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# SUMMARY OF PAJALA MINE ROAD IMPACT ANALYSIS – ROADEX IMPLEMENTATION

## ABSTRACT

Northland Resources Ltd plans to open an iron ore mine in Kaunisvaara in the municipality of Pajala in Northern Sweden In 2013. As there are no railway connections to Kaunisvaara, the company plans to annually haul five million tonnes of mined ore concentrate by trucks on public roads from Kaunisvaara to the Svappavaara railhead. This huge haulage project means that there will be trucks driving at intervals of a few minutes 24h/day every day of the year. The ore will be then hauled by train from Svappavaara to Narvik harbour in Norway.

The road to be used is a relatively weak, low traffic volume road that needs to be strengthened before haulage starts. Northland also has a commercial interest in using heavier trucks for the haulage than the current maximum permitted 60 ton trucks. In order to examine the options available the Swedish Transport Administration and mining company decided to establish a co-operation to determine the best way forward. This involved a risk analysis and socio economic analysis project to study the impact of different haulage options on the current road condition, a study into the need for an improved road for standard 60 ton trucks, and a further investigation into the extra need for further strengthening if heavier trucks (72 ton, 90 ton, 136 ton, 146 ton and 153 ton) were to be used. The goal was to define, based on the socio-economic analysis, what would be the most cost effective transportation solution for all interested parties and for the environment.

The data collection for the investigation was done in winter, spring and summer 2011 using mobile laser scanning techniques, GPR, HWD with time history data, thermal cameras, digital videos and visual inspection, drilling, sampling and laboratory analyses. In addition, historic profilometer data was analysed and local maintenance experience was incorporated into the analysis. The collected data was then analysed in a variety of ways using different software packages and risk and lifetime analysis were made showing that 96 % of the road would have problems within one year of haulage starting. This damage might be so severe that it could totally prevent transportation.

Based on the risk analysis and classification, new structures were designed to meet 20 years of service life. On the weakest section it was recommended that a new third lane should be built alongside the old weak road. This lane would also act as a long passing place for other traffic. In addition, at least two climbing lanes were recommended for steep hills and geometry improvements on one section. The cross section analysis also showed that the current road shoulders were very weak and the road should be designed to be wider than the existing road. Finally it was recommended that the road drainage should be improved to Class 1 before strengthening,

More than 30 different truck options and their impact on road performance were compared in the project. The results showed that the problem with heavier and longer trucks was high vertical displacement in weak subgrade sections during spring thaw periods, and long recovery times. However these problems could be reduced if and when third lanes were built. It was noted on the other hand that the heavier truck options would be friendlier to the asphalt pavements compared to a standard 60 ton truck.

Many new technologies and analysis methods were used for the first time in the world in the project. A good example of this innovation is frost heave analysis based on mobile laser scanner data. These methods have proven to provide extremely valuable data for road diagnostics and design. Using this data in the actual design phase will give tens of millions of Swedish krona in savings and the final road will be better and safer, particularly in respect of any unpleasant structural surprises that could cause problems to the project logistics.

## PREFACE

The “Pajala Mine Road Impact Analysis” project has been a good example of an implementation project of ROADEX technologies. The results of the project can be used in similar circumstances where extremely heavy haulage is being planned on a weak low traffic volume road. The project is also an excellent example of an open-minded co-operation between participants with different viewpoints.

The work was a real challenge for Roadscanners Oy. First of all, it was an extremely challenging scientific and engineering task with no previous examples of similar projects available as a reference, and secondly because it involved an extremely tight time schedule. Almost all of the entire Roadscanners Oy crew has somehow worked on the project. Svante Johansson from Roadscanners Sweden Ab helped with the project design and the practical data collection arrangements. The core team in Roadscanners Oy overseeing the data analysis and reporting was Tomi Herronen (project manager), Annele Matintupa, Petri Varin and Timo Saarenketo. Anssi Hiekkahti has also carried out great work in data analysis and reporting. Throughout the project the project team has received extremely valuable support and scientific help from Pauli Kolisoja of SPK Consulting, which has helped to ensure the quality of the calculations. Furthermore, Pekka Maijala, Timo Saarenpää and Jani Irvankoski from Roadscanners software team should be acknowledged. Without their support and writing of new software the project could not have finished by the deadline. Ron Munro checked the language.

Several subcontractors helped with the data collection in the field. Sampling was done by DMC Ab from Sweden, HWD data collection with different load levels and with time history data was done by KUAB, whose Olle Tholen also provided great help when Roadscanners was writing the HWD data analysis software. GeoVap Ltd from Czech Republic did the Quantum 3D Mobile Laser scanning mapping and analysis. Karl Thyni provided extremely valuable help to the project. His knowledge of the history, structures and problems sections of the road helped the research team avoid many pitfalls. The Svevia Ab crew in Pajala also provided excellent help with their traffic safety arrangements and other issues related to the field surveys. Laboratory analysis was done by the Tampere University of Technology.

The authors of the report would also like to acknowledge the active steering group for this project, Magnus Sundling, Jenny Keskitalo, Johan Ullberg, Kenneth Enbom, Anders Stenlund, Henry Degerman and Karl Thyni from Trafikverket, and Robert Näslund from Northland Resources.

Finally the great support of ROADEX project and especially from Per Mats Öhberg, Krister Palo, Johan Ullberg and Ron Munro has been essential in getting the research project organized within such a short time. The results of the project will also be of great value to all ROADEX partners with similar heavy transportation problems.

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# 1. INTRODUCTION

Northland Resources Ltd has decided to open an iron ore mine in Kaunisvaara in Pajala municipality in Northern Sweden in 2012-2013. Starting in January 2013, the company plans to transport annually five million tonnes of the mined ore concentrate on trucks to the Svappavaara railhead from where it will be hauled by train to Narvik harbour in Norway.

The transportation route first follows road 99 to Pajala, then road 395 to Vittangi, road 45 to Svappavaara and finally E10 to the Svappavaara railway marshaling yard. The total length of the public transportation is roughly 157km (Figure 1). All of the roads involved are owned and managed by the Swedish Transport Administration (Trafikverket) and the greatest part of them are typical of the low traffic volume roads in Northern Sweden with problems including frost action and permanent deformation as well as weak peat subgrades. As such, Trafikverket needed to have a risk analysis of the lifetime of the current road if and when heavy haulage begins. It was decided that this should be made using the risk analysis techniques proven to work well in the ROADEX project. In addition, new and emerging road survey technologies, such as laser scanning, were approved to be used for the first time in this project.

Due to the enormous amount of ore concentrate to be hauled to Svappavaara, Northland was naturally interested in optimizing the transportation costs which meant, in practice, considerations of exemptions to allow for the use of heavier and longer trucks than the standard 60 tonne trucks. On the other hand the Swedish Transport Administration was aware that the roads in this route were too weak even for haulage with standard 60 tonne trucks and the road had to be strengthened before haulage started anyway. It was therefore also prudent to analyze and evaluate the impact of the heavier vehicles on the road. To make this analysis a range of different total weight options was proposed: 72 tonnes, 90 tonnes, 126 tonnes and 170 tonnes with axle weights varying from 8 tonnes to 12 tonnes. The length of the longest option was 37 m. After preliminary evaluations, the trucks options were changed to be 60 ton, 72 ton, 90 ton, 136 ton, 145,5 ton and 153 ton.

This final report summarizes the survey and research carried out during the project in 2011 and how the ROADEX research results were implemented. The report provides information about road structures and their current structural and functional condition. It also reports the results from the final life time calculations for the road for after the haulage starts. In addition the report suggests and details new design structures and cost estimates for the road strengthening that should be completed before transportation starts.

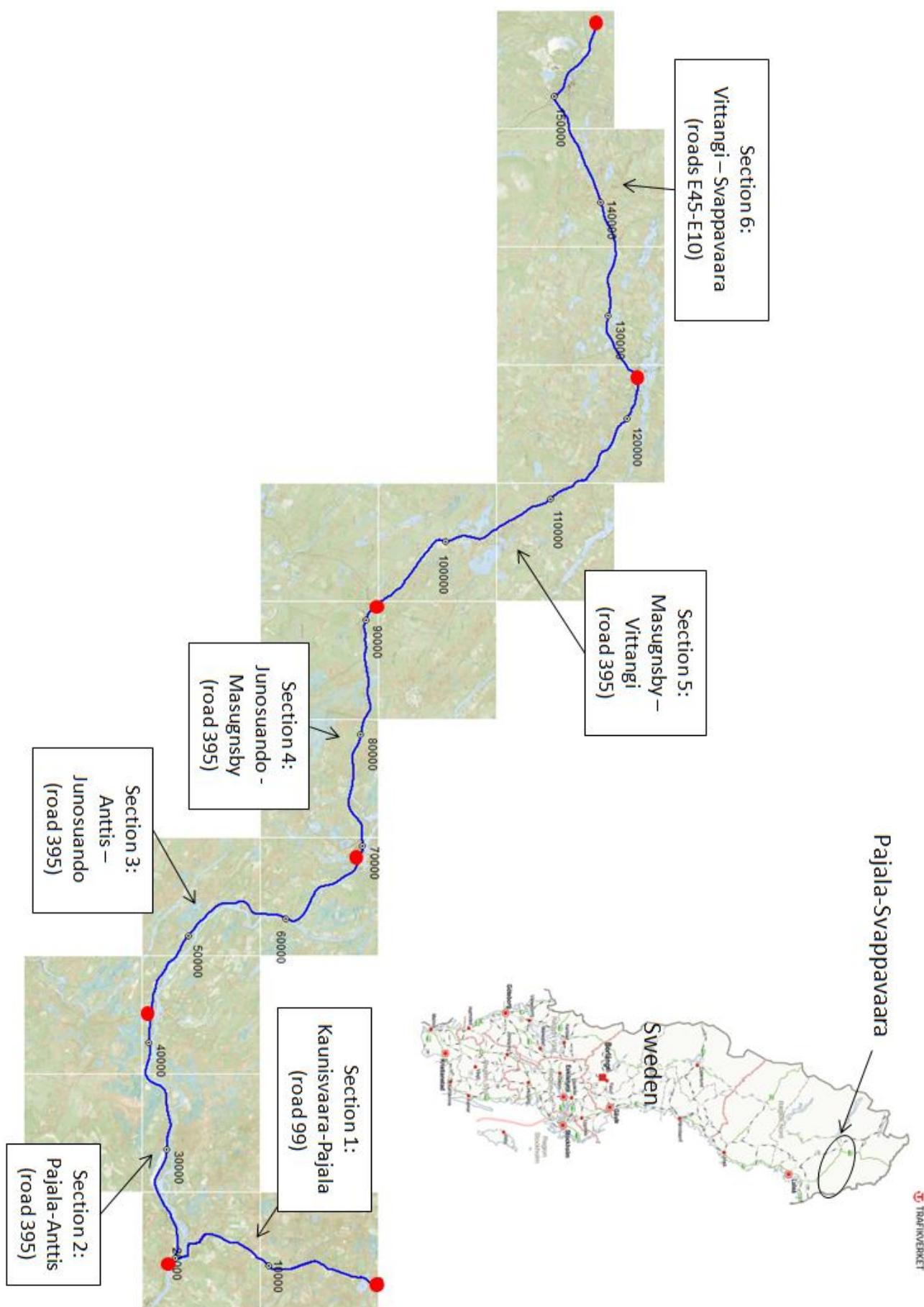


Figure 1. Pajala – Svappaavaara road and its subsections.

