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VEHICLE AND HUMAN VIBRATION DUE TO ROAD CONDITION

A Report from Studies on Low Volume Roads in the EU Northern Periphery of:

- Demonstrations of Truck Ride Measurements in ROADEX Partner Areas
- Effectiveness on Isolation of Ride Vibration by a Tyre Pressure Control System
- Impact from Road Maintenance Standard on Truck Drivers Working Environment

ABSTRACT

This report is a follow-up on the ROADEX III report "Health Issues Raised by Poorly Maintained Road Networks", which stated: "*Northern European road users may be exposed to unacceptable health and safety risks, in terms of ride vibration and skid accidents*". That report included a case study of a timber logging truck that showed that the test truck drivers on Road 331 in the summer of 2007 had been exposed to daily vibration doses higher than the Action Value A(8) in Directive 2002/44/EC. The EC-directive includes limits to allowed vibration at work with respect to health and safety risks. The ROADEX III test truck drivers were also exposed to significant spinal compression stress when their trucks had passed over severe road damage. Truck vibration modes included lateral buffeting during transient roll vibration in road sections with non-uniformly deformed weak shoulders. These transient side forces are recognized for increasing the skid crash risk on wet ice and other slippery road surfaces.

The ROADEX III study also validated a new road condition parameter, *Rut Bottom Cross Slope Variance (RBCSV),* as an indicator of road damages that cause "truck roll motion". The validation was done by collating RBCSV road data with heavy truck ride data on transient roll vibration and roll-related lateral buffeting. A limit value of 0.30 % for RBCSV was derived on the basis of several inputs, including skid crash records, truck driver perceived skid risk and RBCSV statistical distribution on good and bad roads.

This present ROADEX IV follow-up report describes results from demonstration projects in Scotland, Finland, Norway and Sweden over the period 2010 to 2012, where the case study from the Beaver Road 331 has been reproduced. This document also reports on a study of the influence of road maintenance standard on truck ride vibration and vehicle internal noise, with special focus on winter road condition. Furthermore it reports on a study on vibration isolation from road to truck driver's seat, by use of a Tyre Pressure Control System (TPCS). All measurements were carried out in the period 2010 - 2012.

A high repeatability between similar truck round trips was confirmed when using the ROADEX method to assess truck drivers' daily vibration exposure A(8). **Results** from measurements of truck ride quality during the demonstrations included:

- Unacceptably high levels of driver´s daily vibration dose A(8) were recorded in all of the ROADEX Partner areas (the Norwegian E6-measurements were lower than the others but still at about the EU Action Value).
- Significant *compression stress in the truck drivers spine* were recorded at severe road damages, such as sharp frost heaves, settlements at bridges and culverts, improper road/bridge joints and uneven transversal joints at both old and new asphalt repairs.
- In all Partner areas, intense truck roll vibration and *lateral buffeting* was recorded. This confirmed a special health and safety problem in the EU Northern Periphery (NP) cold climates.
- The pavement condition parameter RBCSV (a "*truck roll vibration indicator*") was further validated in addition to the previous ROADEX III study in Sweden. At sites with very high RBCSV, there is a risk that *cargo latches might break due to high lateral acceleration*.
- Winter conditions in the NP can result in *significant corrugations in thick ice covering non-salted roads, and extremely uneven frost heaves*. The project results show that these conditions can make the ride vibration and noise much worse than during summer conditions.
- The use of a Tyre Pressure Control System (TPCS) has previously been shown to reduce ride vibration. The present study used a more detailed analysis to quantify the TPCS vibration isolating effect. Results from Scotland and Sweden show that *TPCS was very efficient in isolating "shake" vibration from short wave road roughness (megatexture < 0.5 m) such as potholes and corrugated ice surfaces*.
- Vehicle body "bounce" vibration with lower frequencies (1 – 3 Hz) were not isolated by the TPCS. Such low frequency bounce vibration can only be reduced by pavement maintenance.

- High side friction demand due to improperly banked horizontal curves was found to be a contributing factor behind many loss-of-control crashes, including rollovers. Several curves with tragic crash records were found to be improperly banked despite being newly resurfaced.

A number of overall **conclusions** and **recommendations** for NP road agencies and truck operators are offered:

- Truck hauliers, both self-employed and those with employees, who find themselves operating under conditions comparable to those in this study – typically representative for the EU Northern Periphery (NP) – are obliged by their national laws under the 2002/44/EC Directive *“to make risk assessment for health and safety issues raised by exposure from vibration as well as mechanical shock”*. For winter operations this should also include assessing the *skid risk associated with lateral buffeting on slippery ice.*
- *The assessment of NP truck drivers’ exposure to daily vibration at work should take account of winter operation*. In this study, the daily vibration in the winter was +39 %, and the daily compression stress dose in the spine was doubled, compared to same operation (truck, route) despite significant higher driving speed in the summer.
- *Foreign hauliers should be subject to the same level of supervision of vibration risk assessment as native hauliers to avoid unfair competition*. In Sweden, the current share of foreign heavy trucks in long haulage is estimated to 40 % and it is rapidly growing.
- It was concluded that *a significant share of the ride vibration problems identified in the surveys could be eliminated in a relatively short time* by improved road construction and maintenance practices as they originated from manmade sources, such as culvert trenching, transversal joints at bridges and at improperly performed resurfacings.
- The new pavement condition parameter *RBCSV is a useful tool to identify hazardous sites with high risk for instability crashes such as rollovers*. High RBCSV can also explain crashes involving strapped heavy goods on trucks or trailers that have slipped and/or overturned.
- An under-estimated source of poor ride quality is corrugation in gravel roads and in thick ice covered paved roads. This study showed that the current smoothness specification for winter roads in Sweden is unable to penalize unacceptable corrugations. *More research is needed to establish a measurement method and a limit value for maximum acceptable corrugation*.
- Public road network condition surveys with laser profilers are traditionally only carried out in the summer time in the NP area. In regions with “white winter roads” (not the Scottish Highlands or Ireland), frost actions may locally cause significant differential ground heave, resulting in a seasonal increase of road roughness that can be dramatic. *The road condition assessment procedures of the ROADEX Partners may therefore need revision in order to become credible for seasons other than the summer* (which is short in the Northern Periphery). Norway already has started to incorporate road condition data such as IRI-values from the teleløsning (“spring thaw”) season in their Pavement Management System. Sweden is currently developing an improved practice for the measurement of frost-related road roughness.
- *Trucks that regularly operate on rough surfaces should be equipped with a TPC-System and be frequent checked and corrected for wheel imbalance*. This will significantly reduce daily vibration A(8), as required by law.
- *Trucks without a TPC-System should employ “continuous correction of wheel imbalance” by balancing powder.* The use of “Counteracting Balancing Beads” or similar products will significantly reduce daily vibration A(8), as required by law.
- The traditional methods of repairing roads have been developed for dealing with structural condition and with short wave roughness (up to some 5 m waves). These methods are not however appropriate for dealing with the health and safety issues covered by this report. For these, road agencies will also need to *implement a practice for repair and improvement of the pavement geometry*, so unevenness with wavelengths up to some 30 m as well as improper cross slope is eliminated. This calls for a modernized asphalt work process, with re-design of road surface geometry and computerized asphalt machine control.

- The study identified horizontal curves with tragic crash records that were still improperly banked after resurfacing. Improper superelevation results in an excessive need for side friction between road and tyre, which in turn is a key factor behind loss-of-control crashes including rollover of heavy vehicles. Up to some 15 % of all fatal crashes (in Sweden: 50 deaths/year) on the road network could be prevented, by *implementing a strategy for repair and improvement of pavement geometry*. Such a strategy could identify what curves need to be improved, and ensure that the necessary improvement of pavement geometry (and improved warning signs for sharp curves) is made at a minimum of cost in conjunction with traditional pavement resurfacing or reinforcement works. Critical curves may need to be elevated some 2 – 5 dm at the outer side compared to the road centreline. By doing this on the improperly banked curves, the need for side friction typically drops by some 50 - 80 %. This will significantly reduce the disproportionally high risk for fatal single-vehicle crashes in outercurves. The cost/benefit of a scheme for such road safety improvement is likely to be so high, that it could set a new reference for deliverable rates of return for road agencies on low volume roads.

KEYWORDS

Human whole-body vibration (WBV), perception, comfort, driver performance ability, health, heavy goods vehicles (HGV), suspension, isolation, amplification, damping, stiffness, mass, inertia, dynamic force, jerk, jolts, transients, mechanical shocks, tyre pressure control system (TPCS), unbalanced wheels, counteract balancing beads, road roughness, IRI, texture, side friction, rut bottom cross slope variance (RBCSV), roll-related lateral buffeting, improperly banked curves, adverse camber, drainage gradient, skid crashes, rollover (overturning), road safety, traffic safety, pavement bearing capacity, frost heave, permafrost, corrugation, dirt roads, road maintenance, repair and operation, winter, thick ice, thin black ice, ride quality, noise, low frequency vibration, motion sickness, replacement of frost susceptible road materials, drainage, long wave unevenness, pavement slopes, 3D, laser scanning, computer aided re-design (CAD) of road surface geometry, computer aided manufacturing (CAM), asphalt machine control, building information modelling (BIM), cost/benefit, sustainability.

PREFACE

This is a final joint report from Tasks D3 and RE6 of the ROADEX IV "Implementing Accessibility" project, a technical trans-national cooperation project between The Highland Council, Forestry Commission Scotland and the Western Isles Council of Scotland; The Northern Region of The Norwegian Public Roads Administration; The Northern Region of The Swedish Transport Administration and the Swedish Forest Agency; The Centre of Economic Development, Transport and the Environment of Finland; The Government of Greenland; The Icelandic Road Administration; and The National Roads Authority and Department of Transport of Ireland. The lead partner for the project was The Northern Region of The Swedish Transport Administration and the project consultant was Roadscanners Oy (Finland), with sub-consultant Vectura Consulting AB (Sweden).

This report gives an insight into ride vibration as a health and safety risk, by relating ride experienced by professional drivers to the European legislation on vibration at work. The report includes daily vibration exposures, A(8)-values, sampled during representative transport tasks on typical Northern Periphery (NP) low volume roads in Finland, Scotland, Norway and Sweden. The report includes illustrations of typical road damages found to yield health risks due to high spinal compression stress. The report also relates ride to road standards, with special focus on how winter conditions can affect both vehicle internal noise and ride vibration. This demonstrates that ride quality is dependent even more on high standards for roads in a winter perspective (i.e. design of pavement frost protection and operations such as snow-ploughing and grading icy roads), than in a summer perspective. The new pavement condition parameter "Rut Bottom Cross Slope Variance" demonstrated by the ROADEX III in Sweden is further validated in good correlation with lateral buffeting of trucks. Since vehicle lateral buffeting strongly increases the risk for skid crashes on ice-slippery roads, the new RBCSV parameter can be used as a tool to help prevent skid crashes by identifying those road sections that need maintenance and/or repair. The effect of vibration isolation by a Tyre Pressure Control System on a truck driver was quantified. It was found that a TPCS improves the ride in a vehicle, especially on potholed and on corrugated dirt roads and ice. However the use of TPCS is not a generic solution for poor truck ride on paved highways.

The report was prepared by Johan Granlund, Chief Technology Officer at Vectura Consulting AB. Road profilometer data were taken from road network surveys in Finland (Destia Oy), Norway (NPRA) and in Scotland (WDM Ltd). Vectura's road profilometry in Norway and Sweden, and ride measurements were undertaken by Max Risberg, Marcus Wettermark, Fredrik Stensson, Fredrik Lindström and Johan Granlund, all of Vectura Consulting. The analyses were carried out by Fredrik Lindström and Johan Granlund. Ron Munro, Project Manager of the ROADEX "Implementing Accessibility" Project, checked the language. Mika Pyhähuhta of Laboratorio Uleåborg designed the report layout.

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CONTENTS

1. INTRODUCTION

1.1. RIDE VIBRATION - A SERIOUS HEALTH AND SAFETY RISK

Road roughness is source of vibration in vehicles and a well-known cause of wear and damage to sensitive payloads[1], to the vehicle itself, as well as to bridges and pavements. Vehicle vibration in turn, also brings whole-body vibration (WBV) exposure to drivers and passengers. WBV is a root cause of work-related accidents (in road traffic: crashes) and work-related diseases. Hence Directive 2002/44/EC has set limits to the allowed vibration at work, with respect to health and safety risks. These limits are implemented in all EU member states, and also by the Schengen Agreement in the ROADEX partner areas in Norway, Iceland and Ireland.

This report is a follow-up report on the ROADEX III report "Health Issues Raised by Poorly Maintained Road Networks": That report concluded "*Northern European road users may be exposed to unacceptable health and safety risks, in terms of ride vibration and skid accidents*" based on a case study that mapped the risks on the Beaver Road 331 in Sweden. The report demonstrated methods to efficiently prevent or reduce risks on similar roads. The Beaver Road case study in particular showed that truck drivers on the road were, in summer time, exposed to daily vibration doses higher than the Action Value A(8) in Directive 2002/44/EC. The truck drivers were also exposed to significant spinal compression stress, when their trucks passed over potholes, uneven bridge joints and road sections with various forms of severe deformations. The ROADEX III study validated the new pavement condition parameter *Rut Bottom Cross Slope Variance (RBCSV)* by collating it with data of transient roll vibration and of roll-related lateral buffeting in a timber logging truck. Furthermore, a limit value of 0.30 % for RBCSV was derived on basis on several inputs, including how lateral buffeting increased the risk of skid crashing on wet black ice and other slippery road surfaces.

It is now recognised that professional truck drivers who frequently drive on rural low-volume roads in poor condition can be exposed to human whole-body vibration (WBV) higher than the Action Value set by EU directive 2002/44/EC. These drivers may suffer risks of stress related heart diseases and of musculoskeletal problems in the neck, shoulders and back. Furthermore they can be at high risk of being involved in instability crashes, where other road users may also be severely injured when colliding with the heavy vehicle being out of control.

The main causes of ride vibration in vehicles are road defects. While vehicle suspension systems are engineered to efficiently isolate the chassis from wheel vibration with higher frequencies, they typically tend to amplify vibration frequencies somewhat lower than 4 Hz. Such vibrations are excited from pavement deformation comparable to, or even longer/wider than, the vehicle dimensions.

While most previous research projects on truck ride vibration have focused on vertical axis and pitch axis oscillations, recent truck ride measurements on roads in the Northern Periphery (NP) of the European Union have shown surprisingly high levels of both quasi-static and transient lateral vibration. Unexpected high lateral forces in "egg-shaped" sharp improperly banked curves, and roll-related lateral buffeting, are of major concern for traffic safety in cold climates, as they can initiate skidding on ice-slippery surfaces. Buffeting in ambulance vehicles can also give rise to health issues for vulnerable patients.

The Swedish National Institute of Public Health (2008) found that the most common types of preventable mortality in Sweden were lung cancer (death rate of 17.1), suicide (15.4) and cerebral-

[1] An example of payload damage can be seen in the road transportation of chilled salmon from the Norwegian Northern Periphery to the consumer markets in the South. Due to frost actions in the late winter, roads such as the E6 in Nordland can become very rough. The resulting transient ride vibration (mechanical shock-loads) at road bumps can collapse the bottom layer of the polystyrene thermo-containers and destroy the valuable salmon cargo.

vascular disease (11.8). Among the therapeutic treatable death causes, diabetes mellitus was the worst “big killer” with a death rate of 4.5. However, motor vehicle crashes were worse, with a death rate of 4.9. This still places Sweden in the “top-three” position in the EU when it comes to safe road traffic. However, there are large regional, and urban versus rural, differences in the risk of being killed in a road traffic crash. While the metropolitan areas of Stockholm, Gothenburg and Malmoe have a Standardized Mortality Ratio (SMR) of 70 for vehicle crashes, the rural areas in Sweden have a SMR of 177. This means that vehicle users in the rural areas have (177 – 70) / 70 = 153 % higher risk in ending up in a fatal crash, as compared to urban vehicle users. In the rural areas of Northern Sweden, vehicle crashes take 39 % more lives than diabetes does.

1.1.1. Bumps and ride vibration cause stress, poor health and road crashes

Back disorders are costly to society and are the main causes of sick leave in the working community. They cause great pain to those suffering, and are a significant economic burden to society. Professional drivers are a group of workers that have been found to be at high risk for back disorders. Many epidemiological studies have been made on the relationship between back disorders and vehicle operation with vibration exposure. The results show overwhelming evidence of a relationship that is consistent and strong, which increases with increasing exposure, and is biologically plausible. Numerous back disorders are involved, including lumbago, sciatica, generalized back pain, and intervertebral disc herniation and degeneration. The risk is elevated in a broad range of driving occupations, including truck and bus drivers. Elevated risk is consistently observed after five years of exposure; see Teschke et al (1999).

Two recent Swedish reviews[2] of the scientific evidence of the relation between vibration at work and adverse health effect are summarized in Table 1:

Table 1 Status of scientific knowledge for health effects by high vibration exposure at work

Low Back Pain:	*Confirmed!*
Sciatica / Herniated discs:	*Confirmed!*
Arthrosis:	*More research needed.*
Miscarriage:	*Special regulation[3] is implemented.*
Male fertility:	*Indicated, more research needed*
Viscus/Guts:	*No scientific support.*
Heart:	*Several findings, more research needed.*
Prostate cancer:	*Handful studies, more research needed*
Motion sickness:	*Confirmed!*
Performance:	*Several findings, more research needed*
Mortality:	*Complex findings, more research needed*

Severe negative consequences from ride vibration on the performance, drowsiness and safety for professional drivers of road vehicles has been concluded in several studies, such as Arnberg & Åström (1979) and Gillespie et al (1982).

Amongst older commercial drivers, musculoskeletal problems and cardiovascular diseases are the primary reasons for changing their occupation. An increased risk of myocardial infarction among professional drivers was first reported about 50 years ago, and has been reported repeatedly since then. Stress under certain driving conditions is considered to explain the raised level of stress hormones found in commercial drivers, and is believed to cause a large proportion of the health problems, see Hedberg (1993). Bigert et al (2004) showed that the high incidence of certain heart disease among Swedish truck drivers was constant over time.

[2] Swedish Work Environment Authority Report 2011:8 and Arbete & Hälsa (Work & Health) Report 2012:46.
[3] Regulation in Sweden: AFS 2007:5 *Gravida och ammande arbetstagare*. Arbetsmiljöverket.

McFarlane & Sweatman (2003) studied the lane-keeping behaviour of heavy trucks on rough road sections and found that where the road width was narrow, lateral “bumpsteer” disturbances could require the driver to increase concentration into a stress level significant for driver fatigue.

Opinions of professional road users on road service levels across the EU NP area were mapped by Saarenketo & Saari (2004). Truck drivers stated that the worst road sections had bumps at culverts, weak pavement shoulders, poor road alignment and incorrect cross slope with respect to road curvature. Improperly banked sharp curves yield high cornering lateral forces and very high demand for side friction between tyre and road. They also reported continual stress when driving on some long routes that the road agency believed to be in good driving condition. This happens when unexpected poor road conditions force the driver to drop the vehicle speed far below the planned speed for safety reasons. The result is a stressing conflict within the driver, between making a delayed delivery and causing a major traffic safety risk.

Bray et al (2006) studied physiological stress responses to vehicular buffeting during a 5 minute mild ‘off road’ exposure in a motion simulator, producing transient low frequency roll vibration with 1 m/s^2 lateral vibration (root-mean-squared value). This level is not unusual during normal truck driving on rural roads in the EU NP. The controlled exposure provoked an increase in heart rate and blood pressure and a significant hypocapnia of $P_{ET}CO_2$ 34 mm Hg caused by tachypnea, which took the test persons 5 minutes to recover. The authors concluded that buffeting in everyday transport can affect people with cardiovascular disease.

The ROADEX III project made an in-depth assessment of truck driver’s exposure to vibration, see Granlund (2008). Measurements were made in a timber logging truck during ten roundtrips of 140 - 170 km, with most time spent on Road 331 between the Swedish inland forest area and the coast. The results showed that for all measured working days, the daily vibration exposure A(8) was above 0.65 m/s^2, including normal pauses with zero vibration, and that A(8) = 0.76 m/s^2 was a fair estimate for an 8 hour shift on this kind of route. This is significantly above the EU Action Value of A(8) = 0.5 m/s^2.

Employers of truck drivers performing long and bumpy driving are required by EU harmonized laws to take necessary technical and/or organizational actions to minimize drivers’ exposure to vibration. EU employers are also obliged to perform a special risk assessment for workers exposed to repeated mechanical shock, such as from bumpy rides.

Unless a proper risk assessment has been made, or the required action taken, the standard fine in Sweden has been set at 100,000 Euros following a pioneering case of bus drivers driving over speed bumps in the City of Täby. Directive 2002/44/EC is implemented in national laws, which apply to domestic employers. There is an open question on how the supervision of foreign truck companies should be made.

One of the first cases in the EU where employees won annuities after a court case about adverse health effects from vibration at work ended in 30 September 1997, when the UK High Court awarded £127,000 compensation to 7 miners. The judge ruled that British Coal had been negligent in not taking preventative actions against vibration since 1975. After losing an appeal to the 1997 ruling, the UK government set up the world's biggest ever compensation scheme. By the time it closes the scheme is expected to have dealt with over 750,000 compensation payments to former miners and their families, paying out an estimated £4.1 billion. Lawyers specialized on insurance issues are now comparing diseases caused by “vibration at work” with casualty catastrophes such as Exxon Valdez, the Asbestosis scandal and Agent Orange[4].

[4] Harding, et al. *Casualty Catastrophes*. (2009). General Insurance Convention. Internet 2012-05-08: http://www.actuaries.org.uk/research-and-resources/documents/casualty-catastrophes

1.2. THE ROADEX PROJECT

The ROADEX Project is a technical co-operation between road organizations across northern Europe that aims to share road related information and research between the partners. The project was started in 1998 as a 3 year pilot co-operation between the districts of Finland Lapland, Troms County of Norway, the Northern Region of Sweden and The Highland Council of Scotland. It was subsequently followed and extended with a second project, ROADEX II, from 2002 to 2005, a third, ROADEX III from 2006 to 2007 and a fourth, ROADEX IV "Implementing Accessibility" from 2009 to 2012.

