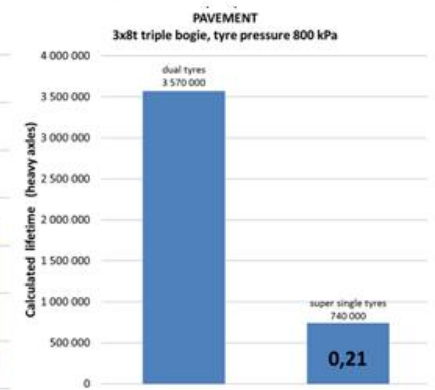
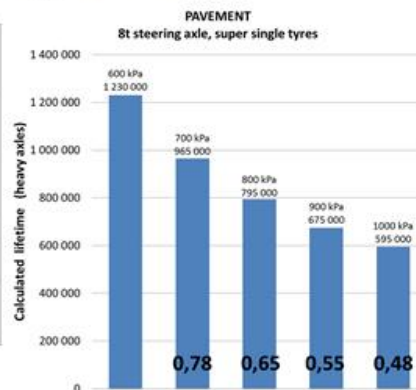
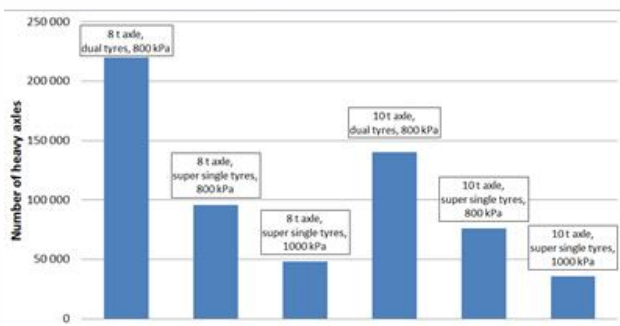
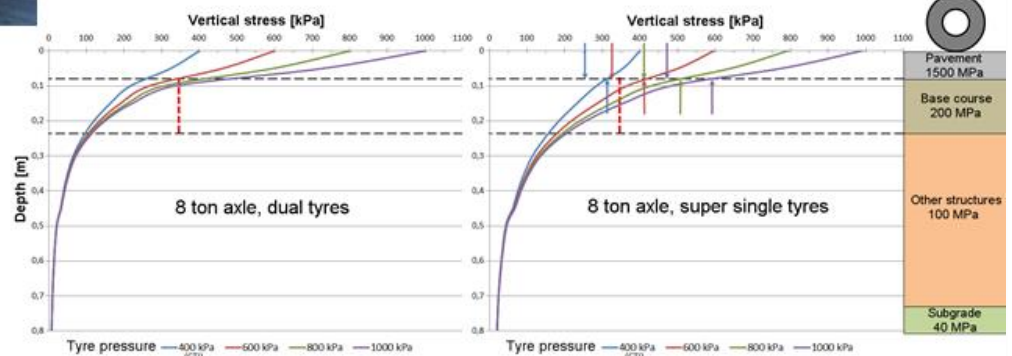




**ROADEX**  
Network  
For better rural roads



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# EFFECT OF AXLE AND TYRE CONFIGURATIONS ON PAVEMENT DURABILITY – A PRESTUDY

Report 2014

# ABSTRACT

Over the last decade there has been a trend in the transportation industry to move towards longer and heavier trucks and heavier axle configurations. As an example Sweden has recently proposed raising the maximum total weight of trucks to 74 tons and in Finland first 76 ton trucks are already in use. In addition the use of super single tyres has been increasing rapidly in ROADEX countries.

The aim of this prestudy was to produce a general information package on the effect of different truck options, axle configurations, tyre types and tyre pressure options on pavement structures. A secondary goal was to model stresses and strains and perform calculations of pavement lifetimes caused by the different variables mentioned above on typical pavement structures used in the ROADEX Network area.

The prestudy proves false the commonly held belief that increasing the total weight of heavy vehicles will not have an effect on road damages if the number of axles is correspondingly increased and the axle weights are not raised. What is not understood is that increasing the number of axles on the same vehicle causes the pore water pressures in the road structure and/or in the subgrade to rise, causing the stiffness of the structural materials in the road to decrease. Under several consecutive heavy loading repetitions this leads to increased deformations and rutting speed. More axles on the same vehicle also result in more tyres loading the same wheel path.

Increasing axle weights increase the damaging risk to pavement structures. For instance with 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 an 8 tonnes axle.

Tyre type has however a much greater impact on pavement lifetime than small increases in total weight. This is because the stresses induced by super single tyres are significantly higher than the stresses induced by dual tyres. An important fact to remember is that the effect of narrow single tyres on pavement rutting is greater the thinner the pavement. With thin pavements, typical in many ROADEX countries, the rutting speed can be 8-18 times higher with super single tyres than with dual tyres.

The prestudy additionally shows that tyre pressure can have a surprisingly great effect on stresses and strains in the upper parts of pavement structures, pavement fatigue and Mode 1 rutting. As an example the pavement lifetime of a road subjected to tyre pressures of 1000 kPa can be half that subjected to tyre pressures of 800 kPa, i.e. the tyre pressures normally recommended by tyre manufacturers. Higher tyre pressures however are seen to help reduce fuel consumption and transportation costs, and for this reason are being increasingly used. In the future more attention should be paid to high tyre pressure regulations.

The theoretical lifetime calculations and prestudy field tests confirm that the new heavy axle and tyre configurations, especially the use of super single tyres, can have a great impact on pavement structure lifetime. The results of the calculations made for predefined Swedish truck configurations showed that the truck wear factor of the 74 tonnes truck is about 1.2 times greater compared to traditional 60 tonnes truck. Other heavier combinations with more super single axles can have significantly higher truck wear factors. The truck wear factor of the new Finnish 76 tonnes truck is approximately 1.5. If the increase in net weight per vehicle is taken into account, the loading effect of these new truck combinations on the road will be less because of the decreased number of vehicles passing over the road. But as already mentioned above, the effects of the increased number of axles must not be ignored.

One of the best methods to improve the load bearing capacity of pavement structures is the use of thicker pavements. But even before that, a highly cost-effective measure is to improve the drainage. Also improving the road surface evenness can be beneficial.

Over the next few years the ROADEX countries will be facing the effects of increasing number of super single tyres and higher tyre pressures, even in those countries where the total truck weights or axle weights are not being raised. For example in Scotland the most critical issue will be the subgrade, and in Norway the fatigue of pavement under super single loading will be important. The main challenge in Finland and Sweden will be the new heavier trucks and the problems that arise from their use.

**KEY WORDS:**

heavy trucks, axle weight, dual tyre, super single tyre, tyre pressure, road damage, pavement life time, permanent deformation

# PREFACE

The prestudy project "Effect of Axle and Tyre Configurations on Pavement Durability" was ordered by the ROADEX Network Partners. These comprised at the time of writing: the Swedish Transport Administration, the Centre for Economic Development, Transport and the Environment of Lapland of Finland, the Norwegian Public Roads Administration, and the Highland Council, Transport Scotland and Comhairle nan Eilean Siar from Scotland.

This report sets out to provide a general information package on the effect of different truck options, axle configurations, tyre types and tyre pressure options on pavements, other road structures and subgrades. The report also summarizes the key results of the research carried out in Finland, Sweden, Norway, Scotland and other countries regarding the effect of heavy traffic on pavement durability.

The main part of the research presented in the report, as well as the writing of this prestudy report, was carried out by Roadscanners Oy in Finland. The authors would like to express their gratitude to all the persons making possible to make this prestudy and the report

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# 1. INTRODUCTION

During the last decade a great number of new challenges have arisen concerning the durability of pavement structures under heavy traffic. There has been a trend in the transportation industry to move towards longer and heavier trucks and heavier axle configurations. Changes in tyre types have also brought their own issues. For example in the UK, Ireland and Norway the situation is changing because of the increasing use of super single tyres, even though total truck weights have remained unchanged. Tyre pressures are however likely to increase in these countries.

Sweden has already tested 90 tonnes “En Trave Till” timber trucks in timber transportation operations between terminals, and recently there has been a proposal to raise the maximum total weight of trucks to 74 tonnes. As part of these changes ROADDEX has analyzed the effects of different heavy truck options on the Pajala mine road project in Sweden.

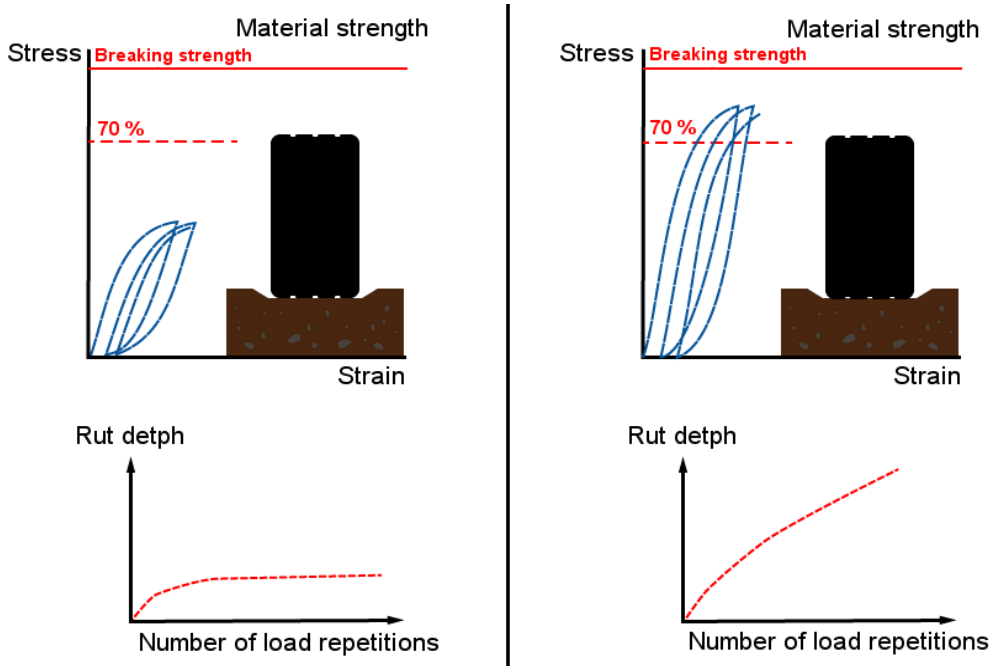
The government in Finland also recently decided that the maximum total weights of trucks in Finland can be increased from 60 tonnes to 76 tonnes. The maximum allowed axle weights have been increased as well; for example the maximum total weight of a triple bogie on a truck can now be 27 tonnes instead of the earlier 24 tonnes. The maximum allowed total weight of a triple bogie on a trailer however still remains at 24 tonnes. A transition period of five years has been agreed during which the maximum total weight of former 60 tonnes vehicles can be increased to 64 tonnes, if certain technical requirements are fulfilled. Partly thanks to ROADDEX research results the Finnish government also decided that if the new maximum total weights are utilized, at least 65% of the trailer weight will have to be distributed on dual tyre axles to minimize pavement damage. In addition to these new changes, Finland is also about to start a five year long program of tests with up to 110 tonnes trucks between predefined terminals.

With the above background, discussions between road engineers, truck engineers, transportation companies and political decision makers in Finland and in Sweden have identified a lack of know-how based scientific research on the effect of heavy traffic on pavement structures. Totally opposite opinions exist on the real effect of different truck weights, axle configurations and tyre types on the lifetimes of old road structures in cold climate areas. There is therefore a great need for “easy to access” published information regarding heavy trucks and pavement structures.

The defenders of heavier axles and total weights have used the old AASHO results to justify their views. For example, the existing linear-elastic fatigue models used in most European design standards are based on AASHO guidelines. However, in the AASHO tests the road structures were new, pavements were thick, seasonal changes were small and used American trucks, axles and tyres. Accordingly the results of the AASHO tests are well suited to newly built roads with thick pavement layers and well performing drainage. On these roads the stresses and strains in the roads structural layers induced by heavy trucks are well below 70 % of the breaking strength of the material and the lifetime of the pavement is usually millions of axles (Figure 1).

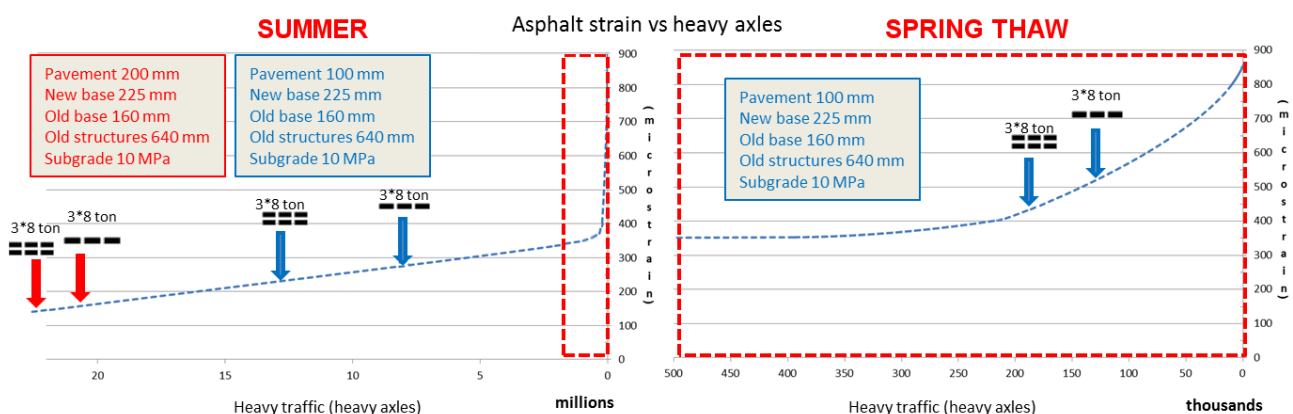
However, with the introduction of new generations of trucks, these old models are no longer suitable for the existing northern European road networks, where the most important factors affecting the lifetime of pavements are the permanent deformations taking place in the base course layer during frost 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.

It is now generally recognized that the condition of the weakest 10 % of the road section length is the ruling factor on pavement lifetime, and consequently the maintenance cost of the road. In the future these weakest sections will play an important role in discussing the risks caused by heavy traffic to the road network.



**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.

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 change 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, as Figure 2 shows.



**Figure 2:** Pavement lifetime under triple bogie axles equipped with dual and super single tyres on a relatively strong pavement structure with 200 mm and 100 mm asphalt. The pavement fatigue curve is derived from the Finnish design standard. The figure on the right shows the structure during early spring thaw when the top 300 mm of the pavement structure has thawed and the rest of the road is still frozen.

A further new challenge for pavement fatigue will be the new truck “dynamic steering systems” as recently introduced by truck manufacturers, such as Volvo. The operational benefits to the haulage industry of these systems are clear and most likely these systems will soon be widely used in most trucks in Europe. The bad thing for the road pavement however 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 3 derived from Said (2013) shows.

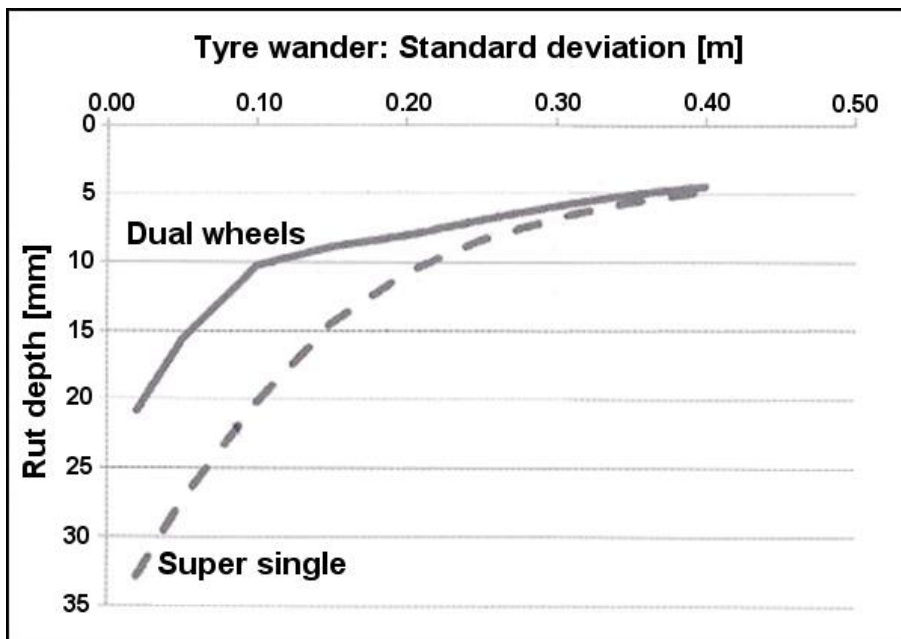


Figure 3: Effect of tyre wander on pavement rutting (Said, 2013)

The aim of the prestudy project was to produce a general information package on the effect of different truck options, axle configurations, tyre types and tyre pressure options on pavements and on roads' structural performances across the seasons. As a consequence the package tries to cover all the critical issues that decision makers should be aware of when deciding new truck policies. The project also summarizes some of the key results of the current research being carried out in Finland, Sweden, Scotland and other countries.

The prestudy also carried out some modelling of stresses and strains and calculations of pavement lifetimes for typical pavement structures used in the ROADDEX Network area. These calculations were made using a software package based on linear-elastic theory. The study also discusses the options that road owners could have to prevent or minimize damage by heavy trucks, the options of better maintenance policies, road strengthening, road friendly vehicles and load restrictions.

## 2. ROADS DAMAGE MECHANISMS AND RUTTING MODES

### 2.1. GENERAL

The fatigue and damage mechanisms of a road can be classified into five main categories based on their origin:

1. The fatigue of the pavement and unbound structural layers under repeated loading. On a new road this normally requires millions of heavy axle load repetitions.
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 ROADDEX 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 4 gives a diagrammatic summary of the four ROADDEX rutting classifications. Mode 3 is the only mode that is not related to permanent deformations caused by heavy vehicles. The main reason for this rutting mode in the Nordic Countries is the abrasion on paved roads caused by studded tyres.

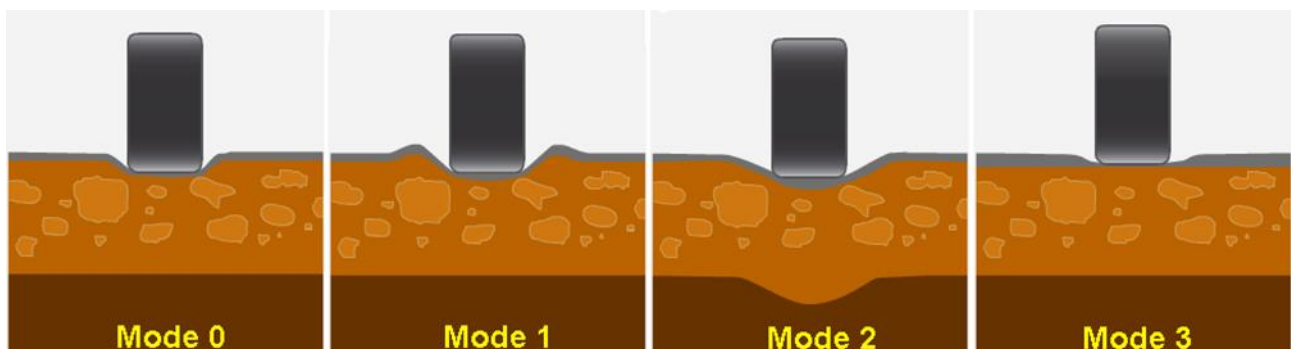


Figure 4: The ROADDEX rutting classifications

### 2.2. DAMAGES RELATED TO LOADING AND BEARING CAPACITY

#### 2.2.1. Pavement Fatigue

Usually pavement fatigue is presumed to take place as a function of the number of heavy axles passing and it is usually evaluated using linear-elastic fatigue models. In other words, the thinner is the pavement, the higher is the number of load repetitions and the heavier is the loading; the quicker the fatigue and damages that take place. The most common damages due to pavement

fatigue are rutting and cracking on the wheel paths. Net cracks are the most typical, but super single tyres have created a new crack type, commonly called “top down cracking”. On different roads and different geographical areas the lifetime of a pavement is determined either by rutting or by cracking. The reason for this difference is not known precisely. For example in western Finland pavements are more likely to crack, whereas in Lapland they usually start rutting when fatigued. The explanation might be the interaction of pavement materials and climatic conditions.