## 2. SURVEY TECHNIQUES AND SOFTWARE USED

The road data in the project was collected using the latest survey technologies in order to provide as good a diagnosis as possible. These surveys included the following techniques:

- mobile laser scanning mapping for point cloud data, technical road maps and frost heave measurements,
- ground penetrating radar (GPR) surveys for structural analysis,
- heavy weight deflectometer surveys (HWD) for bearing capacity analysis,
- digital video data collection for pavement distress analysis and drainage analysis,
- sampling and laboratory analysis for material quality evaluation,
- profilometer data analysis for road performance history,
- accelerometer and GPR bouncing analysis for road roughness evaluation, and
- local maintenance crew interviews together with site visits were carried out to find out the road construction history.

Mobile laser scanning using the Quantum 3D mobile laser scanner technique (Figure 2) by GeoVap Ltd from the Czech Republic was used for first time in the world to analyse continuous frost heave over the whole road section.



*Figure 2. GeoVap Quantum 3D mobile laser scanner vehicle on the Pajala road in April 2011.*

Most of the collected data was processed and analyzed using RoadDoctor Pro software. This software enables the combining of GPR, HWD, IRI, rutting and other data together with videos and maps. When all the data is linked together it is much easier to carry out an integrated data analysis utilizing comparisons and correlations between different factors affecting the road behaviour. The RoadDoctor Pro software includes Swedish Bearing Capacity calculation modules. The ROADEX Odemark dimensioning analysis, also built-in, was used for initial bearing capacity calculation. Frost heave analysis excel sheets were additionally created based on Finnish TPPT project frost heave publications.

Swedish PMS-objekt software was used in the strengthening design. Elmod 6 is a software package that can be used to back calculate layer moduli values. Elmod 6 software was used in an integrated module within the Road Doctor Pro software.

In this project, Bisar® software was used for the strengthening design for the extra heavy loads and for the evaluation and comparison of the different truck options. It is based on linear elastic theory. Bisar® calculates the horizontal and vertical stresses and strains induced in the various layers in the road structure by the selected loads. It also outputs horizontal and vertical displacements at selected points in the subgrade and structural layers.

### 3. STRUCTURAL AND FUNCTIONAL CONDITION OF THE ROAD

#### 3.1 HISTORY

The structural history of the Kaunisvaara to the Svappavaara road varies along the route. Part of the road is old gravel road that has been widened and strengthened, and some parts have been constructed later in the 1970's, and after. Road strengthening and repair of local frost heave damages has been done. Trend analysis has shown that both rutting and roughness of the road have become somewhat worse over the last five years.

#### 3.2 GEOMETRY

As a part of the functional condition analysis of the road, a road geometry analysis was done in order to find potential problem sections with steep hills and tight curves. Based on this analysis, it was proposed that climbing lanes should be built at two locations: Section 1 from point 8,900m to 10,200m, and Section 4 from point 86,990m to 89,090m. Horizontal geometry was in general quite good and only one curve with a radius less than 200 m was detected. This was located in road Section 1 between 17,760 m and 18,160 m. Based on the local maintenance expert's experience it was also proposed that the road horizontal geometry should be improved due to traffic safety reasons in Section 5 from point 118,350m to 119,750m.

The road vertical geometry was fairly even. The slope gradients varied mainly between -2% and +2%. Road Section 1, from Kaunisvaara to Pajala, was mostly built on embankment (53.7%), but a great part of it (34.4%) was also on side sloping ground. The road profile on Section 2, from Pajala to Anttis, was mostly (67.9%) embankment. Section 3, from Anttis to Junosuando, was located for the greater part (40.9%) on side sloping ground as it followed the river. The road profile on Section 4, from Junosuando to Masugnby, is mostly (50.6%) embankment. The road profile on Section 5, from Masugnby to Vittangi, was mostly (46.4%) embankment, but there was also a significant length (40.8%) of side sloping ground. The road profile in Section 6, from Vittangi to Svappavaara, was mostly (46.8%) embankment, but also 27.0% was on side sloping ground and a fairly large amount (17.3%) was road cut.

#### 3.3 PAVEMENT

The thickness of the bituminous pavement over the whole of the Kaunisvaara-Pajala-Svappavaara road was quite thin and varied from a few millimetres to twenty centimetres. The general pavement thickness was 35–45 mm, with only Section 4 having thicker pavement sections of any length, where 200 mm was exceeded in places. Pavement strain values were calculated from the FWD measurements using Swedish bearing capacity formulas. The smallest (best) strain values were measured in the more recently built road Section 6 and the highest, and worst, strain values were measured in Sections 1 and 2. Even though strain values were high, pavement distress analysis showed that more than 90 % of the pavement was in reasonable condition with no visual damages. The biggest problems were longitudinal cracks and shoulder deformation.

### 3.4 UNBOUND LAYERS

Because of the varying construction and rehabilitation history of the road the thickness of the unbound base course layers varied greatly. The thinnest measured base course thickness was only a few centimetres and the thickest ones were more than half a metre. The base course was especially thick in sections where old steel nets were located. The total thickness of the pavement structure also had great variations but generally it varied from 50 cm to 80 cm. Laboratory analysis results showed that the problem with the road was that quality of unbound base course material was quite poor. Practically all of the base course samples had high fines content and adsorbed too much water and thus will have permanent deformation problems during spring thaw weakening. The poor quality of the base course materials was also verified from the Surface Curvature Index values of the FWD data which showed that the SCI was mostly higher than 250 um, a value that can be observed as an alarm value for paved roads. A further problem is that, during the sampling it was detected that in some sections there were remnants of old coal tar just below the pavement. The good news was that the steel net structure built in the frost problem places was functioning quite well and in these sections there was no significant damage.

Twelve drill core samples and a tube suction test sample were taken from the full length of the surveyed road. The drill cores were used as references for the interpretation. Figure 3 shows an example of a drill core from road Section 2 at chainage 21,755m. Old pavement can be seen in the structure in the drill core at a depth of 500-528 mm.

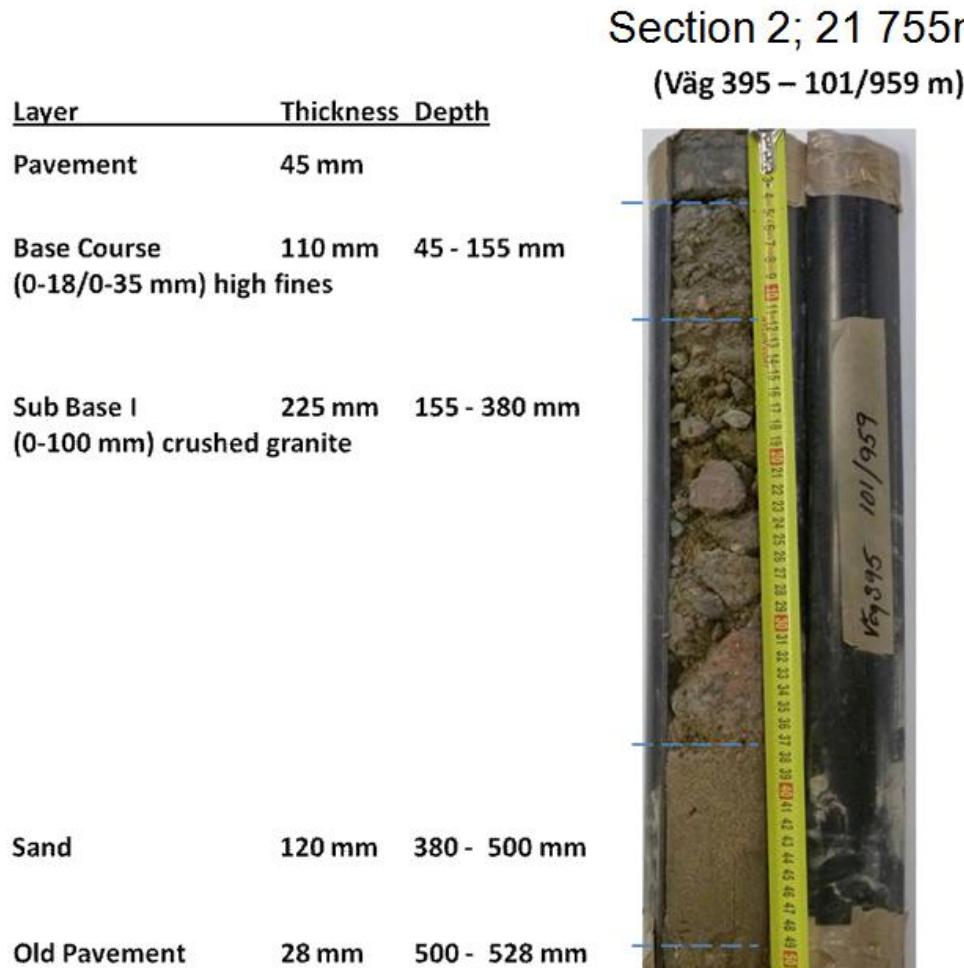


Figure 3: Example of drill core sample from road Section 2.

