. The stresses measured from the structures of the tested roads also indicate the same and verify the theoretical results. Impacts on pavements will be even more visible in spring thaw weakening periods. The only exceptions from this will be roads with very thick pavements, i.e. more than 250 mm.

Results from other research projects show clearly that the best method for improving the load bearing capacity of a pavement structure is to use a thicker pavement. Therefore it can be recommended that the goal for pavement management should be towards thicker pavements. However, before adding any new pavement layers, the road drainage should be improved. Improving the road surface evenness is also recommended, as this can reduce rutting, pavement damage, bumps and the pumping phenomenon. Improving the road surface can similarly improve driving comfort and decrease fuel consumption.

As a summary it can be concluded that there will be two kinds of challenges over the next few years on European road networks. First of all they will face the effects of increasing numbers of super single tyres and higher tyre pressures, even though truck weights and axle weights will remain unchanged. The second challenge will be the new heavier truck combinations and the issues that will arise especially during the spring thaw season. The results show that countries with thin pavements on their road networks could consider permitting increased total weights for trucks with dual tyres. Another parallel issue that is not discussed in this paper is the effect of heavy trucks on bridges.

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