Figure 1 The Northern Periphery Area and ROADEX Partners

The Partners in the ROADEX "Implementing Accessibility" project comprised public road administrations and forestry organizations from across the European Northern Periphery. These were The Highland Council, Forestry Commission Scotland and the Western Isles Council from Scotland, The Northern Region of The Norwegian Public Roads Administration, The Northern Region of The Swedish Transport Administration and the Swedish Forest Agency, The Centre of Economic Development, Transport and the Environment of Finland, The Government of Greenland, The Icelandic Road Administration and The National Roads Authority and The Department of Transport of Ireland. The partner areas are presented in Figure 1.

The aim of the project was to implement the road technologies developed by ROADEX on to the Partner road networks to improve operational efficiency and save money. The lead partner for the project was The Swedish Transport Administration and the main project consultant was Roadscanners Oy of Finland with sub-consultant Vectura Consulting AB. The project was awarded NPP funding in September 2009 and held its first steering Committee meeting in Luleå, November 2009.

A main part of the project was a programme of 23 demonstration projects showcasing the ROADEX methods in the Local Partner areas supported by a new pan-regional "ROADEX Consultancy Service" and "Knowledge Centre". Three research tasks were also pursued as part of the project: D1 "Climate change and its consequences on the maintenance of low volume roads", D2 "Road Widening" and D3 "Vibration in vehicles and humans due to road condition". All of the reports are available on the ROADEX website at www.ROADEX.org.

1.2.1. Objectives of the demonstration and research work on vibration and health

The demonstration projects and research work on vibration and health in the Partner areas of Finland, Scotland, Norway and Sweden had the overall objective to reproduce the ROADEX III case study on the Beaver Road 331 in Sweden (2008). This included:

1. Measuring truck drivers daily vibration exposure and comparing the A(8)-values to the Action Value 0.5 m/s^2 in the EU Directive 2002/44/EC.
2. Measuring spine compression stress, S_{ed}, caused by jolts at severe bumps and compare the values to the 0.5 MPa stress limit in ISO 2631-5 (used as Action Value for bumps in Sweden).
3. Relating truck roll & lateral buffeting in heavy trucks with a high Centre-of-Gravity to laser-scanned non-uniform deformation at the pavement edge (the latter quantified by the pavement condition parameter “Rut Bottom Cross Slope Variance”).

The selected test roads were measured with the normal profilometers locally used for road network condition surveys. One goal was to implement the use of the Rut Bottom Cross Slope Variance parameter in the Partner areas.

The overall objective for the ROADEX IV research project was to identify standards of road maintenance & operations that give acceptable effects on health.

Vibration data obtained for winter conditions, such as from corrugations in a thick ice layer on the road surface, were normalized to summer roughness. By this means the differing winter operational component could be quantified.

A secondary research objective was related to the benefits of tyre pressure control systems on the transfer of vibration from the tyre footprint to the driving seat. The research goal for this part of the study was to quantify the transfer as function of vibration frequency (roughness wavelength x speed).

2. INSTRUMENTS

2.1. RIDE QUALITY MEASUREMENT INSTRUMENTS

Vectura instrumentation was used for recording truck ride vibration and ride quality as per the international standards ISO 8041, ISO 2631-1 and ISO 2631-5. These were:

- A multi-functional instrument "Dewetron 3020" for 16 channel data logging up to 200 kS/sec per channel, signal conditioning and filtering via dynamic differential signal amplifiers and digital anti-aliasing filters, see Figure 2;
- A tri-axial seat-accelerometer "MMF KB103" at the pan of the drivers´ seat;
- A tri-axial accelerometer "MMF KS813B", attached to the base of the drivers´ seat;
- A six-axial "Oxford Technical Solutions RT3000" precision inertial and GPS system for measuring motion, position and orientation, mounted on an extensional carbon-fibre strut in the truck cab, with dual GPS antennas on magnetic feet at the truck roof;
- A set of miniature accelerometers "Brűel & Kjaer TEDS 4507 B" (z-axis) mounted with glue on axles and on the truck frame;
- A GPS with single antenna on the truck cab roof was used in the second measurements in Norway and in Sweden, as the six-axial unit and its dual GPS antennas were omitted.
- A class 1 microphone "MMF MI17" for interior noise in the truck cab;
- A webcam for right-of-way pictures taken from the test truck dashboard;
- A Canon EOS550D 18 megapixel digital single-lens reflex camera with a Sigma 18 – 200 mm compact superzoom lens for freehand photos.

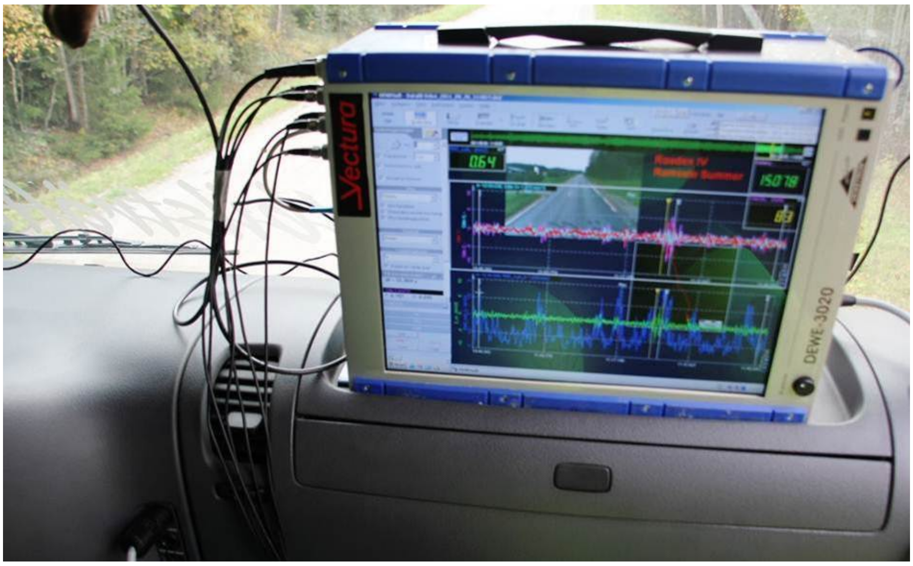

Figure 2 A *Dewetron 3020* is the heart of Vectura's ride quality measurement system

Vibration sampling was carried out at 1 kHz, except for the RT3000 system which operated at 100 Hz. The quality of the "main" ride measurements were very high, as can be seen in the section "*Precision in the measurements of truck ride quality*" which reports the results from repeated measurements.

Initial vibration analysis was made in MatLab software. Final analysis was made in MS Excel, using the "Vibration Calculator" developed by the UK Health and Safety Executive[5].

Coarse <u>indicative</u> mapping of ride quality problems due to poor winter road maintenance was also carried out in the test vehicles with an Apple Iphone, using the apps *Buller* ("Noise", provided by

[5] UK HSE Vibration Calculator on Internet 2012-05-15: http://www.hse.gov.uk/vibration/wbv/

the Swedish Work Environment Authority) and *Vibration* (provided by DLD-LLC in AppStore). These measurements do not comply with the ISO standards listed above and have a much lower accuracy than the “main measurements”.

2.2. ROAD ROUGHNESS PROFILOMETRY

In Finland and at the first trip in Norway, road alignment, slopes and road condition parameters, for roughness and texture, were measured with a laser/inertial Profilograph from Greenwood Engineering A/S (GE), such as the one shown in Figure 3 (left). The Profilograph typically makes some 20,000 samples per metre, of which about 400 data values are stored. The accuracy is very high. For many parameters the inaccuracy is in fractions of millimetres, as certified by a third party.

The road roughness on the Swedish routes was measured with Vectura’s portable GE LaserProf System, shown in Figure 3 (right). The LaserProf fulfils the requirements for a Class 1 profiler in the ASTM E950 standard. The road data in Finland was sampled by Destia OY with a Profilograph system identical with Vectura’s P45.

In Norway, the road data was measured in 2011 and 2012 (frost weakening season in April) was measured with a ViaPPS sweeping laser system (similar to the system at the bottom of Figure 3) operated in-house by Norwegian Public Road Administration.

Figure 3 Vectura’s GE Profilograph P45, GE LaserProf and ViaPPS systems

The road condition on the test routes in Scotland was measured with a profilometer somewhat similar to a Profilograph, operated by WDM Ltd. The accuracy of the profilometer used in Scotland is unknown to the author.

3. DEMONSTRATION PROJECTS

The ROADEX IV demonstration projects in Scotland (512 km), Finland (763 km), Norway (636 km) and Sweden (1.867 km) aimed to reproduce the 10 roundtrips on the 2 x 140 km long ROADEX III case study on the Beaver Road 331. The Beaver Road case study was in ROADEX IV also repeated again on a 70 km section on Road 331 south of Ramsele. The locations of the demonstration projects are shown in Figure 4.

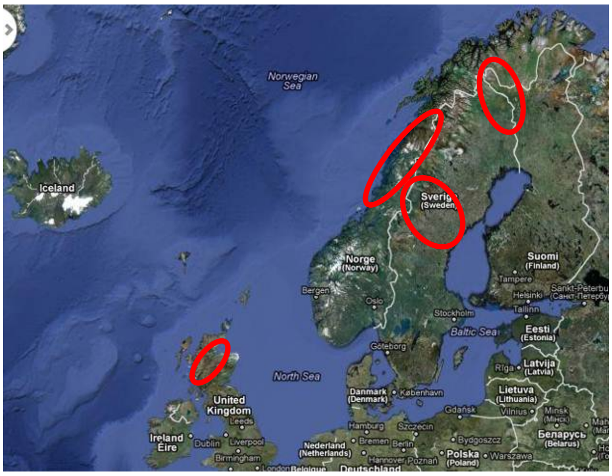

Figure 4 Locations of the ROADEX IV demonstration routes for truck ride quality

The demonstrations included:

- Truck driver´s daily vibration dose A(8), as per Directive 2002/44/EC.
- Compression stress in the truck driver's spine, as per the ISO 2631-5 standard.
- Roll vibration and/or related lateral buffeting, a root cause to many skid crashes on icy roads.

Based upon recorded seat vibration values, the truck driver´s daily exposure A(8) was assessed for various transport tasks and normalized to daily work patterns as per standard EN 14253, using the "Vibration Calculator" developed by the UK Health and Safety Executive[6].

Previous research results show that the magnitude of spinal compression stress is related to transient shock loads by an exponent of about 6. This high exponent makes assessment of spinal compression stress very susceptible to the accuracy of the measurement of the transient seat vibration. There have been several cases where one single shock load has caused compression fracture in the spine of humans, i.e. when riding with a bus driver that drove over a traffic calming speed bump at speed. Furthermore there can be huge differences between the peak stress of various vehicles and even in human individuals. Bearing in mind such facts, the author, and this report, will focus on the importance of preventing high compression stresses, rather than concentrating on a (relatively) small number of transient sampling. Hence the report will aim to emphasize illustrations of risk situations / road features, rather than comparing exact values of compression stress.

A main source of truck roll vibration is deformation at the pavement edge, caused by high traffic loads on edges with poor bearing capacity. Data on truck roll vibration / lateral buffeting will be used for validation of the new road condition parameter RBCSV as described in the later section "*Relating ride to road standard*".

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[6] UK HSE Vibration Calculator on Internet 2012-05-15: http://www.hse.gov.uk/vibration/wbv/

3.1. OVERVIEW OF THE MEASURED A(8)-VALUES

The daily vibration exposures A(8) of each of the demonstration routes were computed after normalization to daily work patterns as per the European standard *EN 14253 (2007) "Measurement and calculation of occupational exposure to whole-body vibration with reference to health*". An overview of the results of the demonstrations is given in Figure 5. These results show that the all of the truck drivers tested had a daily exposure that exceeded the EU Action Value of A(8) = 0.5 m/s^2. An exception is the result from the new truck on European Highway E6 in Northern Norway, which had an A(8) = 0.47 m/s^2 being slightly below the Action Value. However when normalizing this to the effects of driving on winter road conditions (where additional roughness is present almost half the year), driving a worn truck, and having higher vibration when driving with low/no payload, the exposure of Norwegian drivers is also expected to exceed the Action Value of 0.5 m/s^2. Unacceptably high daily exposures of ride vibration are therefore a confirmed problem for professional truck drivers in the ROADEX partner areas.

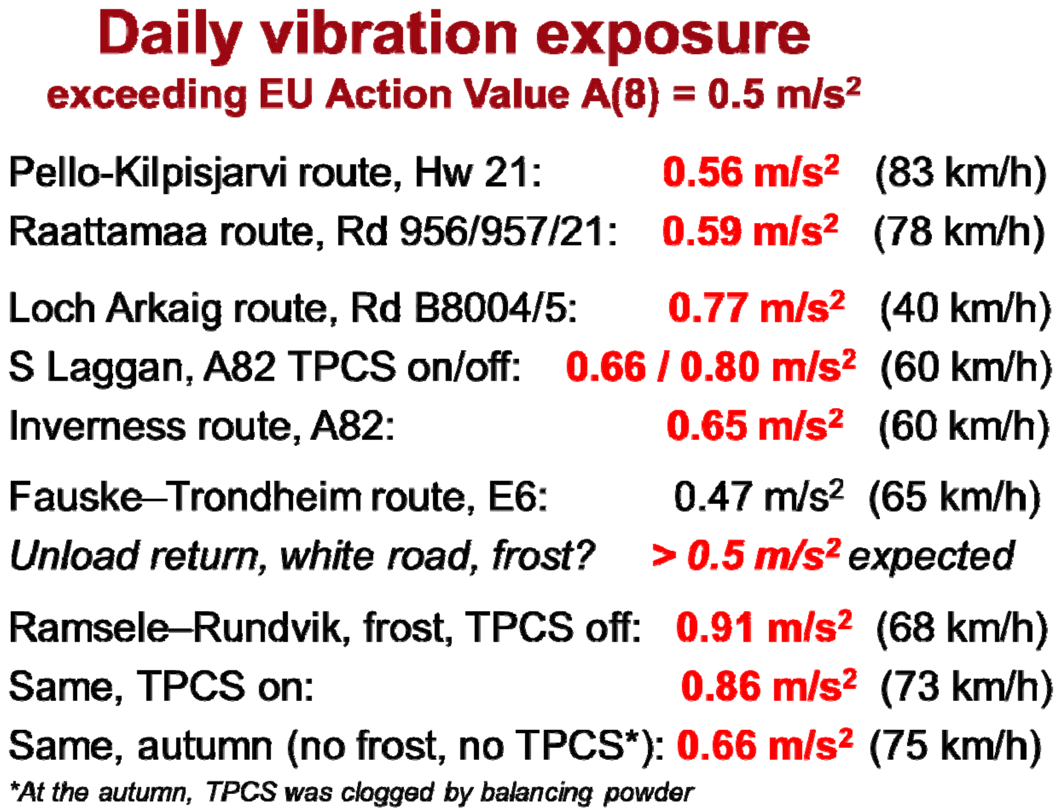

Figure 5 Resulting A(8) values form Lapland, Highlands, Northern Norway and Sweden

3.2. POOR TRUCK RIDE QUALITY IN FINNISH LAPLAND

The demonstration project in Finnish Lapland resulted in A(8)-values in the range 0.56 – 0.59 m/s^2, after normalizing to daily work patterns. This daily exposure exceeds the EU Action Value of 0.5 m/s^2. Truck hauliers in Lapland with employees working under similar or worse conditions* to those in this study, should carry out a risk assessment with associated measurements to clarify if actions have to be taken to protect their drivers from health and safety risks caused by ride vibration and mechanical shocks.

**Road roughness IRI 1.8 mm/m (plus worse roughness due to frost actions and corrugated ice-cap in winter / early spring), vehicle type & condition, speed and daily hours at the steering wheel.*

The average spinal compression stress during the two days of testing was modest; S_{ed} = 0.42 MPa. The value 0.42 MPa is below the health caution value of 0.5 MPa in the standard ISO 2631-5 on human response to transient vibration. However, occasional observations were made of spinal compression stress over 0.5 MPa, as per calculations from transient accelerations in the seat pad. The worst contributor to the average compression stress came from the bumpy Road 956/957 at Raattamaa. Truck drivers operating on similar roads for a large part of their working day, especially during winter/spring periods with additional frost related roughness, are likely to suffer special health risk due to high spinal compression stress.

A special root cause of high ride vibration on the route in Lapland was extreme settlements in sections were the road was founded on permafrost, which is exposed to long-term thawing due to solar heat captured by the black road surface. Another problem on many roads in cold climate is freezing boulders rising up through the road.

Many of the unhealthiest bumps come from man-made problems: improper edges of patch repairs, and improperly built transitions between bridges and road. These kinds of problems are of course preventable, and can be relatively quickly eliminated by improving road work practice.

3.2.1. The route, the transport task, the truck and its instrumentation

The location of the studied route in Finnish Lapland is shown in Figure 6.

Figure 6 Location of the Lapland demonstration route

The demonstration vehicle carried a cargo of brewery products and groceries. The demonstration route was 763 km long as shown in Figure 7. The demonstration started on 21 September 2012 on National Highway 21 (a.k.a. European Highway 8) northbound from the Kurth Oy truck garage in

Pello up to Kilpisjärvi, on the border to Norway. From Kilpisjärvi the route returned south on Highway 21 to Palojoensuu, where it went east on Highway 93 to a stop-over in Enontekis. On the second road day, the truck was driven from Enontekis south-east on Road 956/957 via Raattamaa and then Highway 79 westbound to Muonio. In Muonio, the route again took Highway 21 southbound to the starting point in Pello at the Kurth Oy garage. A note of historical interest: The main part of Highway 21 was built by prisoners of WW2, while Finland was under German occupation.

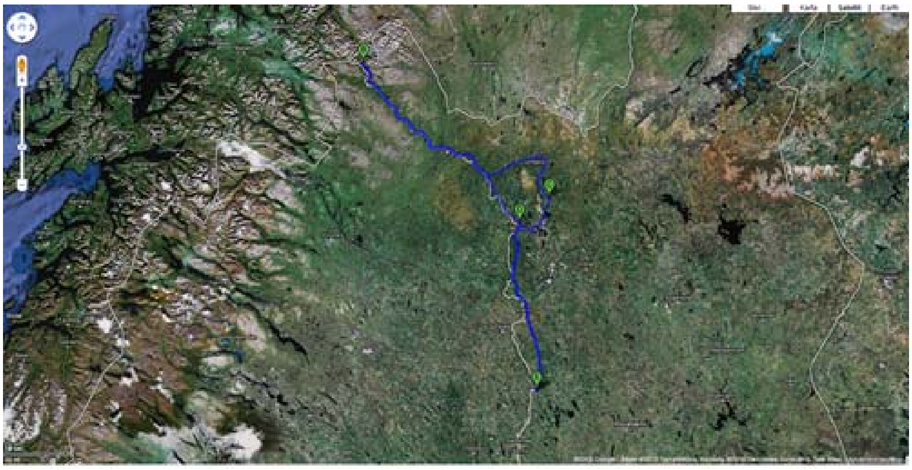

Figure 7 Map of the Finnish demonstration route

The haulage partner for the demonstration project was Kurth Oy from Pello, operating the Scania 124 L420 seen in Figure 8.

Figure 8 The Scania truck used for the ride quality study in Finland

The truck license plate was "EYP 258", and it had some 677,000 km on the meter at the test. The driver seat was a Scania original mounted air-suspended ISRI seat. All tyres were made by Michelin. The steer axle had XZE2+ 315/70 R22.5 tyres, inflated to 7.85 and to 8.15 bar pressure. The drive axles had pair-mounted X-IceGrip STUDLESS SNOW 295/80 R22.5 XDW. The bogie axle had pair-mounted X Pilote XZA 295/80 R22.5. A remarkable note is that on both drives and on bogies there was no realistic "easy access" to the tyre air valves. This is further discussed in the section "*TPCS prevents driving with under-inflated tyres*".

The transport task was such, that the trailer was detached and parked at a stop in Muonio. Thus, the trailer was only included on Highway 21 from Pello to Muonio and from Muonio back to Pello.

The truck was instrumented as per Figure 9 with accelerometers on left and right side at both the front axle and on the truck frame, tri-axial accelerometers at the base and on the pan of the driver seat, a webcam, an interior microphone and a six-axial inertial/GPS unit at the centre of the cab with dual antennas on the roof of the cargo cabinet.

Figure 9 Instrumenting the Scania test truck in Pello

3.2.2. High daily vibration exposure; A(8) exceeds the EU Action Value

The first day of the trip was spent on Highway 21 northbound from Pello up to Kilpisjärvi. From Kilpisjärvi the route returned southbound on Highway 21 to Palojoensuu, where it went east on Highway 93 to a stop-over in Enontekis.

Normalization of the test journey to daily work patterns was done using the UK Health and Safety Executive´s “Vibration Calculator”. The resulting A(8) value for the 512 km driven on the busy day 1 was 0.56 m/s^2, as per the calculation in Table 2. This is above the EU Action Value A(8) = 0.5 m/s^2.

Table 2 Truck driver’s vibration exposure, day 1 (7 hour driving time)

		Vibration intensity	Exposure time		Partial exposure	Distance [km]
		m/s²	hours	minutes	m/s²	
Pello - Muonio	Truck w trailer	0.65	1	45	0.304	144
Muonio - Palojoensuu	Only truck	0.55	0	40	0.159	48
Palojoensuu - Karesuvanto	Only truck	0.48	0	35	0.130	37
Karesuvanto - Kilpisjärvi	Only truck	0.63	1	28	0.270	109
Kilpisjärvi - Karesuvanto	Only truck	0.63	1	28	0.270	109
Karesuvanto - Enontekis	Only truck	0.53	0	53	0.176	65
Pause, non-driving time		0.00	1	12	0.000	0
		Daily exposure value, m/s² A(8)			0.56	512

On the second day, the truck travelled south-east on the small Road 956/957 from Enontekis via Raattamaa and then westbound on Highway 79. In Muonio the route again took Highway 21, now southbound, back to Pello. The A(8) value for the 251 km driven on the half day was 0.42 m/s^2, as per the calculation in Table 3. After normalization to an 8 h “normal full day” work pattern of similar conditions, as per Table 4, the A(8) value for a daily route of about 500 km would be about 0.59 m/s^2. This is above the EU Action Value A(8) = 0.5 m/s^2. Truck hauliers with employees working under conditions similar to those in this study, should make a risk assessment with associated measurements to clarify if actions must be taken to protect their drivers from health and safety risks from ride vibration and mechanical shock.