### 3.5 SUBGRADE

Subgrade soils varied from river sands and gravel to glacial moraine silt and peat. Bedrock was present close to the road surface only at a few locations. The weakest subgrade soils could be found in road Sections 1, Kaunisvaara – Pajala, and 2, Pajala – Anttis, where subgrade moduli were less than 20 MPa in almost 20 % of the road section (Figure 4). In these sections the calculated Odemark bearing capacity, based on the FWD and GPR data, was less than 100 MPa, values normally found on forest roads. The good news was that there were no major geotechnical risks for the road.

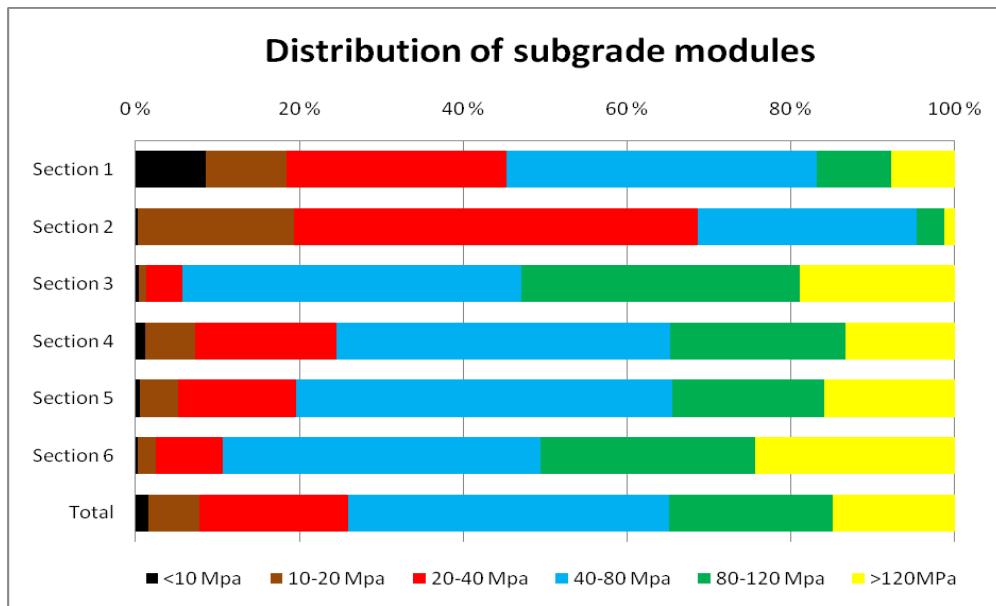


Figure 4. Distribution of subgrade moduli in each road section.

### 3.6 FROST HEAVE

According to the mobile laser scanner data the highest frost heave values were found in road Section 1 where the frost heave was generally more than 120 mm, and in some sections even more than 200 mm. In other the road sections the frost heave was less and the measured values varied from 40 mm to 120 mm. The smallest frost heave values were measured on the recently built road Section 6, where the majority was less than 40 mm. Small frost heave values were also measured close to river banks where the subgrade was sand. An example of a frost heave map is presented in Figure 5. Figure 6 shows an example of frost heave together with IRI values and a risk classification. In these sections one reason for the frost heaves was poor drainage. Figure 7 gives an example of a moisture profile calculated from GPR data. Road sections with excess moisture and/or ice lenses in the structure can be located from the moisture profile.

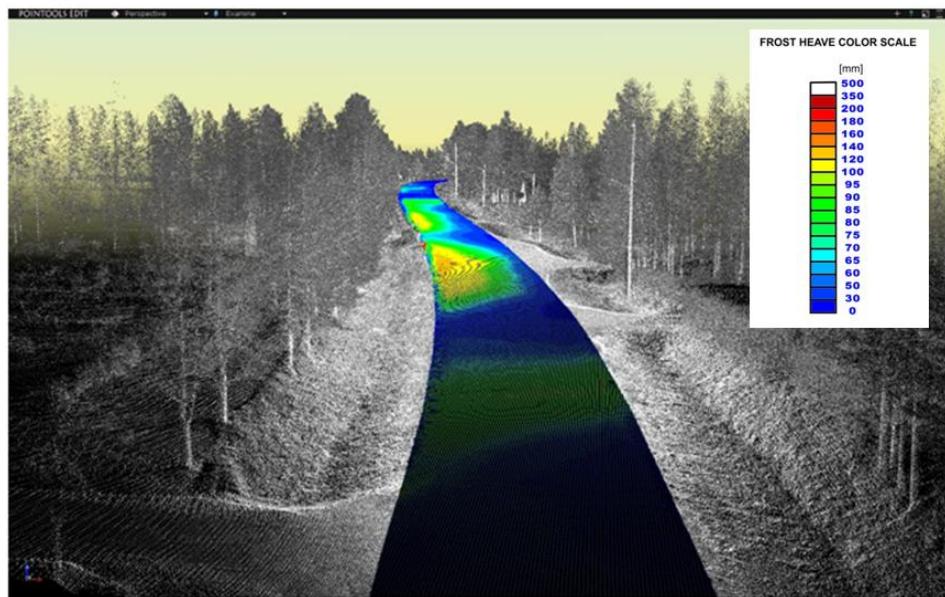


Figure 5. Example of a frost heave problem caused by a clogged, frozen or missing access road culvert. High frost heave values could be measured both sides of the private access road. The figure is based on the mobile laser scanner frost heave analysis data. Note the minor frost heave anomaly close to the nearest access road.

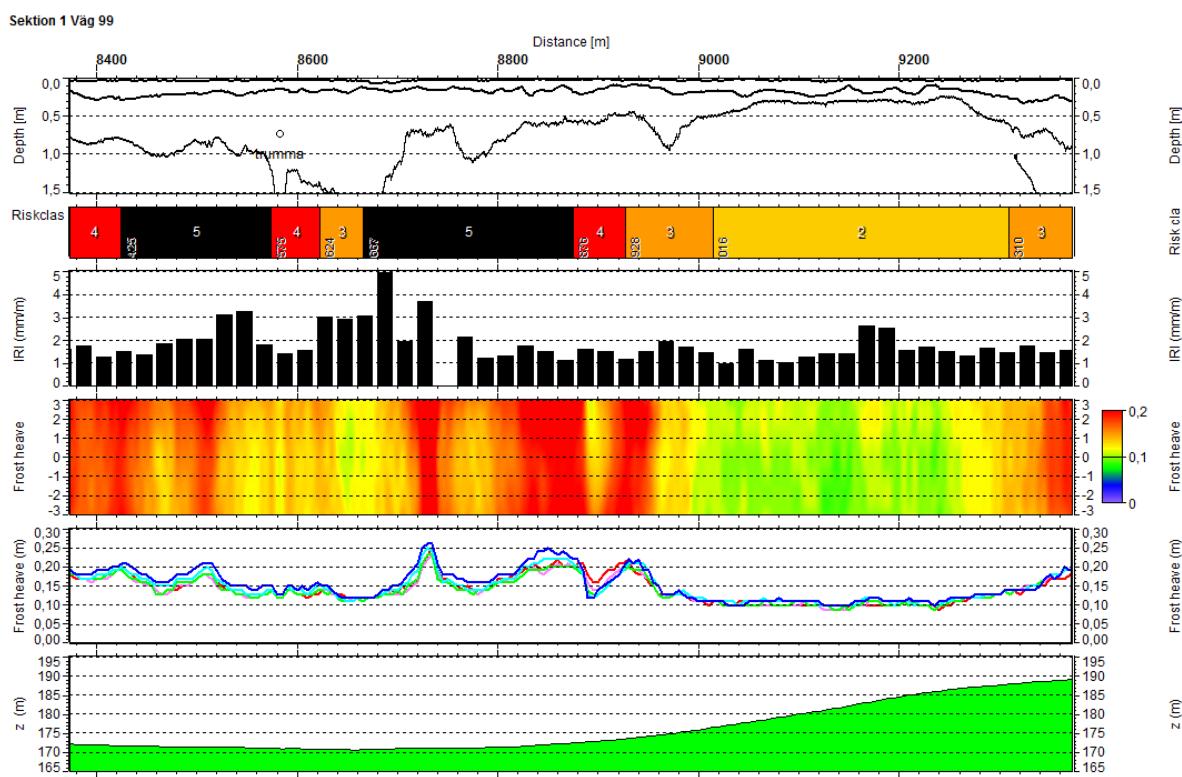


Figure 6: The upper frame gives the interpreted layer thicknesses, the second bar shows the risk classification and then IRI values. Below that the frost heaves are shown as a surface map and then as lines. The bottom frame describes the road profile.