### 2.2.2. Mode 0 Rutting

Mode 0 rutting takes place through the compaction of the non-saturated materials in the pavement structure, and in practice some level of Mode 0 compaction always takes place in a road structure after its construction. Normally the construction compaction prior to trafficking is sufficient to prevent further compaction under trafficking. This mode of rutting is usually self-stabilizing - i.e. the compaction that happens prevents further compaction. It also causes the compacted material to stiffen and thereby spread load better. Better load spreading leads to a reduced stress on the subgrade, thereby reducing the risk and amount of rutting at that level (see Mode 2 rutting). ([www.roadex.org](http://www.roadex.org))

### 2.2.3. Mode 1 Rutting

Mode 1 rutting happens in weaker granular materials where local shear occurs close to the wheel. This gives rise to dilative heave immediately adjacent to the wheel track where the granular material can undergo large plastic shear strains and consequent dilation, leading to relatively loose material. This type of rutting can therefore be considered to be largely a consequence of inadequate granular material shear strength in the aggregate near to the pavement surface. On the other hand, Mode 1 rutting can also be observed on roads with thick pavement during hot summer days at bus stops and traffic lights.

Ideally in Mode 1 rutting there would be no deformation at the subgrade surface and this type of deformation can be regularly seen when the subgrade is strong bedrock. A typical feature that can indicate Mode 1 rutting is small diameter net cracking (or alligator cracking) in the overlying asphalt. This type of rutting is frequently observed in Nordic areas affected by seasonal frost. In many cases in these areas Mode 1 rutting is the main contributor to the accumulation of rutting, especially where a poor quality aggregate with excess moisture content completely loses its load carrying capacity when it thaws in the spring. The same material when re-compacted (see Mode 0 rutting) and drained, can have an entirely adequate performance for the rest of the year. ([www.roadex.org](http://www.roadex.org))



**Figure 5: A paved road suffering from severe Mode 1 rutting during the spring thaw period. An example from Finnish Lapland. The damages take place early in the spring when the lower part of the road structure and the subgrade are still frozen.**

### 2.2.4. Mode 2 Rutting

With Mode 2 rutting problems the critical deformations take place in the interface between the structural layers and the subgrade. Mode 2 rutting occurs where the aggregate quality is better and the pavement structure as a whole ruts or deforms. This can be viewed in an idealized fashion as the subgrade deforming with the granular layer(s) deflecting bodily on it (i.e. without any thinning). The surface deflection pattern of Mode 2 rutting takes the form of a broad rut with slight heave remote from the wheel (as it is the displacement of the soil which causes the rut to form).

When the ruts on a road suffering from Mode 2 rutting are repeatedly infilled, the rutting at the subgrade surface still continues with the new aggregate following the original rut shape. The subgrade squeezes upwards between the wheel tracks and in the shoulders ([www.roadex.org](http://www.roadex.org)). A crack between the wheel paths can also be common on roads suffering from Mode 2 rutting. An example of such a failure can be seen in Figure 6.



**Figure 6: An example of a paved road suffering from Mode 2 rutting. The ruts are wider compared to those of Mode 1 rutting. Note also the cracks between the wheel paths. Poor drainage condition can often be a contributory factor in Mode 2 rutting problems.**

### 2.2.5. Mode 3 Rutting

As already mentioned earlier, Mode 3 rutting is not a consequence of permanent deformations caused by heavy vehicles. In the Northern Periphery Mode 3 rutting is mainly due to the abrasion of the pavement due to studded tyres used in passenger cars. However the proportion of this rutting type is important to be identified when assessing the rutting of roads as a whole.

## 2.3. OTHER DAMAGES

### 2.3.1. Drainage Related Damages

Poor drainage of roads and insufficient maintenance of drainage systems is a major cause of permanent deformations under heavy traffic. Poor road drainage can lead to faster rutting rates than predicted by the design lifetime based on fatigue models. In addition, poor drainage can also cause frost damages with their resultant traffic safety issues. The following drainage related problems and deficiencies caused by heavy vehicles are the most critical, and they should be taken carefully into account in the future as heavier trucks come on to the road network.

- Late removal of snowwalls in the spring when the snow starts to melt. This causes the base course layer under the pavement to saturate, which further causes rapid Mode 1 rutting.
- The bottom of the ditch being much higher than the bottom of the road structure. This causes water, melting from snow, to infiltrate into the frozen road structure due to capillary action. This in turn leads to the development of ice lenses causing frost heave. When these ice lenses start to thaw the road structure can rut rapidly under heavy traffic. Problems can occur also during summer time, if roadside ditches do not have sufficient gradients causing water to pond in the ditch and infiltrate into the road structure. This free water raises the pore water pressure of saturated materials within the road, exposing the structures to permanent deformation.
- Clogged exit road culverts and main road culverts causing water in the ditches to pond and rise, resulting in the trapped water to infiltrate into the road structure causing frost heave and/or saturation of the road materials. Under heavy traffic loading these sections can rut quickly.
- Trapped sheet ice in the ditch causing the bottom of the ditch to rise, which again leads to water level rise and infiltration.
- Snow from bus stops and parking lots being dumped into roadside ditches. This results in the formation of a snowbank that can block the water running in the ditch, which again leads to water level rise and infiltration.

### 2.3.2. Frost Damages

In addition to the damages presented in previous chapter, ice lenses can be formed inside road structures and subgrades during winter causing frost heave, bumps and pavement cracks. When these ice lenses thaw, the risk of Mode 1 and Mode 2 rutting is high. Uneven frost bumps can also cause high rutting in the road after the bump due to dynamic loading effects caused by heavy vehicles.

### 2.3.3. Settlement

Settlements on roads usually have gentle slopes that do not cause a significant extra risk for rutting. However the new heavier trucks with more axles that are coming on to road networks can cause larger displacements over weak subgrades, and can have the potential to cause new quick settlements and road failures. These types of settlements and failures typically happen at locations where a road goes from an embankment constructed on a peat subgrade to a firm subgrade, or vice versa. Examples of this have been seen in Swedish mine road projects. Settlement does not need to be uniform across a road. Heavy traffic in only one direction of the road can cause the active lane to settle much more quickly than the unloaded return lane, especially on the inner curves.

### 2.3.4. Design and Construction Errors

Design and construction errors can quickly become visible on road networks, and this can be expected to be the case in the future when the new heavier trucks are in use. Damages will be quickly seen on those road sections that have thinner pavement structures than designed. Bumps in the road caused by poorly designed and/or constructed culvert transition wedges and other transition wedges can cause high dynamic loading peaks to the pavement, and these can lead to local rutting and pavement damages. Similarly thin roads constructed on bedrock or blasted rock embankment will probably rut quicker – especially if the local road drainage is insufficient. In addition, reflection cracks on road widening joints will increase due to the heavier traffic loading.

## 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:

- I. Structural condition
- II. Functional condition
- III. Road width, geometry and optical guidance
- IV. Heavy vehicles that are using the road
- V. Traffic volume
- VI. Climate conditions
- VII. Load restrictions

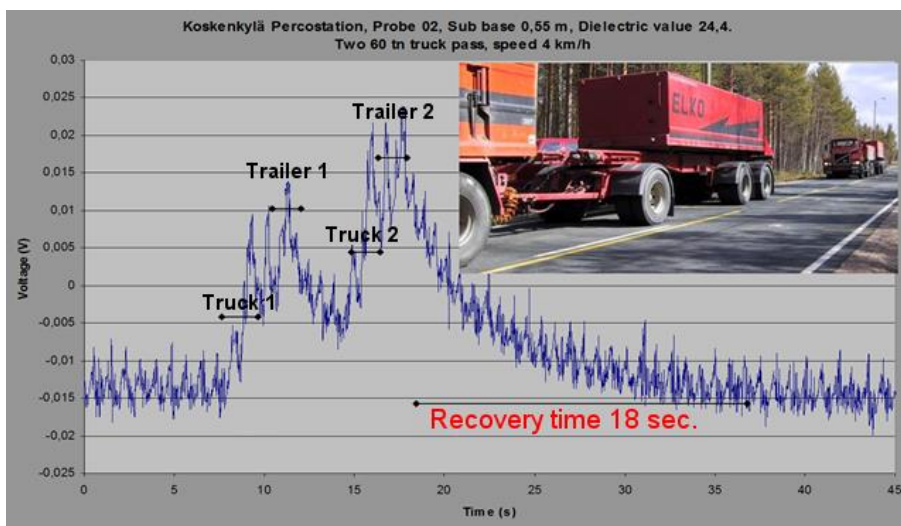
The effects of these factors on the condition of paved roads will be discussed in the following sections.

### 3.2. HEAVY VEHICLES AND TRAFFIC VOLUME

#### 3.2.1. Total Weights and Number of Axles

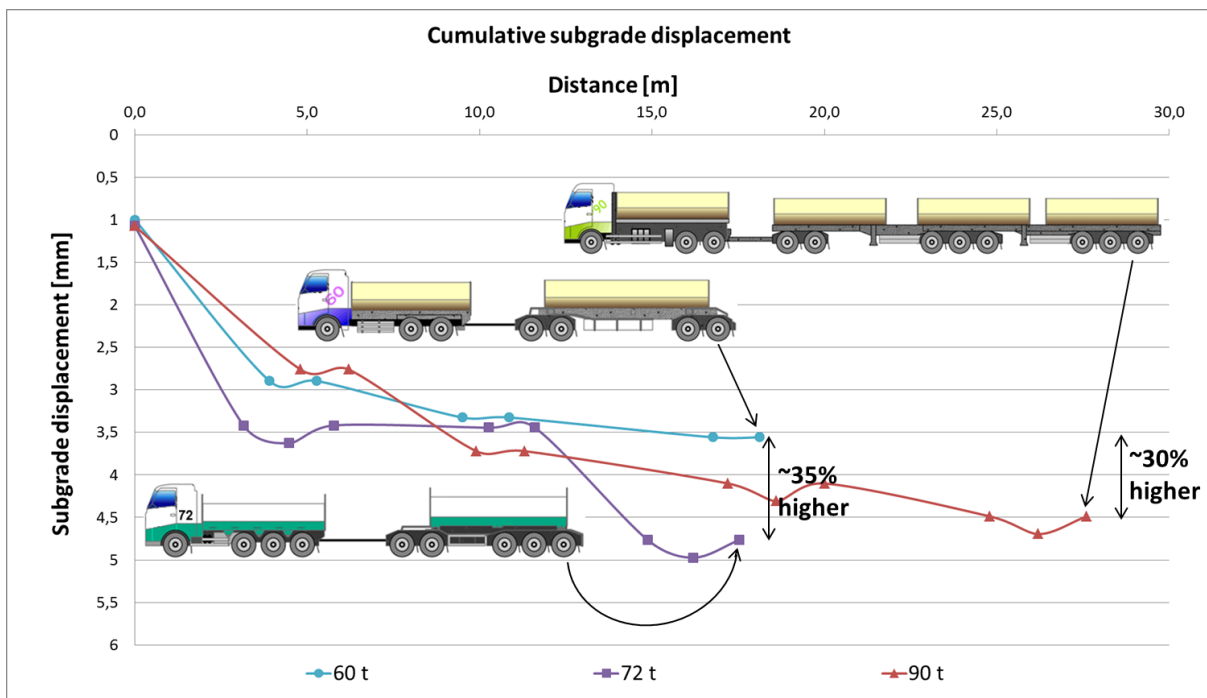
It is often stated that increasing the total weight of heavy vehicles does not have effect on road damages if and when the number of axles is increased. This is however false. The number of axles does matter. There are three factors that reduce pavement lifetime if the number of axles is increased.

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 7 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 porewater 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 7:** 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 sufficiently 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 loads the same spot. This reloading raises the porewater pressure in the subgrade and weakens it. Figure 8 shows an example from the ROADEX analyses of the effects of different heavy truck options on the Pajala mine road project. On the basis of the cumulative subgrade displacement evaluation, the 72 tonnes truck (with 9 axles) and the 90 tonnes truck (with 11 axles) are approximately on the same displacement level with each other with maximum cumulative displacement of approximately 30 - 35 % higher than the traditional 60 tonnes truck (with 7 axles). The higher displacements cause higher porewater pressure in the subgrade, which again leads to increased deformations and rutting speed.



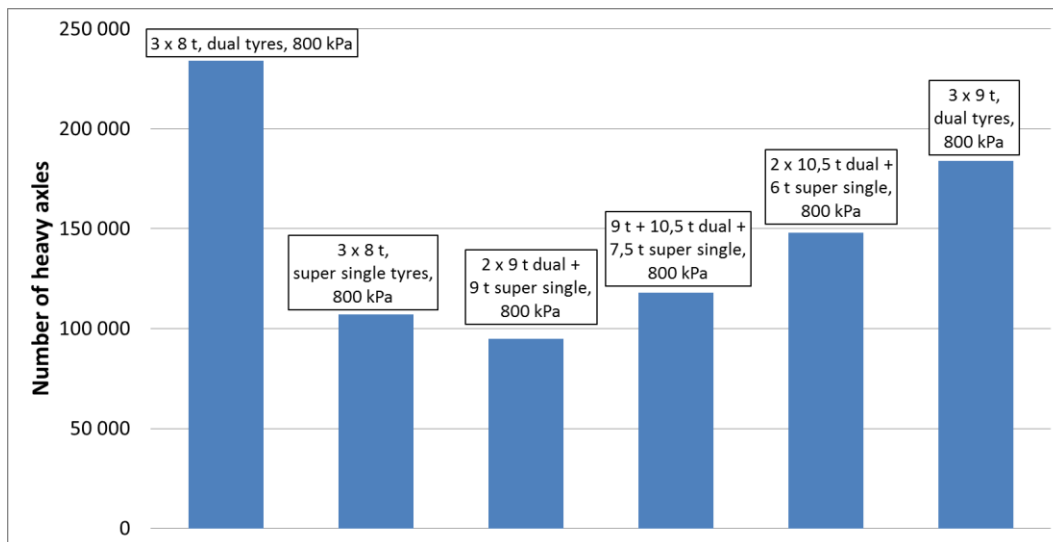
**Figure 8:** The cumulative displacement of a weak subgrade (modulus 10 MPa) calculated for three truck options. The horizontal axis presents the distance from the first axle of the truck. Zero is the first axle and the dots along the displacement curve represent the locations of the consecutive axles. The vertical axis displays the cumulative subgrade displacement calculated at one point. The maximum cumulative subgrade displacement with 72 tonnes truck (9 axles) and the 90 tonnes truck (11 axles) is approximately 30 - 35 % 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 the same wheel path, which leads to greater rutting speed.

### 3.2.2. Axle Configurations and Axle Weights

Different axle configurations cover the variation of axles on heavy trucks and the suspension of those axles. Section 3.2.1 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 ROADDEX 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 value which has been used in most of the calculations presented in this report. 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. (Saarenketo et al 2012).

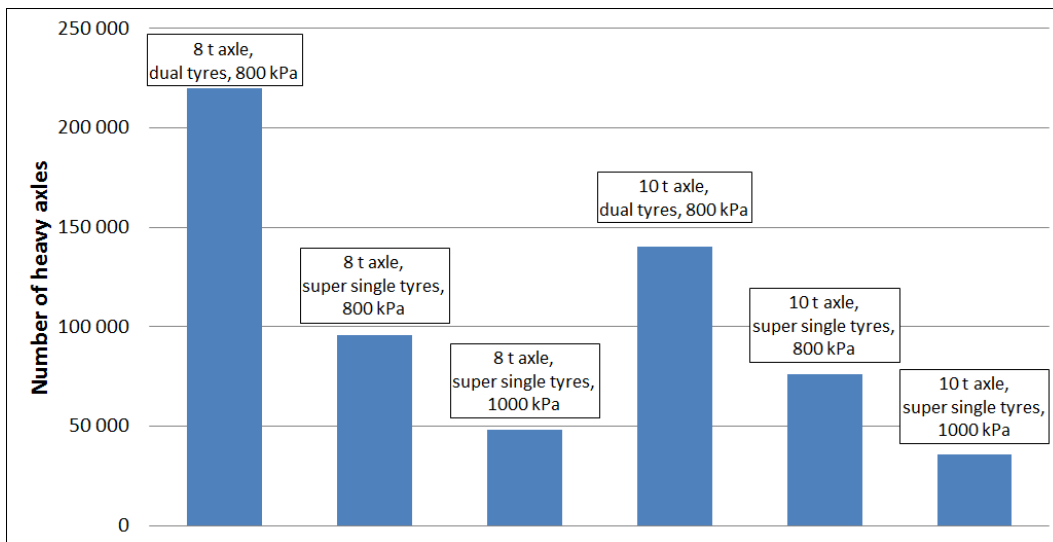
Axle weights have a great effect on the damage risk to a road. For instance in the new Finnish regulations the most critical dimensioning element is the triple bogie with maximum total weight of 27 tonnes. At least two axles of this triple bogie are required to be equipped with a dual tyre assembly. 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. Figure 9 shows an evaluation on the effect of different triple bogie axle configurations on pavement lifetime according to the calculations performed in the Finnish “Massat & Mitat” project. The road structure is from road 659 from Finland. It can be noted that even one axle with super single tyres has a dominant effect.



**Figure 9: The effect of different triple bogie axle configurations on pavement lifetime (number of heavy axle passes) in the normal (summer) conditions. The critical factor is the strain at the pavement bottom. The structure used in this calculation is from road 659 from Finland: pavement thickness is 84 mm and pavement modulus 1850 MPa, base course 110 mm / 260 MPa, other structures 860 mm / 100 MPa and subgrade modulus 25 MPa.**

Figure 10 presents a comparison 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.

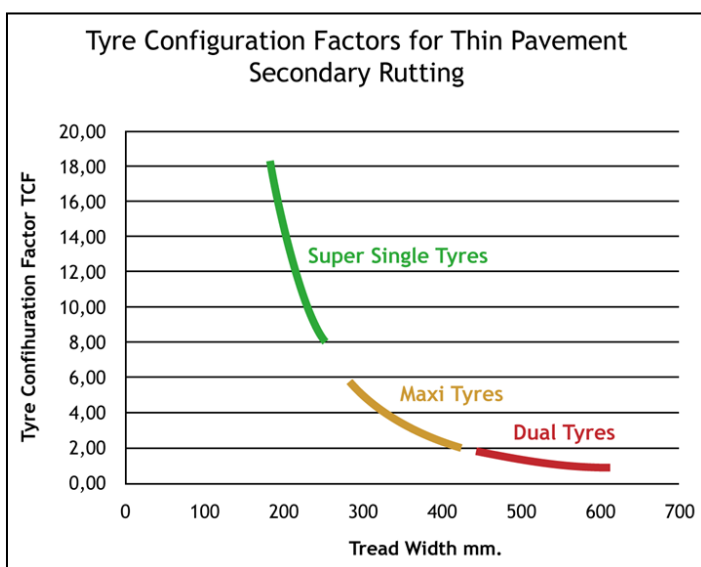
It can also be noted that the pavement lifetime with 1000 kPa tyre pressures can be half of the lifetime compared to 800 kPa tyre pressures. But as can also be seen, the effect of tyre type is even greater than the effect of tyre pressure. With same axle weight the estimated lifetime with dual tyres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



**Figure 10: 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. The structure is the same as in figure 9.**

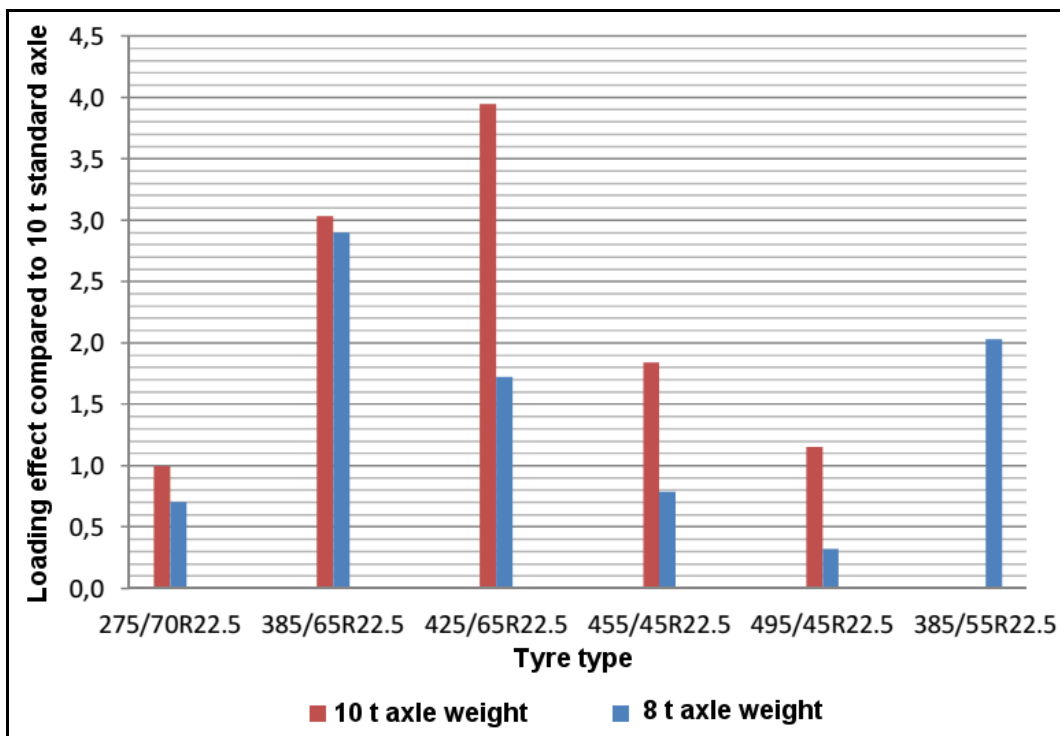
### 3.2.3. Tyre Types

Tyre type, and especially tyre width, has a great effect on the road stresses. Tyre type has the greatest effect on pavement fatigue and on Mode 1 rutting. However tyre width does not have significant effect on Mode 2 rutting. The stresses induced by single tyres are significantly higher than the stresses induced by dual tyres, as can be seen from Figures 9 and 10. In Europe in the 90's almost all heavy vehicles were equipped with dual tyres, but 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 ROADDEX countries the rutting speed can be 8-18 times higher with super single tyres than with dual tyres (Figure 11). The "Tyre Configuration Factor" value, presented in Figure 11, 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 11: 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. (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 (Saarenketo et al. 2014). For instance the results of the tests on the Vesilahti road, presented in Figure 12, 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 (Haakana 2014).