Table 3 Truck drivers vibration exposure, day 2 (only 3.5 h driving time)

		Vibration intensity	Exposure time		Partial exposure	Distance [km]
		m/s²	hours	minutes	m/s²	
Enontekis - Raattamaa	Only truck	0.65		58	0.226	63
Raattamaa - Särkijärvi	Only truck	0.68		30	0.170	33
Särkijärvi - Muonio	Only truck	0.53		8	0.068	11
Muonio - Pello	Truck w trailer	0.65	1	45	0.304	144
Pause, non-driving time		0.00	4	36	0.000	0
		Daily exposure value, m/s² A(8)			0.42	251

Table 4 Truck drivers vibration exposure, day 2 (normalized to 8 hours work; 7 hours of driving)

		Vibration intensity	Exposure time		Partial exposure	Distance [km]
		m/s²	hours	minutes	m/s²	
Enontekis - Raattamaa	Only truck	0.65		58	0.226	63
Raattamaa - Särkijärvi	Only truck	0.68		30	0.170	33
Särkijärvi - Muonio	Only truck	0.53		8	0.068	11
Muonio - Pello	Truck w trailer	0.65	1	45	0.304	144
Similar driving		0.63	3	30	0.417	251
Pause, non-driving time		0.00	1	6	0.000	0
		Daily exposure value, m/s² A(8)			0.59	502

3.2.3. Thawing permafrost is one of the root causes of high ride vibration

Many sections of Highway 21 are very undulating, with frequent dips and crests. The subarctic climate is very cold and some parts of the road are built on permanently frozen ("permafrost") soils. In frozen condition, soft soils such as peat and clay can have high bearing capacity almost comparable to cured Portland cement concrete. After paving the road with black asphalt, increased absorption of solar energy makes the ground warmer. This causes the soil beneath the road structure, otherwise permanently frozen, to begin to thaw during the warmest summer days. As the peat slowly thaws, it dramatically loses bearing capacity. As a result thawing permafrost can bring extreme settlements, as seen on the photographs in Figure 10, and thus very poor ride quality.

Figure 10 Thawing permafrost under Highway 21 gives severe settlements and a rough ride

3.2.4. Occasional high spinal compression stress

For the measurements in Finnish Lapland, the average spinal compression stress over the two days was modest; S_{ed} = 0.42 MPa. The worst contributor to the average stress came from the bumpy Roads 956 and 957 from Enontekis, via Raattamaa, to Särkijärvi. The value 0.42 MPa measured is below the health caution value of 0.5 MPa in the standard ISO 2631-5 on human response to transient vibration. However, occasional observations were made of spinal compression stress over 0.5 MPa using calculations of transient accelerations in the seat pad. Truck drivers operating on roads like Roads 956 and 957 for a large part of their working day, especially during winter/spring periods with additional frost related roughness, are likely to suffer health risks due to high spinal compression stress. Some illustrative examples of root causes to unhealthy[7] truck ride in Lapland are given below.

Two large man-made problems causing unhealthy truck ride are improper transversal joints (road profile steps) and high road profile slope variance at patch repairs and at transitions between bridges and road. The problem with improper joints at patches is illustrated in Figure 11. The graph at the bottom shows the vertical acceleration (green) and the root-mean-square of x,y,z vibration (blue) along 2 minutes of the ride. The yellow marker shows the position along the graph where the webcam picture was taken. Analysis of the webcam pictures showed that all of the transients noticeable in the bottom green graph had occurred at freshly made asphalt patch works (here only a sample is showed).

Good practice in the ROADEX Partner areas recommends that the transversal edge of the new asphalt should not be placed “layer-on-layer” with the old asphalt, but cut down into the same elevation as the surface of the old asphalt. For this, good asphalt patch works require the use of a small milling machine. Such machines are available on the market, but are currently not used in all highway pavement maintenance projects.

Figure 11 Patch repair zone at Highway 21: Intense mechanical shocks on the driver seat

[7] Note: The graphs do not report spinal compression stress [MPa], only seat accelerations [m/s^2] – the input used when computing spinal compression stress. The compression stress goes high in sections where seat acceleration is high. Thus, high seat acceleration indicates high spinal stress.

At many bridges, the backfill behind the bridge front wall is inadequately compacted during construction. This can result in severe settlement at the bridge joint, and thus also to intense ride vibration in vehicles. Measurements taken in the study show numerous cases of high compression stresses in the truck driver's spine at improper bridge joints, such as seen in the 1 minute graph at the bottom of Figure 12.

Figure 12 Intense ride vibration at an improper bridge backfill

There are of course also non-manmade root causes to road features that excite high spinal compression stress. One example is pavement edge slump, where the lack of a robust pavement shoulder has led to deformation of the pavement edge as seen in Figure 13. This kind of road damage can result in intensive ride vibration as shown in the 1 minute graph at the bottom of Figure 14.

Figure 13 Exterior of test truck approaching the pavement edge damage seen in Figure 14

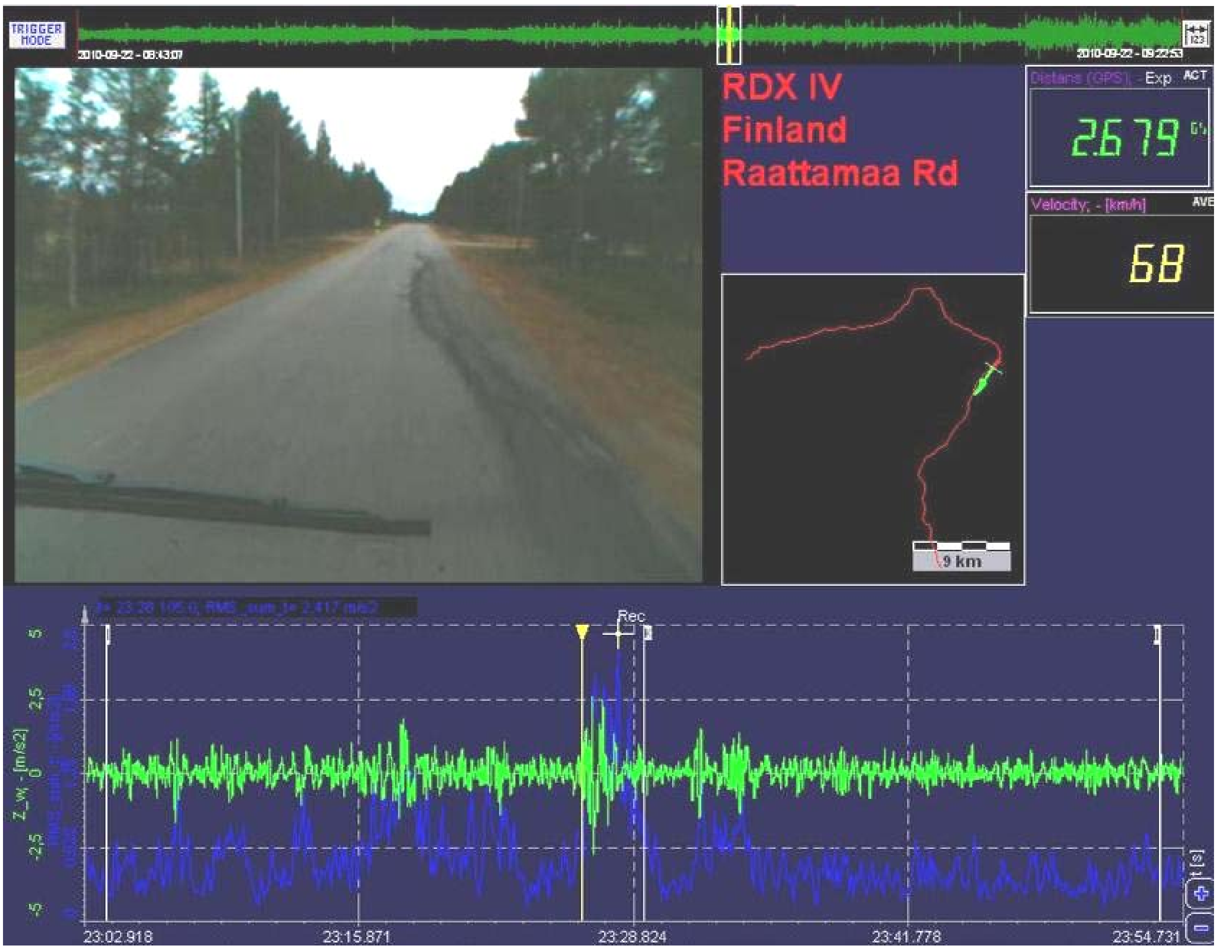

Figure 14 Intense truck ride vibration at deformed pavement edge on Road 956/957

3.2.5. Observations of hazards and various road features in Lapland

3.2.5.1. LATERAL ACCELERATION EXCEEDS CARGO SECURING DESIGN?

An objective for cargo securing is to assure that the goods and the vehicle are kept tight together, in other terms: that they accelerate similarly. The accelerations of an object under transport can be classified in three groups:

- Single event shock / transient vibration
- Low-frequency motion
- High-frequency vibration

The design acceleration values in the IMO/ILO/UN ECE Guidelines for cargo securing have been developed with reference to accelerations with durations that can be described as quasi-static, or at least as having low frequency. All bodies that are not ideally stiff will experience oscillating elastic deformations during transport. Acceleration in most points on the object will therefore have peak values higher than the Centre of Gravity (CoG) of the object. In order to slide or tilt the object, the CoG acceleration must exceed certain intensity. The Guidelines refer to this intensity related to the CoG of the goods rather than to its surface. When measuring vibration in one or a handful of points of the object for high frequencies, the recorded amplitudes will most certainly be significantly higher than the amplitudes at the CoG. However, it is unclear what the relation is between amplitudes at the CoG and at any other point of the object, depending on acceleration duration or frequency. In railway transport, recorded peak amplitudes at frequencies above 8 Hz are filtered down to as little as 5 %. It is not clarified how to filter amplitudes at frequencies between 2 and 8 Hz, but below 2 Hz no filtering should be applied. A simple conclusion is that if lateral acceleration exceeds the 0.5 g limit of the Guidelines, (0.5 g = 5 m/s^2), there is a risk of overloading the capacity of the cargo latches. This risk should not be dismissed, until the character of the accelerations has been investigated in detail. An example of this from a truck passing over edge damage at 80 km/h can be seen in Figure 15, where the truck cab experienced a transient lateral acceleration of 5.9 m/s^2 as seen in the bottom graph. This clearly exceeds the 0.5 g lateral acceleration to be considered when latching loads on road vehicles, as per the IMO/ILO/UN ECE Guidelines for cargo securing.

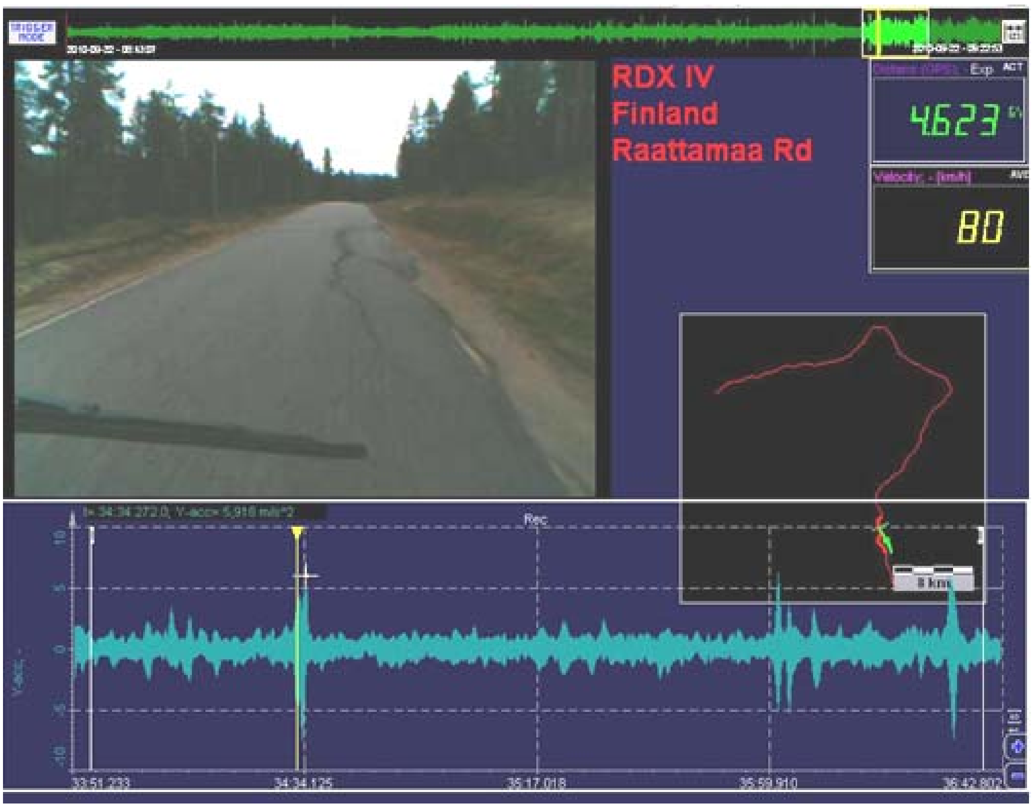

Figure 15 Hazardous truck cab lateral vibration at deformed pavement edge on Roads 956/957

A similar example of lateral buffeting from Highway 21 is shown in Figure 16. Here the cab lateral acceleration peaked at 7.5 m/s^2, with an intensity of about 3.5 m/s^2 during a half second.

At roads with pavement edge damages as severe as those seen in Figure 15 Hazardous truck cab lateral vibration at deformed pavement edge on Roads 956/957 Figure 15 and Figure 16, accelerations can be so high that there may even be a risk that cargo latches break. As result of this, and the motion of the heavy cargo (slide or tilt), the truck may crash. These accelerations should therefore be investigated beyond the scope of this report.

Often investigations of truck crashes do not include competent analysis of the role of the properties of the road. This is in fact true also in many investigations of fatal crashes. Given this context, the new RBCSV road condition parameter could be a useful tool to identify road damages that may have contributed to a rollover crash.

Road sections with severe edge damage can yield a RBCSV value above the limit value 0.30 %, which was established in the ROADEX III project on "*Health Issues Raised by Poorly Maintained Road Networks*". Pavement edge damages worse than RBCSV 0.30 % should therefore be repaired as soon as practically possible, with a warning sign being raised until the road repair is completed. Truck operators should also educate their drivers to drive slowly at this kind of pavement damage.

Figure 16 Hazardous lateral truck vibration at deformed pavement edge on Highway 21

When driving on many roads in the cold climates of the EU Northern Periphery, other sources of both roll-related lateral buffeting and high compression stress in the driver's spine are freezing boulders rising up through the road. Every winter the road structure in cold climates heaves due to frost. In case of a large boulder in the structure, during the spring thaw period, fine material may migrate down through the soil via voids and come to rest under the boulder. This makes it impossible for the boulder to sink down as much as the rest of the road. This process is repeated annually. So as years pass by, the boulder rises more and more by the accumulation of fines beneath. Eventually the rising boulder will create such a large bump, that it will require to be dug out by an excavator. This is a very costly road repair action in paved roads but, as seen in example in Figure 17, a rising boulder can result in hazardous lateral buffeting of the truck (here 6.3 m/s^2). The high cost for the repair of rising freezing boulders can therefore be paid back by the large benefit of preventing hazardous lateral buffeting of heavy trucks and buses with a high positioned centre of gravity (CoG).

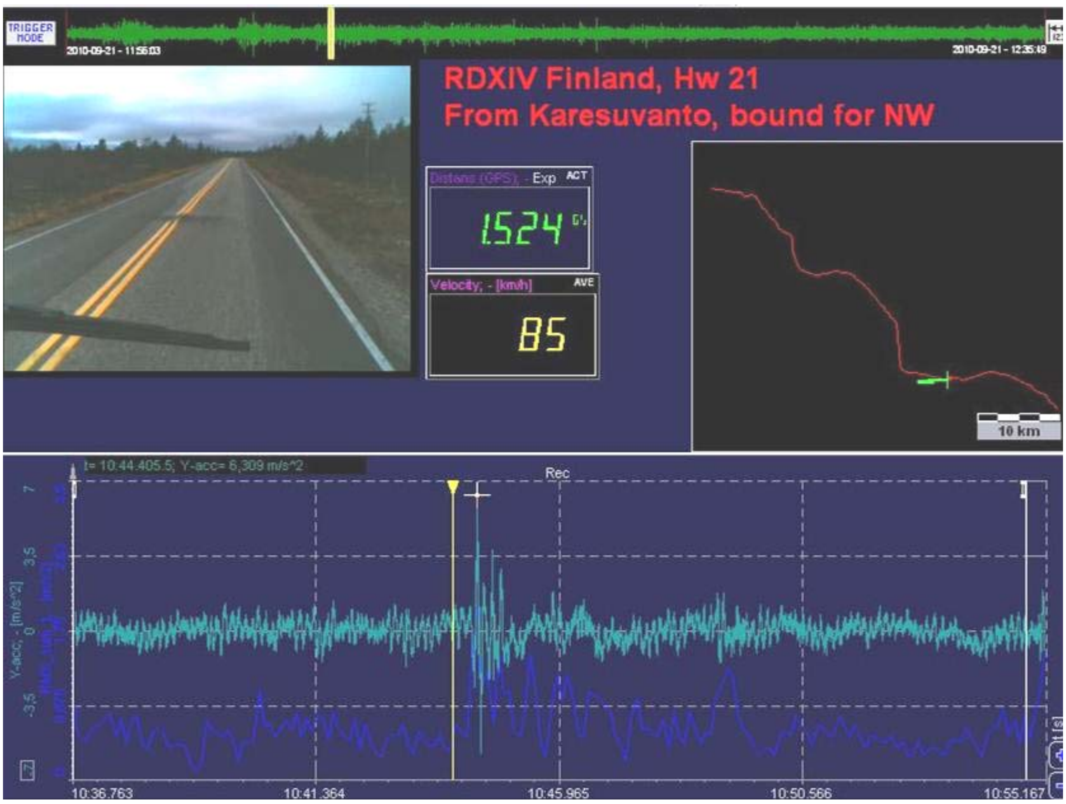

Figure 17 Lateral buffeting of test truck at a rising boulder on the road centreline on Highway 21

3.2.5.2. IMPROPERLY BANKED CURVES

Several outercurves on the demonstration route in Finnish Lapland were perceived to be improperly banked. One example was at the sharp curve at Kilpisjärvi, as seen in Figure 18.

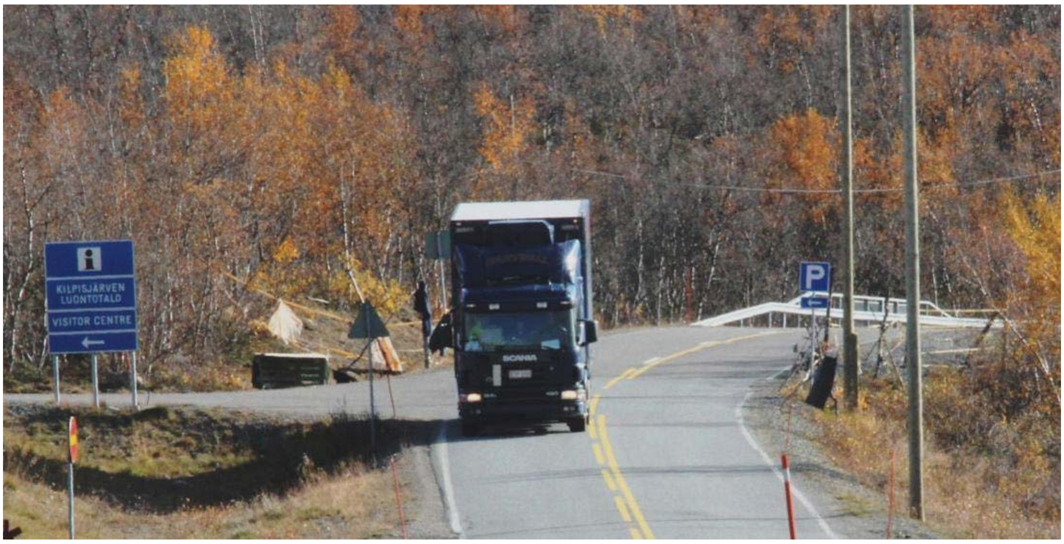

Figure 18 Test truck at an improperly banked outercurve on Highway 21 in Kilpisjärvi

With accurate data from a laser/inertial Profilograph (see Figure 3) averaged over 1 m steps, it is relatively easy to objectively identify sharp outercurves with adverse cross slope (camber). Such curves have a high need for side friction, which can bring a high risk for loss-of-control crashes. Risky outercurves are recognized by having a combination of negative curvature and negative cross slope, as seen in the left hand graph in Figure 19. Curvature expressed as 1000/radius [m] is plotted on the x-axis, while crossfall [%] is plotted on the y-axis. By filtering the Profilograph database, it is easy to find the coordinates of the improperly banked road curve, such as marked in the right hand map of Figure 19.