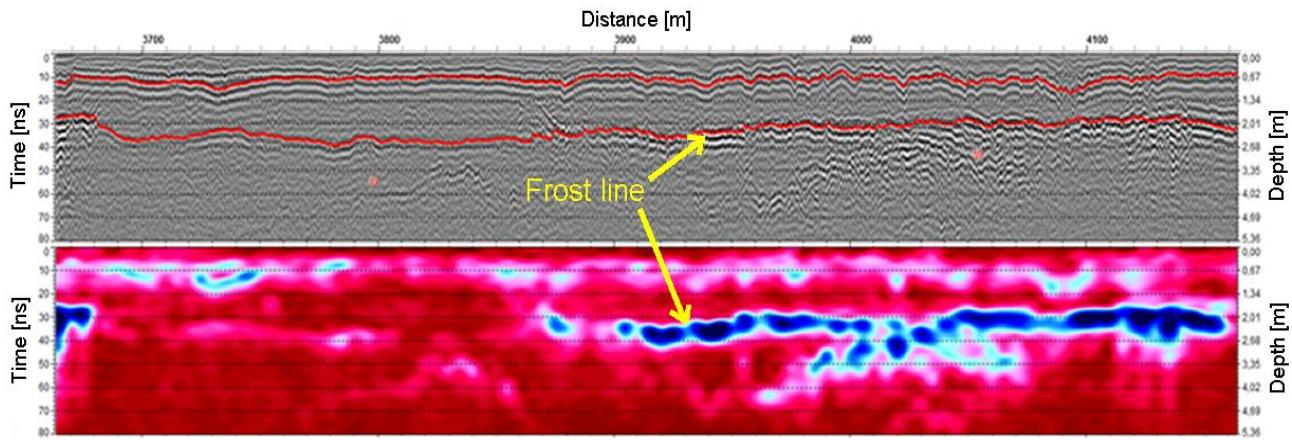


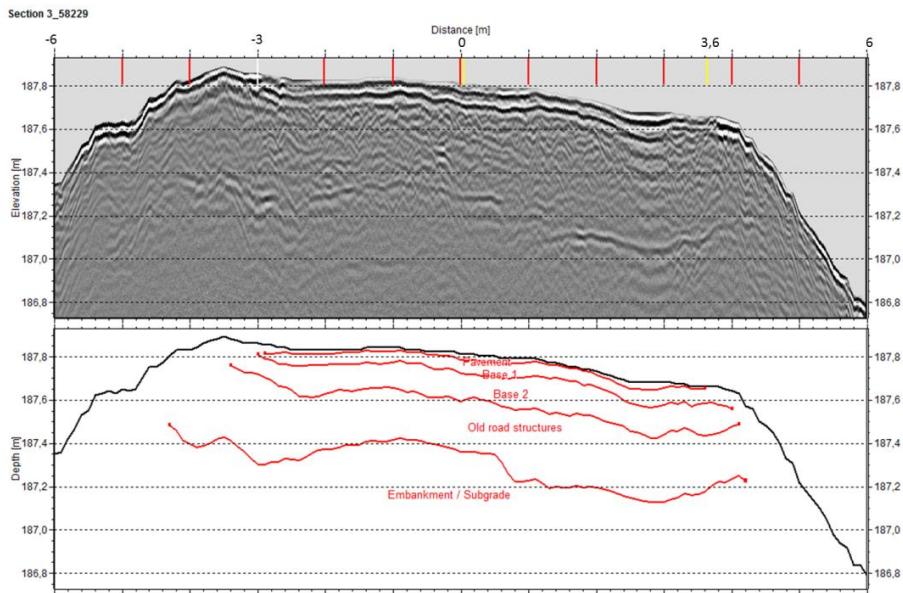
Figure 7: An example of moisture profile calculated from GPR data. The blue colour indicates areas with excess moisture and/or ice lenses in the structure.

### 3.7 DRAINAGE CONDITION

The drainage condition of the Kaunisvaara-Svappavaara road at the time of the surveys was surprisingly good compared to similar roads in Northern Sweden and the results showed that Class 1 drainage condition was identified in 60-90 % of the length of the road sections. In this analysis, Section 1 was clearly the worst compared to any other section. In addition, the locations of culverts that had frost heave problems were analysed and listed. Frost heave analysis also showed that there were many frost heave problems that could be related to drainage problems and to clogged private access road culverts. A special drainage problem on the road was flooding close to the Torne river and there were critical locations with such severe flooding problems that the road had been closed in places for several days 2-3 times in the last 20 years. It was obvious that these problems would appear again in the future. The drainage analysis results were presented on a map.

### 3.8 ROAD CROSS SECTIONS

Road cross section analysis based on laser scanning and GPR data from the 1.5 GHz antenna showed that the road has both Mode 1 rutting (related to upper part of road structures) and Mode 2 rutting problems (related to weak subgrade). This analysis also showed that the road shoulders were very weak and that permanent deformation was taking place in the outer wheelpaths. Figure 8 presents an example of a cross section with Mode 2 rutting problems.



*Figure 8. Example of a cross section with severe Mode 2 rutting problems in the right lane in the inner curve, Section 3, 58+620 m.*

### 3.9 BEARING CAPACITY

The Heavy Weight Deflectometer (HWD) measurements were carried out using three different loadings; 50kN, 70kN and 90 kN. However for the layer and subgrade modulus and bearing capacity index calculations only standard 50kN loads were used. In order to evaluate the effect of heavy loads on the subgrade stresses and strains BCI values from 70kN and 90kN loadings were compared to BCI values from 50kN loading. The results in Table 1 show that the average 70kN BCI values are 1.44 times larger, and 90kN BCI values are 1.83 times larger, than 50kN BCI values. This was a clear indicator that the effect on subgrade strains is quite linear at the tested load levels. The average values were quite near the theoretical values, i.e. 70kN/50kN=1.4 and 90kN/50kN=1.8.

*Table 1. Average values of BCI values compared to 50kN load.*

	70kN	90kN
<b>Section 1</b>	1.41	1.80
<b>Section 2</b>	1.47	1.83
<b>Section 3</b>	1.44	1.84
<b>Section 4</b>	1.47	1.88
<b>Section 5</b>	1.42	1.84
<b>Section 6</b>	1.40	1.77
<b>Total</b>	1.44	1.83

The Odemark bearing capacity, calculated using the ROADEX Odemark method, varied substantially within and between the different road sections. The lowest bearing capacities were calculated on road Section 1 (Road 99) and the highest bearing capacities were from the new road Section 6 (Roads E10 and E45). Road Section 1 (Figure 9) had several weak sections and the weakest and longest sections were from 2,500m to 4,000m and from 11,500m to 13,000m. In road Section 6 the bearing capacity was mainly 300MPa or more. In other the road Sections 2-5 (Road 395) the bearing capacity varied between 150MPa and 300MPa. Here and there were some short weak (<150MPa) and good (>300MPa) sections.

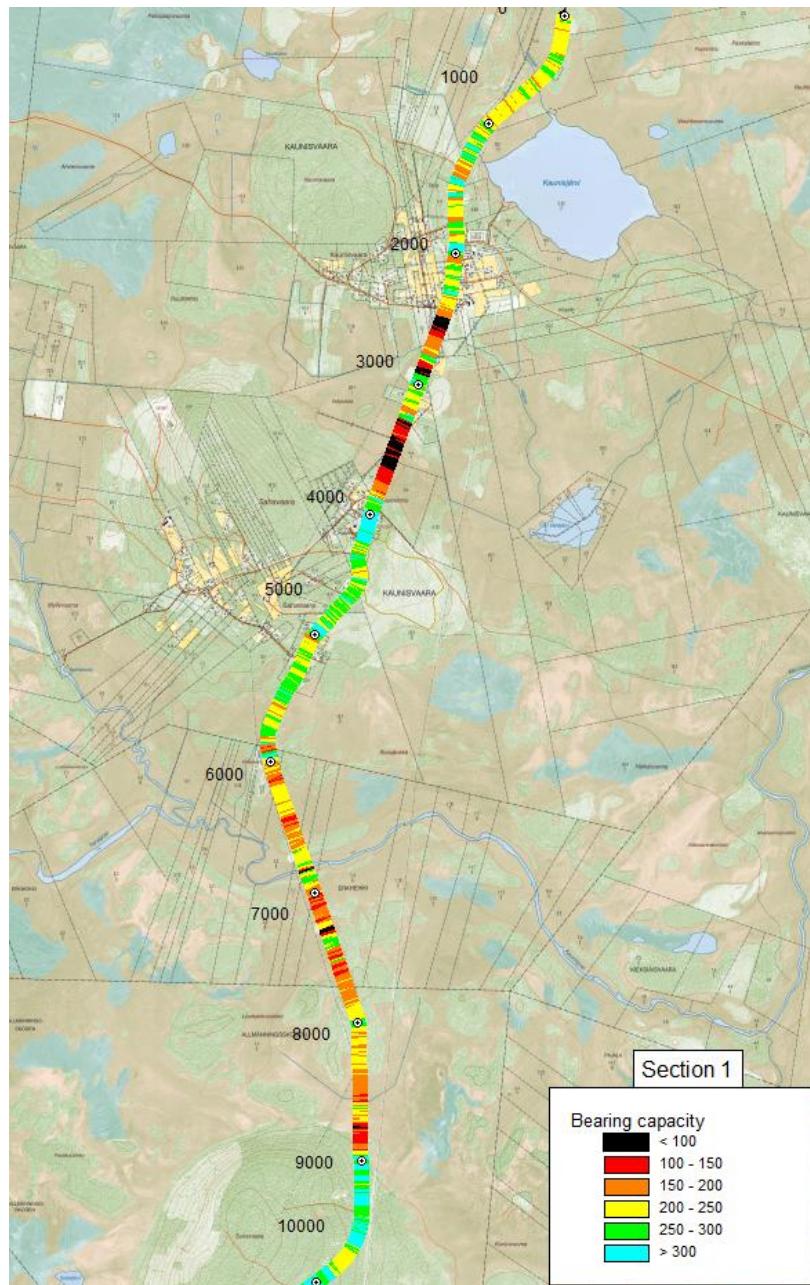
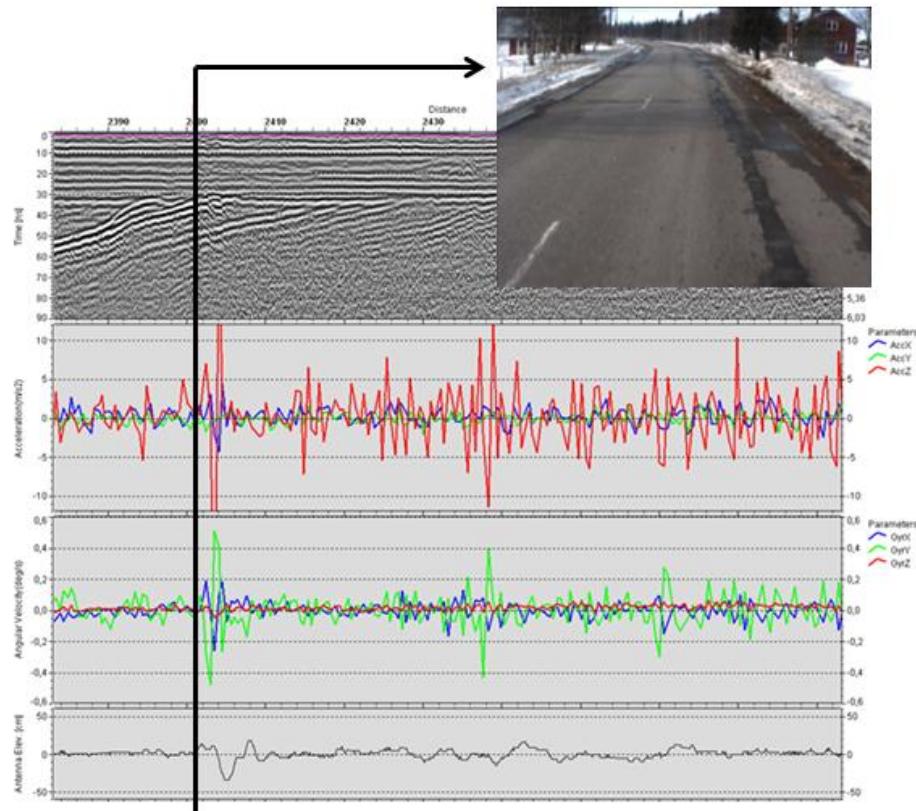


Figure 9. Bearing capacity on road Section 1, part 1.