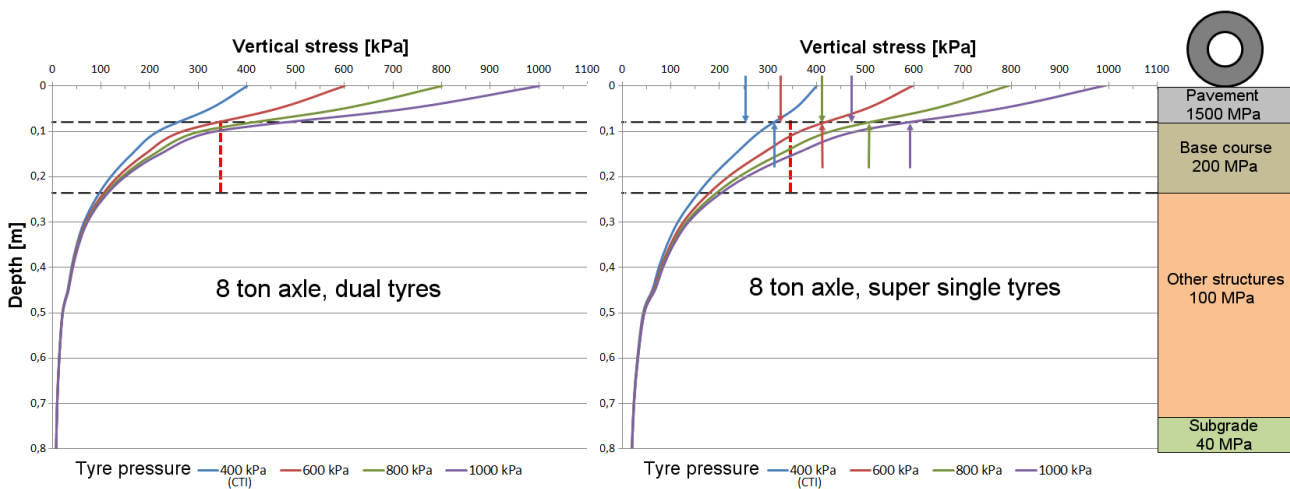
**Figure 12: The loading effect of different tyre type and axle weight configurations compared to standard axle (dual tyres 275/70R22.5, axle weight 10 tonnes). The bar on the right represents the front tyre of the truck with a 7.4 tonnes axle weight. (Haakana 2014)**

### 3.2.4. 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 and transportation costs. Tests on Finnish roads in 2013 have shown that the trucks tested were using tyre pressures even higher than 1100 kPa (Finnish Massat & Mitat project 2014). This is not illegal in most countries of course 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 a lot of information on these systems (available on ROADEx website [www.roadex.org](http://www.roadex.org)). 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 13 presents an example 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 10). 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 13: 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.**

### 3.2.5. Pumping Effect and Recovery Times

When discussing the effect of heavy vehicles on road structures it is also important to take pumping effects and recovery times into account. Their negative effects can be controlled by using appropriate road friendly vehicles and by ensuring long enough time slots between heavy haulage units with enough time for the road to recover from the stresses caused by the previous vehicle.

Minor public roads and weaker forest roads will deflect under the weight of a truck. Much of the stress created by the load is however temporary and the road will recover after a period, leaving little or no permanent strain in the surface layer or subgrades. Pumping problems develop when the road structure deflects on a weak subgrade under a heavy axle loading and squeezed against saturated subgrade. When the loading has passed and the deflection has recovered, water in the road structure cannot flow away as quickly as previously. Due to this water rises higher and higher in the structure under consecutive load repetitions, which weakens the structure, increases deflections and makes the pumping effect even worse. This can lead to both Mode 1 and Mode 2 rutting problems.

Pumping effects can also be seen on major highways during spring thaw periods when the subgrade is still frozen, but the base course is thawing and saturated with water. Where this happens consecutive heavy axle load repetitions can cause water to pump up through the pavement (Figure 14).

Ideally truck traffic on weaker roads should be well-spaced throughout the day. Convoys of heavy vehicles should be avoided on all weak roads. The spaces between vehicles should be monitored using for instance GPS and mobile data transfer technologies. These systems could even be an alternative to load restrictions in the future.



**Figure 14: Water pumping through the pavement due to heavy vehicle super single tyre loading, an example from Finland from highway 4 between Oulu and Jyväskylä. The base course is thawing a little bit quicker below darker areas of the pavement.**

### 3.2.6. New Vehicle Technology

As the new partially automated steering systems on trucks come into wider use in the future the stresses on exactly the same wheel path will be heavily increased. These trucks drive ‘like a train’ with every wheel loading exactly the same spot on the road cross section. This action will increase the potential for rutting, as the benefit of tyre wander is lost (see Figure 3).

Another vehicle technology that has effect on the stresses and strains induced into a road structure is the vehicle suspension. The axle weight (and further the static loading component) remains the same regardless of the suspension system, but compared to traditional suspension the use of air suspension may reduce the dynamic loading component caused by the unevenness of the road surface.

## 3.3. ROAD STRUCTURES AND THEIR CONDITION

### 3.3.1. General

The factors affecting the bearing capacity of a road structure are: the thickness of the structural layers, the quality of the construction materials, and the moisture conditions. Seasonal changes should be taken into account as well. A road structure that is frozen to the depth of 30 cm is so stiff that it in practice does not fatigue at all, apart from studded tyre wear.

When the bearing capacity of a road is evaluated and measured using a falling weight deflectometer, the loading used is a point-like pulse rather than a moving load. In roads however

the moving traffic load causes a more complex dynamic loading phenomenon and this is normally considered as having 3 effects: 1) the stresses in the pavement structure caused by the moving wheel load, 2) the time dependent response of the road materials, and 3) the stresses induced by impact loads ([www.roadex.org](http://www.roadex.org)). At this time only the variables of effect 1 can be evaluated. The effects 2 and 3 can be identified using modern measurement devices, but the amount of those effects cannot be measured with current instrumentation yet.

### 3.3.2. Structural Condition

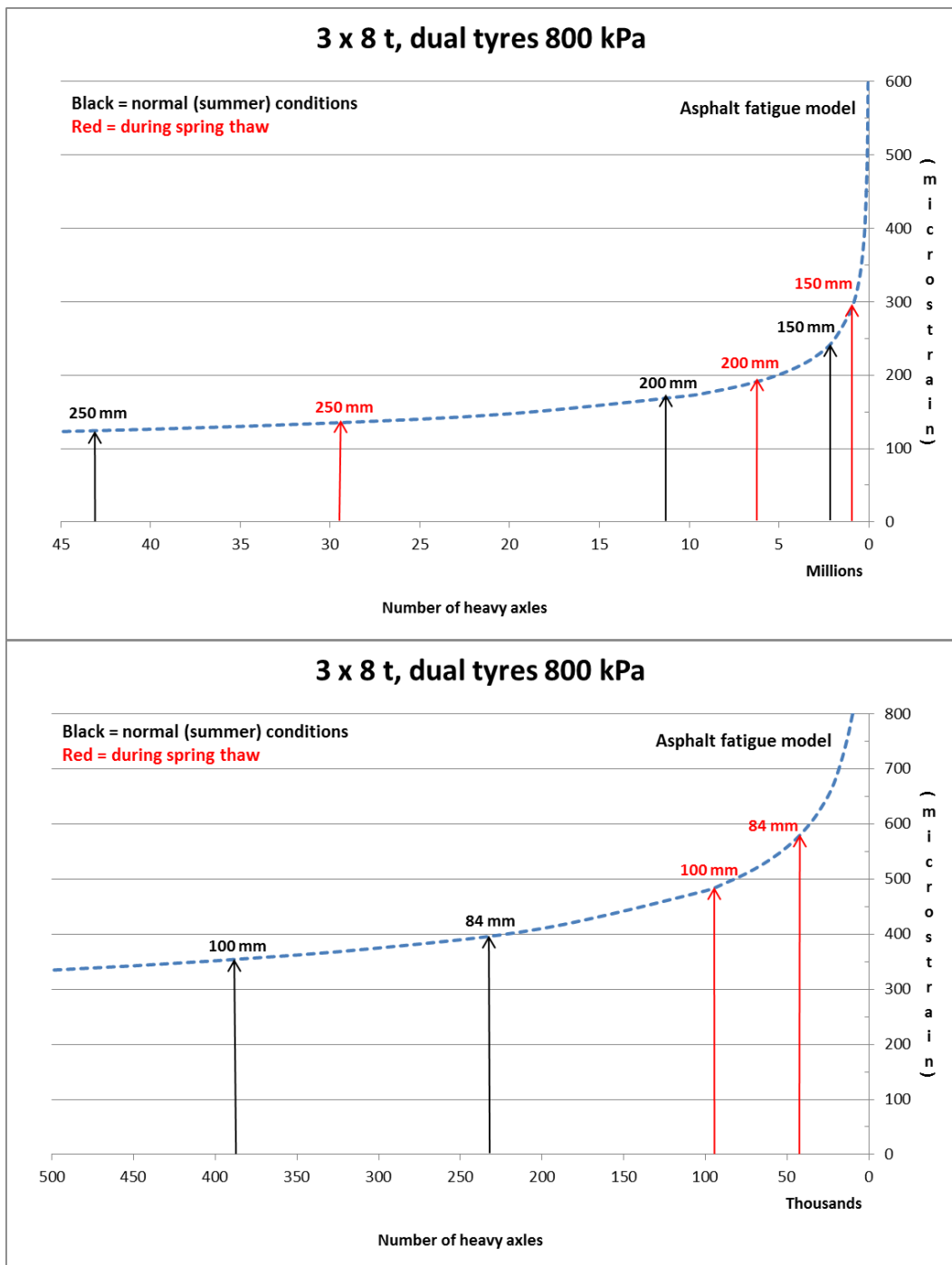
The most critical factors related to pavement fatigue or Mode 1 rutting are the pavement thickness, the total thickness of the bound layers, and the quality of the base course material. The corresponding critical factors relating to Mode 2 rutting are the total thickness and the stiffness of the whole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

Figure 15 presents an example on the effect of pavement thickness on asphalt pavement fatigue and lifetime based on BISAR software calculations. The curve in the figure presents the fatigue model for asphalt pavement derived from Finnish design guideline. On the horizontal axis there is the number of heavy axle passes and on the vertical axis the strain at the pavement bottom. Normally pavement fatigue curves are presented as log-log scale but in this case the effect of increasing strain at the end of pavement life time is more visual. The figure shows clearly how dramatic the effect of increase pavement thickness is for the pavement lifetime. For example with 84 mm pavement thickness, which is normal in Nordic countries, the lifetime is 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 will be about 11million axles during summer and 6 million axles during the spring thaw.

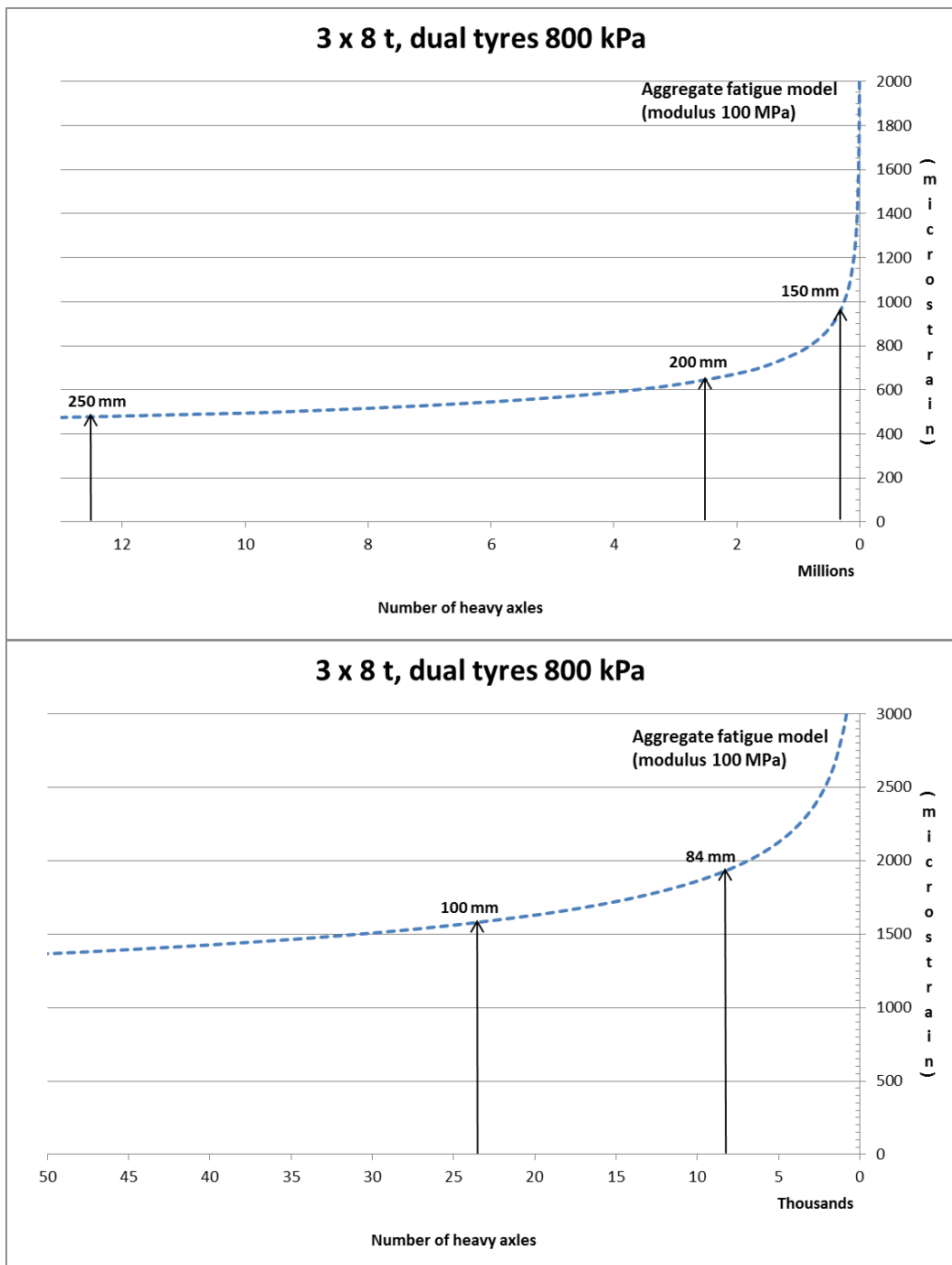
If asphalt is the “weakest link” during the summer condition, during the spring thaw the most critical factors are the deformations taking place in the weakened unbound base course, as can be seen from Figure 16. The curve in this figure presents the corresponding fatigue model for crushed rock aggregate with modulus of 100 MPa. The figure shows that increasing the pavement thickness from 100 mm to 200 mm increases the lifetime during spring thaw from less than 25 thousands of axles to almost 25 millions of 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 Massat & Mitat project. The main reason for this is probably frost and thawing ice lenses.

The maintenance level and particularly the drainage condition are also important factors affecting the structural condition of a road. The most common damages due to poor drainage are presented in chapter 2.3.1.



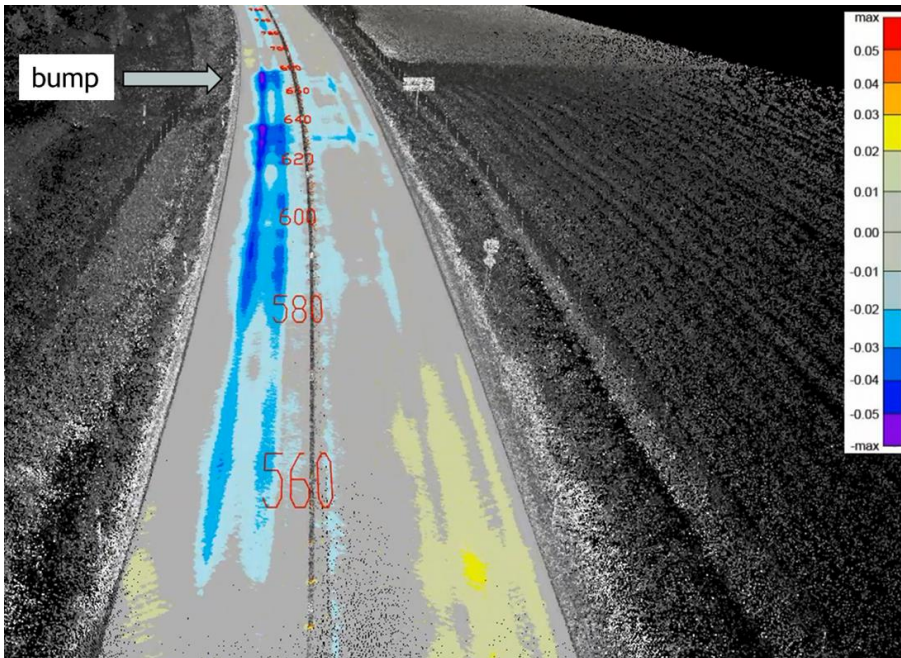
**Figure 15: An example of the effect of pavement thickness on ASPHALT PAVEMENT fatigue and lifetime (number of heavy axles) during summer conditions and during spring thaw period based on BISAR calculations. The upper curve presents the whole series of 45 million axles and the lower curve presents the last 500,000 axles from the same series. The axle and tyre configuration used in the example calculation is 3\*8 tonnes triple bogie with dual tyres and 800 kPa tyre pressure. The example structure is from road 659 from Finland: pavement modulus 1800 MPa, base course 110 mm / 260 MPa, other structures 860 mm / 100 MPa and subgrade modulus 25 MPa.**



**Figure 16: An example of the effect of pavement thickness on UNBOUND BASE COURSE fatigue and lifetime (number of heavy axles) during spring thaw period based on BISAR calculations. The upper curve presents the whole series of 13 million axles and the lower curve presents the last 50,000 axles from the same series. The axle and tyre configuration used in the example calculation is 3\*8 tonnes triple bogie with dual tyres and 800 kPa tyre pressure. The example structure is the same as in the previous figure and the road has thawed from the surface to the depth of 300 mm.**

### 3.3.3. 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 17 shows an example of such case from Sweden. A 120 metre long section of high rutting can be seen after the single bump on the road.