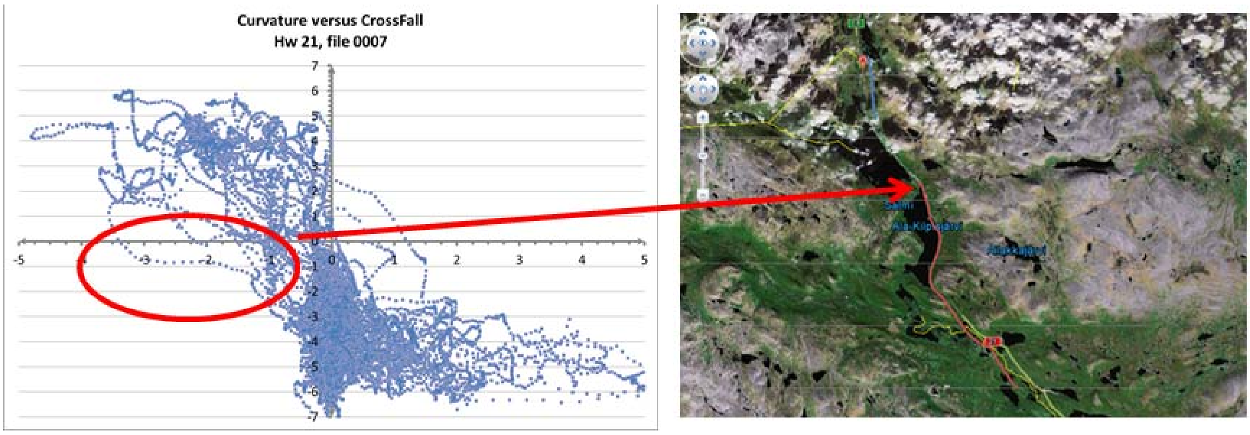

Figure 19 Profilograph data reveals an improperly banked sharp outer-curve at Kilpisjärvi

3.2.5.3. WILD ANIMALS AND HAZARDOUS ROAD WORK SITES

Reindeers are nice and cute in front of Santa´s sledge, but they do post a serious crash risk when in front of a car at highway speed on an icy road. Wild reindeers, as seen in Figure 20, are a common crash risk in Lapland. Roadside fencing may be an effective measure against wild animals on these roads.

Figure 20 Wild reindeers are a crash risk on Lapland roads

At several road work zones, collision hazards were present without relevant warnings for stationary or low speed heavy road construction machines on the road. An example is shown in Figure 21.

Figure 21 An excavator blocking part of the National Highway 21 without any warning signs

3.2.5.4. NOISY ROAD SURFACES AND BUMPY FROST DAMAGES

Long sections of the Finnish roads surveyed showed surface damage "ravelling", as illustrated in Figure 22. This kind of damage brings many waves in the 50 – 500 mm Megatexture band. Megatexture is known to cause high tyre/road noise, bringing vehicle internal noise as well as external noise.

Figure 22 Pavement surface ravelling at Highway 21

Severe frost-related permanent damages as seen in Figure 23 are also common in Lapland.

Figure 23 Road damages caused by frost action in the late winter season

3.3. POOR TRUCK RIDE QUALITY IN THE SCOTISH HIGHLANDS

The demonstration project in the Scottish Highlands resulted in A(8)-values in the range 0.66 – 0.90 m/s^2 at two repeated round-trip routes near Ft William. A single one-way trip from Corpach to Inverness resulted in 0.55 m/s^2 for a half day of driving. However, after normalizing to a full 8 h working day, driving from Ft William to Inverness and back on A82 resulted in A(8) = 0.65 m/s^2. For all three tested routes, after normalizing to 8 hour daily work patterns, the resulting exposures exceeds the EU Action Value of 0.5 m/s^2. Therefore truck hauliers in the Highlands with employees working under similar or worse conditions* to those in this study, should carry out a risk assessment with associated measurements to clarify if actions need to be taken to protect their drivers from health and safety risks caused by ride vibration and mechanical shocks.

**Road conditions, vehicle type & condition, speed and daily hours at the steering wheel.*

The average daily spinal compression stress during the three days of measurements in the Scottish Highlands was systematically high; S_{ed} = 0.9 – 1.1 MPa. This is far above both the health caution value of 0.5 MPa and above the “high health risk” value of 0.8 MPa in the standard ISO 2631-5 on human response to transient vibration. One of the worst contributors to the average compression stress came from Road B8004 from Gairlochy to the A82 (bound for Spean Bridge). This road had a high incidence of long-wave unevenness.

A root problem of the high ride vibration in Scotland is long-wave undulating road profiles. This problem is particularly pronounced at ancient bridges, many of which have a slight arc-shaped road profile.

3.3.1. The routes, the transport task, the truck and its instrumentation

The location of the demonstration area in Scottish Highlands is shown in Figure 24.

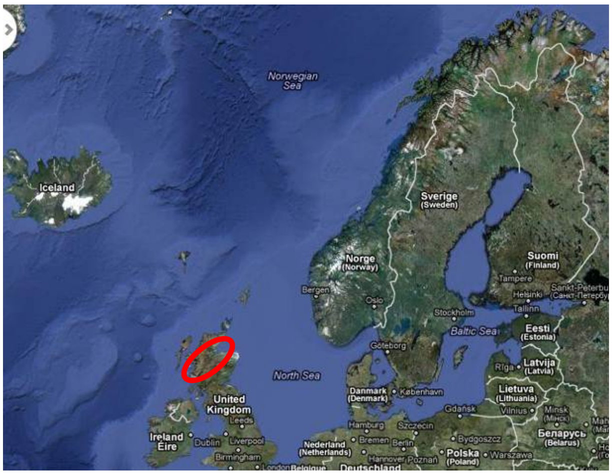

Figure 24 Location of the Highland demonstration area

The vehicle for the demonstration was a timber truck hauling timber on round-trips between timber storage areas, at either Loch Arkaig or South Laggan, and the BSW Sawmills (Kilmallie) in Corpach. The final test trip was a one-way journey from the timber storage at Loch Arkaig to the Norboard OSB factory in Inverness.

The three demonstration routes were in total 238 km long as shown in Figure 24. Due to repeated round-trips on two routes, the total measured distance was 512 km. The first route was a round-trip of about 60 km between BSW Sawmills (Kilmallie) Ltd in Corpach and Loch Arkaig, mainly on roads B8004 and B8005, as seen in Figure 25. The second route was a round-trip of about 70 km between the same sawmills and South Laggan, mainly on road A82 as seen in Figure 26. The third route was a one-way drive of 153 km from Banavie via Loch Arkaig to Inverness, mainly on road A82 as seen in Figure 27. The measurements were made on 4th to 6th October 2010.

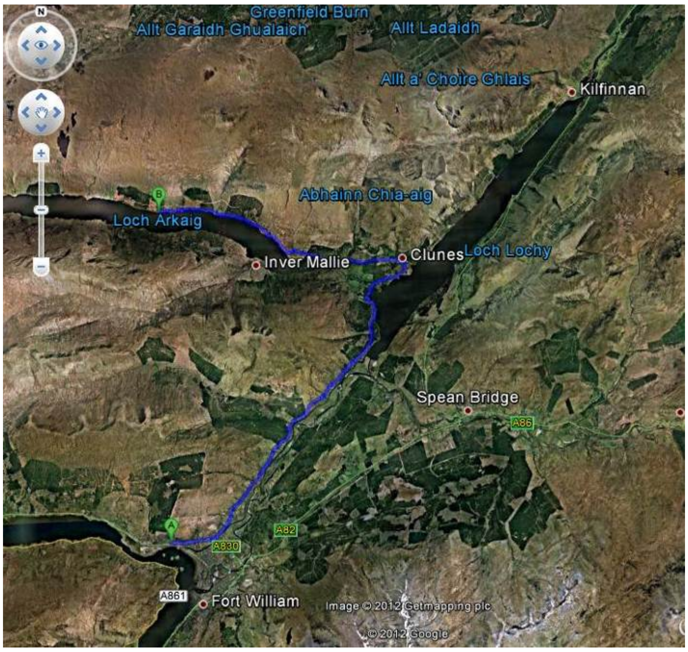

Figure 25 Overview of the demonstration route between Corpach and Loch Arkaig

Figure 26 Overview of the route between Corpach and South Laggan

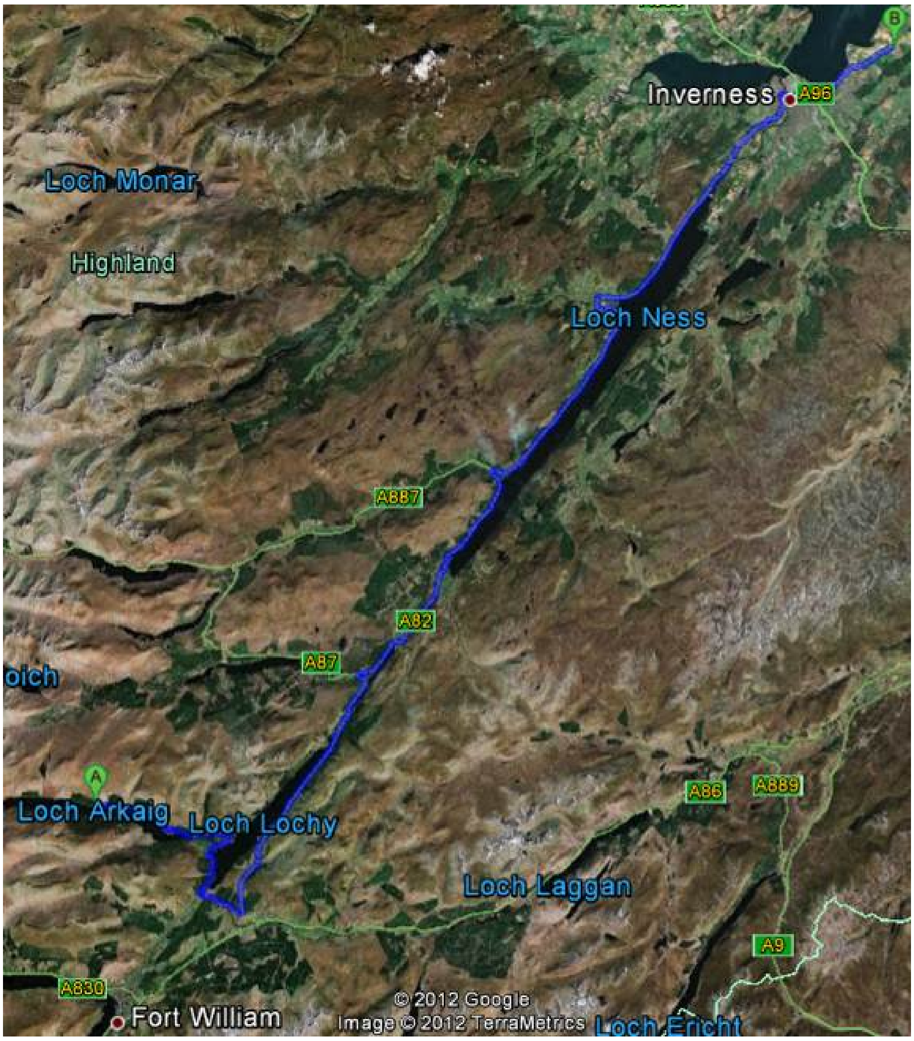

Figure 27 Overview of the demonstration route from Loch Arkaig to Inverness

The haulage partner was Ferguson Transport (Spean Bridge) Ltd, operating the 480 hp Volvo FH seen in Figure 28, and some 30 other trucks.

Figure 28 The TPCS-equipped Volvo truck used for the ride quality study in the Highlands

The truck license plate was “N40 AFT”, and it had some 187,000 km on the meter at the test. The driver seat was a Volvo original mounted air-suspended seat. The truck carried a Jonsered 1080 timber crane.

The steer axle had Michelin XZE2+ 315/80 R22.5 tyres, inflated to 7.95 and to 8.15 bar pressure. The drive axles had pair-mounted tyres. Left side had Michelin 315/80 R22.5; maybe model XDY3 (scratch damages made it impossible to read clear). Right side had Bridgestone M729 315/80

R22.5. The bogie axle had pair-mounted Bridgestone R297 315/80 R22.5. The tyres on the drive, bogie, as well as on the triple axles on the wagon were connected to a “Tireboss” Tyre Pressure Control System (TPCS). The inflation pressure in all tyres, except on the steer axle, was varied during the ride vibration measurement trips. The TPCS had 6 different settings that the driver could set with a quick press on the buttons to adapt to truck operation mode; low/high speed, loaded/unloaded and on/off highway.

The truck was instrumented as per Figure 29 with accelerometers on the left and right side of both the front axle and on the truck frame, tri-axial accelerometers at the base and on the pan of the driver seat, a webcam, an interior microphone and a six-axial inertial/GPS unit at the centre of the cab with dual antennas on the roof. Note the deep crack in the rubber bumpstop, marked with a red circle, indicating an intensive bump exposure before the ROADEX tests.

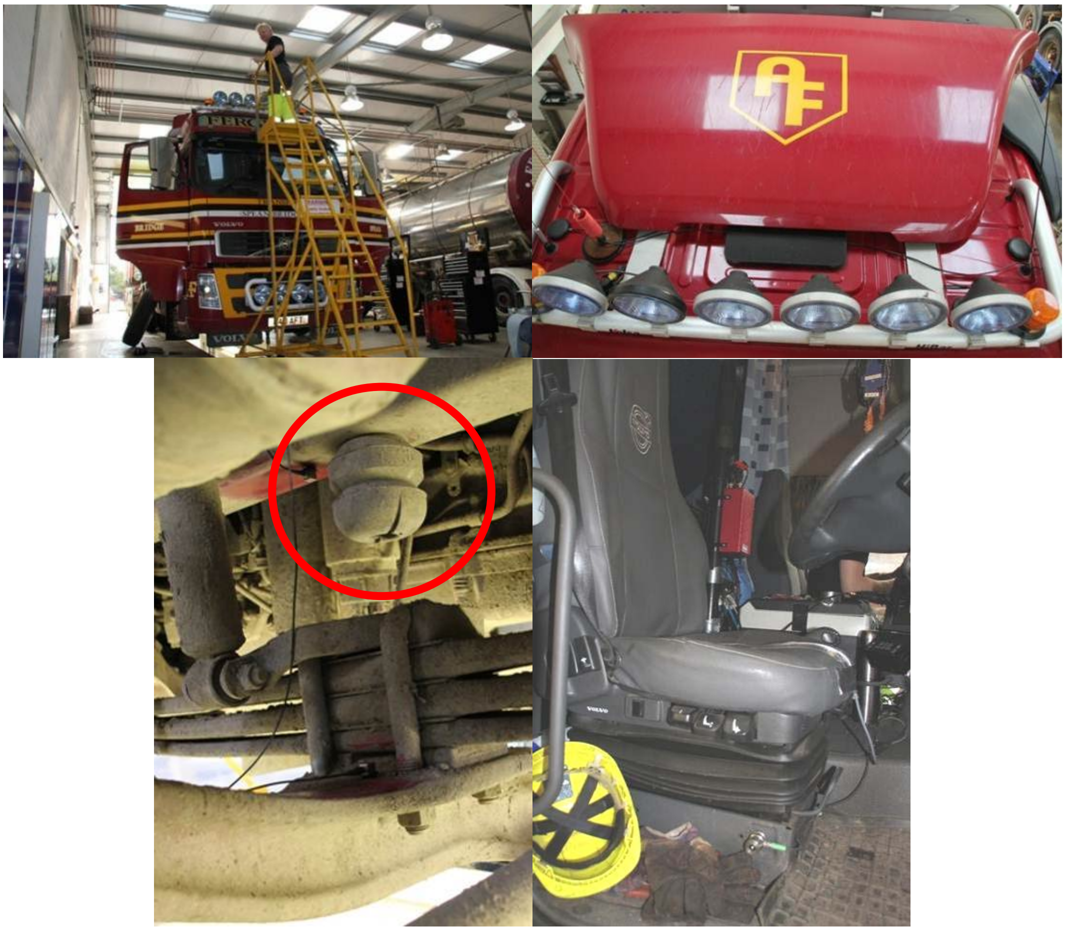

Figure 29 Instrumenting the Volvo test truck at Ferguson Transport’s excellent workshop

3.3.1.1. PHOTOS FROM THE DEMO-ROUTES

The road to Loch Arkaig was very narrow and the timber storage was on a stony and very rough dirt road, see Figure 30.

Figure 30 Photos from the Loch Arkaig route

The timber storage area at South Laggan was on a muddy and thus very soft dirt road. There was a road work zone on the A82 public road on the route back to the BSW sawmill in Corpach, see Figure 31. The test truck had to wait in line, as traffic was directed to pass by the zone where asphalt was being milled off. This caused a bias in the measured ride vibration exposure, reducing repeatability between round trips.

Figure 31 Photographs from the South Laggan route

3.3.2. High daily vibration exposure; A(8) exceeds the EU Action Value

The measurements commenced with several round-trips between the BSW Sawmills in Corpach and the forest stockpiles at Loch Arkaig. The first trips were taken just as the driver normally did, using the tyre pressure control system to adapt the inflation pressure to the truck operation mode (speed, load etc). Then a round-trip was made with full inflation pressure. During this round-trip, the vibration logger bounced from the truck dashboard and fell hard on to the cab floor. This gave a tangible proof of a harsher ride when the TPCS was not in use. The floor crash caused some damage to some cable parts in the vibration logging system. Afterwards, the data from the subsequent trips to Loch Arkaig with full inflation pressure were found to be corrupted and had to be discarded. After changing cables, the measurements were completed under normal circumstances.

For three daily typical round-trips between the BSW sawmill and Loch Arkaig, under normal use of the TPCS, the A(8) value was 0.77 m/s^2, as per the calculation in Table 5. This is above the EU Action Value A(8) = 0.5 m/s^2.

Table 5 Truck drivers' vibration exposure, Sawmill – Loch Arkaig with active TPCS

TPCS active		Vibration intensity	Exposure time		Partial exposure	Distance [km]
		m/s²	hours	minutes	m/s²	
Sawmill - Loch Arkaig	Empty	1.00		37	0.278	25
Dirtroad	Empty	1.53		9	0.210	2.3
Loading	-	0.00		30	0.000	0
Dirtroad	Loaded	1.28		9	0.175	2.3
Loch Arkaig - Sawmill	Loaded	0.79		37	0.219	25
Unloading	-	0.00		20	0.000	0
Sawmill - Loch Arkaig	Empty	1.00		37	0.278	25
Dirtroad	Empty	1.53		9	0.210	2.3
Loading	-	0.00		30	0.000	0
Dirtroad	Loaded	1.28		9	0.175	2.3
Loch Arkaig - Sawmill	Loaded	0.79		37	0.219	25
Unloading	-	0.00		20	0.000	0
Sawmill - Loch Arkaig	Empty	1.00		37	0.278	25
Dirtroad	Empty	1.53		9	0.210	2.3
Loading	-	0.00		30	0.000	0
Dirtroad	Loaded	1.28		9	0.175	2.3
Loch Arkaig - Corpach	Loaded	0.79		37	0.219	25
Unloading	-	0.00		20	0.000	0
					0.000	0
Pause, non-driving time		0.00		54	0.000	0
		Daily exposure value, m/s² A(8)			0.77	164

For three daily typical round-trips between the BSW sawmill and South Laggan, under normal use of the TPCS, the A(8) value was 0.70 m/s^2, as per the calculation in Table 6. This is above the EU Action Value A(8) = 0.5 m/s^2. As can be seen from the calculation, the three round-trips to South Laggan make a long day. The measurements on Day 2 included three such round-trips and took 11 hours, pauses included.

For three daily typical round-trips between the BSW sawmill and South Laggan, without using the TPCS to reduce the inflation pressure when appropriate, the A(8) value was 0.86 m/s^2, as per the calculation in Table 7. With TPCS engaged, the A(8) was lowered from 0.86 to 0.70 m/s^2, a reduction of approximately 18 %. This figure is based on a few measurements and at very low speeds, so the uncertainty is significant. Using the TPCS, the vibration was 6 % higher when the truck was unloaded, than when loaded. The same relationship without TPCS was 13 %. This makes sense, since the TPCS is able to reduce vehicle body pitch resonance from rear wheel hopping in the unloaded condition. The steer axle was not fitted with TPCS.

Table 6 Truck drivers' vibration exposure, BSW sawmill – South Laggan with active TPCS

TPCS active		Vibration intensity	Exposure time		Partial exposure	Distance [km]
		m/s²	hours	minutes	m/s²	
Sawmill - S Laggan	Empty	0.87		31	0.221	31.5
Dirtroad up & down, incl loading	Empty / loaded	0.66	1	14	0.259	9
S Laggan - Sawmill	Loaded	0.82		32.5	0.213	31.5
Unloading	-	0.00		20	0.000	0
Sawmill - S Laggan	Empty	0.87		31	0.221	31.5
Dirtroad up & down, incl loading	Empty / loaded	0.66	1	14	0.259	9
S Laggan - Sawmill	Loaded	0.82		32.5	0.213	31.5
Unloading	-	0.00		20	0.000	0
Sawmill - S Laggan	Empty	0.87		31	0.221	31.5
Dirtroad up & down, incl loading	Empty / loaded	0.66	1	14	0.259	9
S Laggan - Sawmill	Loaded	0.82		32.5	0.213	31.5
Unloading	-	0.00		20	0.000	0
					0.000	0
Pause, non-driving time		0.00		6	0.000	0
		Daily exposure value, m/s² A(8)			0.70	216

Table 7 Truck drivers' vibration exposure, BSW sawmill – South Laggan without using TPCS

TPCS off		Vibration intensity	Exposure time		Partial exposure	Distance [km]
		m/s²	hours	minutes	m/s²	
Sawmill - S Laggan	Empty	0.93		31	0.236	31.5
Dirtroad up & down, incl loading	Empty / loaded	0.97	1	14	0.381	9
S Laggan - Sawmill	Loaded	0.82		32.5	0.213	31.5
Unloading	-	0.00		20	0.000	0
Sawmill - S Laggan	Empty	0.93		31	0.236	31.5
Dirtroad up & down, incl loading	Empty / loaded	0.97	1	14	0.381	9
S Laggan - Sawmill	Loaded	0.82		32.5	0.213	31.5
Unloading	-	0.00		20	0.000	0
Sawmill - S Laggan	Empty	0.93		31	0.236	31.5
Dirtroad up & down, incl loading	Empty / loaded	0.97	1	14	0.381	9
S Laggan - Sawmill	Loaded	0.82		32.5	0.213	31.5
Unloading	-	0.00		20	0.000	0
					0.000	0
Pause, non-driving time		0.00		6	0.000	0
		Daily exposure value, m/s² A(8)			0.86	216

For a single one-way trip from Corpach/Banavie via Loch Arkaig to the Norboard factory in Inverness, the exposure was 0.55 m/s^2, as per the calculation in Table 8. Despite being only a half working day, still the exposure is above the EU Action Value A(8) = 0.5 m/s^2.