No major geotechnical risks for the road were detected.

### 3.10 ACCELEROMETER TEST RESULTS

Accelerometer surveys were performed in order to locate potential vibration problem sections. These were especially focused on those sections with a human settlement near the road as roughness in these locations would be the most critical. There were several villages/houses along the route that were very close to the road with major roughness. Figure 10 gives an example of such location.



*Figure 10. The first window presents the GPR data from the ground coupled antenna, the second gives the acceleration in the x (blue), y (green) and z (red) directions, the third presents gyration speed in all directions. The bottom shows the antenna elevation from the air coupled antenna GPR measurements.*

### 3.11 REPEATED LOADING TRIAXIAL TESTS

The permanent deformation response of the base course material was investigated using the large diameter repeated loading triaxial test facility available in the Laboratory of Earth and Foundation Structures at the Tampere University of Technology. The test material was taken from the unbound base course of Road 395 101/959 (Section 2 at 1,675 m). According to the Tube Suction tests the quality of the crushed gravel moraine aggregate having a fines content of 14.3 % and the maximum grain size of 20 mm was expected to be questionable. The original fines content of the aggregate was 9.2 % and the maximum grain size 32 mm as shown in Figure 11.

The main purpose of the repeated loading triaxial tests was to qualitatively investigate the effect of moisture condition on the mechanical behaviour of the Pajala – Svappavaara road base course material when it was exposed to long lasting cyclic loading with different intensities. Meantime, due to the very different boundary conditions of the loaded aggregate in a laboratory test and in the actual road structure it was not expected that any direct correspondence between the applied loading series and the passages of a certain type of heavy vehicles could be achieved.

The test results summarized in Figure 12 clearly indicate the drastic effect of moisture content on the permanent deformation response of the tested base course aggregate. In a low moisture content, corresponding to a saturation ratio of about 44 %, the material could resist the accumulation of marked permanent deformations up to a repeated axial loading level of 360 kPa. When saturated the test specimen, having an estimated saturation ratio of about 90 %, started to collapse already in the early stage of the repeated axial loading pulse series of 180 kPa.

The physical reason for the big difference between the two test specimens is clearly in accumulation of excess pore water pressure and respective lowering of the effective stresses in

the saturated test material during the cyclic loading. Unfortunately the available test arrangements did not enable the continuous recording of the developing amount of excess pore water pressure in the middle of the test specimen. However, the manually recorded maximum value of excess pore water pressure in a tube connected to the lower end of the specimen No. 2 was observed to be of the order of 14 kPa at the end of loading. During the repeated axial loading series of 100 kPa the development of excess pore water pressure could not be observed.

As pointed out above the boundary conditions in the triaxial test, like in any other type of laboratory experiments, were quite different from those prevailing in the actual road structure. In spite of that, the results of the repeated loading triaxial tests performed lead to two important conclusions:

- Operative drainage is an utmost important issue for proper performance of the tested aggregate corresponding to a typical base course layer material on the Pajala – Svappavaara road.
- If there is any, even temporary, risk for the occurrence of high saturation ratio in the structural layers of the actual road, convoy driving of the heavy vehicles should be strictly avoided.

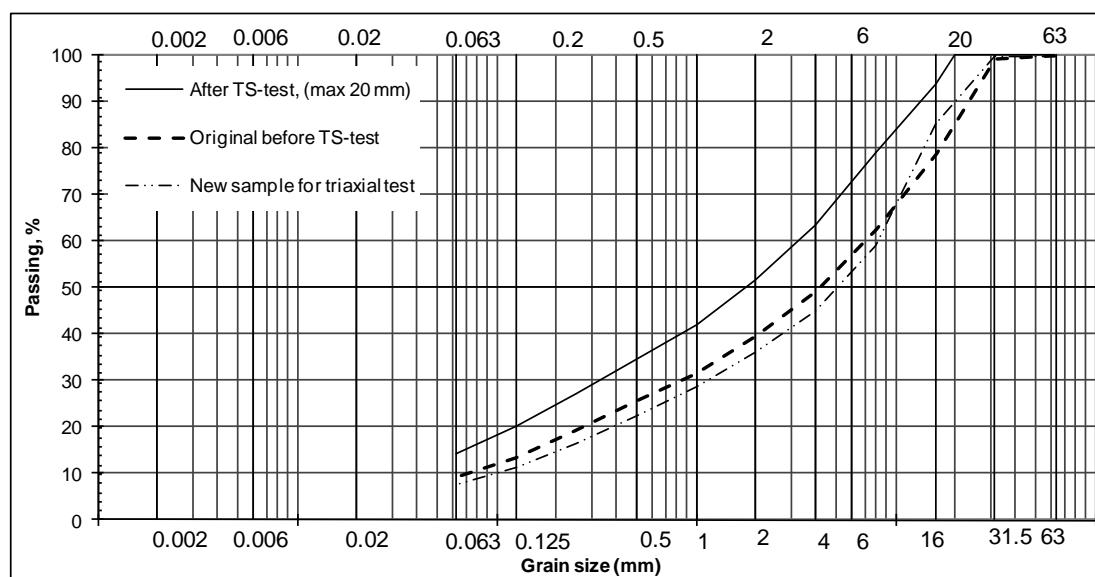


Figure 11. Grain size distribution of the base course aggregate from Road 395 101/959.

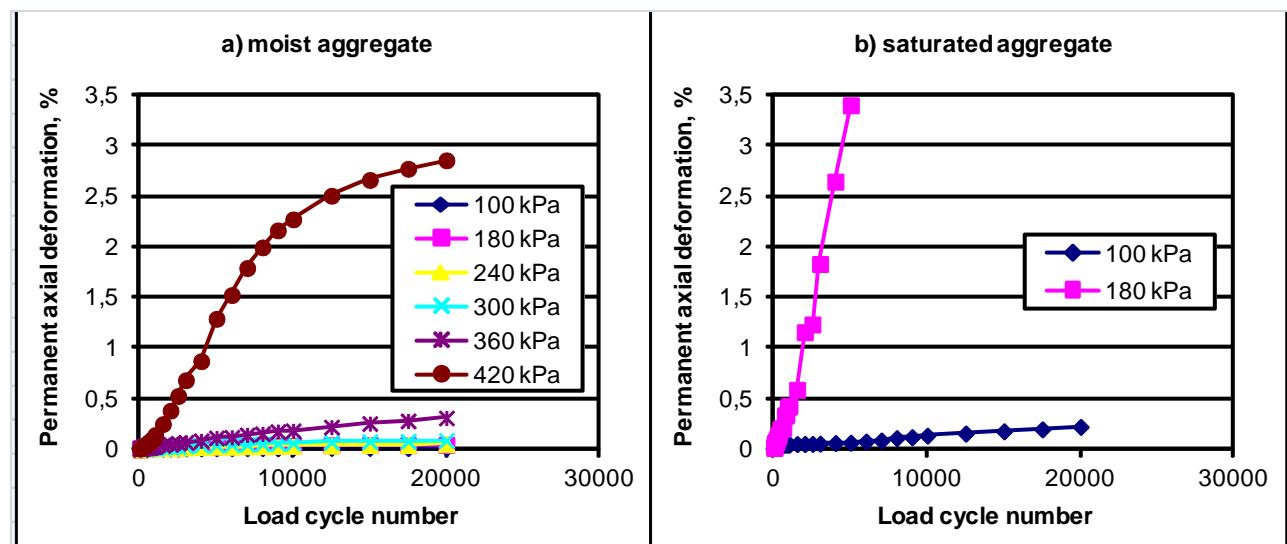


Figure 12. Accumulation of permanent axial deformation during the repeated loading triaxial test series: a) in moist base course aggregate and b) in base course aggregate saturated with water.

# 4 STRENGTHENING DESIGN

## 4.1 RISK CLASSIFICATION

In the first design process the six road sections were further divided into five risk classes determined by evaluations of the road condition based on, among other things, GPR data and FWD data. In these risk classifications the subgrade (modulus and BCI value) was given a high weighting as previous analyses had showed that the subgrade was the weakest link in the design.

The risk classification was made according to following principles:

- Risk class 1: Strong road section, no risk major for immediate failures. Pavement fatigue will follow normal road life time prediction models.
- Risk class 2: Relative strong road. Road damage will appear quickly only in extreme loading conditions or due to poor drainage maintenance etc. Strengthening is recommended also for this class.
- Risk class 3: Adequate road section. The risk will mainly appear during particularly bad spring thaw weakening periods. Strengthening is also recommended for this class.
- Risk class 4: Weak road section. High risk for road failures especially during the spring thaw weakening period. Strengthening strongly recommended.
- Risk class 5: Extremely weak road section. Severe damages can be predicted immediately after heavy haulage starts – should be strengthened immediately.

The subgrade soil properties were given greater weight in this risk as the subgrade was considered to be the critical point in the road structure. The distribution of the calculated risk classes in each road section is shown in Figure 13.