**Figure 17: 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.**

## 3.4. ROAD WIDTH, GEOMETRY AND OPTICAL GUIDANCE

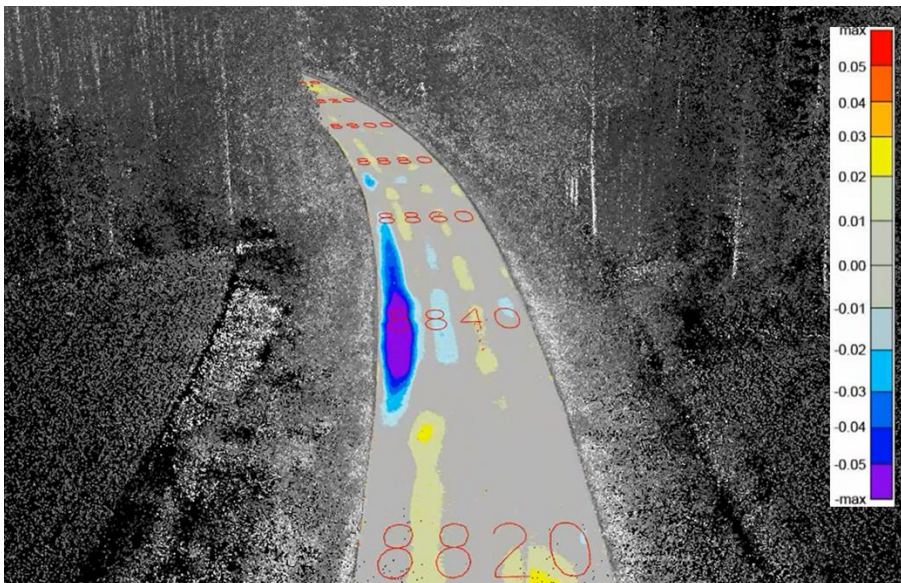
Road width can have an appreciable effect on the deterioration and rutting of a road. On main roads the wide road shoulder acts as a supporting structure and effectively prevents shoulder deformation problems taking place. Also on wider roads, vehicles are not so likely to drive on the same wheel paths, which decreases the studded tyre wear and pavement fatigue due to heavy vehicles. As already mentioned earlier, in the future rutting is likely to increase as the benefit of tyre wander is lost due to the new partially automated steering systems on trucks.

Drivers, and hence vehicles, tend also to drive on the same wheel path when exposed to optical guidance. As an example, the rate of rutting on road sections with adjacent side and mid rails is often much quicker than on sections without any rails. An example of such a case is illustrated in Figure 18.



**Figure 18: High rutting and top down cracking on a road section with side and mid rails due to optical guidance.**

Road geometry can also have a great effect on the amount of rutting incurred on a road. Typical of such areas are tight inner curves where the truck trailers cut corners near the road edge. At these locations, especially if the drainage is not working properly, rapid deformation may take place (Figure 19).



**Figure 19: An example from a rutting video based on laser scanner point cloud technology. High deformation can be observed on the inner curve close to the road edge. The drainage condition on the left side of the road is clearly poor.**

### 3.5. LOAD RESTRICTIONS

The load bearing capacity of a road can be managed by using load restrictions, meaning that the axle weights and/or total weights of heavy vehicles are limited from the maximum allowed values, either temporarily or permanently. However, load restrictions are often regarded as an extreme way of protecting the very weakest roads.

Permanent load restrictions are normally used on a road when it is considered that the road has insufficient construction to carry the expected heavy traffic, other than when it is frozen during winter. The aim of a permanent restriction is to reduce the imposed stresses on a road structure, and the risk of permanent deformation. Permanent restrictions can also be used where there are weak bridges. Within the ROADDEX partner areas, permanent restrictions are commonly used in Norway, but they are also used to some extent in Sweden, Finland and Scotland.

Temporary weight restrictions are used in most areas where the road structure is frozen for at least part of the year. During the critical seasons, when the bearing capacity of the road is at its weakest, many weak low volume roads need protection. Examples of this can be found in Scandinavia, Russia, northern China, Canada and the northern USA. Scotland also uses temporary weight restrictions. Norway is an exception to this general practice. Temporary weight restrictions have not been permitted there since 1995 and only permanent weight restrictions are used on weak roads ([www.roadex.org](http://www.roadex.org)).

In the event that a road organisation begins to consider applying a road restriction the questions normally asked are: a) Which are the roads/road sections should be restricted? b) Is there a need for a temporary load restriction every year? c) When it should be applied? d) What is the maximum axle load or total weight that should be imposed? e) When can the load restrictions be removed? and f) How will the loads be monitored during the restrictions? Each country has their own policy and these systems are described in detail in ROADDEX reports on spring thaw weakening.

## 4. CALCULATION EXAMPLES

### 4.1. GENERAL, SURVEY SITES AND SURVEY METHODS

A number of calculations of estimated lifetimes were carried out on a range of example road structures from Finland, Scotland, Norway and Sweden in order to present the effect of different axle and tyre configurations, tyre pressures and truck options on various pavement structures.

#### Finland

This section will refer mainly to the results of the Finnish “Massat & Mitat” (weights & dimensions) project, where the main goal was to evaluate the structural and functional condition of the Finnish road network and the main risks and consequences after the new heavier trucks start trafficking them. Detailed surveys were carried out on ten road sections across Finland. Three of the sections were on main roads, and seven of the sections were on regional roads. The sections were chosen based on the information that they would be soon trafficked with the “new” heavy trucks. The length of each section was about 15-20 km.

A short, weaker sub-section (from few hundred metres to one kilometre) was selected from each of the ten road sections for more detailed calculation using BISAR® software. Each section had fairly uniform GPR and falling weight deflectometer measurements over its length. Average thickness values from the selected sections were used for the lifetime calculations. The moduli of each structural layer and the subgrade were backcalculated from FWD measurements. These values represented the normal unfrozen situation, the so called “summer conditions”.

The frost thawing period was simulated as follows: the pavement was assumed to be thawed and its modulus was set to be the same as in summer. 250 mm of thawed material was assumed under the pavement and beneath that a frozen layer (modulus 1000 MPa). The moduli values for the thawed layer were chosen on the basis of the results of the base course material quality tests. The moduli values used were: 200 MPa for good quality, 150 MPa for medium and 100 MPa for poor quality material. The properties of the Finnish example structures are summarised in Table 1.

**Table 1: Properties of the Finnish example structures**

Road / distance interval	Pavement		Base course		Other structures		Subgrade
	thickness [mm]	modulus [MPa]	thickness [mm]	modulus [MPa] / modulus thawing [MPa]	thickness [mm]	modulus [MPa]	modulus [MPa]
<b>Hw 4 / 12700 - 13700</b>	153	2110	204	450 / 150	1175	130	38
<b>Hw 8 / 8500 - 8900</b>	197	2650	155	350 / 200	422	175	63
<b>Hw 15 / 9100 - 10000</b>	266	3500	176	400 / 150	220	108	41
<b>Rd 204 / 21800 - 22400</b>	150	2700	145	400 / 150	774	138	22
<b>Rd 325 / 350 - 1650</b>	85	3500	161	450 / 150	1119	150	38
<b>Rd 434 / 5350 - 6000</b>	96	2650	539	269 / 200	-	-	49
<b>Rd 531 / 4500 - 4900</b>	84	2860	101	346 / 150	865	138	44
<b>Rd 659 / 6450 - 6650</b>	84	1840	110	263 / 150	860	101	25
<b>Rd 800 / 10900 - 11700</b>	92	2210	150	350 / 150	395	200	70
<b>Rd 924 / 7450 - 7750</b>	110	1170	130	440 / 150	560	172	22

### Scotland

As there was no intention to raise the total weights of trucks in Scotland the Scottish calculations were focused on evaluating the effect of tyre type and tyre pressure on the lifetime of the road.

These lifetime calculations were made for selected structures already surveyed within ROADDEX demonstration projects in Scotland. Four example structures were chosen for the calculation along the surveyed road A83. The properties of the example structures are shown in Table 2. It can be observed from these that the pavement thickness was generally around 200 mm on each of the sections, but that the pavement modulus was lower on the first and the third section. The modulus of the unbound structures was lower on these sections as well. The subgrade modulus was around 20 MPa on three sections and according to the FWD measurements on those sections the Base Curvature Index (BCI) values were high (>60). On one section the subgrade modulus was 43 MPa and the BCI value was also better (<40). The total thickness of the whole structure was quite thin, varying between 0.5 and 0.6 metres.

**Table 2: Properties of the Scottish example structures**

Road / distance interval	Pavement		Unbound structures		Subgrade
	thickness [mm]	modulus [MPa]	thickness [mm]	modulus [MPa]	modulus [MPa]
<b>A83 / 750 - 1250</b>	197	1470	362	183	19
<b>A83 / 1250 - 1840</b>	195	2160	389	403	43
<b>A83 / 1840 - 2340</b>	209	1400	317	154	20
<b>A83 / 3300 - 4300</b>	219	2550	346	356	23

### Norway

Similar lifetime calculations to those in Scotland were carried out for selected structures surveyed in Norway. Three example structures were chosen for the calculation along the surveyed road Rv94. The properties of the Norwegian example structures are presented in Table 3. The main differences in the Norwegian structures compared with the Scottish structures was that the pavement thickness was thinner (slightly over 100 mm) on each of the sections, and the total thickness of the whole structure was somewhat thicker (between 0.7 and 0.8 metres) and the subgrade modulus was a bit higher. According to the FWD measurements on all of these three sections the horizontal strain values at the pavement bottom were high (400-600  $\mu$ strain).

**Table 3: Properties of the Norwegian example structures**

Road / distance interval	Pavement		Base course		Other structures		Subgrade
	thickness [mm]	modulus [MPa]	thickness [mm]	modulus [MPa]	thickness [mm]	modulus [MPa]	modulus [MPa]
<b>Rv94_HP2 / 3000 – 6500</b>	106	1690	110	278	511	146	50
<b>Rv94_HP3 / 4100 – 5800</b>	117	1840	107	177	589	94	33
<b>Rv94_HP3 / 8800 – 9450</b>	118	1920	71	222	604	114	25

For Scotland and Norway the calculations were performed for an 8 tonnes axle with super single tyres (representing the steering front axle of a truck) using tyre pressures of 600, 700, 800, 900 and 1000 kPa to simulate the effect of tyre pressure on the stresses and strains induced into the road structure. In addition, calculations were also carried out for a 3\*8 tonnes triple bogie equipped with super single tyres and dual tyres to compare the effect of different tyre types on the stresses and strains, and further on the lifetime of road structures.

There are three positions in the road structure that are the most critical for the development of damages and permanent deformation. 1) The horizontal tensile stress and strain at the bottom of

the bound layers. High values of strain indicate a risk of pavement fatigue. 2) The vertical compressive stress and strain at the upper part of the unbound layers. The stresses and strains in this position are the most critical for the development of Mode 1 rutting. 3) The vertical compressive stress and strain on the top of the subgrade. The stresses and strains in this position are the most critical for the development of Mode 2 rutting.

In the example calculations the effect of tyre pressure and tyre type were evaluated separately for each of the three critical parts of the road structure: the pavement (bound layers), the unbound layers and the subgrade. The resilience models and the failure criteria of different structural layers were derived from the Finnish design standard that is quite similar to corresponding practices used in other countries. Based on this the remaining number of load cycles (10 tonnes standard axles) was obtained. However, the absolute values of the calculated lifetimes are not so important in this case, only the differences between options.

For the Finnish example road sections the remaining lifetime as years or as days was also calculated on the basis of the heavy traffic AADT of each road section (assumption used: 3.0 standard axles/heavy vehicle).

### Sweden

The calculations carried out for the example road structures in Sweden were somewhat different to the other countries. Calculations were made for five different predefined truck configurations, including the proposed new 74 tonnes combination, to evaluate the loading effect of these trucks compared to standard axle (10 tonnes axle with dual tyres), and further to evaluate the “truck wear factor” of the new heavier combinations compared to traditional 60 tonnes truck.

At first the equivalent loading effect of each truck option compared to standard axle (10 tonnes axle with dual tyres) was calculated. In other words, the number of standard axle passes that corresponded to one pass of the whole truck combination was calculated. For instance the equivalent number of a standard 60 tonnes truck with 7 axles equals 5.61 standard axles. These calculations enabled a comparison of truck options with different axle and tyre configurations with each other.

Following this first stage, truck wear factors were calculated by comparing the equivalent loading effects of each of the heavier truck options to the equivalent loading effect of the 60 tonnes truck. The truck wear factor follows the same principles as presented in Scottish “Tread Softly” report (2014).

Table 4 shows the properties of the example structure used in the calculations for Sweden. The structure is the same as that of the proposed rehabilitation structure for the Pajala mine road during the impact analysis project, except that the calculations were carried out on two different pavement thicknesses. Example calculations of the cumulative displacement of a weak subgrade, presented in Figure 8, were also made for the Swedish structure. However it should be noticed that the top part of the pavement structure is relatively strong and much stronger than on weak low volume roads in Sweden.

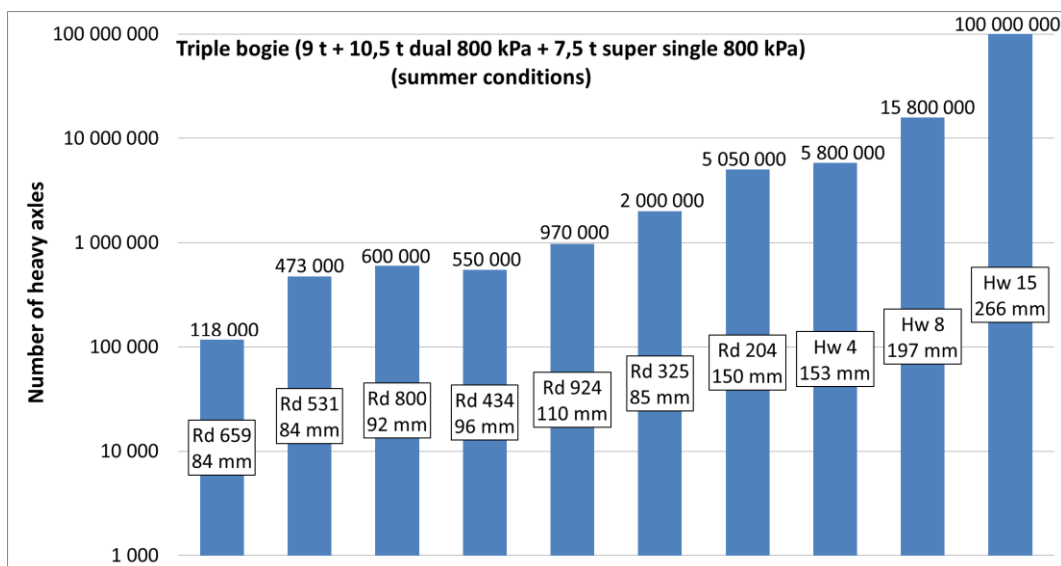
**Table 4: Properties of the structure used in the Swedish calculations**

Pavement		Base course		Subbase course		Other structures		Subgrade
thickness [mm]	modulus [MPa]	thickness [mm]	modulus [MPa]	thickness [mm]	modulus [MPa]	thickness [mm]	modulus [MPa]	modulus [MPa]
100 / 200	3000	225	300	128	200	643	100	10

## 4.2. FINLAND

The results of the Finnish calculations show that tyre type, and especially tyre width, has a great effect on road stresses. The stresses induced by single tyres are significantly higher than the stresses induced by dual tyres, which in turn means significantly shorter pavement lifetime. Besides tyre types, tyre pressure has also an effect on the pavement surface pressure, and further on the stresses and strains in the upper parts of the pavement structure as well as pavement fatigue.

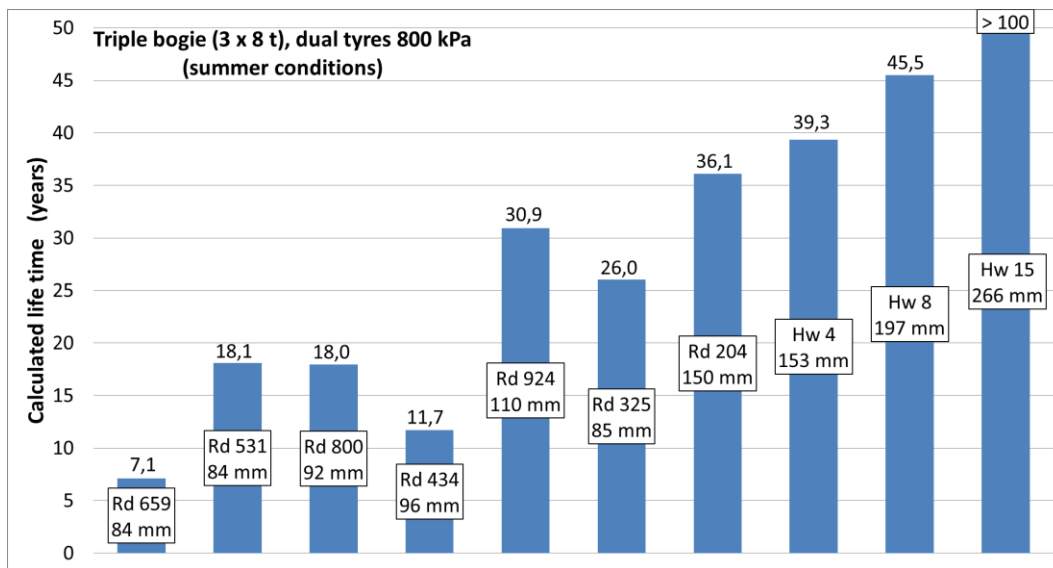
Figure 20 shows the theoretical lifetime as a number of heavy axles for each of the ten test sites during summer conditions. The calculations were based on the 27 tonnes triple bogie axle configuration allowed for trucks (not trailers) in Finland. The distribution of the axle weights inside the triple bogie is an estimate made by experts representing Finnish Transport and Logistics. The pavement thickness of each section is shown below the road number. Please note that the vertical axis in the figure is a logarithmic scale. Even though the properties of the structural layers differ from each other, the effect of pavement thickness can be clearly seen in the figure. The results from the Finnish calculations generally showed that if the pavement thickness is approximately 200 mm or more, the stresses and strains in the pavement and in the base course are usually so low that the theoretical lifetimes obtained are in the order of at least 10 million axles. Even with a pavement thickness of 150 mm millions of heavy axle passes are still calculated. However, if the pavement thickness is less than 100 mm, the number of heavy axle passes obtained is reduced significantly even in the summer conditions, but especially during the spring thaw.



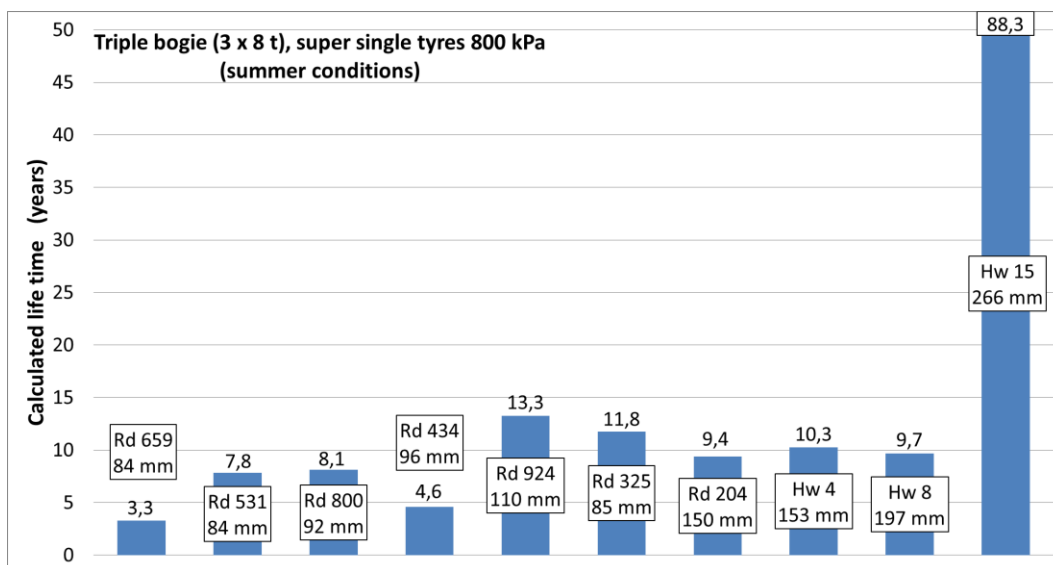
**Figure 20: Calculated theoretical lifetimes as a number of heavy axle passes for each of the ten test sites during summer conditions calculated with the new 27 tonnes triple bogie axle configuration allowed for trucks (not trailers) in Finland. The pavement thickness of each section is shown below the road number. Note that the vertical axis in the figure is to a logarithmic scale.**

These theoretical calculations clearly show that the axle and tyre configurations of new heavy trucks can significantly increase the stresses in the upper layers of road structures. The calculated stresses were however generally on the same level with pavement lifetime predictions using super single tyres, already allowed in Finland. This has a great effect on the remaining lifetime of the road (see Figures 21, 22 and 23). In a normal (summer) case the theoretical number of load cycles with the new trucks will be approximately half of the number of those using existing trucks. On roads with higher AADT the effect will be even higher. The only exception was highway 15 with its thick pavement (>250 mm).