Table 8 Truck drivers' vibration exposure, Banavie - Loch Arkaig - Inverness with active TPCS

TPCS active		Vibration intensity	Exposure time		Partial exposure	Distance [km]
		m/s²	hours	minutes	m/s²	
Banavie - Loch Arkaig	Empty	1.00		37	0.278	24
Dirtroad	Empty	1.53		9	0.210	2.3
Loading	-	0.00		30	0.000	0
Dirtroad	Loaded	1.28		9	0.175	2.3
Loch Arkaig - B8004 (Gairlochy)	Loaded	0.84		28	0.203	17
B8004	Loaded	0.94		5	0.096	4
A82 (1)	Loaded	0.63		32.5	0.164	28
A82 (2)	Loaded	0.77		34	0.205	37
A82 (3)	Loaded	0.70		27	0.166	27
A96	Loaded	0.56		9	0.077	9
Unloading	-	0.00		20	0.000	0
					0.000	0
Pause, non-driving time		0.00	4		0.000	0
		Daily exposure value, m/s² A(8)			0.55	151

Using the above result of "*6 % higher ride vibration when the TPCS truck was unloaded*", a rough estimate of a full working day on a round-trip Spean Bridge (Ft William) – Inverness has been calculated. The estimated A(8) value is 0.65 m/s^2, as per Table 9. This is significantly above the EU Action Value A(8) = 0.5 m/s^2.

Table 9 Truck drivers' vibration exposure, Ft William – Inverness round-trip on A82

TPCS active		Vibration intensity	Exposure time		Partial exposure	Distance [km]
		m/s²	hours	minutes	m/s²	
A82 (1)	Loaded	0.63		32.5	0.164	28
A82 (2)	Loaded	0.77		34	0.205	37
A82 (3)	Loaded	0.70		27	0.166	27
A96	Loaded	0.56		9	0.077	9
Unloading	-	0.00		20	0.000	0
A96 home	Empty	*0.59*		8	0.077	9
A82 (3) home	Empty	*0.74*		26	0.173	27
A82 (2) home	Empty	*0.82*		32	0.211	37
A82 (1) home	Empty	*0.67*		31	0.170	28
Loading	-	0.00		20	0.000	0
A82 (1)	Loaded	0.63		32.5	0.164	28
A82 (2)	Loaded	0.77		34	0.205	37
A82 (3)	Loaded	0.70		27	0.166	27
A96	Loaded	0.56		9	0.077	9
Unloading	-	0.00		20	0.000	0
A96 home	Empty	*0.59*		8	0.077	9
A82 (3) home	Empty	*0.74*		26	0.173	27
A82 (2) home	Empty	*0.82*		32	0.211	37
A82 (1) home	Empty	*0.67*		31	0.170	28
					0.000	
Pause, non-driving time		0.00		18	0.000	0
		Daily exposure value, m/s² A(8)			0.65	404

3.3.3. Systematic high spinal compression stress

The average daily spinal compression stress during the three days of the measurements in the Scottish Highlands was systematically high; S_{ed} = 0.9 – 1.1 MPa. One of the worst contributors to the average compression stress came from Road B8004 from Gairlochy to the A82 (bound for Spean Bridge). This road had several long-wave bumps. These bumps are difficult to see on photographs, but are easy to "perceive" when watching the video from the webcam on the truck´s dashboard.

The measured spinal compression stress exceeded both health caution values in the standard ISO 2631-5 on human response to transient vibration. Exposures below 0.5 MPa are claimed by the standard to bring "Low probability of an adverse health effect" and over 0.8 MPa to bring "High probability of an adverse health effect". In Sweden, S_{ed} = 0.5 MPa is frequently used as the action value for maximum compression stress. Truck drivers operating like the test driver in this Highland study, with S_{ed} = 0.9 – 1.1 MPa, are at high health risk due to intense spinal compression stress.

Truck hauliers with employees working under conditions similar to those in this study, should carry out a risk assessment with associated measurements to clarify if actions need to be taken to protect their drivers from health and safety risks from ride vibration and mechanical shock.

3.3.4. Undulating profile at bridges is a root cause of high ride vibration

The round-trips of the study included crossings of several ancient and often beautiful small bridges. Many of these bridges have an arch-shaped road profile, with high amplitude and short ramps; such that at normal low volume rural road speeds the road profile acts as a speed hump causing vehicle body bounce. These small bridges can be extreme "hot-spots" when it comes to poor truck ride quality. A further bridge problem encountered during the demonstration was a damaged and rough bridge deck. Below are some examples of unhealthy[8] truck ride over bridges.

The first "unhealthy" example is a bridge with a severely damaged deck on Road B8005, as shown in Figure 32. The graph at the bottom of Figure 33 shows the vertical acceleration (green) and the root-mean-square of x,y,z axis vibration (blue) along 30 seconds of the truck ride at 36 km/h. The yellow marker shows the position where the webcam picture was taken. The maximum vertical vibration (frequency-weighted as per ISO 2631-1) was 6.1 m/s^2. The Maximum Transient Vibration Vector Value (MTVVV) averaged over 1 sec was 5.1 m/s^2. Both these values are extremely high and the latter value corresponds to "extremely uncomfortable" (exceeding 2 – 2.5 m/s^2) as per the discomfort scale in the ISO 2631-1 standard.

[8] *Note: The graphs do not report spinal compression stress [MPa], only seat accelerations [m/s^2] – the input used when computing the spinal compression stress. The compression stress goes high in sections where seat accelerations are high, so high seat acceleration is an indicator of high stress in the spine.*

Figure 32 Damaged bridge deck at Road B8005 from Banavie to Loch Arkaig

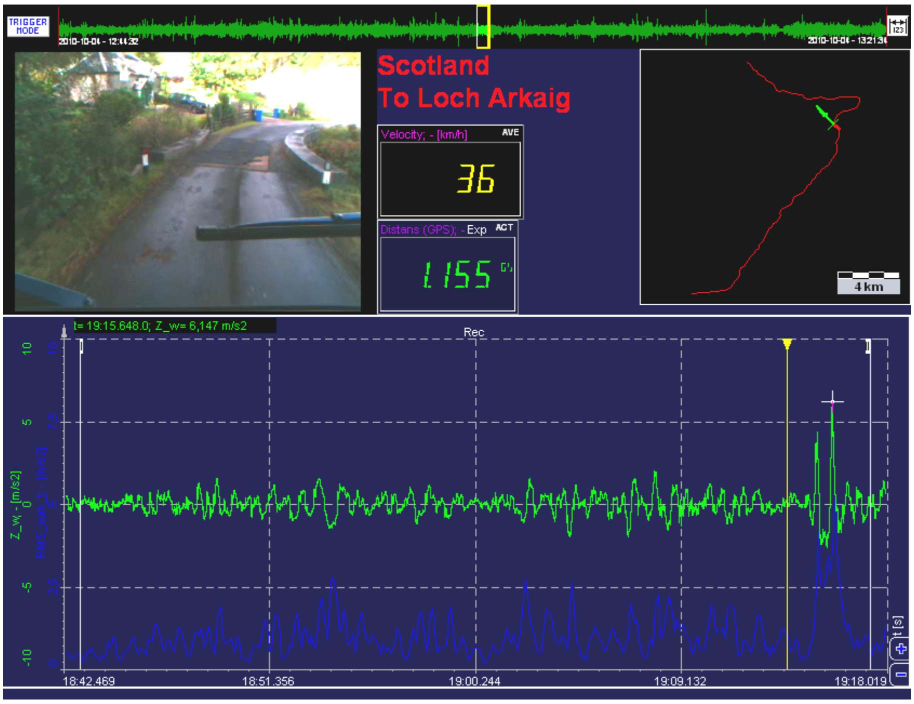

Figure 33 Powerful bumps at one of the ancient bridges on Road B8005

The second example of an “unhealthy” bump is an arch-shaped bridge, also on Road B8005, as shown in Figure 34 and Figure 35. Travelling northbound at 56 km/h, the truck almost went airborne, when it was accelerated vertically with 0.9 G. Take-off occurs at 1 G (10 m/s^2). When the truck went southbound at the lower speed of 43 km/h, the driver incurred a maximum vertical vibration of 5.7 m/s^2, as seen in the 40 second long graph. Note that the intensive vibration started tens of metres before the bridge itself, when riding southbound. This indicates that the causes of the truck ride problem included settlements in the backfill behind the bridge abutment.

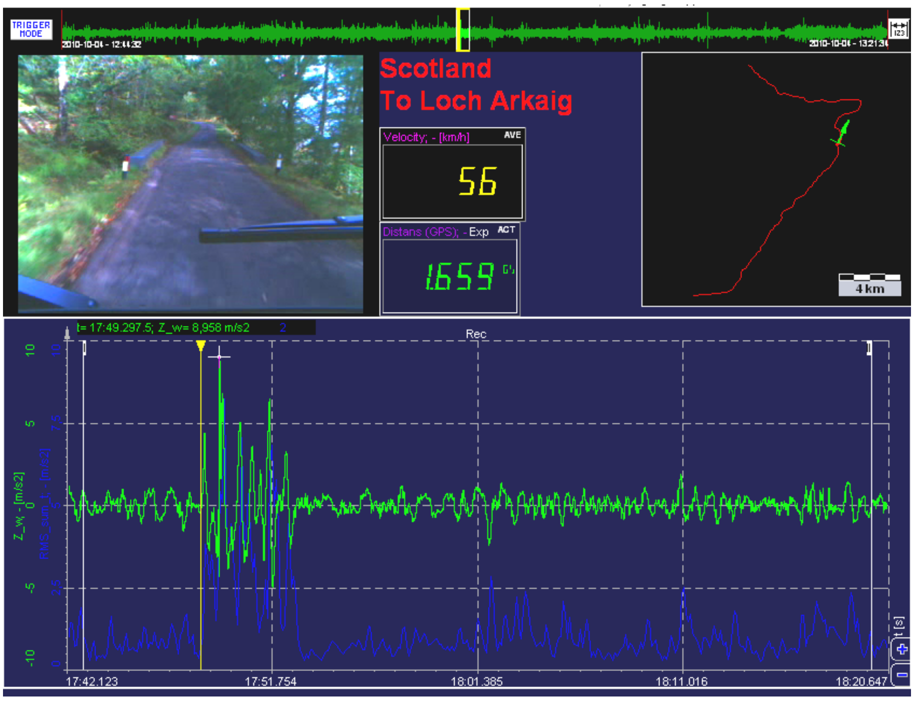

Figure 34 The Northbound truck almost went airborne (0.9 G) at the bridge on B8005

Figure 35 The truck felt severe bumps also when Southbound on B8005

The problem with bumpy rides at bridges was present also on national road A82, as seen in Figure 36. The frequency-weighted vertical acceleration of the driver seat peaked at 5.9 m/s^2; almost 0.6 G. This can be compared to the 0.7 G (unweighted) vertical acceleration being used in many countries as design target value for traffic calming speed bumps on urban low speed streets.

Figure 36 The truck incurred severe bumps on a bridge on the A82 bound for Inverness

3.3.5. Rough ride on patch work

Patch repair can be necessary before an overlay is funded. However, the result of the patch work is often still a rough road, as can be seen in the results from highway A82 in Figure 37.

Figure 37 Rough truck ride over patches on A82 bound for Inverness

3.3.6. Bumpy transversal joints

In the Highlands, as well as in the other ROADEX Partner Areas, a frequent bumpy problem is the transversal joint at the start of overlays and patch repairs. See the example in Figure 38.

Figure 38 Impulse-response in the truck at a rough transversal joint on A82

3.3.7. Bounce resonance at long wave unevenness

As reported in the ROADEX III case study on Road 331 in Sweden, truck suspension systems can magnify bounce, pitch and roll vibration at frequencies in a range between 0.7 and 3 Hz due to resonance. At highway speeds around 80 km/h (50 mph), these frequencies are excited by unevenness with wavelengths in a range of about 7 - 31 m. An example of truck resonance on an uneven section of highway A82 from Ft William to Inverness is shown in Figure 39.

Figure 39 The truck suspension shows resonance at low frequencies / long wave unevenness

This kind of long wave unevenness is difficult to repair with a traditional asphalt overlay, since the paver tends to “roller-coast” in undulations of more than some 10 m long. Good practice in repair of such unevenness is careful filling of the hollows, and preferably also gentle milling of the ridges, before resurfacing. The procedure should preferably be done after laser-scanning the undulations, computer aided design of the undulation repair, and computer aided control of the milling works. Extensive experience from Sweden shows that the final paving layer should preferably not be laid with computer aid due to the complexity of controlling the paving plants floating screed. The final paved wearing course layer should be laid on the prepared surface with correct slopes, preferably created with a milling machine controlled with computer aid.

3.3.8. Precision in the measurements of truck ride quality

The three series of measurements of truck seat vibration data recorded on A82 with full payload from South Laggan bound for Corpach are shown in Figure 40. It can be seen that there is noticeable variance between the three series of data, with standard deviation 0.13 m/s^2 in an arbitrary section. Such variance is inevitable however, given the complex nature of the truck driving task with differences in truck speed and in the lateral driving position on the roads (roads are generally rougher closer to the pavement edge). However, the differences between the three series are averaged out when a longer section is analysed instead of only a single section. The average values for the three series of 12 km were 0.744, 0.734 and 0.745 respectively. The minimal difference shows that there was no significant bias between the three measurements.

From an overall perspective, the demonstrated precision was very good down to the second decimal place. Any single measurement, longer than a couple of kilometres, gives a robust estimate of truck ride quality on the measured route. There is no practical need for repeated measurement, unless the ride conditions are changed (which is a matter of reproducibility, not of repeatability). Three examples of significant change in conditions are: 1. resurfacing the road, 2. rideability during summertime and during wintertime on a road with severe frost actions, and 3. differences between a driver who avoids potholes and a driver who does not avoid road surface damages by yawing and/or braking.

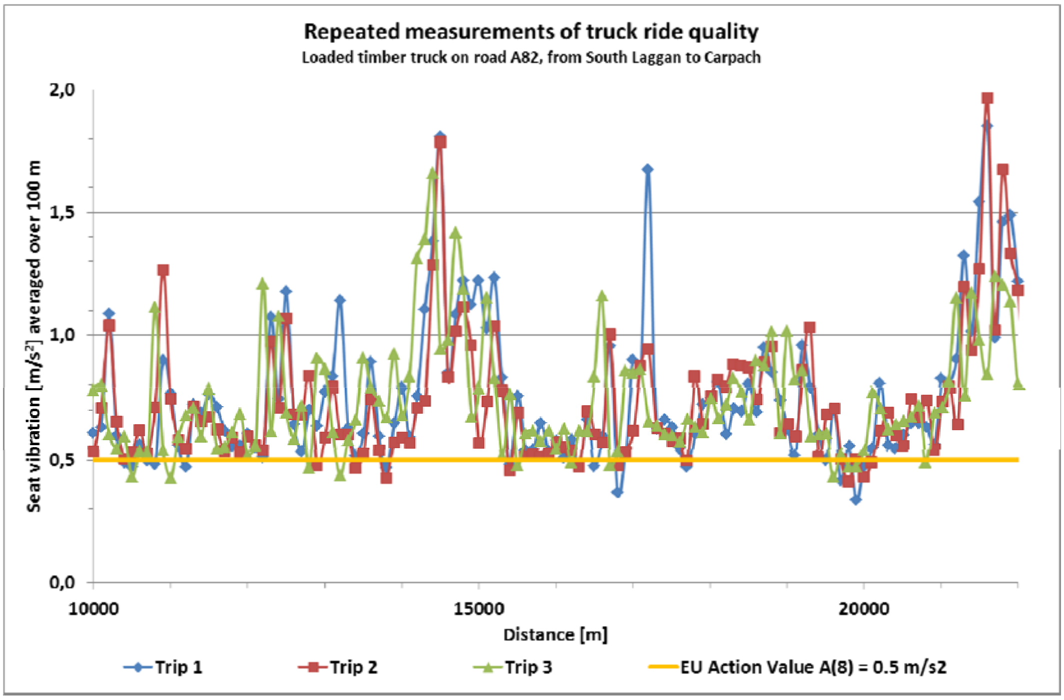

Figure 40 Three repeated measurements of truck seat vibration

3.3.9. Observations of hazards and various road features in Highlands

3.3.9.1. IMPROPERLY BANKED CURVES

Just as with the route in Finnish Lapland, the route in the Scottish Highlands included several outercurves that were seen to be improperly banked. One example was the sharp curve shown in Figure 41. Rollover and various other types of loss-of-control crashes cluster at this kind of "flat curve", indicating that they are extremely hazardous. With accurate data of crossfall and curvature from a road network condition survey, it is easy to identify curves with adverse camber, such as demonstrated in the data from Finland in Figure 19. A more advanced analysis of improperly banked outer-curves, relating to design codes for geometry of new roads, was presented in the ROADEX III study "Health Issues Raised by Poorly Maintained Road Networks" (2008).

Figure 41 A82 has many improperly banked and thus hazardous sharp outer-curves

3.3.9.2. NARROW ROADS AND SHARP CURVES

The test truck and trailer were modern vehicles with fairly high capacity and thus large dimensions and weight. These types of wide long vehicles can be incompatible with narrow lanes and sharp curves, as seen in evidence in the form of the deformed grass verge in Figure 42. The lack of horizontal clearance at many sections of the test roads is visible also in Figure 43 and Figure 44.

Figure 42 Water pooling in deformed shoulder at the exit of a sharp inner-curve on narrow A82

Figure 43 Hazardous rock edges at the pavement edge on Road B8005 at Loch Arkaig

Figure 44 Narrow sections cause frequent scratching on tyre sidewalls and fenders

3.4. HAZARDOUS TRUCK OPERATION IN NORTHERN NORWAY

The demonstration project in Northern Norway resulted in an A(8) value of 0.47 m/s^2, normalized to daily work patterns. This is just below the EU Action Value of A(8) = 0.5 m/s^2. The measurement was made during very good conditions on European Highway E6 with a new truck, a full payload and in the autumn. When considering the influence of factors like lower payload (empty trucks vibrate more than full loaded), vehicle ageing and wear, corrugated thick ice on the road surface and frost actions in the pavement, an annual generic estimate would be rather higher than the Action Value. The average spinal compression stress during the two driving shifts was moderate; S_{ed} = 0.44 MPa. This is below the health caution value of 0.5 MPa in the standard ISO 2631-5 on human response to transient vibration.

Truck hauliers operating in Nordland/Trøndelag with employees working under somewhat worse conditions (late winter with frost damages, worn truck…) to those in this study, should still make a risk assessment with associated measurements to clarify if actions need to be taken to protect their drivers from health and safety risks caused by ride vibration and mechanical shocks.

An obvious risk for any truck driver on the tested E6 route is rollover crashing. This was firmly demonstrated by the original test truck being crashed the night before the ROADEX measurements. Roll-related lateral buffeting on slippery road surfaces is a serious risk factor that all hauliers in Norway should address in their risk assessment. High rollover risk is, together with high speed and poor driving, related to lateral forces (both quasi-static and transient), low friction, as well as a lack of sufficient road width to recover control of the vehicle when an incident occurs. Root causes to rollover crashes include sharp, long and egg-shaped curves, improper banking of outercurves, lack of sufficient road width to recover control of the vehicle, deformation of weak pavement shoulders and insufficient road friction management. The high rollover risk can be reduced by implementing road signs with a radar-based display, giving warning for vehicles with high curve approach speed.

3.4.1. The route, the transport task, the truck and its instrumentation

Originally, the ROADEX demonstration project in Norway was scheduled for a trip on the E6 Bodø – Tromsø road, with a fish-truck from Transportsentralen Lillestrøm (TSL) on Saturday 15 October 2011. However, on the cold night between 13 and 14 October, the truck from TSL was destroyed in a rollover-crash near Svartåstjønna, located between Smalåsen/Smeelehaesie and Namsskogan. The crashed truck is shown in the left photograph (by Anne Brekkvassmo) of Figure 45. The crash site is showed in the right photograph, taken by J Granlund while riding the replacement test truck. Fortunately the truck driver survived the crash with minor injuries.

Figure 45 The original test truck crashed between Smalåsen and Namsskogan

With the kind assistance of the Norwegian Haulier's Association (NLF), Kulseng-Hansen Thermo-Transport A/S was identified as an alternative haulage partner with a replacement truck. Luckily the owner, Reidar Kulseng-Hansen, had read the ROADEX III report "*Health Issues Raised by Poorly Maintained Road Networks*" on the case study on Road 331 in Sweden. Since Mr Kulseng-Hansen appreciated the ROADEX research, he was delighted to marshal one of his trucks to reproduce the study; now on European Highway E6 in Norway. By this means the measurements were able to be completed without delay and additional costs, just a change in route. With respect to the ROADEX objectives, the final route was as good a test section as the originally planned test route E6 Bodø – Tromsø. Since the final route was much longer than the original, the results are even more representative for long haulage in the Northern Periphery.

The location of the studied route on the E6 from Fauske (Nordland) down to Trondheim (Trøndelag) in Norway is shown in Figure 46. The test truck was carrying a cargo of chilled fish from the Nordlaks Atlantic fish-harbour in Stokmarknes south to the market in Oslo.

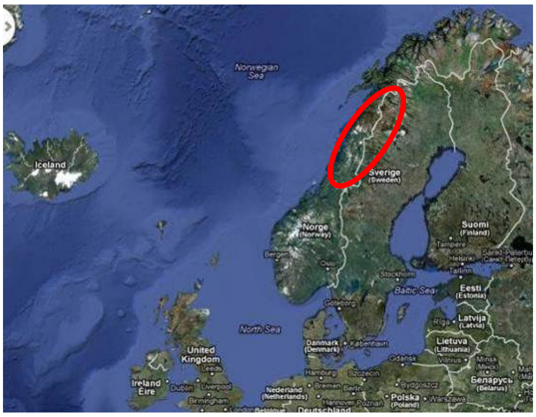

Figure 46 Location of the Nordland/Trøndelag demonstration route on E6

The route Fauske – Trondheim, see Figure 47, was in total 636 km long. The traffic volume was about 1300 AADT over the northern mountains (of which some 25 % were heavy trucks), and some 18 000 AADT (10 % heavy trucks) close to Trondheim in the south. The speed limit was mainly 80 km/h. About 1 hour drive south of Fauske, the E6 goes over Saltfjellet. This high mountain area regularly causes problems in the winter. The road is typically totally closed 10 – 25 times per winter, with a similar number of occasions per winter when traffic is restricted for safety reasons to travelling only in organized columns.