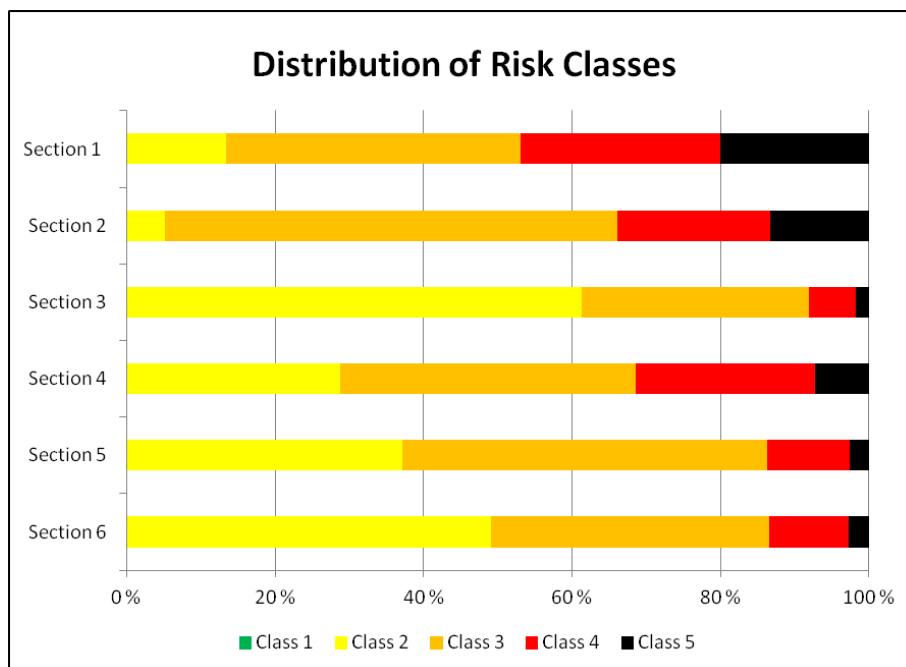


Figure 13. Distribution of risk classes in each road section.

## 4.2 LIFETIME ANALYSIS

The calculations of the remaining lifetime on the unimproved road at the time heavy haulage start would start were made using Swedish PMS-object software. In the adjusted calculations an examination was made separately of each risk class. It should be kept in mind that PMS Objekt software assumes that only standard 60 tn trucks are used in the haulage.

The results of the analysis clearly showed that if and when the heavy haulage started on the unimproved road without strengthening the remaining lifetime of the road would be very short and 96 % (Table 2) of the road length would have serious problems within the first year. The remaining lifetime on the bound layers was approximately 0 years, except in Section 4 risk Class 2 where it was one year. At the foundation level the remaining lifetime varied between 0-8 years, and generally 1-2 years.

*Table 2. Proportion of remaining lifetime less than one year in each section of the Pajala road if and when heavy haulage starts. In these calculations the lifetime of the bound layers and the foundation level has been taken into account.*

Section	Lifetime < 1year
1	100 %
2	100 %
3	100 %
4	71 %
5	100 %
6	100 %
Total	96 %

#### 4.3 NEED FOR ROAD STRENGTHENING AND OTHER IMPROVEMENTS

Structural solutions were designed and tested based on PMS Objekt software with a goal for designing a structure with a lifetime of 20 years. This analysis showed, for instance, the importance of a 200 mm bound layer thickness on the top of the new structure. Using 150 mm bound layer thickness gave only 6-8 year lifetime for the new structure.

Based on evaluations of numerous structural options, three main structural solutions were selected with practically all structural solutions containing 200mm of bound layers. The only exceptions were sections with a third lane, where the old road would be used mainly by empty trucks and would have only 100mm of bound layers. The most general solution was to add new layers (unbound base and bound layers) on the top after the old pavement had been removed and the old unbound base surface had been shaped (Figure 14).

The strengthening of the old road over a weak subgrade proved to be difficult and that is why, in the weakest sections (mostly risk Class 5), it was recommended that a third lane should be built for the heavy trucks. In these sections savings can be achieved because the old road will not be so heavily strengthened: the structure will be 100mm bound layer and 100mm unbound layer (Figure 15). In the extremely weak sections (peat areas) with potential pumping problems it was recommended that steelnets should be used (Figure 16).

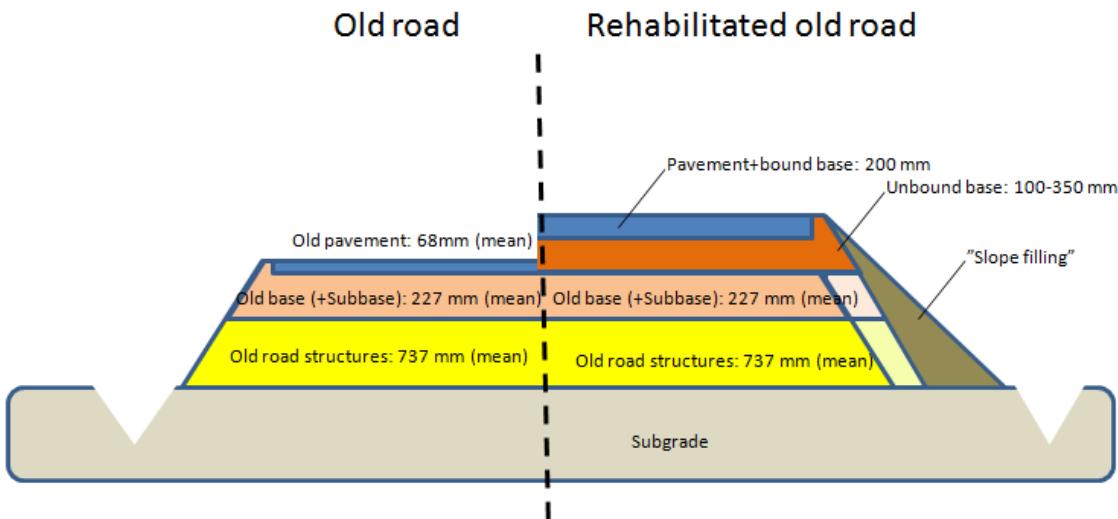


Figure 14. The principles of the basic structure used in strengthening.

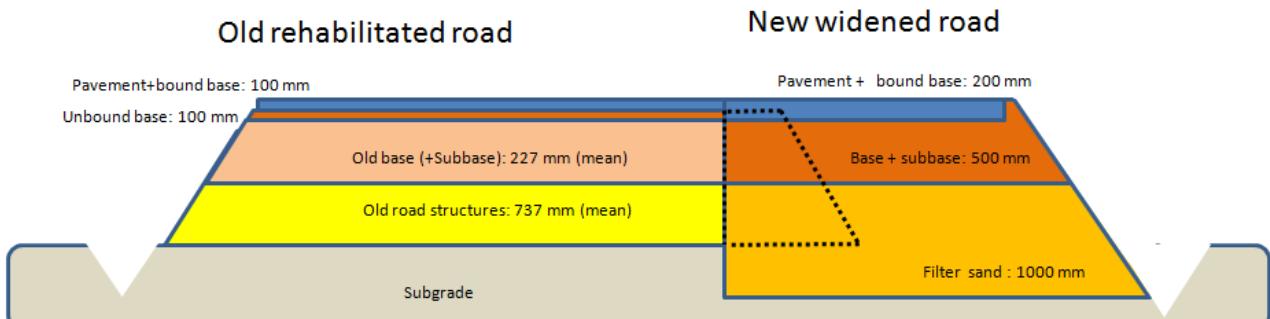
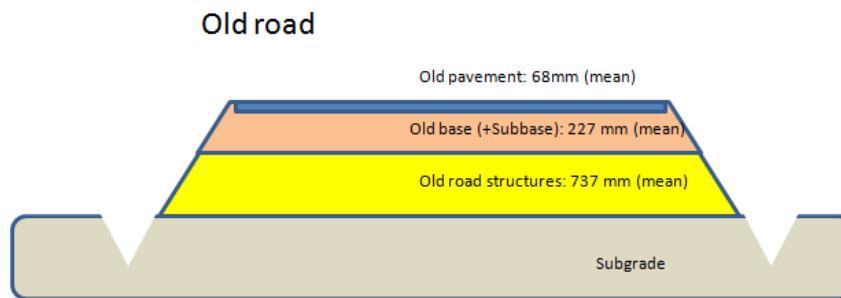
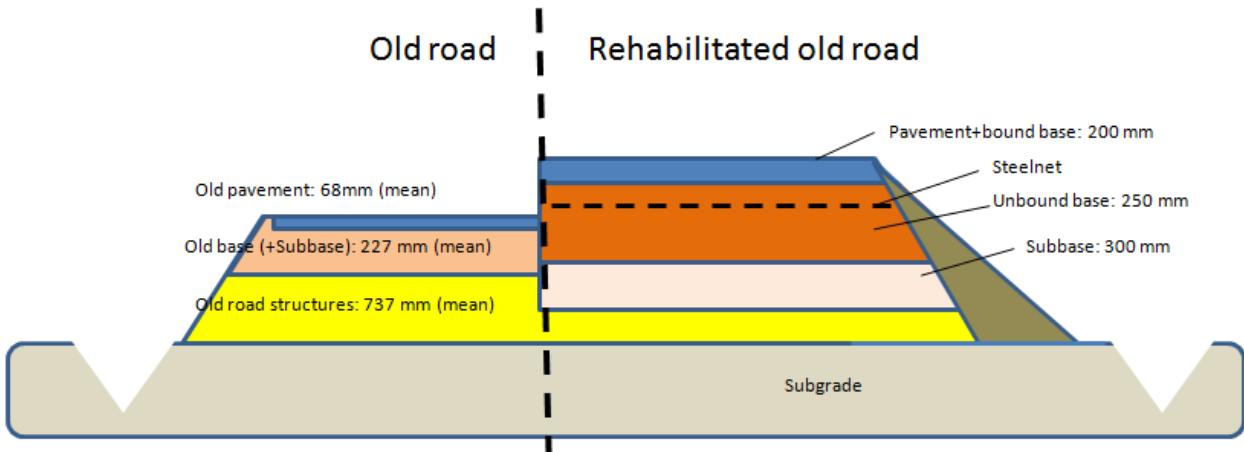


Figure 15. The principles of a third lane structure. If there is big difference in frost heave between the old road and new lane, then it is recommended that the third lane be separated from the old road in some way.