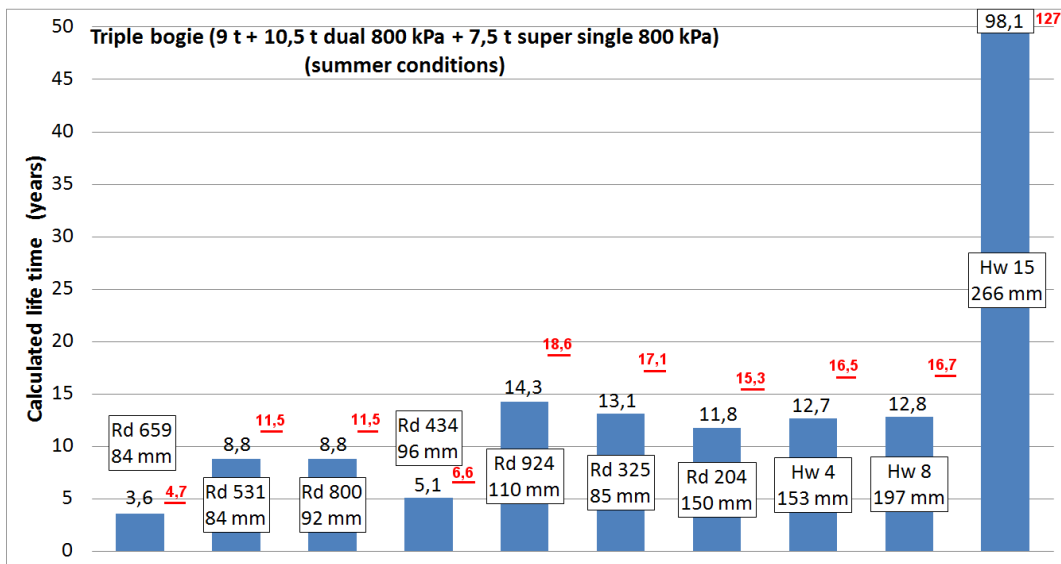
Comparing figures 22 and 23 it will be seen that the new triple bogie 27 tonnes axle is more road friendly option for Finnish roads compared to the case where all the truck would have been equipped with 2\*8 tonnes axles with super single tyres.



**Figure 21: Predicted theoretical lifetime in years for each of the ten test sites during summer conditions calculated with 24 tonnes dual tyre triple bogie axle configuration. This represents the earlier situation, before the maximum allowed axle weights were raised and super single tyres were not yet in use.**

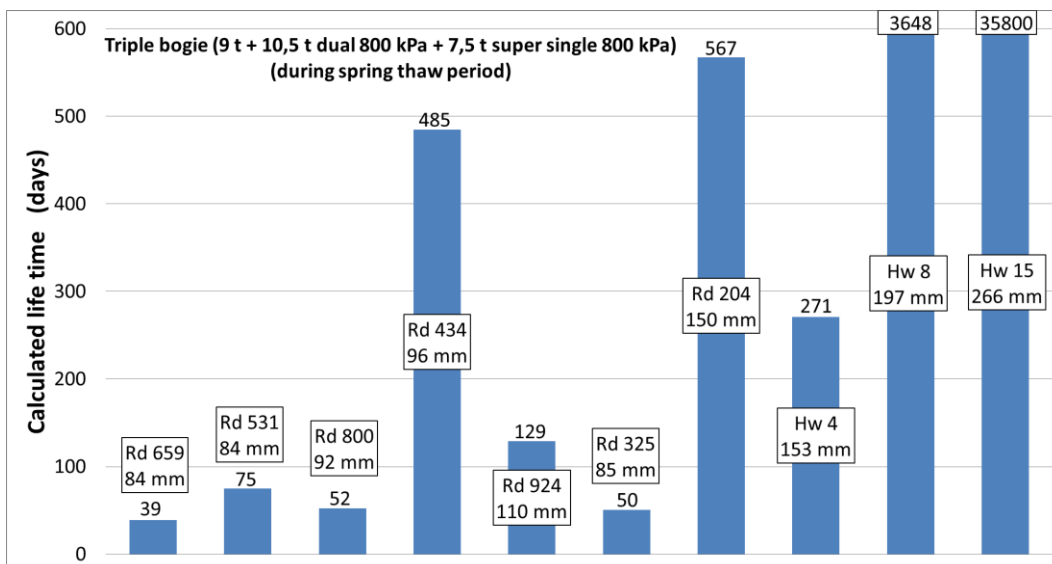


**Figure 22: Predicted theoretical lifetime in years for each of the ten test sites during summer conditions calculated with 24 tonnes super single triple bogie axle configuration. This represents the situation if all heavy trucks were using super single tyres. The total weight of the bogie is still the same as in Figure 21.**



**Figure 23: Predicted theoretical lifetime as years for each of the ten test sites during summer conditions calculated with the new 27 tonnes triple bogie axle configuration allowed for trucks (not trailers) in Finland. This represents the situation in the future if all heavy trucks were equipped as new combinations. The lifetimes marked in red represent the situation if the AADT of the heavy vehicles would decrease in same proportion as the net weight is increased.**

The effects on lifetimes however are much worse during the spring thawing season; on almost half of the analyzed regional roads the calculated remaining lifetime during spring thaw conditions was less than 100 days (Figure 24). Normally the critical spring thaw period in Finland lasts 2-3 weeks/year, so this means that some roads would have only a few years lifetime. And if the spring thaw period is difficult major failures could appear within one year.



**Figure 24: Predicted theoretical lifetime (days) of each of the ten test sites during spring thaw period calculated with the new 27 tonnes triple bogie axle configuration allowed for trucks (not trailers) in Finland.**

## 4.3. SCOTLAND

### 4.3.1. The Effect of Tyre Pressure

Figure 25 shows the results of the pavement lifetime calculations with different tyre pressures on each of the four structures considered in Scotland. Here, the effect of tyre pressure on the lifetime of pavement is very clear. Although the total calculated amounts of heavy axles are different, the same trend can be seen on each of the figures: the calculated pavement lifetime reduces approximately to half if the tyre pressure rises from 600 kPa to 1000 kPa.

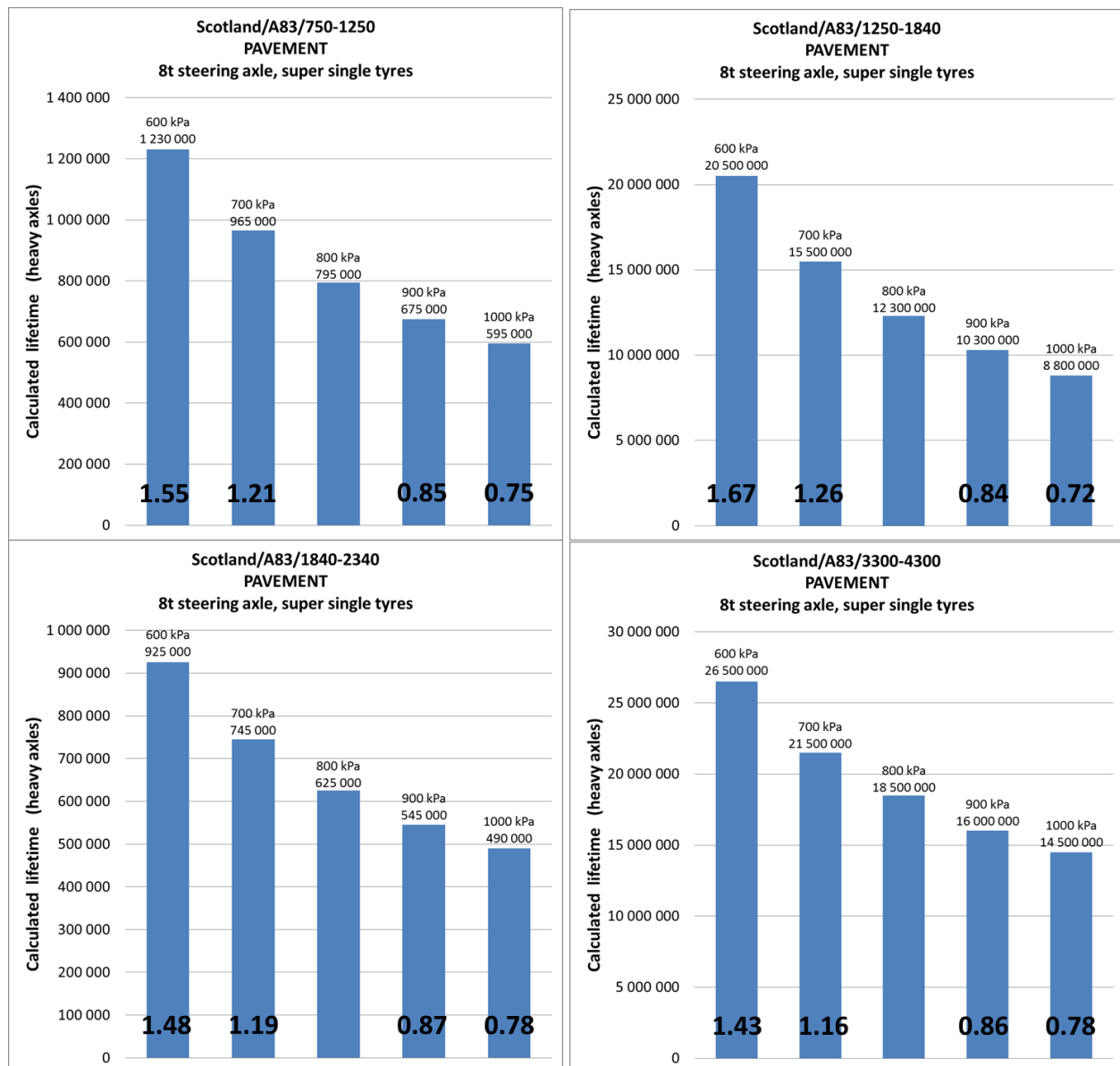


Figure 25: The effect of tyre pressure on pavement lifetime. NB Note the different scales on the vertical axes of the different structures.

The same trend can be seen in the unbound structures with a slightly greater effect. The results of the unbound structure lifetime calculations on each of the four sections are summarised in Figure 26. The calculated lifetime with 1000 kPa tyre pressure is less than half of the lifetime obtained with 600 kPa.

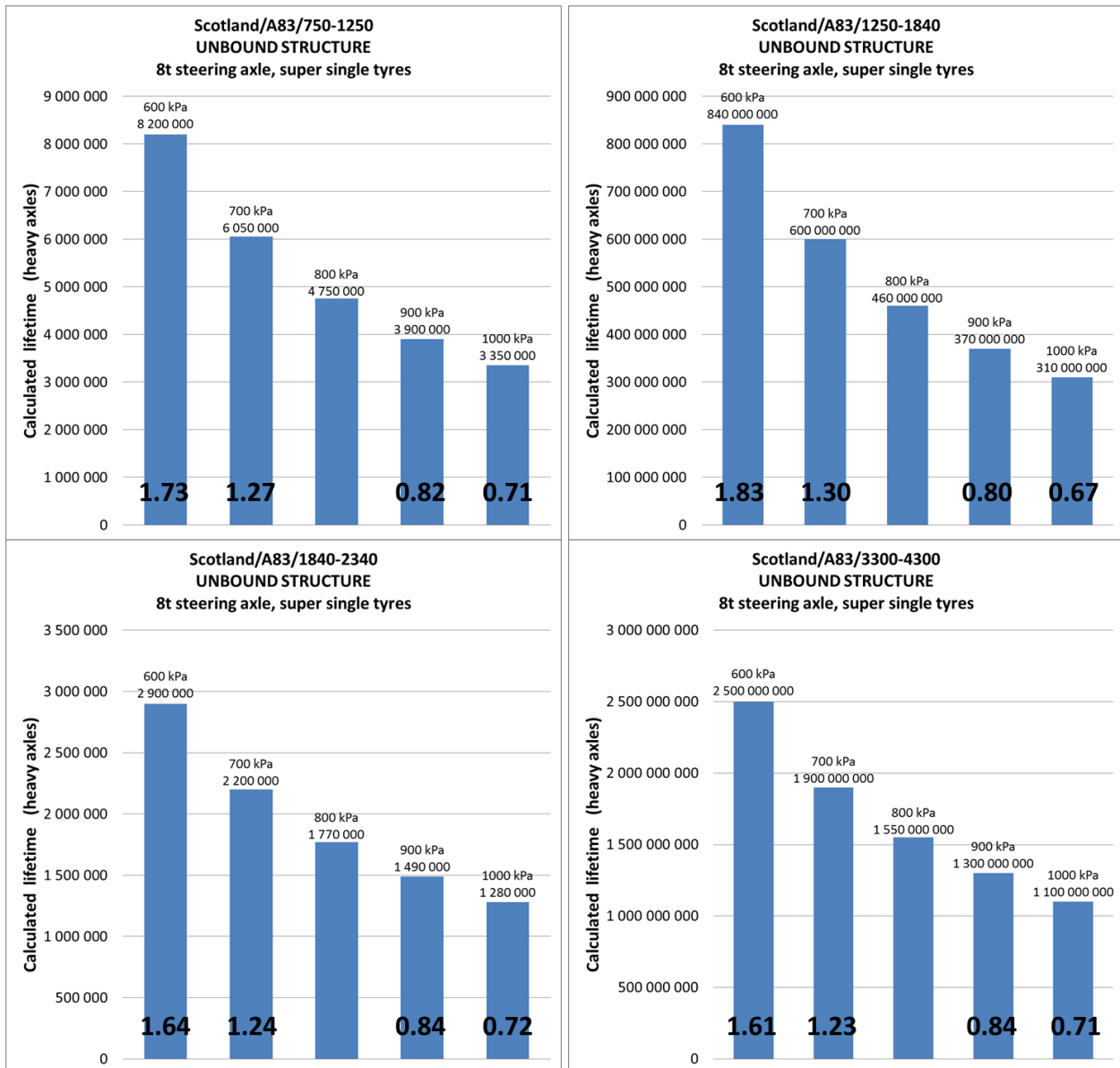
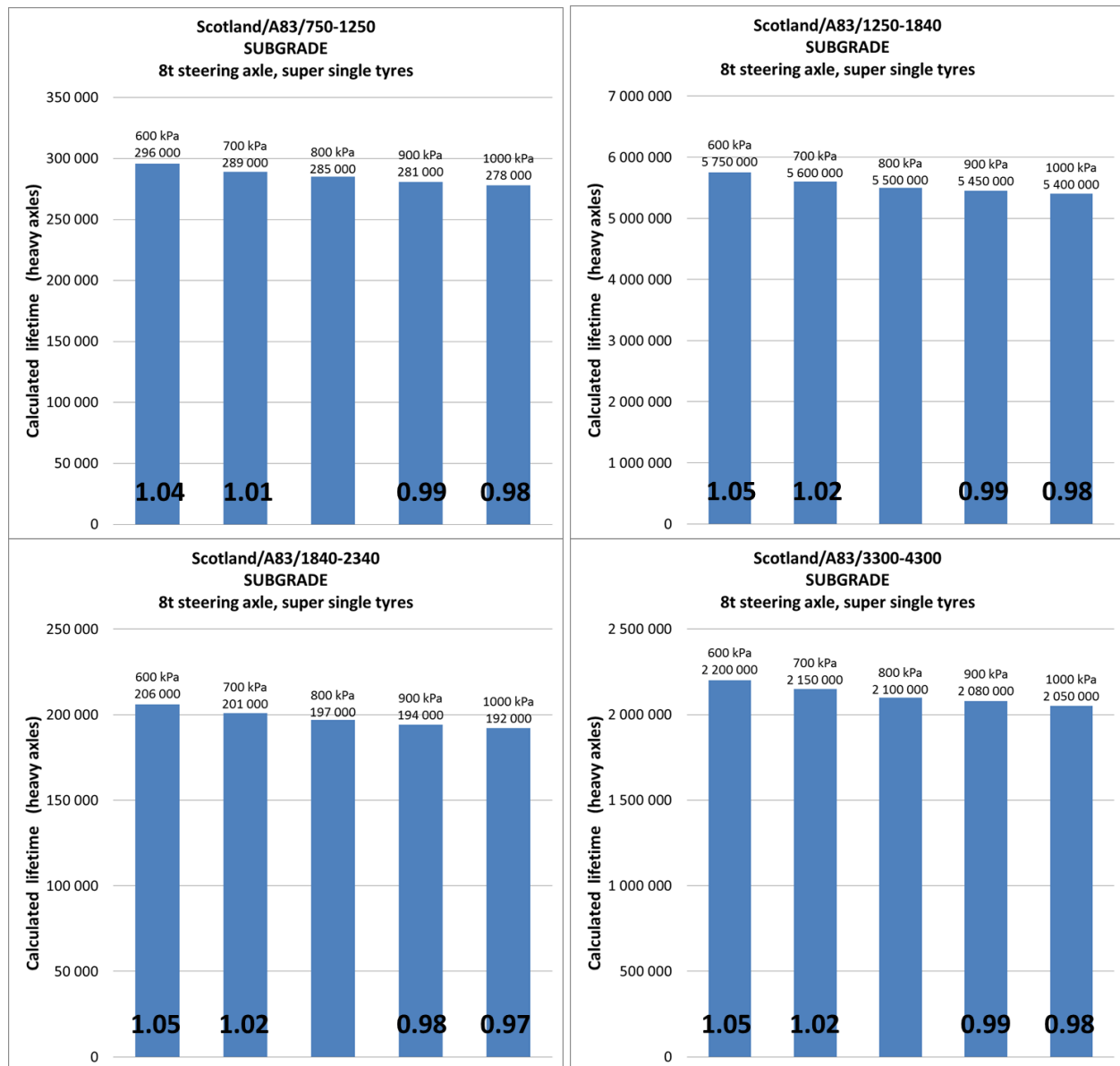


Figure 26: The effect of tyre pressure on unbound structure lifetime. NB Note the different scales on vertical axes of the different structures.

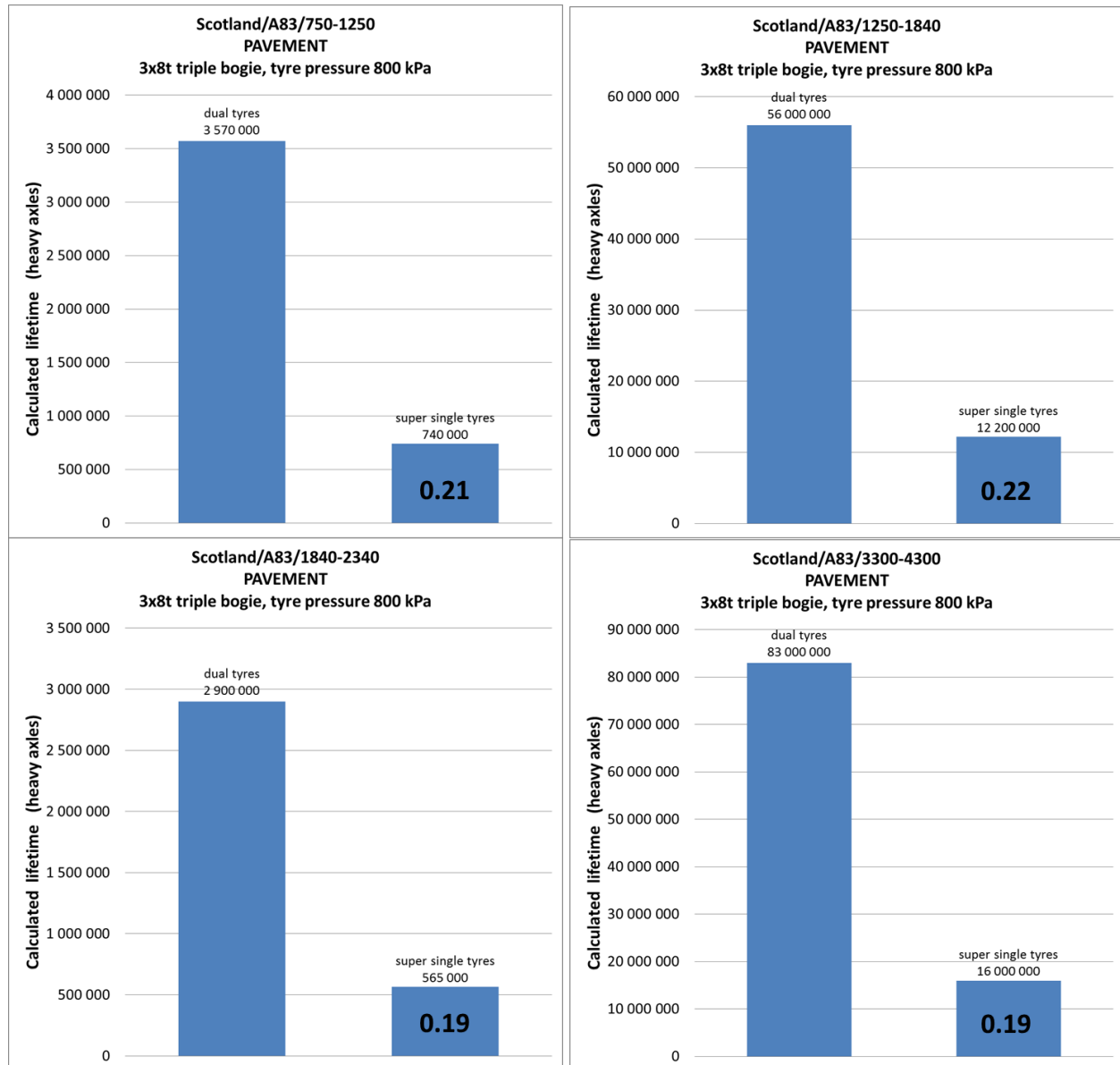
Even though the total thickness of the road structures is little more than 0.5 metres, the calculations show that tyre pressure has no longer a significant effect on the predicted lifetimes at the subgrade level (Figure 27). Changing the tyre pressure changes only affects the stresses and strains in the top part of a road structure, as shown in Figure 13 in Chapter 3.2.4.