Figure 47 Overview of the demonstration route on E6 between Fauske (north) and Trondheim (south)

The demonstration measurements were carried out on 14 and 15 October 2011. The ROADEX haulage partner was Kulseng-Hansen Thermo-Transport A/S, operating a Volvo FH16 540 as seen in Figure 48. The truck had license plate “KH 76414”, and was almost brand new. The driver seat was a Volvo original mounted air-suspended seat. The steer axle had Michelin ENERGY 385/55 R22.5 tyres. The drive axles had pair-mounted Michelin XDN2 GRIP 315/70 R22.5. The length between the first and the second axle was 3.40 m.

Figure 48 The Volvo truck used for the ride quality study on E6 in Nordland/Trøndelag

The truck was equipped with advanced equipment for safety and traction, such as a video camera monitoring the “hidden angle”, on-board sand gritting aggregate, and a trailer rollover-stability system (TRS) made by Haldex. It also carried snow chains, but these had never been used. As the driver, Mr Pettersen, said “*Chains are not good. They cause extreme noise and make any ice-*

capped road surface extremely rough, so all following trucks will get a harsher ride. When the road condition is so poor that it calls for chains, then I simply pull over, park the truck and phone the road maintenance contractor responsible for ploughing and gritting".

Best practice for climbing icy long steep upgrades, proven over decades by native truckers in Northern Scandinavia, is to increase the ground pressure on the drive axle by temporary raising the bogie axle. This way traction is increased without time-consuming and hazardous near-roadside work with mounting on/off snow chains. Despite the increased tyre/road pressure, this practice is not recognized as causing additional damage to the road. The explanation is that when the road is icy and stiff-frozen, it simply can withstand extreme traffic load. In fact, road agencies in the Nordic countries consider abrasion by studded passenger car tyres as the only significant mode for traffic-related wear of pavements in wintertime. The traditional practice of "bogie-lift" at stiff-frozen icy upgrades is also not recognized as significantly damaging to truck components such as axles and tyres, since bogie-lift is done during short periods and at modest speed. On the other hand, snow chains are recognized for damaging the road surface, especially when used on a drive axle with insufficient load. The result is wheel spin destroying the ice cap, often also causing permanent damage to the underlying asphalt surface from the spinning steel chained wheels.

Mr Pettersen drove the route between Stokmarknes and Oslo 2 – 3 times per week throughout the year. He had a very long driving experience, including several years transporting aid supplies in Arctic conditions in Russia. His strategy is to drive with a good margin on the speed limit, to get a relaxed but efficient ride with a minimum of braking and acceleration. This kind of driving results in minimized fuel consumption and emissions. Mr Petersen's experience is that the retarder (one of the brake systems in the truck) tends to cause the wheels to lock on wet asphalt if set in position 3 and 4. In the winter, Mr Pettersen adjusts the settings in the truck computerized control system so the retarder is in position 1 for the smoothest retardation, and hence the lowest skid risk, on extremely slippery wet thin ice.

The truck was instrumented with tri-axial accelerometers at the base and on the pan of the driver seat, webcam and an interior microphone, as seen in Figure 49.

Figure 49 Instruments in the Volvo test truck used on European Highway E6 in Norway

3.4.1.1. PHOTOS FROM THE E6 DEMO-ROUTE

The E6 in northern Norway can be a very demanding road, as seen in Figure 50. In winter time, many Norwegian professional drivers prefer, if possible, to use the 100 km longer route on the European Highway E45 through Sweden instead.

As seen in the bottom right photograph, a newly resurfaced section was also in a hazardous condition. The wearing course had delaminated from the old surface, obviously when a heavy vehicle had braked hard. It is of no use to have good brakes on heavy trucks if pavement layers aren't glued with enough amount of tack-coat to each other, sufficient to withstand the brake forces.

Figure 50 Photographs from E6 Fauske - Trondheim

3.4.2. Daily vibration exposure and spine compression stress

The ROADEX measurements started just before midnight on 14th October 2011 in Fauske. Earlier the same day, the truck driver had started his work with about a 5 hour long drive from the fish harbour in Stokmarknes down to Fauske. Normally, long haulage road transport, as in this study, contains a minimum of non-driving time. For the 8 hours of driving during the two working shifts from Fauske down to Trondheim, the A(8) value was 0.47 m/s^2, as per the calculation in Table 10. This is below the EU Action Value A(8) = 0.5 m/s^2. The longest section with "high partial exposure per hour" was the first two hour drive South of Mosjøen. In theory it could be possible to exceed the EU Action Value by driving repeatedly back and forth on this section. In reality however, no transport task is designed for such "medium length haulage" without pauses for loading on/off the truck and thereby lowering the vibration dose. So, at first glance, the truck operations on the E6 seem to be below the EU Action Value.

Table 10 Truck drivers' vibration exposure on E6 Fauske – Trondheim; Loaded trailer

		Vibration intensity	Exposure time		Partial exposure
		m/s²	hours	minutes	m/s²
Fauske to Mosjöen, stage 1	Loaded	0.41	0	0	0.000
Fauske to Mosjöen, stage 2	Loaded	0.53		7	0.064
Fauske to Mosjöen, stage 3	Loaded	0.57		37	0.158
Fauske to Mosjöen, stage 4	Loaded	0.42	1	51	0.202
Fauske to Mosjöen, stage 5	Loaded	0.43		19	0.086
Sleep rest in Mosjöen					0.000
Mosjöen to Trondheim, stage 6	Loaded	0.53	1	51	0.255
Mosjöen to Trondheim, stage 7	Loaded	0.52		44	0.158
Mosjöen to Trondheim, stage 8	Loaded	0.41	1	26	0.174
Mosjöen to Trondheim, stage 9	Loaded	0.43		32	0.111
Mosjöen to Trondheim, stage 10	Loaded	0.41		10	0.059
Mosjöen to Trondheim, stage 11	Loaded	0.47		8	0.061
Mosjöen to Trondheim, stage 12	Loaded	0.44		12	0.070
Pause, non-driving time		0.00		0	0.000
		Daily exposure value, m/s² A(8)			0.47

However, the tests on the E6 in Norway were made under favourable conditions not fully representative of a full round-trip operation, not for full year operation, and not for "worn truck" operation.

The circumstances of the demonstration were:

- The new Volvo truck was in excellent condition.
- The road was neither covered with a thick rough ice layer, nor exposed to frost effects.
- The road was in its smoothest condition of the year. The measurements were done in the autumn after maintenance and resurfacing operations during the summer.
- The trailer had a full payload. The return payload can be much lighter, as the fish harbours in the north are much smaller freight receivers than Oslo, and other cities in the South. With low/no payload, the northbound truck ride becomes much harsher.

Based on previous measurements, a modest estimate is that the ride would be at least 12 % worse in empty mode compared with having a full payload. Including also the return trip with low/no payload from the market down South back to the fish harbours in northern Norway, the A(8) estimate would be 0.53 m/s^2 (+12 % intensity) instead of the measured 0.47 m/s^2 at full payload.

Together with any corrections for higher vibration as the truck wears with use, and for rougher road in the other seasons, the long term A(8) can be estimated to be definitely above the EU Action Value A(8) = 0.5 m/s^2.

For the measurements in Norway, the average spinal compression stress during the two driving shifts was moderate; S_{ed} = 0.44 MPa. This is below the health caution value of 0.5 MPa in the standard ISO 2631-5 on human response to transient vibration.

In order to comply with the EU/Norwegian health and safety legislation on vibration at work, truck hauliers operating in Nordland and Trøndelag with employees working under slightly worse conditions (winter road, frost damages, worn truck…) to those in this study, should make a risk assessment with associated measurements to clarify if actions need to be taken to protect their drivers from health and safety risks from ride vibration. An obvious risk for any truck driver on the tested E6 route is loss-of-control and rollover crashing. Roll-related lateral buffeting on slippery road surfaces is a serious risk factor that hauliers in Norway should address in their risk assessment.

3.4.3. Rough road profile at bridges is a root cause to high ride vibration

Just as in the ROADEX demonstration projects in Finland, Sweden and Scotland, the test on the E6 in Norway showed that road/bridge joints can be extreme "hot-spots" when it comes to poor truck ride quality. The problem is preventable however, as properly maintained pavements do not give a ride problem. At the problem sites, the cause is typically settlements in backfills behind the bridge abutment, or an improper road profile over the steel beam transversal joint. The latter is often in the form of "steps" between the asphalt and the bridge joint, or the asphalt surface being below the joint beam, instead of properly being some 3 - 8 mm above the joint.

Two typical examples with an unhealthy truck ride over rough road/bridge joints on the E6 are shown in Figure 51 and Figure 52.

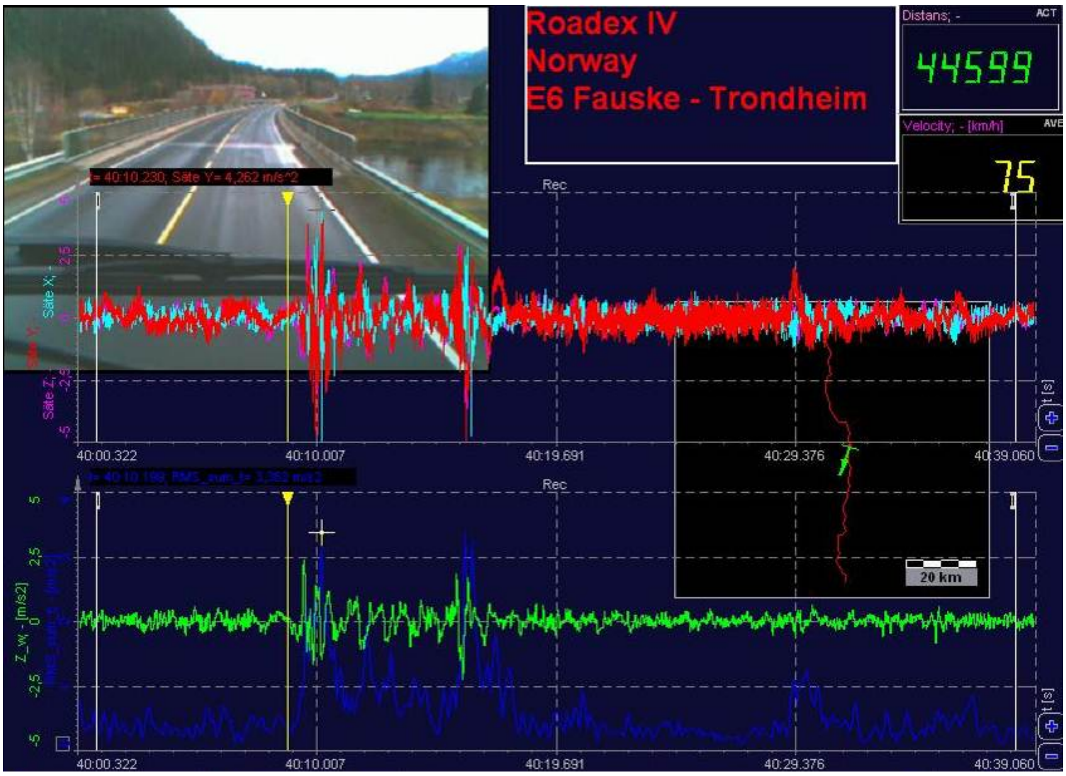

Figure 51 Unhealthy truck ride at a bridge on E6

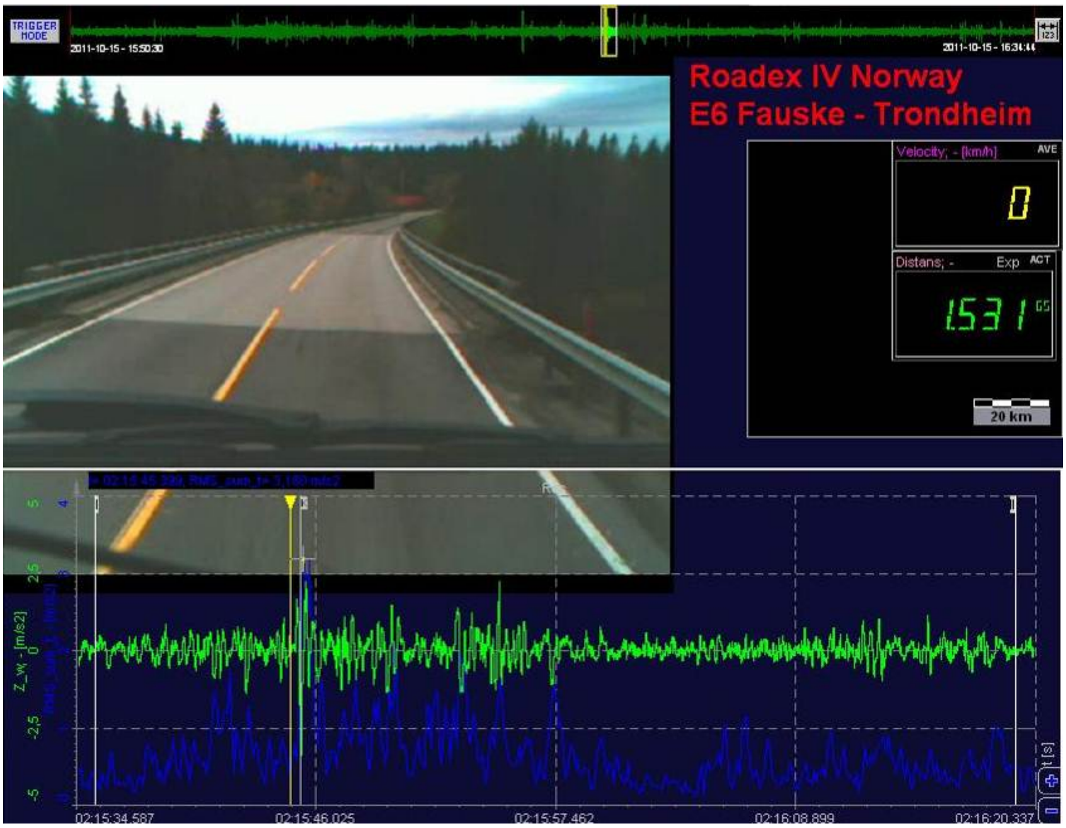

Figure 52 Unhealthy truck ride at a another bridge on E6

3.4.4. Bumpy transversal joints

A frequent bumpy problem, common to Norwegian Nordland/Trøndelag and other ROADEX Partner areas, happens at transversal joints at the starts and ends of overlays and patch repairs. Two examples of bad transversal joints are shown in Figure 53. The left photograph is of a fresh made joint, while the right photograph is of a several years old and well-worn joint. These two rough joints resulted in unhealthy mechanical shock in the truck driver seat, as can be seen in Figure 54 and Figure 55. Another example of a bad new joint is given in Figure 56. While “joint shocks” are typically lower than shocks at “natural” potholes and bumps, the joint shocks are more or less man-made. Thus the joint shocks may be perceived by road users as more “unnecessary” and frustrating, while they are obviously easy to prevent by improving the practice for asphalt repair works on highways.

Figure 53 Improper transversal joints at new and old asphalt patch repairs on E6

Figure 54 Mechanical shocks in the truck driver’s seat at a bad asphalt-joint

Figure 55 Mechanical shocks in the truck driver’s seat at the old bad asphalt-joint

Figure 56 Mechanical shocks in the truck driver's seat at another bad asphalt-joint

3.4.5. Bumps at culverts

A common reason for road roughness is improperly installed drainage pipes or culvert crossings under the road. In order to avoid bumps at culverts, the construction needs to follow certain procedures. According to Scandinavian road construction codes, the trench for a piped culvert should have the specified bottom width and excavated side slopes, making the trench upper width typically some 25 – 45 m. Such large trenches and associated backfills are rather costly and hence many culverts are installed with minimal trenches, often simply a vertical trench just wide enough for the culvert. The result may be acceptable in some cases, but during the late-winter-to-early-spring frost action period the results can often be very bumpy sections at poorly installed pipes. An example of a bumpy culvert on the E6 is seen in Figure 57. This ROADEX measurement was done in October, without any frost action, so this culvert bump is likely to be much worse in the spring.

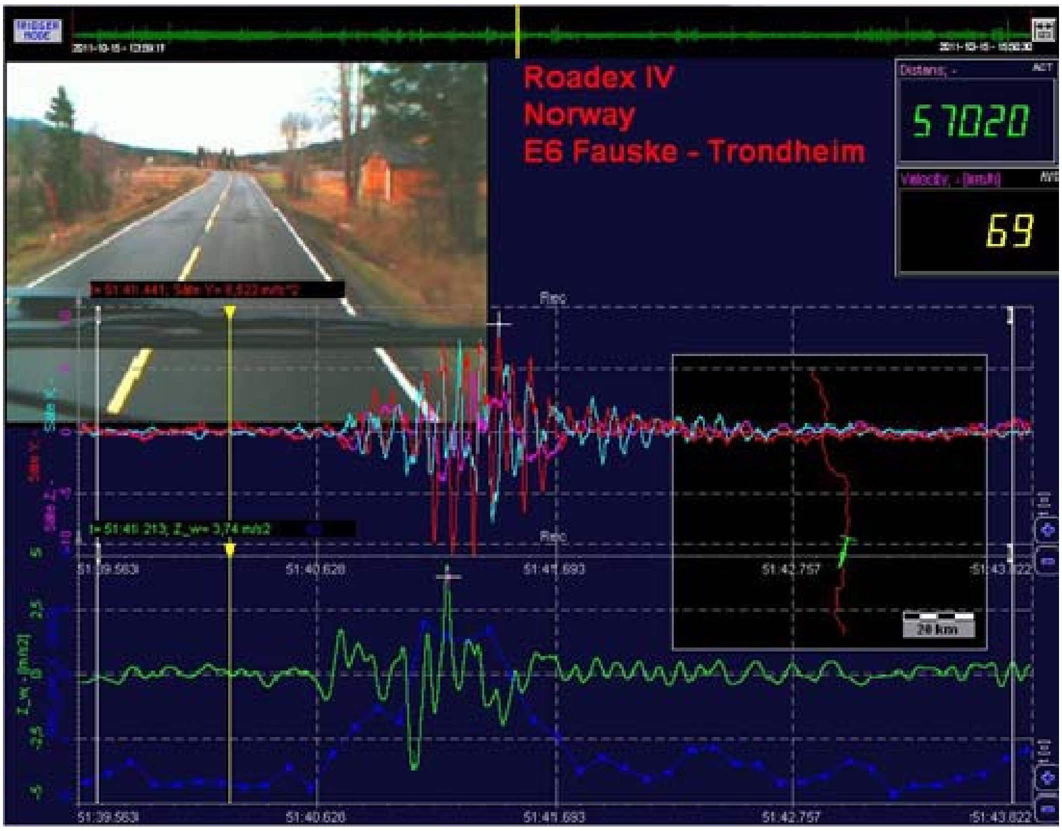

Figure 57 Bumpy truck ride due to settlements at a culvert

3.4.6. Poor truck ride quality at deformed weak road sections

While efficient road transports are carried out with long, wide and heavy trucks and buses, large proportions of the Northern Periphery (NP) road network pavements lack the necessary bearing capacities for these traffic loads. The ubiquitous result of this “overloading” is deformation of the weakest pavement sections. While transversal deformation can be fairly homogenous, in the form of rutting, longitudinal deformation is almost always heterogeneous. Thus weak pavements quickly develop a rough road profile, which excites intense ride vibration. An example of a deformed weak pavement section on the E6 is seen in Figure 58. A common reason for insufficient bearing capacity in the NP is poor road drainage in the form of clogged or insufficient sized ditches.

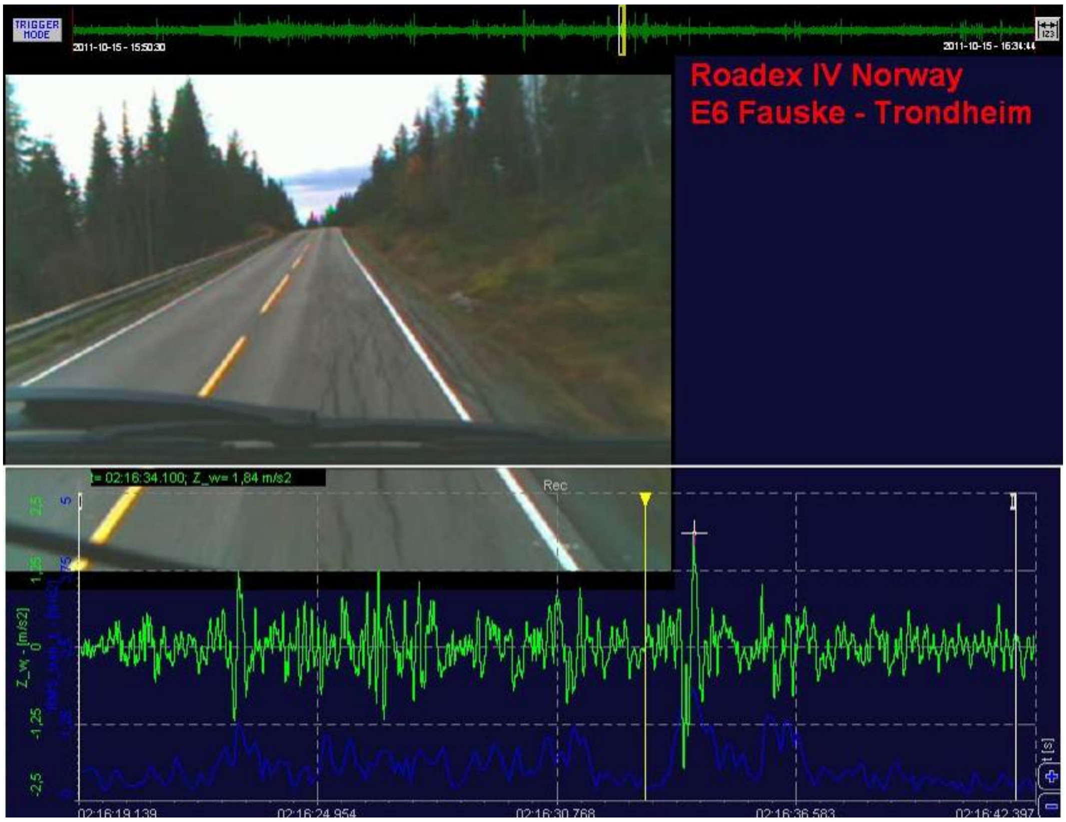

Figure 58 Bumpy truck ride at a deformed and alligator-cracked weak pavement section

3.4.7. Noise from thermo-cooler may disturb the drivers sleep rest

Excessive working time is a major cause of stress, depression and illness, and the purpose of the driving and rest time regulation is to protect professional driver's health and safety. It is assumed that during rest hours, a professional driver will get a good rest of at least 11 hours in any 24 hours. However, during the sleep rest between the long measurements in the demonstrations on the E6 in Norway, the sleep in the truck cab was periodically seriously disturbed by noise from the diesel-powered freight thermo-aggregate (the refrigeration unit at the front of the trailer). The in-cab noise was measured at some 25 – 35 dB, with some transients up to 50 dB from cars stopping and starting at a nearby gas station as seen the noise records in Figure 59 and Figure 60. However, as the thermo-aggregate started up every 1½ hour, the noise rose to a sleep-stopping level of 63 - 67 dB! Conventional thermo-coolers typically operate at 74 – 78 dB outdoor noise, but the rear wall of the truck cab does provide some noise isolation. When wakened several times during the stipulated sleep hours, the driver does not get proper rest and may become a drowsy and hazardous driver. A fairly simple solution would be to install electric power outlets at truck rest areas, to permit thermo-trailers aggregates to be operated on electricity (quiet mode) instead of on diesel fuel (noisy mode) during the sleep hours. Providing infrastructure in format of power outlets is indeed a road safety related service that could be provided by public authorities, rather than organized by truck operators. The cost for the electricity should of course be paid by the hauliers who use the facility, and who in turn will make corresponding savings on reduced diesel fuel consumption by the thermo-cooler during the driver rest hours.