*Figure 16. Principles of the steelnet structure to be used in the weakest peat subgrade sections*

#### 4.4 SPECIAL SOLUTIONS

In addition to building third lanes in weak sections that could also act as passing places it was proposed that a third lane, "climbing lane", should be built at two locations with long steep hills. It was also proposed that road geometry should be improved in one location by straightening the road in a section with potential traffic safety problems.

On road crossings it was recommended that speed transition lanes should be built. The road on both sides of bridges was also considered to be critical if restrictions on usage were implemented (one vehicle at a time on the bridge). In that case, it was recommended that lay-bys at the end of bridges had to be built.

Risk analysis also identified four sections with major flooding risk and the protection of the road and heavy haulage in these sections was recommended to be designed separately.

# 5 RISK ANALYSIS FOR DIFFERENT HAULAGE OPTIONS

## 5.1 GENERAL

Throughout the time of the Pajala road project impact analysis process more than 30 truck options were analyzed and evaluated in order to find the technically most optimal truck configuration from the perspective of preserving the road structures. Some of the options were suggested by the mining company and different truck manufacturers, some of them were modified from those. The possible truck concepts were evaluated based on the axle loads, number of axles, distances between axle groups, net loads etc.

The analysis of pavement responses under the different loading options was carried out using a multi-layer linear elastic modeling approach in the BISAR® software tool. The approach is generally accepted worldwide and a very extensively used method to analyze the mechanical behaviour of various types of pavement structures. In multi-layer linear modeling the pavement structure is described using a set of layers resting on top of each other and underlain by an elastic half space representing the subgrade. In the model both thickness and stiffness of each layer can be selected freely so as to enable as close a resemblance to the original structure as possible. In addition, tyre loads resting on top of the road surface can also be modeled individually as spherical contact areas with an evenly distributed vertical pressure corresponding to the tyre inflation pressure.

The stresses, strains and displacements in different directions at selected points inside of the pavement structure and subgrade can be obtained from the BISAR® analysis. For the purposes of the present project the most interesting result is the vertical displacement on top of the subgrade which can be used as a convenient indicator of the overall severity of the loading action due to the vehicle that is stressing the pavement structure.

An inherent limitation of the multi-linear elastic modeling approach is that the loads are not moving and each acts on a constant point. The model cannot therefore be directly used in assessing the visco-elastic behavior of soft and wet subgrade materials in which excess pore water pressure may develop under repeated loading as discussed later in this chapter. Another well-known limitation of the method affects thin pavement structures typically found on low volume roads having only a thin bitumen bound layer as a wearing course. This limitation did not affect the Pajala road as the thickness of the bound layers and the overall thickness of the analyzed pavement structures were reasonably high.

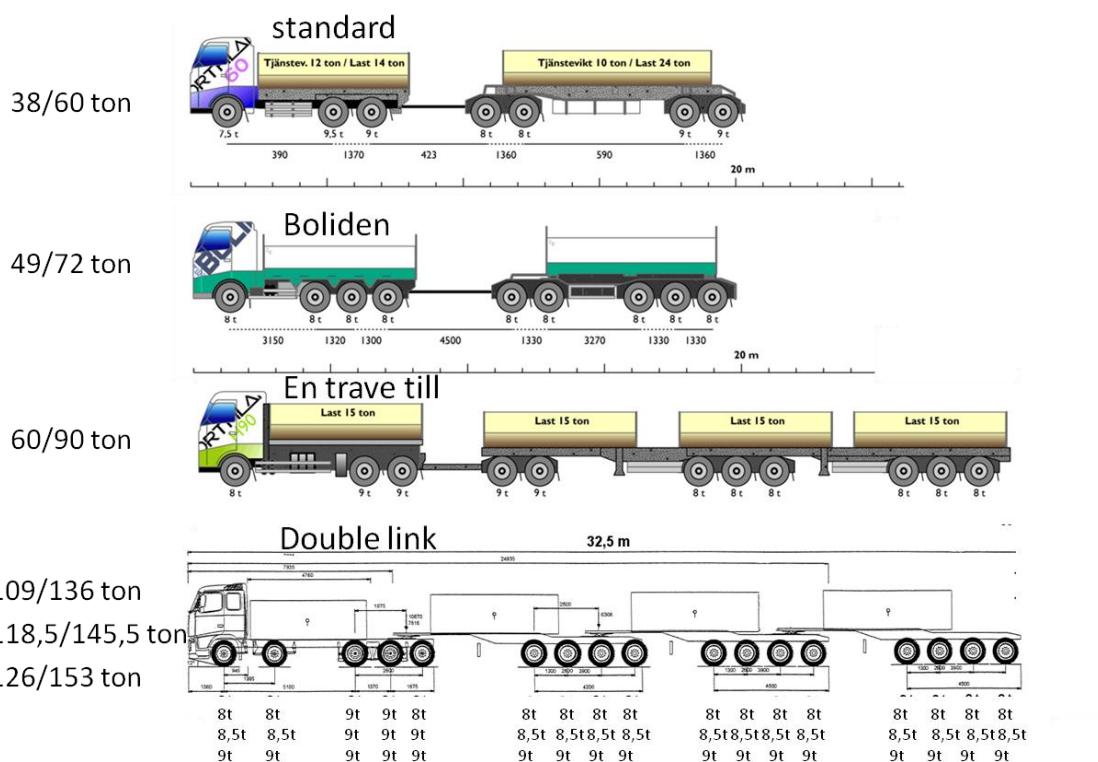
A dual tyre was selected to be the tyre type to be used in the evaluations as experience from the ROADEX project, and a number of other earlier analyses, had shown that dual tyres were much more road friendly on low volume roads compared to super single tyres. The stresses and strains in the top part of the road structure were likely to rise too high if super single tyres were used. This decision was made in conjunction with Trafikverket. The possibility of using tyre pressure control systems (CTI, TPCS) in the trucks was also evaluated, but the calculations quickly showed that CTI did not help in this project, at least from the road structure point of view, as thick bound layers were to be used. Accordingly, the final tyre type selection used in the calculations was a dual tyre with a normal (800 kPa) tyre pressure.

## **5.2 OPTIONS IN FINAL EVALUATION**

More than 30 truck options were analyzed and evaluated during the Pajala road project impact analysis in order to find the technically most optimal truck configuration from the perspective of preserving the road structures. The possible truck concepts were evaluated based on axle load, number of axles, distances between axle groups, net loads etc. The stresses, strains and displacements in different directions at selected points inside of the pavement structure and subgrade were obtained using the BISAR® analysis. In this analysis the most interesting and critical result was the vertical displacement on top of the subgrade.

Major discussions in the work group concerned axle weights. During the evaluation process it became clear that the most beneficial axle load for the road was between 8 and 9 tons. If the axle load was increased higher than that, the subgrade displacement as well as the loading effect on the road pavement assessed according to the fourth power rule calculation started to grow rapidly.

For the final evaluation the standard 60 tonnes truck option was naturally the first choice. The 72 tonnes (Boliden) and 90 tonnes (En trave till) options were also chosen, because they were more or less ready alternatives for the standard truck and had been used in Sweden previously. The 136 tonnes "Double link" truck option was chosen, because it was calculated to be best option according to the fourth power rule evaluation. The 145.5 tonnes and 153 tonnes "Double link" options were chosen in order to evaluate the effect of higher axle loads (8.5 tn and 9 tn) compared to the 136 tonnes option (8 tn). The truck options in the final analysis are described in Figure 17.



*Figure 17. Final truck options used in the evaluation. The difference between the double link options is only the axle weight.*

### **5.3 ANALYSIS OF HEAVIER HAULAGE OPTIONS**

The BISAR® software comparison calculations of the different truck options showed that the induced subgrade displacement was lowest for the standard 60 tonnes truck, but the 72 tonnes and 90 tonnes options were not much worse. The "Double link" options with four axle groups were

slightly worse, but compared with each other there was not a very big difference between the options.

Bigger differences could however be detected when cumulative subgrade displacement calculations were made for each of the truck options. On the basis of the cumulative subgrade displacement evaluation (Figure 18), the 60 tonnes option was again the best. The 72 and the 90 tonnes options were approximately on the same displacement level with each other with maximum cumulative displacement of 1.0 – 1.5 mm (approximately 30 - 40 %) greater than the 60 tonnes option. The "Double link" options were again the worst, with maximum cumulated displacements of between 6.5 mm and 7.5 mm, which were more than 2 times higher compared to a standard 60 tonnes truck. It should also be noted that the calculated cumulative subgrade displacement for the heaviest cases represented an optimistic / conservative estimate because the subgrade recovery in real life would not be as immediate as the BISAR® calculations show. This is for example due to development of excess pore water pressure and in real terms the cumulative effect could in unfavourable conditions be even stronger.

The distance between axle groups in the combination 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.