**Figure 27: The effect of tyre pressure on subgrade lifetime. NB Note the different scales on the vertical axes in the different structures.**

### 4.3.2. The Effect of Tyre Type

The effect of tyre type on the lifetime of pavements is substantial and much greater than the effect of tyre pressure. Figure 28 shows the results of the pavement lifetime calculations on each of the four structures in Scotland. Again the total calculated amounts of heavy axles are different, but the relative proportions are the same in every case. The calculated lifetime with dual tyre configuration is approximately five times higher than the lifetime obtained with super single tyres.



**Figure 28: The effect of tyre type on pavement lifetime. NB Note the different scales on the vertical axes in the different structures.**

The effect of tyre type on the unbound structures is even higher, as can be observed from the results presented in Figure 29. The calculated lifetime with dual tyre configuration is more than ten times higher than the corresponding lifetime with super single tyres.

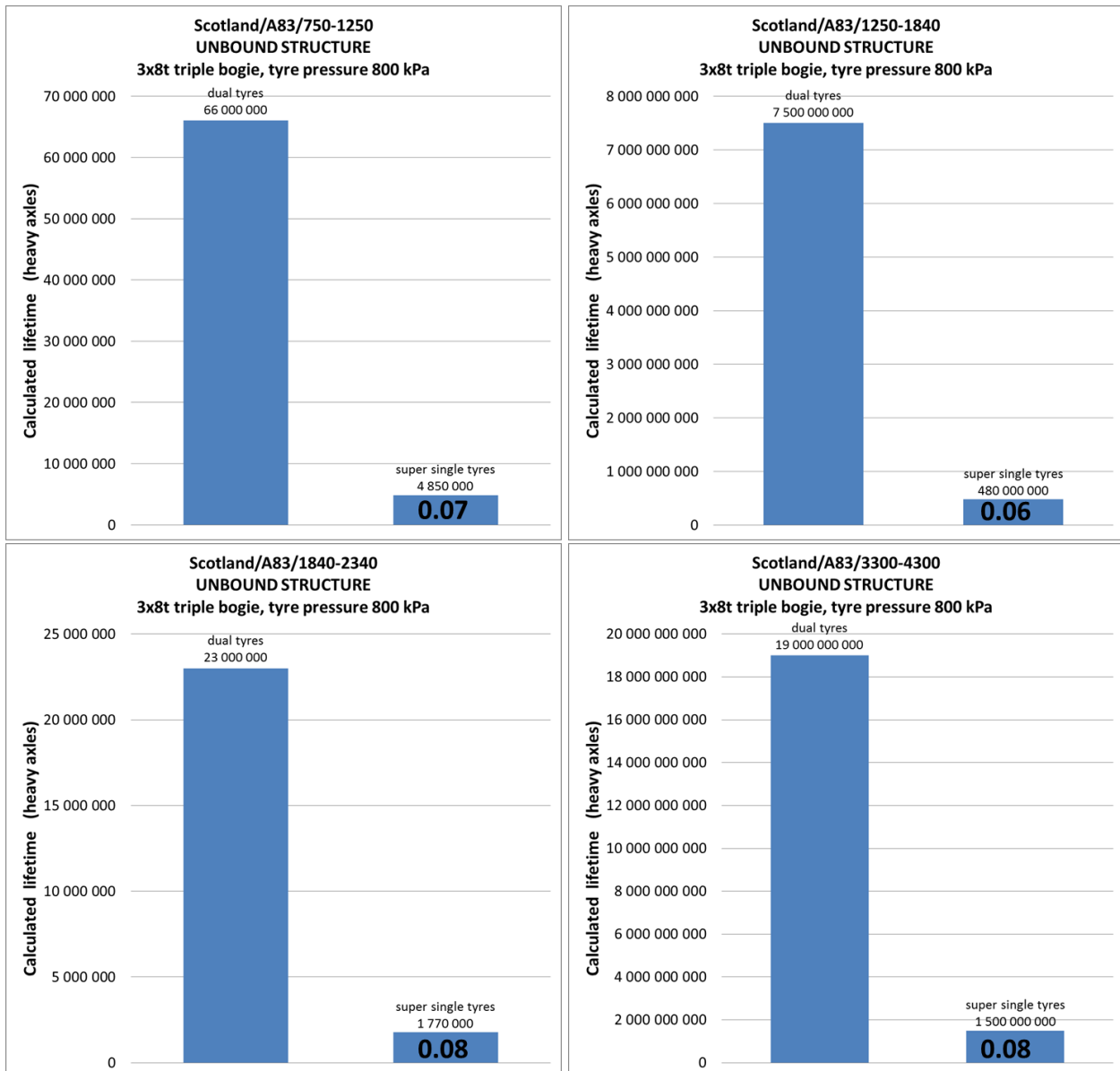
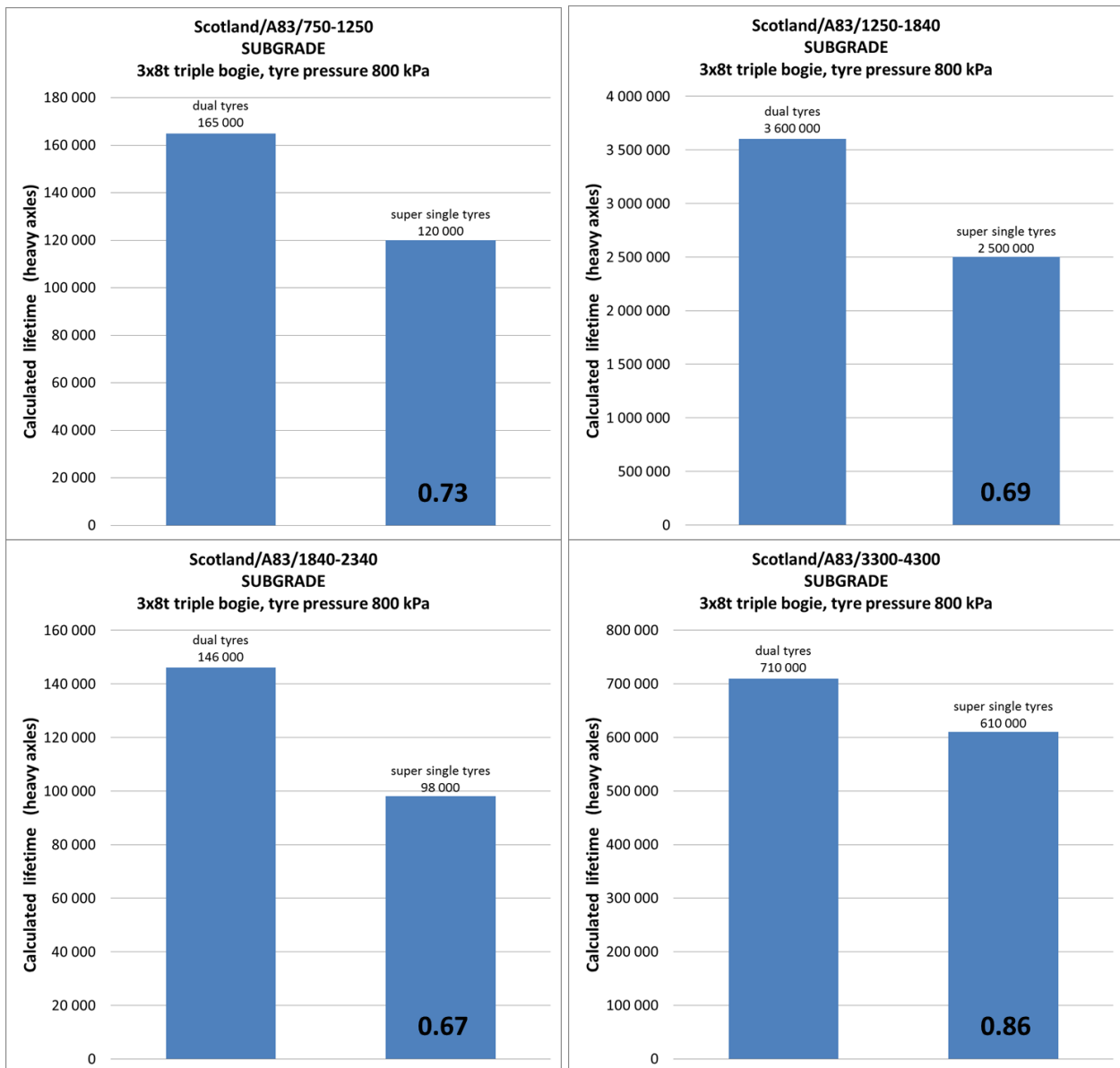


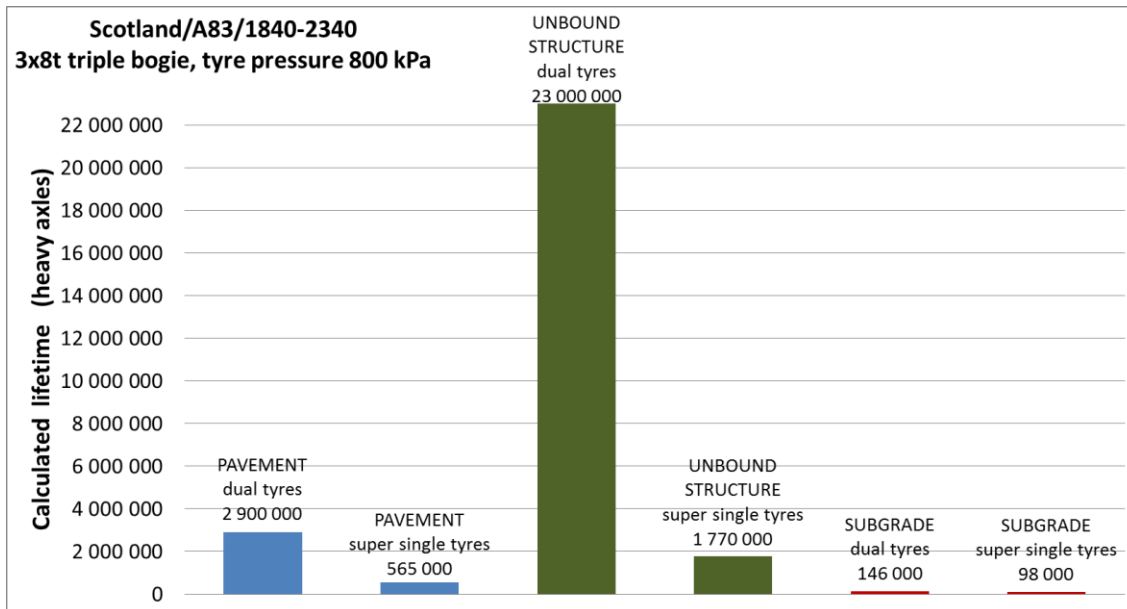
Figure 29: The effect of tyre type on unbound structure lifetime. NB Note the different scales on the vertical axes in the different structures.

Figure 30 shows the results of the subgrade lifetime calculations on each of the four Scottish structures. The effect of tyre type is no longer strong at the subgrade level, but the lifetime expectation with super single tyre configuration is however still about 20-30 % shorter than the lifetime with dual tyres.



**Figure 30: The effect of tyre type on subgrade lifetime. NB Note the different scales on the vertical axes in the different structures.**

The results from Scotland show that for each of the four Scottish example cases the most critical part of the road structure is the subgrade. Although there are great differences in the number of calculated heavy axles between the road sections, in every case the predicted lifetime is the shortest for the subgrade when both the effect of tyre pressure and when the effect of tyre type is evaluated. Figure 31 shows an example from one road section (A83/1840-2340m) that helps to better understand the scale and the differences in lifetimes between layers.



**Figure 31: An example from one Scottish road section that helps to better understand the scale and the differences in lifetimes between layers. For each of the four example cases the predicted lifetime is the shortest for the subgrade for both the effect of tyre pressure and the effect of tyre type.**

## 4.4. NORWAY

### 4.4.1. The Effect of Tyre Pressure

The results of the pavement lifetime calculations on each of the three Norwegian structures are shown in Figure 32. Here the effect of tyre pressure on the lifetime of pavement is again very clear, even much greater than on the Scottish structures as the Norwegian pavement is thinner. The predicted pavement lifetime reduces down to approximately one fourth when the tyre pressure is raised from 600 kPa to 1000 kPa.

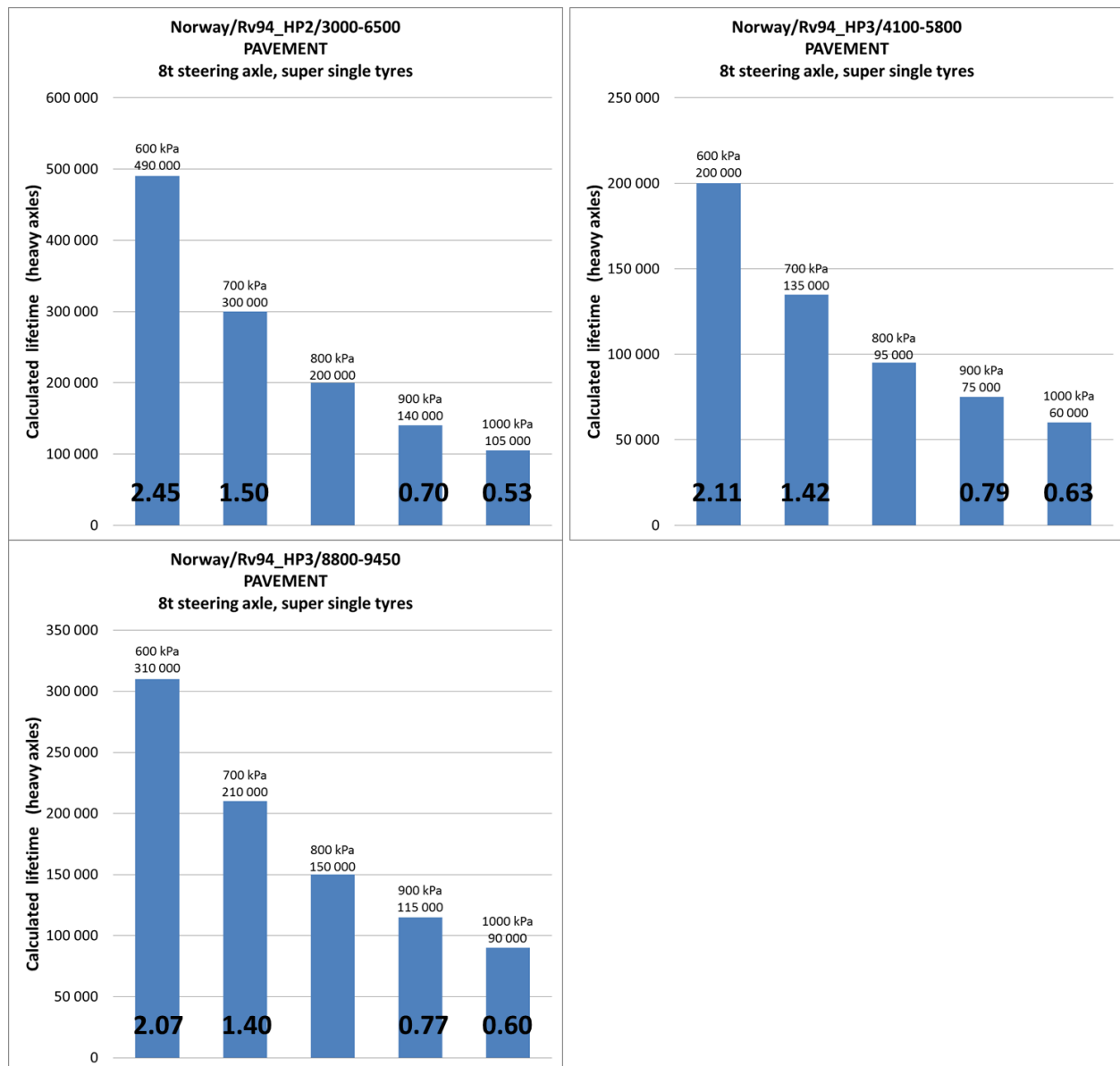


Figure 32: The effect of tyre pressure on pavement lifetime. NB Note the different scales on the vertical axes in the different structures.

The same trend can be seen even better in the Norwegian unbound structures. The results of the unbound structure lifetime calculations on each of the three sections are presented in Figure 33. The calculated lifetime with 600 kPa tyre pressure is about four to five times higher than the lifetime obtained with 1000 kPa tyre pressure.

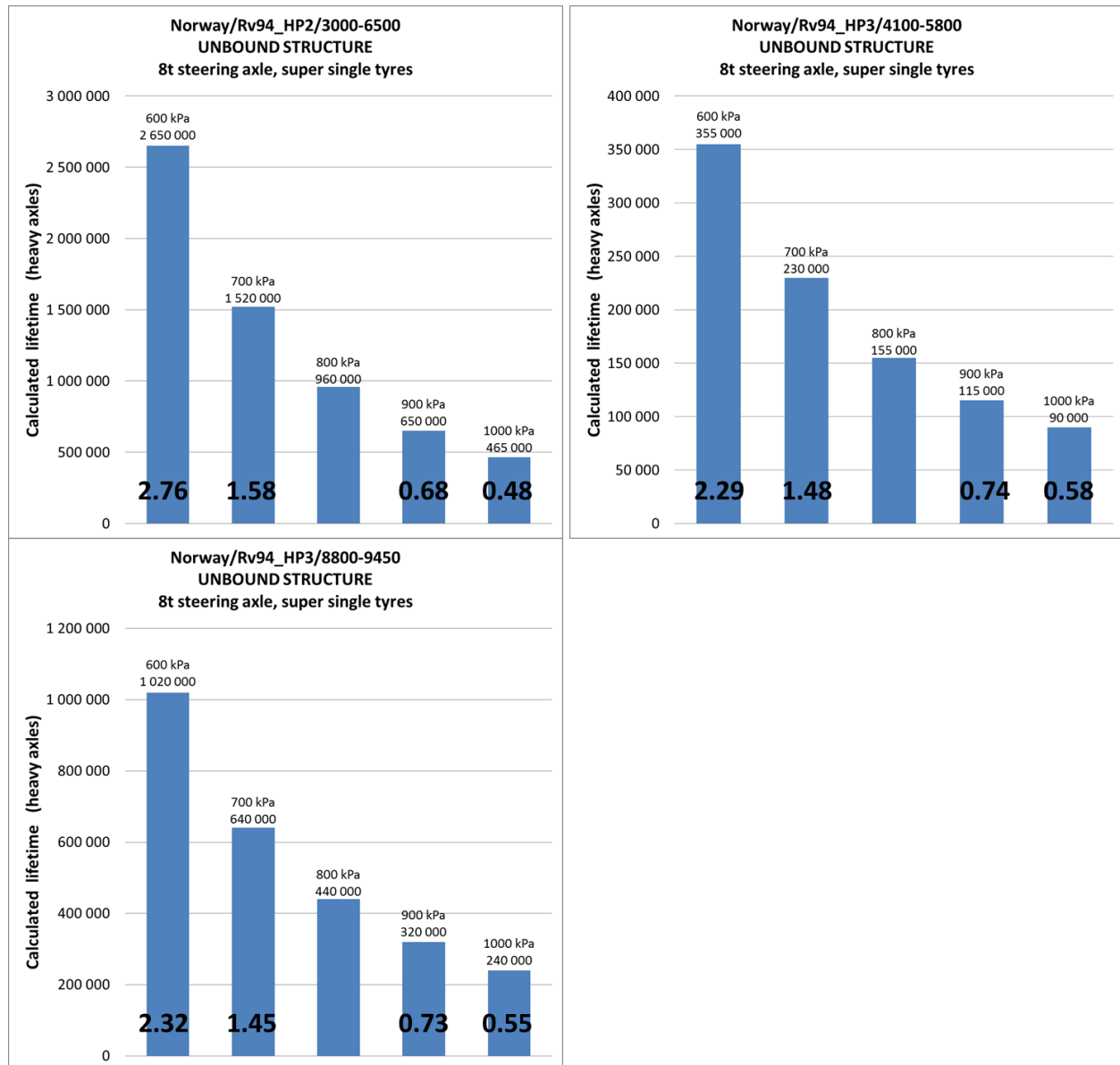


Figure 33: The effect of tyre pressure on unbound structure lifetime. NB Note the different scales on the vertical axes in the different structures.