Figure 59 The driver´s sleep can be disturbed by noise from the freight thermo-cooler

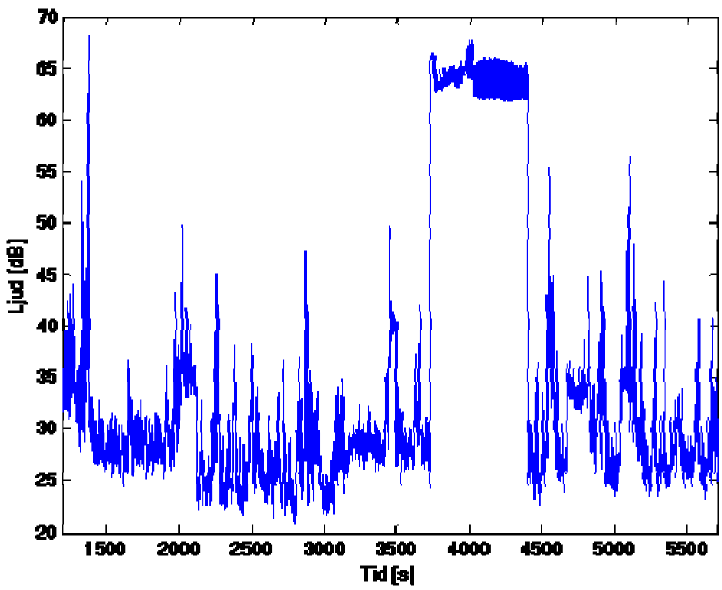

Figure 60 Interior cab noise 65 dB from thermo-cooler disturbed the sleep at time 3700 – 4400 sec

3.4.8. Narrow road width and other hazards in Nordland/Trøndelag

The E6 highway is a remarkably narrow national road, with long sections of only some 6 m width and several bridges and railway underpasses with width down to 4 and 5 m.

When two long haulage trucks of 2.6 m width each meet in a sharp curve on a 5 - 6 m wide highway, as seen in Figure 61, there is not much of safety margin for undesired motions. Some heavy vehicle combinations also suffer from significant trailer off-tracking and lateral displacement of the trailer, caused by rearward amplification of lateral accelerations from the prime moving truck due to wind bursts or deformed pavements. Such phenomena can cause a lateral displacement of up to some 0.8 m. As a result of low road standard, the E6 north of Trondheim suffers from unusually frequent and severe crashes, both in meeting collisions and single-vehicle road departure crashes.

Figure 61 The E6 highway north of Trondheim is remarkably narrow for long haulage transports

3.4.8.1. IMPROPERLY BANKED SHARP CURVES, MANY ALSO “EGG-SHAPED”

Severe truck crashes are frequent on the road section from Stortjønna (in the north) via Smalåsen (a.k.a. Smeelehaesie) to Namsskogan (in the south). Despite a moderate number of vehicles, 1330 vehicles/day AADT, there are severe crashes each and every year on this section.

When approaching the sharp curve shown in Figure 62, the truck driver said “This is a very hazardous place”. The oncoming large truck seen in the photograph was forced out on to the weak 2.5 dm narrow unsealed shoulder to a full stop in order to avoid a collision of the outer mirrors of the two trucks. The curve had been newly resurfaced. Despite this, it was clearly perceived from the truck cab as being insufficiently banked. This view was confirmed by objective pavement measurement. The data recorded on 1st Sept 2011 with a ViaPPS road profiler is presented in Figure 63. Note that reference boxes in the figure are from the Swedish road design code, while the Norwegian road design code calls for a higher superelevation rate (max 8 – 9.5 %, instead of the Swedish max 5.5 – 6 %), and allows much sharper curves than the Swedish road design code. The data in the graph shows that the curve has a severe adverse camber. If the negative cross slope in the outer-curve is corrected to superelevation (see red arrows pointing up), the need for side friction between road and tyres would be dramatically lower and hence the crash risk would be much lower. In Norway, the maximum allowed superelevation when designing curves is 8 % (plus an extra 1.5 % = 9.5 % when considering construction tolerance). The difference from the current -3.3 % cross slope is therefore about 11 units of per cent. For a 2.75 m wide lane, the outer edge needs to be lifted some 0.11 x 2.75 = +0.3 m in the worst 20 m section to reach the target +8 % superelevation. When raising this outercurve (at distance 1230 m in the Road Data Bank), the new safety barrier seen in the photos requires to be dismantled and refitted after the pavement works.

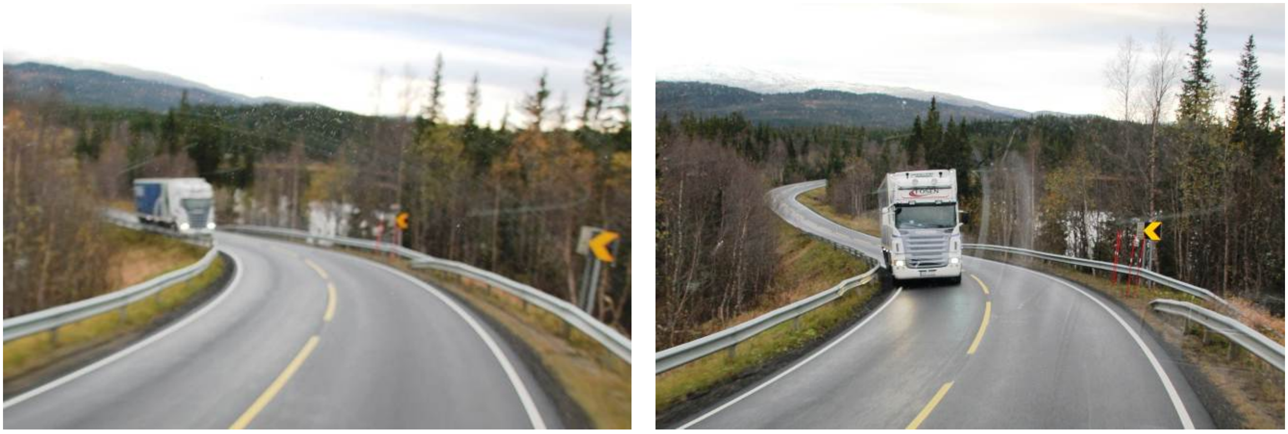

Figure 62 Narrow road for truck meeting on the sharp and improperly banked curve at Stortjønna

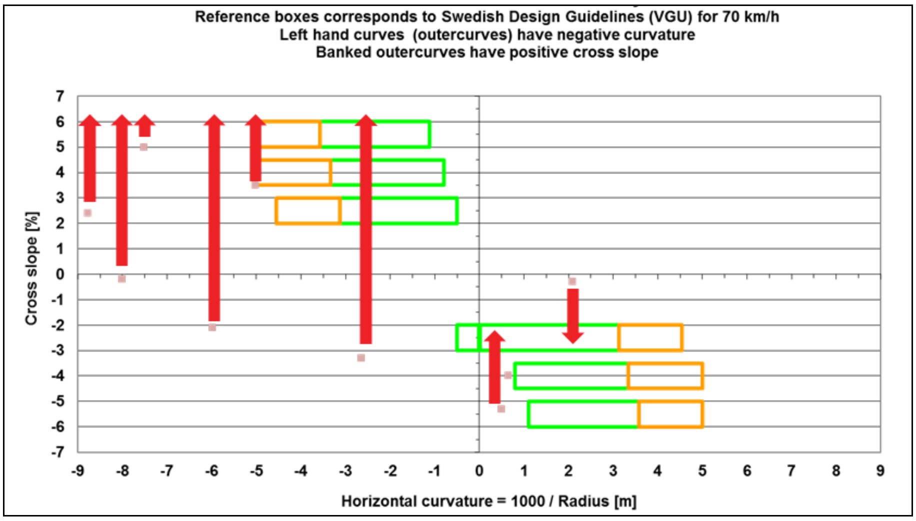

Figure 63 The Stortjønna outercurve needs to be banked up from -3.3 % into high superelevation

At a short S-curve some 3 km south of Smalåsen, there have been three fatal crashes within 44 m, as well as other fatal, and non-fatal crashes within the full length of the curve. Several of the crashes in this curve involve heavy goods vehicles on long haulage. The curve has recently had the safety upgraded, with new crash barriers and curve warning signs, as seen in Figure 64. However, some parts of the recently resurfaced southbound inner-curve are adversely cambered. At 14/720 km on the Road Data Base, the data from 25th August 2011 shows road geometry where vehicles tend to be "pushed into the oncoming traffic". Several of the crashes in the curve, including two fatal, were head-on crashes. Road geometry data show that these sections need to be corrected as per the long red arrows in the graph in Figure 65. There are also some sections both in the innercurve and in the adjacent outercurve that need to be lifted up at the road edge in southbound direction. This will strongly reduce the need for side friction, and hereby also reducing the risk for crashes.

Figure 64 The extremely hazardous curve 3 km south of Smalåsen

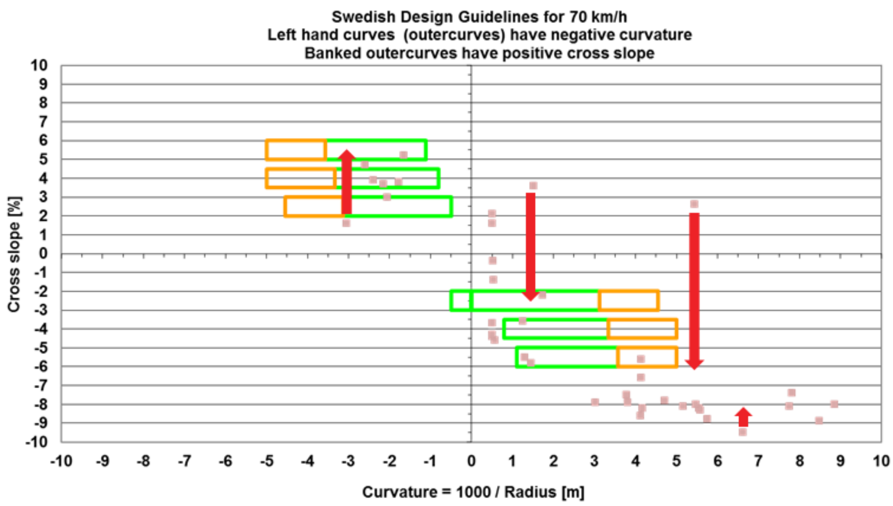

Figure 65 The Smalåsen adversely cambered inner-curve needs reconstruction including lowering

Many of the curves on the E6 are "egg-shaped", i.e. they go from straight into first wide radius and then gradually into much sharper main curve section. This kind of road alignment is often designed on purpose with a geometric element called an Euler-spiral or clothoid. Spirals were implemented on railways in 1829, to decrease the wear of the rail and train wheels at the transition between straight sections and curved segments. Spiral-shaped roads give a benefit to car drivers by reducing the steering wheel torque needed, which is also believed to increase road safety. In the USA, many states use spirals while others have never implemented them in their road design. A study by Tom (1995) compared crash rates with and without spirals. The study showed that spirals increase the crash rate, instead of decreasing the crash risk. One conclusion was that spirals give vehicle drivers the impression of the curve being less sharp, and thus many tend to overestimate the maximum safe curve speed. Drivers entering curves with too high a curve entrance speed must of course brake hard while cornering. Spirals may also “steal space”, so that the main curve segment must be made sharper (and thus more hazardous) with spirals, than if spirals are omitted. Today all multi-wheeled highway vehicles have power steering and thus the steering comfort is as good without spirals on fairly wide roads.

The truck crash in October 2011 seen in Figure 45 took place at an S-curve some 600 m north of the island Storholma, at about the same latitude as the small Svartåstjønna Lake. This curve has been the scene of several other crashes in the past. However, the crash in October 2011 is not registered in the database. The truck driver was a Swede working in Norway. He survived the crash with minor injuries, while the truck had severe damages. This S-curve has several risk factors. One of these is the poorly synchronized transition between the inner and outercurves, as seen in the graph in Figure 66. “Fragments” of superelevation from the innercurve continue into the outercurve, with a cross slope of -0.1 % at curvature 1.4 (radius 731 m). At another section of the innercurve, the cross slope is adversely banked into +0.8 % superelevation. With such road geometry, vehicles tend to be “pushed” into the oncoming traffic. To correct this, the cross slope at the entrance of the outercurve, at about RDB-distance 6130 m, should be lowered by reconstruction down to some -3 %. This is illustrated by red arrows in the graph. “Safe combinations” of cross slope and curvature form a rather large zone, briefly illustrated by the blue transparent field marked in the figure. Data in this blue area are proper combinations, as they result in a modest need for side friction between tyre and road. The equation between side friction demand and the factors horizontal curvature, cross slope and speed is derived and discussed thoroughly in the ROADEX III report by Granlund (2008).

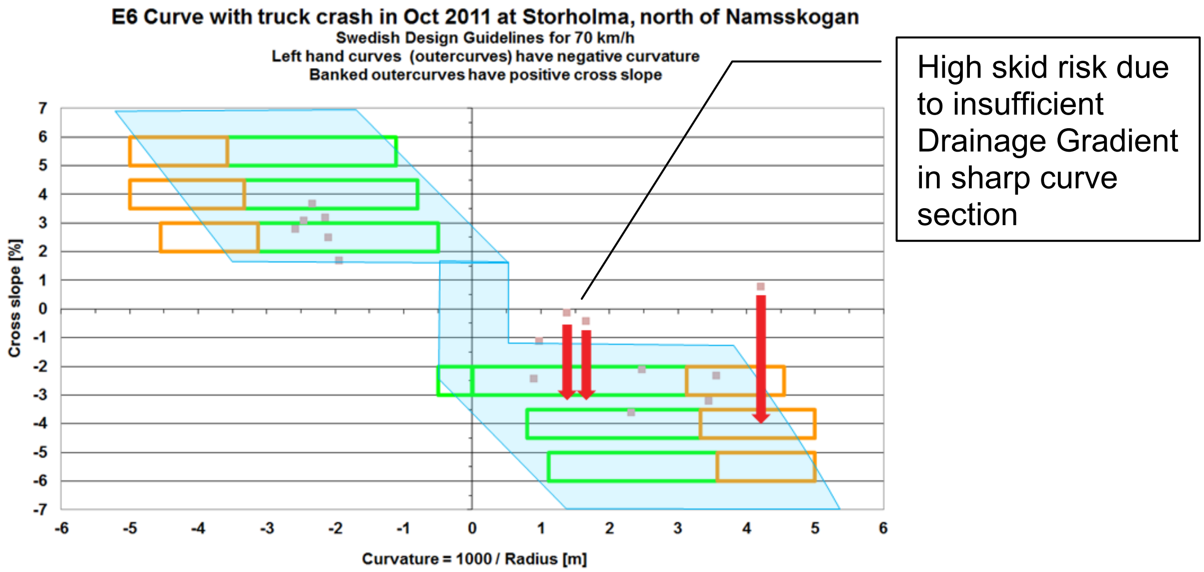

Figure 66 Poorly synchronized transition at the hazardous Svartåstjønna S-curve

The current pavement geometry at the Svartåstjønna curve also raises an issue of insufficient Drainage Gradient at the entrance of the innercurve, where the cross-slope is close to 0 % despite a significant curvature. Unless there is a significant longitudinal grade in this section, the Drainage Gradient (resultant to cross slope and grade) will also be very close to 0 %. This means that water run-off is not assured, and that there can be a wide area of deep water during and after rainfall. At freezing temperatures, this creates a risk for a local, but large, ice-lens formation at this section.

The driver of the test truck from Kulseng-Hansen, Mr Jean Pettersen, had a long experience of truck driving. Mr Pettersen had experienced one truck crash during his career. This crash took place on 5th January 2011 on the old deformed road in the S-curve seen in Figure 67 (photograph by Google in April 2009). Both truck and trailer were totally destroyed as they hit the ditch at the end of the S-curve. Also this truck crash is not registered in the Norwegian crash-database.

Figure 67 The hazardous S-shaped and narrow crash-curve on E6, 2 km north of Fjerdingen

The photograph in Figure 68 was taken during the ROADEX measurement on 15th October 2011, after new resurfacing. The data on the curvature and cross slope is taken from the Norwegian Rosita database and include measurements from both 15 August 2011 and 19 April 2012. The graph in Figure 69 shows that the geometry of the road is at least as hazardous in April 2012 as it was in August 2011. Some mint-green dots from April are even in a worse position than the pink squares[9] from August. This may a result of frost heave in April, on resurfacing works being done after August that did not accord with the road geometry, or on errors in the chain from the Norwegian road profilometer to the Rosita database client.

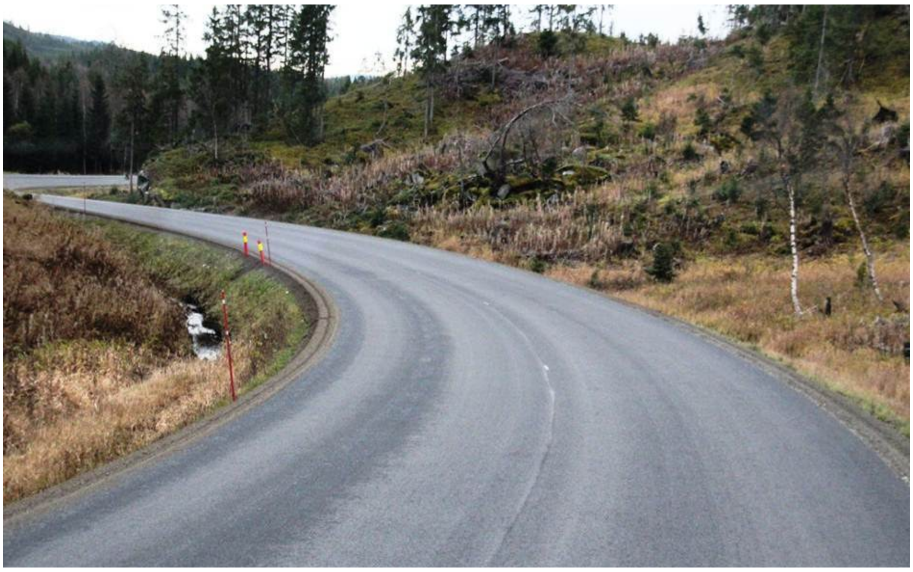

Figure 68 The Fjerdingen S-curve is improperly banked after resurfacing 2011

[9] Each point in this graph represents an average value for 20 m of road. The 20 m averaging in the two series recorded different years has most likely started with an offset (1-19 m), so the points from nearby sections may not be fully comparable in a curvy road section like this.

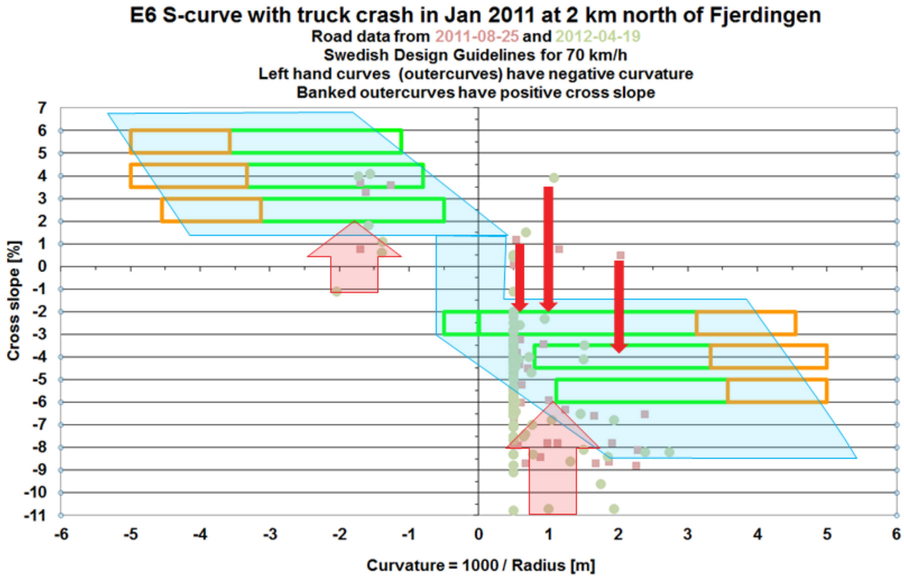

Figure 69 The hazardous S-curve is improperly banked also after resurfacing

3.4.8.2. WILD ANIMALS INCREASE THE CRASH RISK

Wild animals, such as the reindeer, as seen in Figure 70, are a common crash risk on the curvy, narrow and often ice-slippery roads in Northern Norway. Roadside fencing may be an effective measure against these types of large wild animals on the roads.