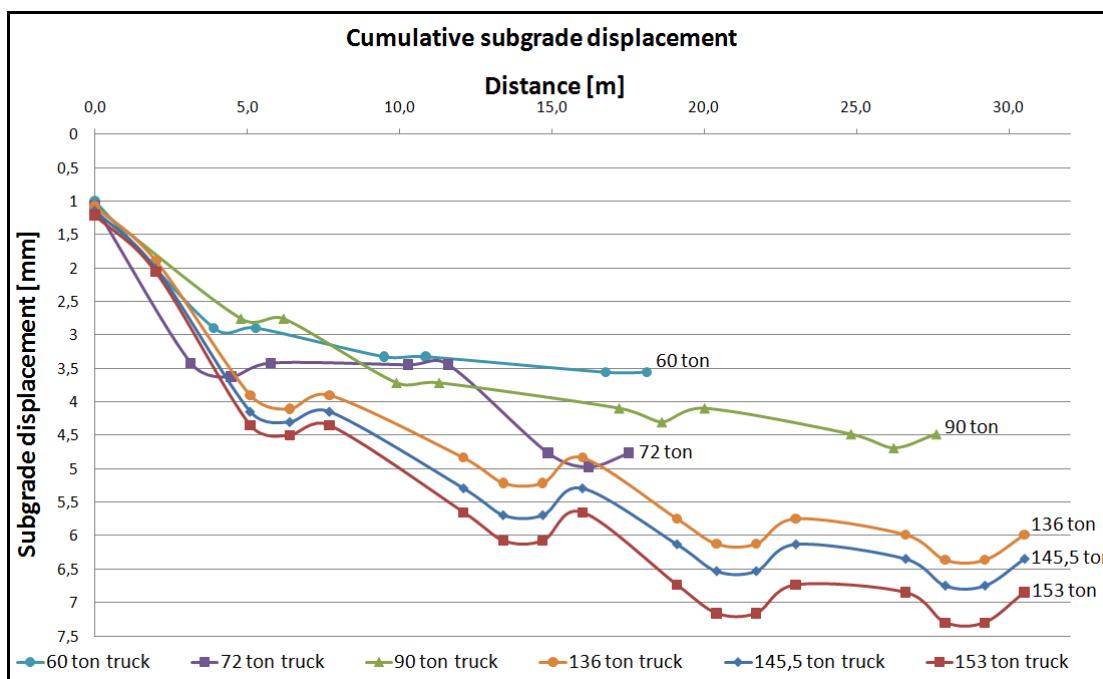


Figure 18. The cumulative displacement of a weak subgrade (modulus 10 MPa) calculated for each truck option. The horizontal axis gives the distance from the first axle of the truck. Zero is the first axle and the dots along the displacement curve represent the locations of the consecutive axles. The vertical axis displays the cumulative subgrade displacement calculated at one point.

In addition to displacement calculations with BISAR® software, another separate comparison of the truck options was also developed based on the classical "fourth power rule used in pavement engineering. This rule slightly underestimates rutting and overestimates pavement distress but in general is still quite reliable in estimating pavement performance under different loadings.

The results of the fourth power rule calculations are presented in Table 3. The value in the last column is the factor of comparison to standard 60 tonnes truck and it shows that, based on this assessment, all truck options were better compared to the standard 60 tonnes truck. For example, the "Boliden" 72 tonnes truck is 27 % better than the 60 tonnes option according to this calculation. The best option in this evaluation was the 136 tonnes double link. The values less than 0.75 are highlighted with green colour representing the best options. The values greater than 0.75 but less than 1 are highlighted with yellow colour representing moderate options.

Table 3. Results of the fourth power rule calculations on the effect of different trucks on pavement performance

Truck option & total weight	Axel loads					Truck EKV	Net weight	Truck loads	Load effect	Comparison to 60 ton
	7,5 ton	8 ton	8,5 ton	9 ton	9,5 ton					
Standard 60 ton	1	2	0	3	1	3,918	38	131579	515581	1
"Boliden" 72 ton	0	9	0	0	0	3,686	49	102041	376163	0,730
"ETT (En trave till)" 90 ton	0	7	0	4	0	5,492	60	83333	457633	0,888
"Double link" 136 ton	0	17	0	0	0	6,963	109	45872	319413	0,620
"Double link" 145,5 ton	0	0	15	2	0	9,142	118,5	42194	385751	0,748
"Double link" 153 ton	0	0	0	17	0	11,154	126	39683	442607	0,858
Annual transportation (ton) =	5000000									
Stress exponent used in calculations =	4									

Finally, the evaluation of the road recovery time after the passing of each truck proved to be the most challenging issue in the Pajala road impact analysis. Recovery times were evaluated by the delay times of KUAB HWD measurements from time history data, which can be considered as minimum recovery time but not the maximum. Data analysis results showed that long delay times could be expected to take place in risk Class 5 road sections with low subgrade moduli values. Based on the results from cumulative deflection modeling, the minimum calculated delay time and distance of a heavy truck driving 80 km/h was roughly 1.5 seconds and 30-40 metres. This means that a long recovery time would even increase the effect of heavy trucks and that there was a possibility that positive pore water pressure would develop. However the time interval between heavier trucks on the road would be correspondingly longer and allow a real recovery time roughly 200 times longer which meant in practice five minutes. This meant that the distance between trucks had to be strictly controlled and convoy driving should be strictly forbidden.

## 6 CONCLUSIONS, DISCUSSION AND RECOMMENDATIONS

An impact analysis using a range of methods recommended by the ROADEX project has shown that more than 90 % of the road will have failures within one year after heavy haulage starts. The main reason for this is that the road structures are weak.

The basic strengthening structure for 20 years of service life should consist of 50 mm of bituminous wearing course, 150 mm of bituminous bound base and 100 – 350 mm of unbound base. The old pavement should be removed from the old road and the top unbound structure should be homogenized and shaped. In addition it is recommended in many cases that a new lane for heavy trucks should be built in the weakest sections. This is because new structure thickness required for the loadings would be so thick, especially on the risk Class 5 sections, that it would make road construction really difficult. This new third lane would act as passing place for other cars. In those sections where a third lane cannot be built it is recommended that soil replacement structures should be used. In some sections raising the gradeline is also an option.

Frost heave analyses showed that there were only a few places where the bearing capacity dimensioning was insufficient for the frost heave, and in these sections the structures should be designed on a case-by-case basis.

In addition to the new third lanes it is also recommended that at least two climbing lanes be built on the steepest hills on the road. The horizontal geometry of one section should also be improved due to traffic safety issues. All of the road intersections should also be redesigned, and acceleration lanes for heavy trucks should be considered wherever it is possible.

Drainage analyses showed that, compared to other Nordic areas tested in the ROADEX project, the drainage on the Pajala road is in general in relatively good condition. However in view of the fact that the TUT laboratory analyses showed that the unbound materials are extremely water sensitive it is recommended that the drainage of the whole road should be improved up to drainage Class 1 before the strengthening works are undertaken. Drainage improvement is without doubt the cheapest option to improve bearing capacity of the road. Also, after the improvement the drainage should be always kept in faultless condition. There are a number of culverts that have problems with frost and they should be repaired or replaced. In addition the mobile laser scanner analysis showed that, where private exit road culverts are clogged, frozen or missing, this had a great impact on road performance. These sections should be checked and fixed, as road surface deformations will cause major vibration problems to houses close by.

Another potential source of extra cost is the road width. The GPR surveys, especially the cross sections, provided very useful information on deformation problems on the road. They clearly showed that road problems were frequently related to weak shoulder support of the road, especially in the areas where inner slopes were steep. These problems will increase once the mine is opened and iron ore haulage starts as the road structure thickness will be increased and the gradeline will be higher. Longer and heavier truck combinations will also be driving close to the road edge. For this reason an appropriate width and cross section for the road will be vital in the final strengthening design of the Pajala road.

Throughout the impact analysis process more than 30 different truck options, suggested by the mining company and different truck manufacturers, were evaluated. These calculations showed that CTI will not help in this project as thick bound layers will be used. The most critical sections on the road are those sections with a weak subgrade (10 MPa), and these sections will be especially weak during the spring thaw. Calculations showed that the displacement in the subgrade with heavier truck configurations can be two times higher in comparison to a normal truck. This is a serious risk that everyone should be aware of if heavier truck options are used. On the other hand

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the cumulative load impact of these heavier trucks on the pavement is much less than if haulage was done using standard 60 tonnes trucks. The comparison of the different truck options gave the best points to 136 tn “double link” truck.

Recovery time measurements and calculations showed that road recovery will be an issue especially in the road sections with Class 5 problems. Positive pore water pressure will be generated under repeated axle loads and this will reduce the stiffness of the subgrade further. Calculations of different truck options showed that the heavier truck options, i.e. greater than 100 tonnes, will need longer recovery times. This will be the case anyway if heavier trucks are used and the distance between the trucks is controlled. On the other hand, if most of the Class 5 risk sections can be replaced with well designed and built third lanes, recovery times will not be an issue when heavy haulage starts.

This project did not solve all the unknown questions with regard to road performance and, as such, structural monitoring should be carried out when the full scale tests are conducted. In addition, a sufficient number of sensors should be installed in the new road so that road performance can be monitored continuously. In addition a routine road monitoring system should be designed to support preventative maintenance actions on the road. In other words, potential failures should be detected before they occur. A special winter maintenance plan should also be made to ensure that trucks do not get stuck on slippery and steep hills during snow storms.

Finally the collected and analyzed data in this project, when properly used in the final strengthening design will be extremely valuable. Examples from the earlier ROADEX projects have shown that a potential savings in the strengthening costs will be between 30 – 100 million SEK. The collected information and analyses should also ensure that there should not be any unpleasant surprises when the road has been strengthened and heavy haulage starts in 2013. The data analysis and calculations with different heavy haulage options will also provide solid background information to the Swedish Transport Administration and Northland Resources when discussing the options for heavy load premiums.



## ROADEX PROJECT REPORTS (1998–2012)

This report is one of a suite of reports and case studies on the management of low volume roads produced by the ROADEX project over the period 1998-2012. These reports cover a wide range of topics as below.

- Climate change adaptation
- Cost savings and benefits accruing to ROADEX technologies
- Dealing with bearing capacity problems on low volume roads constructed on peat
- Design and repair of roads suffering from spring thaw weakening
- Drainage guidelines
- Environmental guidelines & checklist
- Forest road policies
- Generation of 'snow smoke' behind heavy vehicles
- Health issues raised by poorly maintained road networks
- Managing drainage on low volume roads
- Managing peat related problems on low volume roads
- Managing permanent deformation in low volume roads
- Managing spring thaw weakening on low volume roads
- Monitoring low volume roads
- New survey techniques in drainage evaluation
- Permanent deformation, from theory to practice
- Risk analyses on low volume roads
- Road condition management of low volume roads
- Road friendly vehicles & tyre pressure control
- Road widening guidelines
- Socio-economic impacts of road conditions on low volume roads
- Structural innovations for low volume roads
- Treatment of moisture susceptible materials
- Tyre pressure control on timber haulage vehicles
- Understanding low volume pavement response to heavy traffic loading
- User perspectives on the road service level in ROADEX areas
- Vehicle and human vibration due to road condition
- Winter maintenance practice in the Northern Periphery

All of these reports, and others, are available for download free of charge from the ROADEX website at [www.ROADEX.org](http://www.ROADEX.org).



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