The effect of tyre pressure in the pavement and unbound layers was even higher on the Norwegian calculations than on the Scottish example structures because of the thinner pavement. However, the total thickness of the whole road structure in the Norwegian examples were slightly thicker and again the calculations show that tyre pressure does not have a significant effect on the expected lifetimes at the subgrade level (Figure 34).

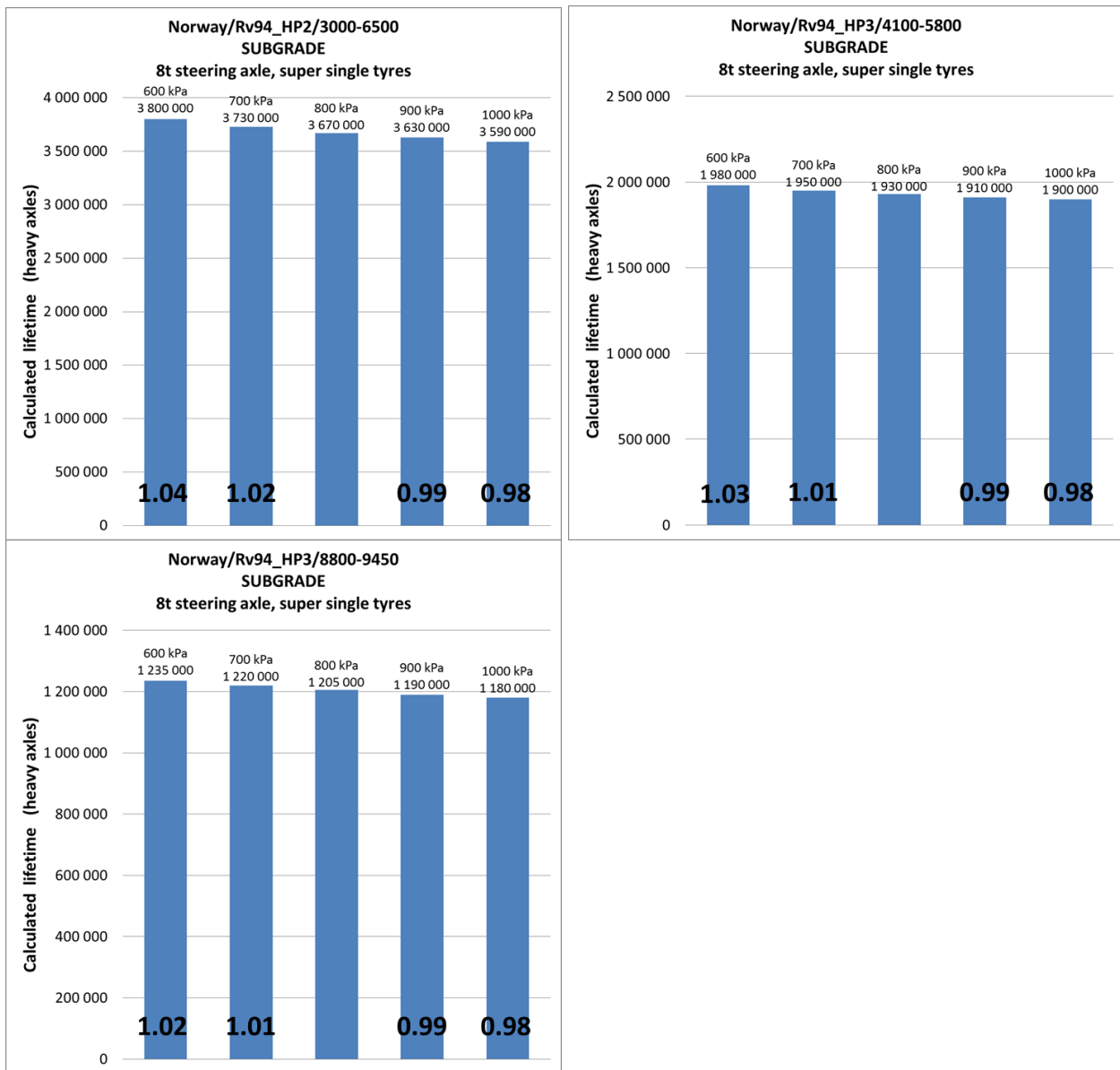


Figure 34: The effect of tyre pressure on subgrade lifetime. NB Note the different scales on the vertical axes in the different structures.

#### 4.4.2. The Effect of Tyre Type

The effect of tyre type on the lifetime of pavement is substantial. Figure 35 shows the results of the pavement lifetime calculations on each of the three structures in Norway. The calculated lifetime with dual tyre configuration is approximately three times higher than the lifetime with super single tyres.

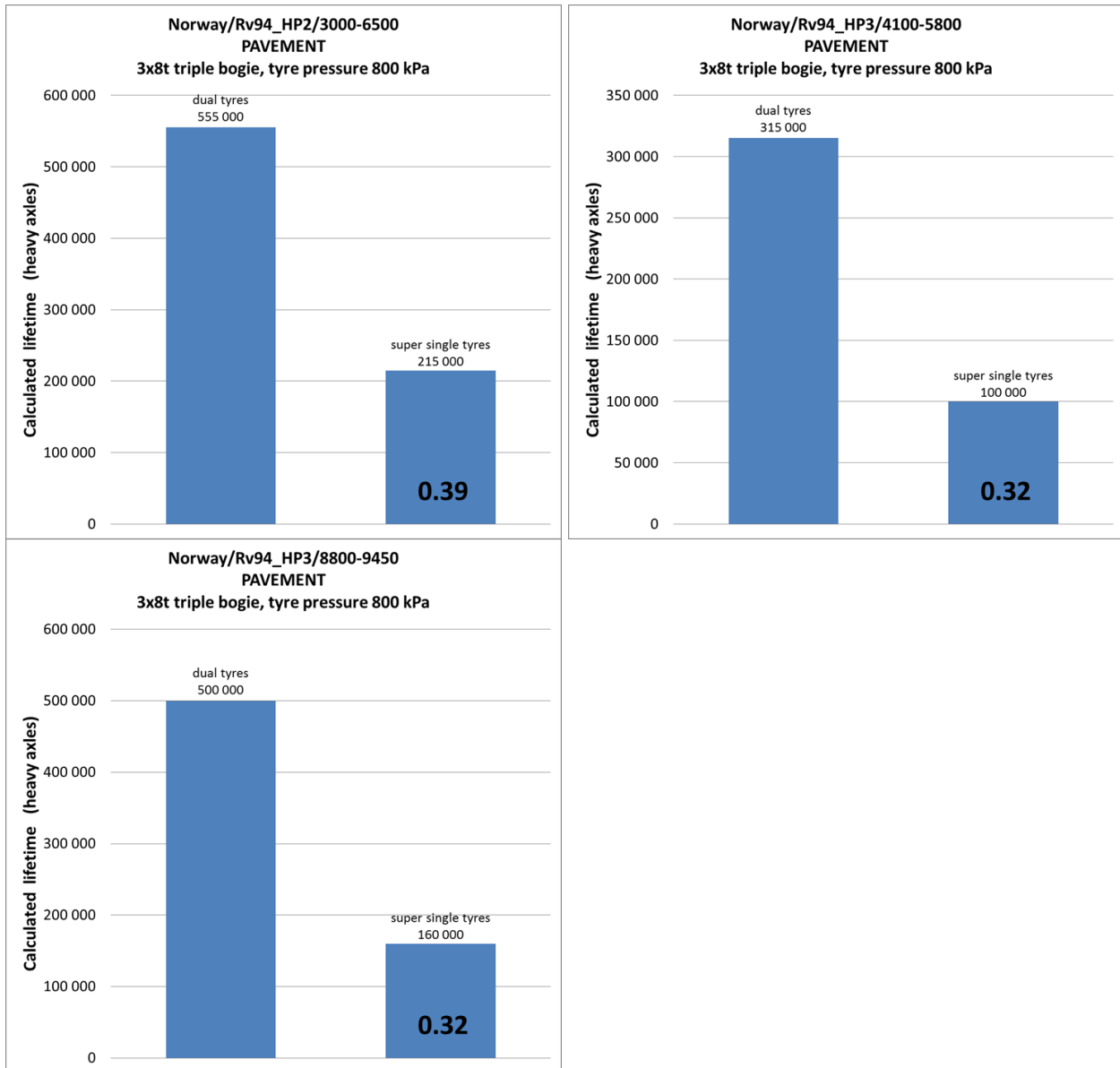
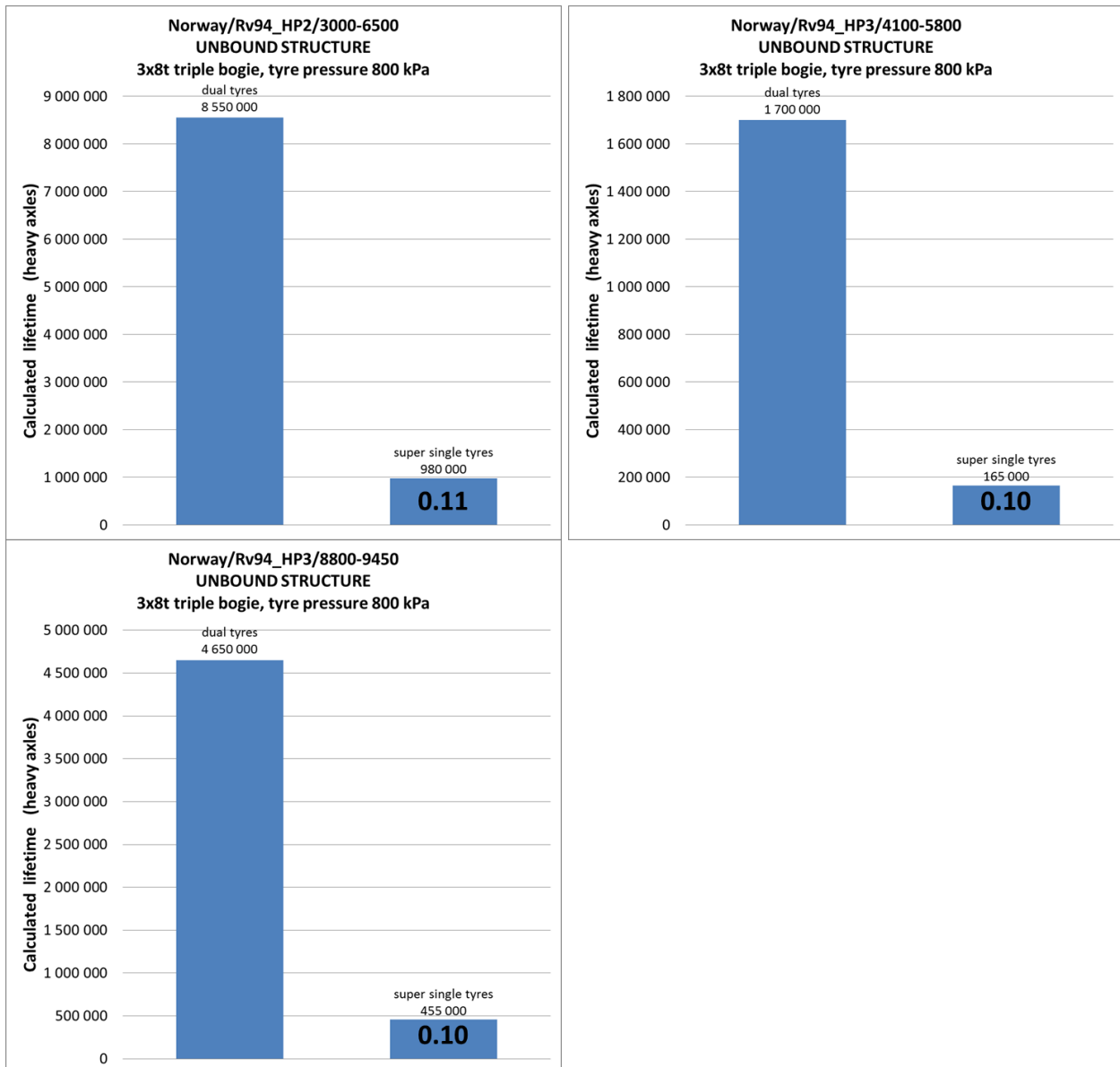


Figure 35: The effect of tyre type on pavement lifetime. NB Note the different scales on the vertical axes in the different structures.

The effect on the unbound structures in Norway is even higher, as can be observed from the results presented in Figure 36. The calculated lifetime with dual tyre configuration is approximately ten times higher than the lifetime with super single tyres.



**Figure 36: The effect of tyre type on unbound structure lifetime. NB Note the different scales on the vertical axes in the different structures.**

Figure 37 shows the results of the subgrade lifetime calculations on each of the three Norwegian structures. The effect of tyre type is no longer strong at the subgrade level, but the predicted lifetime with super single tyre configuration is however still about 20-40 % shorter than the lifetime with dual tyres.

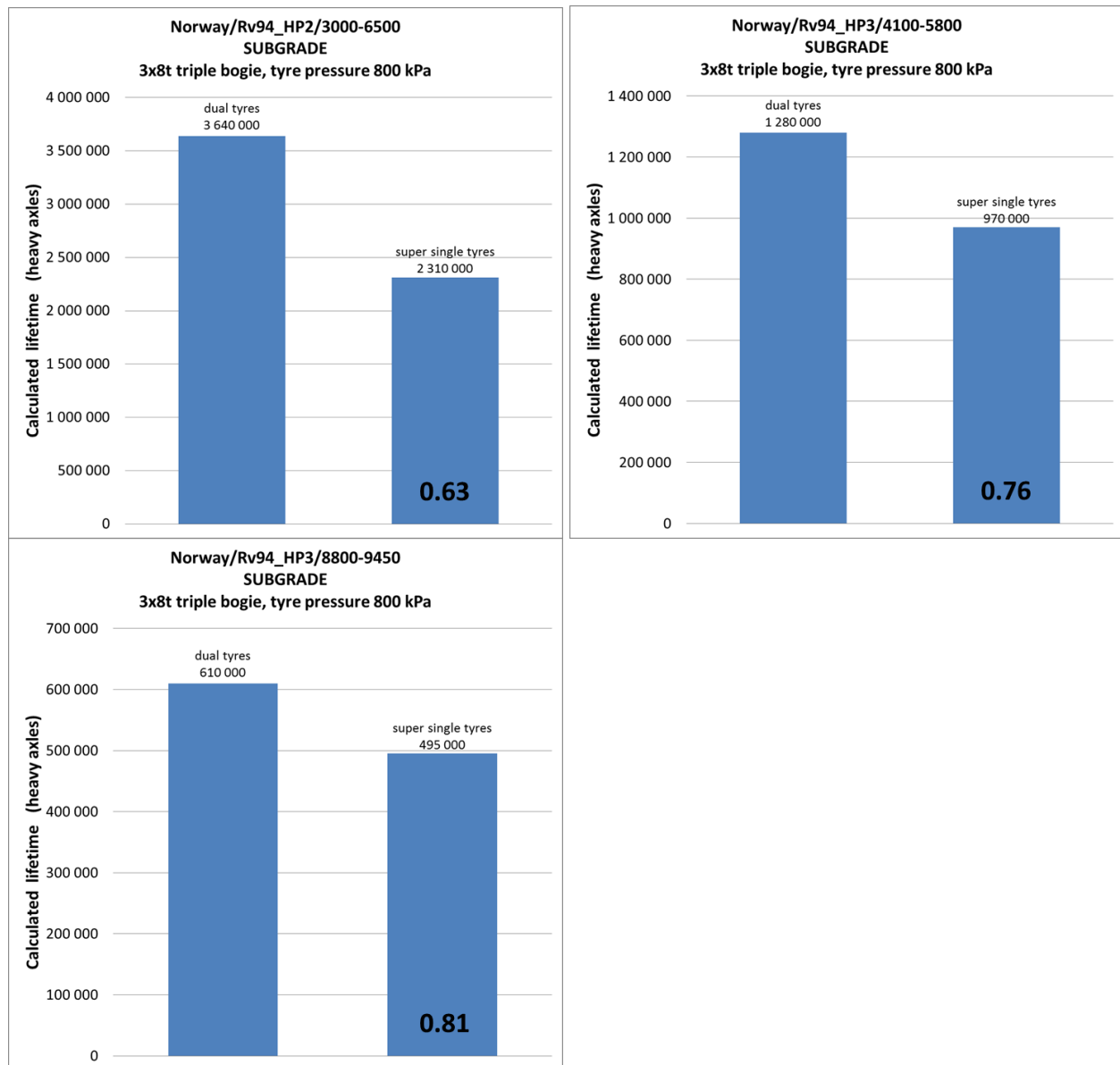
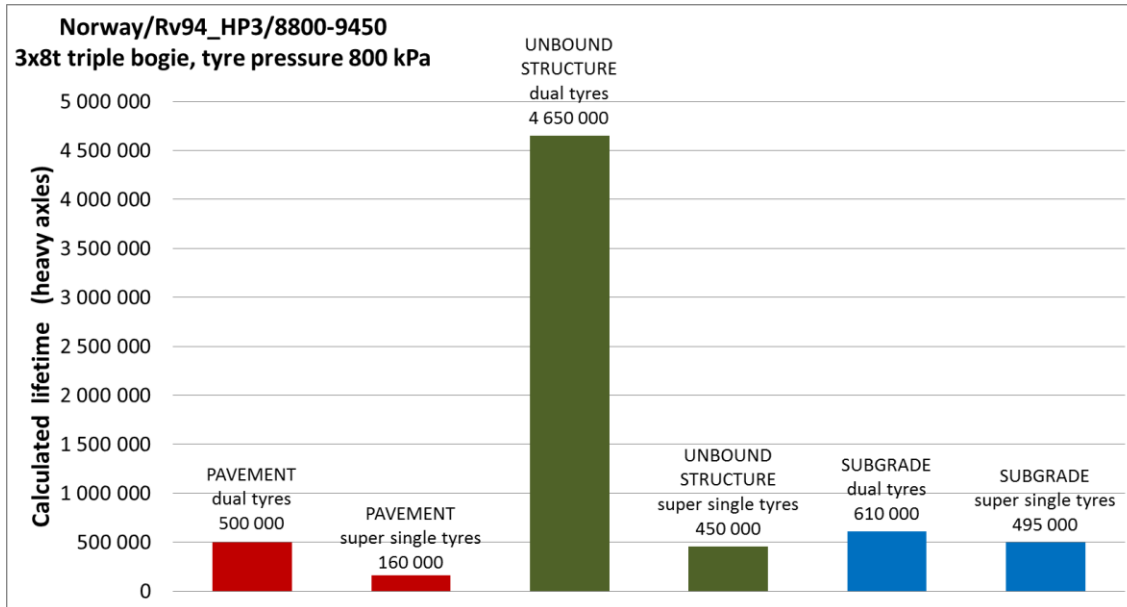


Figure 37: The effect of tyre type on subgrade lifetime. NB Note the different scales on the vertical axes in the different structures.

The results from each of the three Norwegian example cases show that the most critical part of the road structure is the pavement. Although there are great differences in the number of calculated heavy axles between the road sections, in every case the predicted lifetime is the shortest for the pavement layer when both the effect of tyre pressure and the effect of tyre type is evaluated. Figure 38 shows again an example from one road section that helps to better understand the scale and the differences in lifetimes between layers. The results show that the most critical issue for Norway in the future will be the increased pavement rutting due to the use of super single tyres.



**Figure 38:** An example from one Norwegian road section that helps to better understand the scale and the differences in lifetimes between layers. For each of the three example cases the predicted lifetime is the shortest for the pavement when both the effect of tyre pressure and the effect of tyre type is evaluated.


## 4.5. SWEDEN

Swedish calculations were carried out on five different predefined truck configurations, including the proposed new 74 tonnes combination, to evaluate the loading effect of these trucks compared to standard axle (10 tonnes axle with dual tyres), and further to evaluate the “truck wear factor” of the new heavier combinations compared to traditional 60 tonnes truck.

### 4.5.1. Truck Options

The five evaluated truck options are listed in Table 5. The truck options considered were 60 tonnes timber, 66 tonnes general cargo, 74 tonnes timber, 80 tonnes general cargo and 90 tonnes timber transport combinations. The table presents the axle weights and tyre types for each axle of the evaluated trucks.

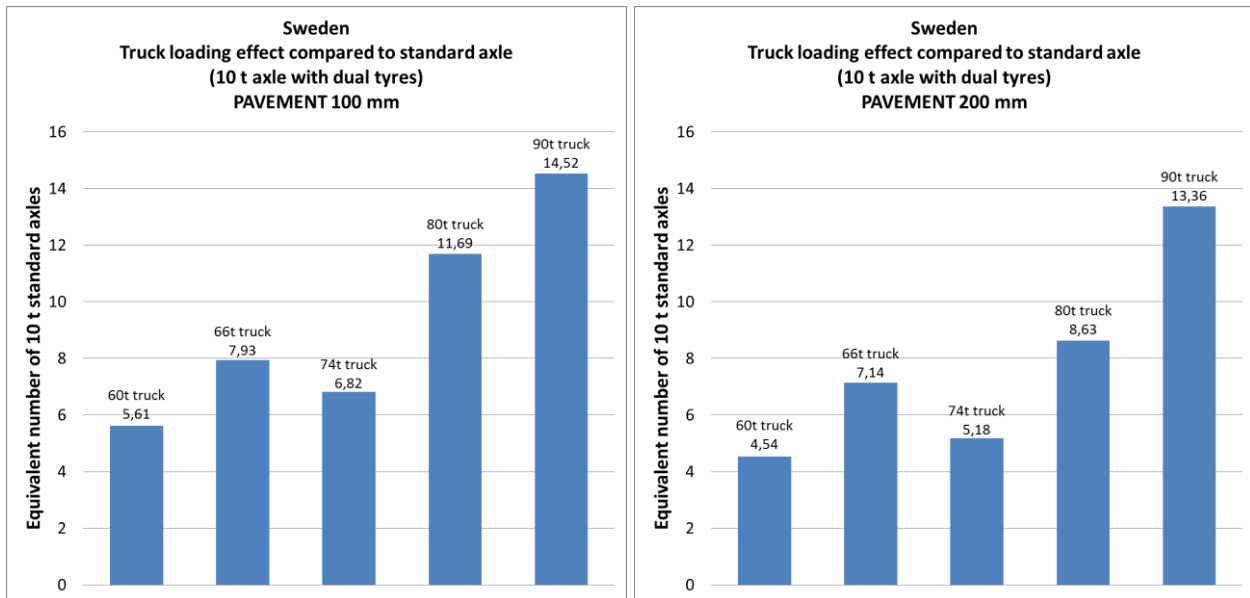
**Table 5: Properties of the truck options evaluated in the Swedish calculations**

	60 ton Timber	66 ton General Cargo	74 ton Timber	80 ton General Cargo	90 ton Timber
	Timber-Traditional	DUO-CAT	ST-Crane	DUO-Trailer ed 2	ETT
Possible road wear compared to 60 t	1	1.6	1.2	2.2	3.5
					
Axle weight / tyre type					
Truck					
axle 1	9 t / super single	8 t / super single	9 t / super single	8 t / super single	9 t / super single
axel 2	8.5 t / dual	9 t / dual	8 t / dual	9 t / dual	8.5 t / dual
axel 3	8.5 t / dual	9 t / super single	8 t / dual	9 t / dual	8.5 t / dual
axel 4			7 t / super single		
Trailing unit 1					
axle 1	8 t / dual	10 t / dual	9 t / dual	7 t / super single	8 t / super single
axle 2	8 t / dual	10 t / dual	9 t / dual	7 t / super single	8 t / super single
axle 3	9 t / dual		8 t / dual	7 t / super single	
axle 4	9 t / dual		8 t / dual		
axle 5			8 t / dual		
Trailing unit 2					
axle 1		10 t / dual		7.5 t / super single	8 t / super single
axle 2		10 t / dual		7.5 t / super single	8 t / super single
axle 3					8 t / super single
Trailing unit 3					
axle 1				6 t / super single	8 t / super single
axle 2				6 t / super single	8 t / super single
axle 3				6 t / super single	8 t / super single

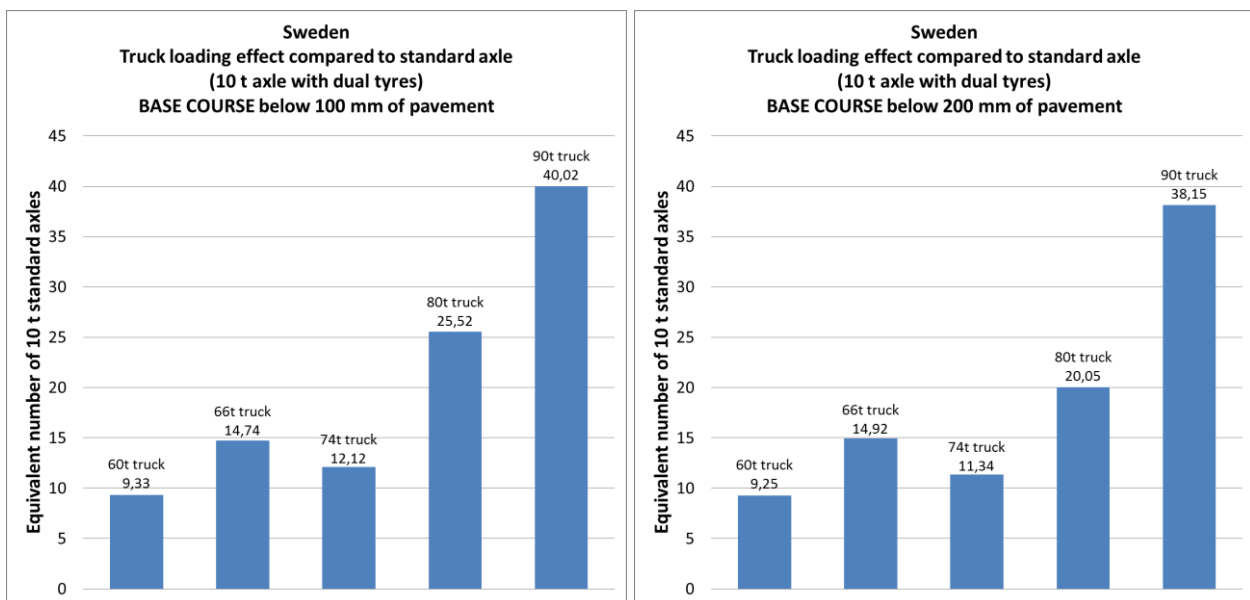
### 4.5.2. The Loading Effect of Different Truck Options

The Swedish calculation results show that the loading effect of the 74 tonnes truck with 9 axles was quite close to the corresponding value for the 60 tonnes truck with 7 axles, the truck wear factor being around 1.2 (see Table 5 in chapter 4.51). The 74 tonnes combination contained two axles more than the 60 ton truck, but only two of the nine axles were equipped with super single tyres. This is the most important reason for the truck wear factor remaining relatively low. The axle weights were also on the same level. However, the heavier 80 tonnes (11 axles) and 90 tonnes (11 axles) combinations that have more axles equipped with super single tyres have significantly

higher truck wear factors, even though the axle weights were even lower than the axle weights of the traditional 60 tonnes truck. With the thin pavements the equivalent number of standard axes increased slightly with every truck combination. The calculated equivalent loading effect of each truck option compared to the standard axle (10 tonnes axle with dual tyres) is presented in Figure 39 for pavement (100 mm or 200 mm layers thickness) and in Figure 40 for base course layer (below 100 mm or 200 mm of pavement).

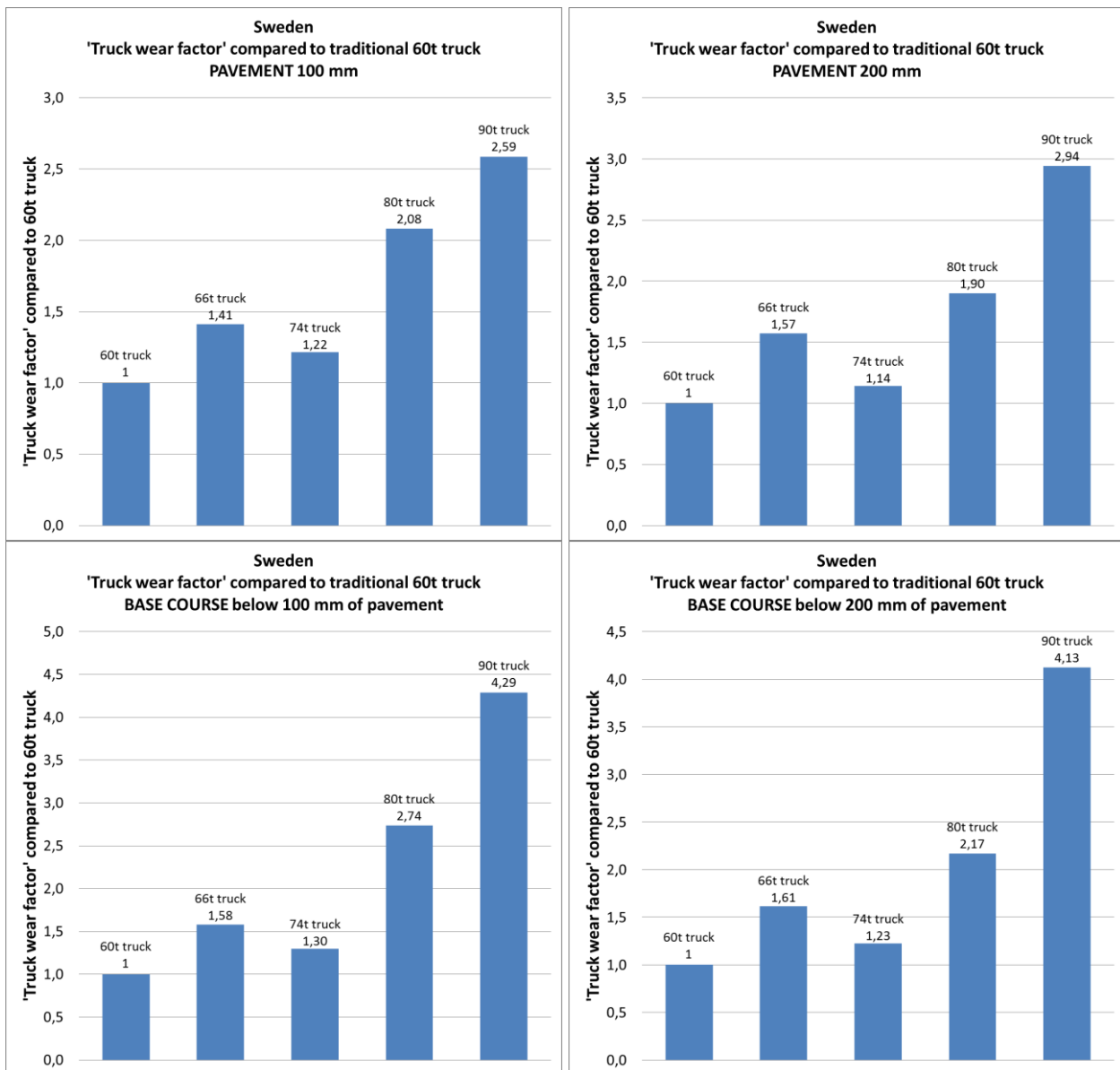


**Figure 39:** The calculated equivalent loading effect of each truck option on the pavement layer compared to the standard axle. On the left the pavement thickness is 100 mm and on the right 200 mm.



**Figure 40:** The calculated equivalent loading effect of each truck option on the base course layer compared to the standard axle below 100 mm or 200 mm of pavement.

Figure 41 shows the truck wear factors calculated for each of the heavier combinations compared to that of a 60 tonnes truck for the pavement (100 mm or 200 mm layers thickness) and for the base course layer (below 100 mm or 200 mm of pavement). The truck wear factors presented in Table 5 are averages calculated from these four values.



**Figure 41: The truck wear factors for each of the heavier combinations compared to a 60 tonnes truck for a 100 mm or 200 mm pavement thickness, and for a base course layer below 100 mm or 200 mm of pavement.**

#### 4.6. COMPARISON OF SWEDISH 74 TONNES WITH FINNISH 76 TONNES TRUCKS

The truck wear factor was evaluated for the Finnish 76 tonnes truck using the same relatively strong road structure as with Swedish truck options. Table 6 presents the axle and tyre configuration used in these calculations. It will be noted that if the axle weights presented in the table are added together, the total sum aggregates to 77 tonnes. This is because the maximum allowed bogie weights were used. So, in reality the maximum allowed total weight of the combination would be one tonne less than that used in the calculations. Also the tyre configuration was chosen so that the maximum allowed number of super single axles was used in the calculation, and that the situation was the worst allowed from the road structure point of view. The distribution of axle weights inside the 27 tonnes triple bogie was again estimated as before by experts representing Finnish Transport and Logistics (Saarenketo et al. 2014).

The results of the comparative calculations show that the truck wear factor of the 76 tonnes truck compared to 60 tonnes truck was approximately 1.5. The 76 tonnes combination contained two axles more than the 60 tonnes truck, and three of the nine axles were equipped with super single tyres. That is one super single axle more than the proposed Swedish 74 tonnes truck, which is the main reason why the truck wear factor of the Finnish truck is higher. The truck's triple bogie is also four tonnes heavier in the Finnish combination than in the Swedish one, which obviously also has an effect on the wear factor. However, the effect of the two heavier dual tyre axles on the triple bogie is not so great compared to the effect of one "extra" super single axle. If either the last axle of the truck or the last axle of the trailer were also to be equipped with dual tyres, which can be often the case, the truck wear factor of the Finnish truck would be between 1.2 and 1.3.

**Table 6: Comparison of the properties of the 60 tonnes truck, the proposed Swedish 74 tonnes truck and the Finnish 76 tonnes truck.**

	60 ton	SWE 74 ton	FIN 76 ton
<b>Possible road wear compared to 60 t</b>		<b>1.2</b>	<b>1.5</b>
<b>Axle weight / tyre type</b>			
Truck			
axle 1	9 t / super single	9 t / super single	8 t / super single
axel 2	8.5 t / dual	8 t / dual	9 t / dual
axel 3	8.5 t / dual	8 t / dual	10.5 t / dual
axel 4		7 t / super single	7.5 t / super single
Trailing unit 1			
axle 1	8 t / dual	9 t / dual	9 t / dual
axle 2	8 t / dual	9 t / dual	9 t / dual
axle 3	9 t / dual	8 t / dual	8 t / dual
axle 4	9 t / dual	8 t / dual	8 t / dual
axle 5		8 t / dual	8 t / super single

The evaluated truck wear factors of the heavier trucks, presented in Figure 41 and in Tables 5 and 6, just tell the ratio of how many times higher the loading effect of a single truck is compared to a 60 tonnes truck. The values do not take into account the increase in net weight. If the increase in net weight, or in other words the decrease in the number of trucks needed to haul the same amount of goods, is taken into account, the loading effect of the heavier combinations will be less in the long run. For example if all the evaluated 60 tonnes timber trucks were replaced with the Swedish 74 tonnes trucks, 17 % less vehicles would be needed to haul the same net weight. In such a case the truck wear factor would be very close to 1, almost the same as with the 60 tonnes truck. Again if all the evaluated 60 tonnes timber trucks were replaced with the Finnish 76 tonnes trucks, 20 % less vehicles would be needed and the truck wear factor would be 1.2. This is also much better than the original value but still far less friendly for the road than the Swedish option.

However, even though the 74 tonnes truck wear factors are quite good compared to standard 60 tonnes truck when calculated using linear-elastic theory, the comparison does not take into account the effects of the increased number of axles, as described in chapter 3.2.1.

## 5. SUMMARY AND CONCLUSIONS

During the last 10 years the pavement structures on the northern European road networks have been exposed to increasing stresses caused by the new axle configurations, tyre types and higher tyre pressures of the new generations of heavy trucks. This has been accompanied by a tendency to increase the total weight and length of trucks due to economic, and also environmental, reasons. However whilst politicians have made new regulations, there has not been enough discussion on what would be the likely impacts of the new regulations on pavement lifetimes and annual paving costs. This is critically important, as at the same time the new rules are taking force many governments are also downsizing the amount of money available for pavement maintenance.

The main aim of the prestudy project was to produce a general information package on the effect of different truck options, axle configurations, tyre types and tyre pressures on pavements, unbound road structures and the subgrade. The prestudy report does this, and additionally presents arrange of case studies and examples from ROADDEX partner countries.

During discussions on the benefits of raising the total weights of trucks 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 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. Similarly, the increased number of axles on the same vehicle results in more and more tyres loading the same wheel path, which leads to greater rutting speed. These effects will be exacerbated in the future as the new partially automated steering systems on trucks come to wider use, causing stresses to be incurred on exactly the same wheel path. This will increase rutting as because the benefit of tyre wander will be lost.

Axle weights also have a great effect on the remaining lifetime of a road. For instance with 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 8 tonnes axle. In the new Finnish heavy truck regulations the most critical dimensioning element from the axle weight point view is the new triple bogie with a maximum total weight of 27 tonnes. At least two (driving) axles of this triple bogie are required to be equipped with a dual tyre assembly, and the weights of these two axles are usually much greater than the weight of the third axle equipped with super singles.

The choice of tyre type, and especially tyre width, can have an even greater effect on road stresses. The stresses induced by single tyres can be significantly higher than the stresses induced by dual tyres, and similarly 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. Tyre width however does not have very significant effect on Mode 2 rutting. In former years almost all of the heavy vehicles in Europe were equipped with dual tyres, but during the last ten years super single tyres have rapidly become very common. 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 typical for many ROADDEX countries the rutting speed can be 8-18 times higher with super single tyres than with dual tyres.

The prestudy shows that tyre pressure has surprisingly great effect on the pavement surface pressure, and further 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 as it is considered to reduce fuel consumption, which is why tyres are often inflated much higher than necessary. This practice is of course not illegal because most countries do not have limits for maximum tyre pressures. In the ROADEX projects there has been substantial research into the effects of reduced tyre pressures (CTI / TPCS) and a number of reports have been published about their benefits. 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.

This prestudy included some modelling of stresses and strains and calculations of pavement lifetimes for typical pavement structures used in the ROADEX Network area. The 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 superstructure, 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 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.

One of the best methods to improve the load bearing capacity of a pavement structure is to use a thicker pavement. 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.

The prestudy carried out calculations for a number of predefined Swedish truck configurations, including the proposed new 74 tonnes combination. This was done in order to evaluate the loading effect of these trucks compared to those equipped with standard axles, and quantify the "truck wear factor" of the heavier combinations compared to traditional 60 tonnes truck. The results showed that the truck wear factor of the 74 tonnes truck was about 1.2. However, the heavier 80 tonnes and 90 tonnes combinations that have most of the axles equipped with super single tyres had significantly higher truck wear factors, even though the axle weights were lower than the axle weights of the traditional 60 tonnes truck. The truck wear factor was also evaluated for the Finnish 76 tonnes truck. The results show that the truck wear factor of the 76 tonnes truck compared to the 60 tonnes truck was approximately 1.5. The 76 tonnes combination contains one super single axle more than the proposed Swedish 74 tonnes truck, which is the main reason why the truck wear factor of the Finnish truck is higher. If the last axle of the truck, or the last axle of the trailer, is also equipped with dual tyres, the truck wear factor would decrease to 1.2-1.3. If the increase in net weight is taken into account, the loading effect of heavier combinations will be less in the long run, as there will be less vehicles on the road. For example, in Sweden, if all of the 60 tonnes timber trucks were replaced with the 74 tonnes trucks, 17 % less vehicles would be needed to haul the same net weight. In that case the truck wear factor would be almost the same as with 60 tonnes trucks. The new heavy truck in Finland was not so good. Its truck wear factor was 1.5 and if all the 60 tonnes timber trucks were replaced with the Finnish 76 tonnes trucks, 20 % less vehicles would be needed. However, these evaluations ignore completely the negative effects of the increased amount of axles. Also these calculations were made assuming relatively strong structures for low volume roads, which in most cases are many times much weaker.

As a summary of the work it can be concluded that there will be two kinds of challenges over the next few years on the road networks of the ROADEX area. First of all Scotland and Norway 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 most critical issue in Scotland will be the subgrade and in Norway the fatigue of pavement under super single loading. In Finland and Sweden the main challenge will be the new heavier truck combinations and the issues that will arise especially during the spring thaw season. This report shows that increasing total weights on the trucks that are forced to use dual tyres can be beneficial for countries with thin pavements on their road networks. Decision makers should start to prepare actions now on how to control overly high tyre pressures as they have a great potential to damage pavements.

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