Figure 70 Wild reindeers and other animals bring crash risk

A safety risk unique on high mountain areas was encountered on the Saltfjell. In the dark night, lemmings suddenly crossed the E6 in such large numbers, so that there was no other option but to run over countless of these animals. This caused a skid risk locally due to low friction between the truck tyres and the road surface. Since the lemmings are so small, fencing would not be an option.

3.4.8.3. MOTION SICKNESS AND OTHER HAZARDS

When passing Trofors, the author felt clear symptoms of motion sickness, a product of accumulated low-frequency (0.1 – 0.5 Hz) oscillations, like in a boat in rough sea. Motion sickness syndrome negatively affects human performance long before the syndrome goes from diffuse inconvenience, pallor and cold sweat to become so severe that the subject has to vomit. Furthermore the negative performance effect may remain for many hours after the difficult ride. Thus motion sickness syndrome may be underestimated as contributing factor in traffic crashes. It is remarkable that a European highway, such as the E6, has such a poor alignment that an adult man can experience motion sickness when travelling within the legal speed.

The E6 route over Hamarøya north of Fauske (not included in the ROADEX demonstration route) often has extreme problems with frost related roughness. Mr Pettersen said that these frost actions in the pavement often cause severe damage to the bottom layers of Styrofoam boxes with fish cargo, especially for drivers less familiar with the road and its bumps. Figure 71 shows a truckload of fish in boxes (left), the principle of crushing the bottom layer of boxes (middle) and damaged fish boxes as the truck arrives to Oslo.

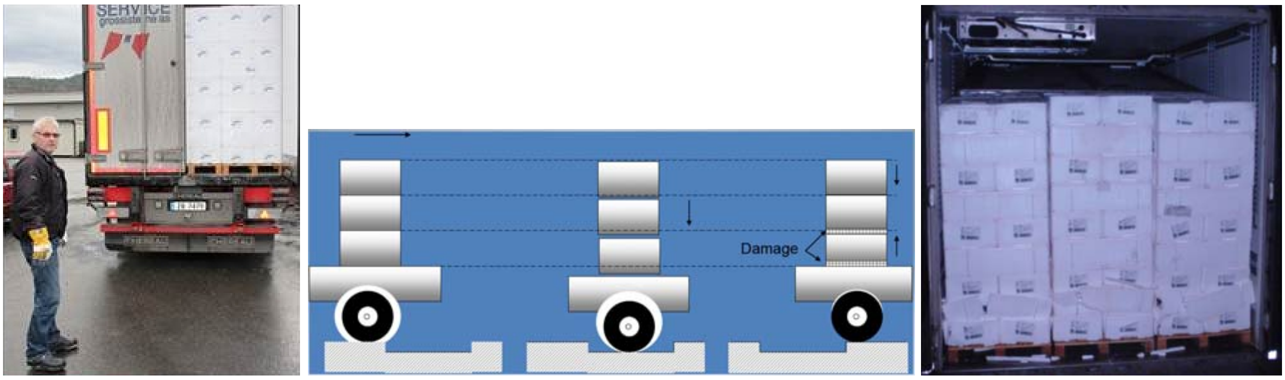

Figure 71 Payload damage on frost damaged road sections

[Left pic: J Granlund; Mid pic: Dr K Chatti; Right pic: DB Schenker, Thermoterminalen Oslo]

Mr Pettersen had also experienced frost problems in tunnels, especially in Røros where freezing leaking water and frost lift within the pavement reduced the posted 4.3 m vertical clearance to the extent that 4.17 m high vehicles had been scratched. Mr Pettersen also called for more overtaking lanes in flat terrain as well as at grades, since this would reduce stress, road rage, crashes, travel time and fuel consumption.

Driving in the dark is a considerable issue according to Mr Pettersen, especially in the subarctic region with almost no daylight at all in the cold and dark winter. Many urban road sections lack streetlights. Rural sections often lack roadside poles. Many guardrails lack proper reflectivity. After new asphalt has been paved, it often takes several months before the road markings are repainted. In Norway, the truck owner can be fined if a truck has more than 2 extra headlights. This is due to an EU regulation that is interpreted in a particular way in Norway than in, for example, Sweden. Norway is actually not an EU-member, but is obliged to follow EU-regulations under the Schengen Agreement. A typical Swedish truck with 6 extra headlights can be seen in Figure 74.

3.5. POOR TRUCK RIDE QUALITY IN SWEDISH NORRLAND

The demonstration project in Swedish Norrland showed large differences in A(8) between late winter / spring and autumn, as well as between driving with full tyre pressure at all times and using a Tyre Pressure Control System to reduce the pressure when driving off-highway, at low speed and when driving unloaded. The A(8) value was 0.91 m/s^2 in the springtime test “without TPCS” on the main route, while it was 0.86 m/s^2 with the TPCS active and driving the same route 5 km/h faster. In the autumn, the A(8) value of the main route was 0.66 m/s^2. All of these values are above the EU Action Value of A(8) = 0.5 m/s^2. They also confirm similar magnitude of A(8) as the 0.76 m/s^2 measured in the case study on partly the same route in ROADEX III in 2007/2008.

The average spinal compression stress during the springtime test was very high; S_{ed} = 1.2 MPa on the main route. This is far above both the health caution value of 0.5 MPa and the “High probability of an adverse health effect” value of 0.8 MPa in the standard ISO 2631-5 on human response to transient vibration. In the autumn test, the spinal compression stress on the same route was much lower; S_{ed} = 0.6 MPa despite a much higher speed. The lower stress level in the autumn test is still above the Action Value S_{ed} < 0.5 MPa used by the Swedish Work Environment Authority.

Truck hauliers operating in Norrland with employees working under similar conditions to those in this study, are obliged by the Swedish AFS 2005:15 Vibrationer (“Vibration at Work”) regulation to make a risk assessment with associated measurements to clarify if actions need to be taken to protect their drivers from health and safety risks caused by ride vibration and mechanical shocks.

3.5.1. The routes, the transport task, the truck and its instrumentation

The location of the demonstration routes in Swedish Norrland is shown in Figure 72. A map of the 438 km surveyed main route is shown in Figure 73.

Figure 72 Location of the Norrland demonstration routes

Figure 73 Map of the Norrland demonstration main route

The demonstration vehicle in the Norrland demonstration was a timber truck hauling logs from inland forest areas to sawmill and paper pulp facilities located mainly on the Swedish east coast. The 438 km long main route started at Ramsele, marked (I) on the map in Figure 73. The initial section was on the Beaver Road 331 down to Österforsse (B). Then on National Highway 87 to Sollefteå (C), a short section of National Highway 90, then along Road 335 to Överhörnäs (D), and finally European Highway E4 to SCA Timber's sawmill in Rundvik (E). The return trip from Rundvik was on E4 south back to Överhörnäs (D), and then on to Road 348 to Bredbyn (F). From Bredbyn the route was on secondary Road 1035 and Road 983 to Junsele (G), Road 346 and Road 977 to Nordankäl (H) and finally Road 331 to the truck garage in Ramsele (I) again.

In addition to the main demonstration route, long single trip measurements were undertaken between the forest areas in Edsele to sawmill in Kälarne, as well as in Bollsta. These however are not shown on the map.

The ROADEX haulage partner in Sweden was Brorssons Åkeri AB from Ramsele, the same partner as in the ROADEX III study of truck ride vibration at the Beaver Road 331. While most of Brorssons 20 trucks are driven in a group served by a separate crane, the test truck was designed for solitary operation. It carried a Jonsered Loglift for independent loading. Carrying a crane of course increases the deadweight and reduces the payload. Sometimes the crane is left behind in the forest to enable the full highway payload of the truck to be utilized. The Gross Vehicle Weight of the truck was 60 tonnes, with some 40 tonnes payload capacity (when not carrying the Loglift crane). The test truck also had a Tyre Pressure Control System. Thanks to the TPCS, this truck was allowed to operate on many roads with reduced bearing capacity.

The test truck was the Scania R500 seen in Figure 74, with license plate "WUW 416" and license plate "BJG 570" on the trailer. It had some 506,000 km on the meter at the spring time test, and approximately 615,000 km at the time of the autumn test.

Figure 74 The TPCS-equipped Scania truck used for the ride quality studies in Sweden

All tyres on the demonstration vehicle were manufactured by Michelin and all, including the steer axle and trailer axles, where connected to a Tyre Pressure Control System, see Figure 75. The steer axle had XZY3 385/65 R22.5 tyres. The twin drive axles had pair-mounted XDN2 GRIP 295/80 R22.5. The length between the first and the second axle was 4.90 m. The truck also had an on-board sand gritting aggregate.

The trailer was fitted with XTY2 265/70 R 19.5 tyres.

Figure 75 The TPCS controls all tyres on Brorssons truck, including on the steer axle

The truck was instrumented as shown in Figure 76 with accelerometers on the left and right side at both the front axle and on the truck frame, tri-axial accelerometers at the base and on the pan of the Scania original mounted air-suspended ISRI seat, a webcam, an interior microphone and a GPS unit.

Figure 76 Instrumentation in the Scania test truck

3.5.1.1. PHOTOS FROM THE DEMONSTRATION ROUTES

The condition of Swedish forest roads varies greatly. Thick snow, as seen in the upper left photograph in Figure 77, can in winter smear out potholes and other roughness on dirt-roads. Private bridges are often simple and in poor condition. Before the commencement of any larger haulage operations, the forest roads are normally reinforced and graded, as seen on the middle photograph. In fact, private forest roads are often in better condition during timber logging operations than public local roads are. The two bottom photographs in Figure 77 are from public local roads in Edsele. The left photograph shows corrugated thick ice, while the right shows a combination of corrugated thick ice with high steps up/down to the bare asphalt, with its severe deformations and wide frost-related cracks. As the truck tyre hits such a step, a mechanical shock is created and sent up through the truck and into the driver's seat. The corrugations in the thick ice on the poorly maintained public road caused terrible noise in the truck cab as well as to the exterior environment.

Figure 77 Late winter on forest roads and local public roads in the Ramsele / Edsele areas

During the late winter / early spring tests, numerous sections of the tested highways had severe additional roughness (see examples in Figure 78) caused by frost actions in the subgrade soil under the pavement.

Figure 78 Roughness with several decimetre amplitudes, caused by frost action

All road engineers in the Nordic know that the freezing of water leads to a volume increase of 9 %. As a result many think that this increase in the volume of freezing water in the soil pores explains the ground lift. However, this assumption is fundamentally wrong. When considering normal values of void content, water content and soil compression, only a ground lift of 2-3 % can be explained in this way. A ground lift of 2-3 % corresponds to only a few cm, as the frost frontier penetrates down to some 2 m depth in the soil. As seen in the photographs above, already the differential in frost heave between adjacent road sections can be several decimetres, and can thereby not be explained by only pore water volume expansion of the frozen soil layers.

Janson discovered in 1914 that the explanation of large frost heaves is the result of additional water flowing into the frozen section of fine-grained soils. This was later confirmed by other researchers, such as Taber, Penner, Hou and Phukan. Taber also showed that the ground will keep swelling when a soil is frozen from top to bottom when water can migrate through the soil profile from an underlying water table. Soil continuously subjected to a negative temperature will keep lifting. The ground surface will keep rising, due to the formation of segregated ice lenses, as long as “the zero degree isotherm” - the freezing front - penetrates deeper into the soil. Beskow

(1935) found out that most important parameter governing the ability of a soil material to swell due to frost actions is its capillary characteristics given by its grain size distribution (Berglund, 2009). Later research has shown that the grain size distribution affects the matric suction of the soil material, while the amount of ionic compounds (i.e. road salts) affects the level of osmotic suction. In cold climates the phenomenon of cryosuction also occurs. The features of soil that affect the amount of unfrozen water available for freezing into ice-lenses and thus causing ground heave are: the mineralogical properties of soil, the salt content, the soil granularity, the specific area of the soil particles and surface tension. Further information on this subject can be found in the ROADEX e-learning lesson on “Drainage”[10], section 2: “*Water in road materials and subgrade soils*”.

When closely examining the frost-related road damages in Figure 78, it is clear that the damage goes from side to side of the pavement, and that the soil has swelled much less in this section than in the sections before and after. The explanation in this case is that a culvert has been installed under the pavement in an improper way. A large differential frost heave has occurred as some 2 m of road at the culvert lies founded on good road material, while the pavement in the adjacent sections lies on frost-susceptible soil. A correct culvert installation in Sweden involves excavating a 25 – 45 m long “transition zone” and refilling with proper road materials, so that the difference in frost heave is spread over an acceptable roughness wave instead of the abrupt and hazardous “steps” seen in Figure 78.

3.5.2. The measurements

The spring time instrumentation was installed on 15 April 2011 and the first measurements were carried out on 16 and 17 April 2011. The season can be described as “late winter” in the inland forest areas of Ramsele, Edsele and Kälarne, while it was rather “early spring” at the East coast with its industries.

The autumn instrumentation was installed on 25 September 2011, with second measurement carried out on 26 September 2011.

For the springtime measurements, the 438 km long main route was measured with the TPCS “active” (i.e. reduced tyre pressure on forest roads, at low speed, and when driving empty) and then reproduced with the TPCS “inactive” (standard full tyre pressure on the whole route). In addition, long single trips were also taken from several forests in the Edsele area to the Kälarne sawmills, as well as the Bollsta sawmills. In total 1,417 km were measured in the spring time test.

In the autumn test, the 438 km main route was measured for reproduction, with the TPCS inactivated at all time. The decision not to use TPCS low pressure modes was not made voluntarily, but had to be taken to prevent a constant alarm noise from the TPCS control box as a consequence of an “accident”. A new practice at the tyre garage servicing all Brorssons trucks was to install so called balancing powder in the tyres to prevent tyre imbalance, instead of mounting old-fashioned static balancing weights on the rims. Following this new routine, the TPCS-equipped truck also had the powder installed (Brorssons only have one TPCS truck). The powder however clogged the air valves of the TPCS so badly, that the air flow dropped to a minimum. Due to the unusually slow airflow, the TPCS considered the exceptionally slow changes of tyre pressure as indicators of a leaking puncture. This caused the TPCS alarm to sound for long periods as soon as the TPCS settings were changed by the driver. In order to avoid this terrible alarm, the decision was taken not to use the TPCS low pressure settings in the autumn test. This spoiled the planned analysis of how the TPCS could isolate vibration as function of frequency (road roughness wavelength x truck speed). However the overall effect of TPCS on vibration isolation was still possible to assess.

[10] Read more in the ROADEX e-learning on water in road materials and subgrade soils, Internet 2012-06-01: http://www.roadex.org/index.php/drainage2

Timber was picked up at various sites in the Ramsele and Edsele areas, and a number of short forest roads in various conditions were driven. While many forest roads can be in terrible condition for decades, they normally get an upgrade before a large timber logging operation is executed. This results in quite smooth forest roads during haulage operations, such as seen on the middle photograph in Figure 77. (The practice is obviously different in Scotland as seen in the photographs from forest roads in the ROADEX demonstration at Fort William.)

For reason of precision, the ride vibration data from forest roads were omitted when comparing data from the spring and the autumn tests in Sweden.

3.5.3. High daily vibration exposure; A(8) exceeds the EU Action Value

The A(8) value for the 438 km driven during late winter with TPCS “off” (i.e. constant full tyre pressure) was 0.91 m/s^2, as per the calculation in Table 11. This can be compared to the 0.86 m/s^2 measured when reproducing the route at 5 km/h higher speed with the TPCS “on” (using lower tyre pressure when not driving with full payload on highways). In both cases, the A(8) was clearly above the EU Action Value A(8) = 0.5 m/s^2. However the daily vibration was 6 % higher without the TPCS, despite 5 km/h higher average speed when the TPCS was active.

These results show that the TPCS not only reduces ride vibration, but also makes it possible to significantly increase productivity due to higher truck operating speed. However, the drivers’ exposure to ride vibration still is too high. A likely reason is that the road profile has high amplitude at long wavelengths that the TPCS cannot isolate. The previous case study on Road 331 in the ROADEX III project showed that this test road had a lot of unevenness with 7 – 31 m wavelengths, causing resonance at low frequencies in several of the truck suspension systems. Such unevenness cannot be isolated by TPCS, or regular truck suspension systems, but has to be repaired by the road agency.

In the autumn measurements the roads were much smoother, since there were no frost-related additional roughness due to swelling frozen soil under the pavement, and no corrugated thick layer of ice on the road surface. On the very same route as studied in the late winter, Ramsele – Rundvik, the A(8) was measured to be 0.66 m/s^2 with the TPCS off, see Table 13. This value can be compared to the 0.91 m/s^2 measured with TPCS off in the spring. The increase in average daily vibration was +39 % due to winter condition.

Table 11 Ramsele – Rundvik route, late winter / spring, TPCS off (driving time 6.4 hours)

Spring; pauses within most stages		Vibration intensity	Exposure time		Partial exposure	Distance [km]
Without TPCS		m/s²	hours	minutes	m/s²	
Ramsele - Rd 331 - Rd 87	Loaded	1.17	1	3	0.424	68
Rd 87 - Sollefteå - Rd 335 (break)	Loaded	0.84	1	3	0.304	53
Rd 335 - E4 - Övik (break)	Loaded	0.83	1	3	0.301	57
Övik E4 - Rundvik, unloading	Loaded	0.84	1	3	0.304	49
Rundvik E4 Southbound (lunch)	Empty	0.70	1	3	0.254	48
E4 - Rd 348, Rd 1035	Empty	1.00	1	3	0.362	70
Rd 1035, Rd 346, Nordankälvägen	Empty	0.97	1	3	0.352	71
Nordankälvägen, Rd 331 - Ramsele (break)	Empty	1.06		25	0.242	20
					0.000	
Av speed 68 km/h		Daily exposure value, m/s² A(8)			0.91	438

Table 12 Ramsele – Rundvik route, late winter / spring, TPCS active (driving time 6.0 hours)

Spring; pauses within most stages		Vibration intensity	Exposure time		Partial exposure	Distance [km]
TPCS active		m/s²	hours	minutes	m/s²	
Ramsele - Rd 331 - Rd 87 - SLÅ	Loaded	1.02	1	3	0.370	73
Sollefteå - Rd 335	Loaded	0.93	1	3	0.337	75
Rd 335 - E4 - Övik (dinner)	Loaded	0.48	1	3	0.174	17
Övik E4 - Rundvik, unloading	Loaded	0.73	1	3	0.265	55
Rundvik E4 Southbound	Empty	0.83	1	3	0.301	57
E4 - Rd 348, Rd 1035	Empty	0.95	1	3	0.344	62
Rd 1035, Rd 346, Nordankälvägen	Empty	1.08	1	3	0.391	83
Rd 331 - Ramsele	Empty	0.88		15	0.156	15
					0.000	
Av speed 73 km/h		Daily exposure value, m/s² A(8)			0.86	438

Table 13 Ramsele – Rundvik route, autumn, TPCS off

Autumn		Vibration intensity	Exposure time		Partial exposure	Distance [km]
Without TPCS		m/s²	hours	minutes	m/s²	
Ramsele - Rd 331 - Rd 87	Loaded	0.96		57	0.331	74
Rd 87 - Sollefteå - Rd 335	Loaded	0.75		59	0.263	76
Rd 335 - E4 - Övik	Loaded	0.77		15	0.136	17
Pause	Loaded	0.00		40	0.000	0
Övik E4 - Rundvik, unloading	Loaded	0.60		46	0.186	55
Pause	Empty	0.00		20	0.000	0
Rundvik E4 Southbound	Empty	0.69		45	0.211	56
Övik to Bredbyn	Empty	0.79		32	0.204	42
Bredbyn	Empty	0.61		5	0.062	6
Ödsbyn to Junsele	Empty	0.76		39	0.217	47
Klappsjö to Lillterrsjö	Empty	0.82		16	0.150	20
Klappsjö to Lillterrsjö II	Empty	0.61		15	0.108	18
Tågsjöberg to Lillterrsjö	Empty	0.95		7	0.115	8
Tågsjöberg to Lillterrsjö II	Empty	0.84		7	0.101	7
Nordankäl to Ramsele	Empty	0.53		10	0.077	13
					0.000	
Av speed 75 km/h		Daily exposure value, m/s² A(8)			0.66	439

3.5.4. Systematic high spinal compression stress

The average spinal compression stress during the springtime test was very high; S_{ed} = 1.2 MPa. This is far above both the health caution value of 0.5 MPa and the “high health risk” value of 0.8 MPa in the standard ISO 2631-5 on human response to transient vibration. In the autumn test, the spinal compression stress on the same route was much lower; S_{ed} = 0.6 MPa. The lower stress level in the autumn test is still above the Action Value for bumps, S_{ed} < 0.5 MPa, used by the Swedish Work Environment Authority.

Truck hauliers with employees working under conditions similar to those in this study should carry out a risk assessment, with associated measurements, to clarify if actions need to be taken to protect their drivers from health and safety risks from ride vibration and mechanical shock.

3.5.5. Rough road profile at bridges is a root cause to high ride vibration

In Sweden, there are several specifications for road profile unevenness at transversal joints between roads and bridges. The requirements differ remarkably between new constructions and maintenance. Furthermore the requirements have changed significantly over the last few years. However one common line that has stood the test of time in all requirements is that “*The pavement surface shall be located X mm above the steel beam at the joint*”. (The value of X varies between 0 mm and 3 – 8 mm across the various specifications). An example of a joint that does not meet any of these basic requirements can be seen in Figure 79. Not only is the pavement far below the steel beam instead of properly being above it, but the paving contractor has also been so sloppy that a thick puddle of asphalt has been spread onto the beam, making the step at the joint even higher and rougher. This very rough joint can cause high vertical acceleration and shock load into the spine of truck drivers, as seen in the response data in Figure 80 recorded in the late winter test run at the modest speed of 39 km/h.

Figure 79 A very rough bridge joint at Nämforsen

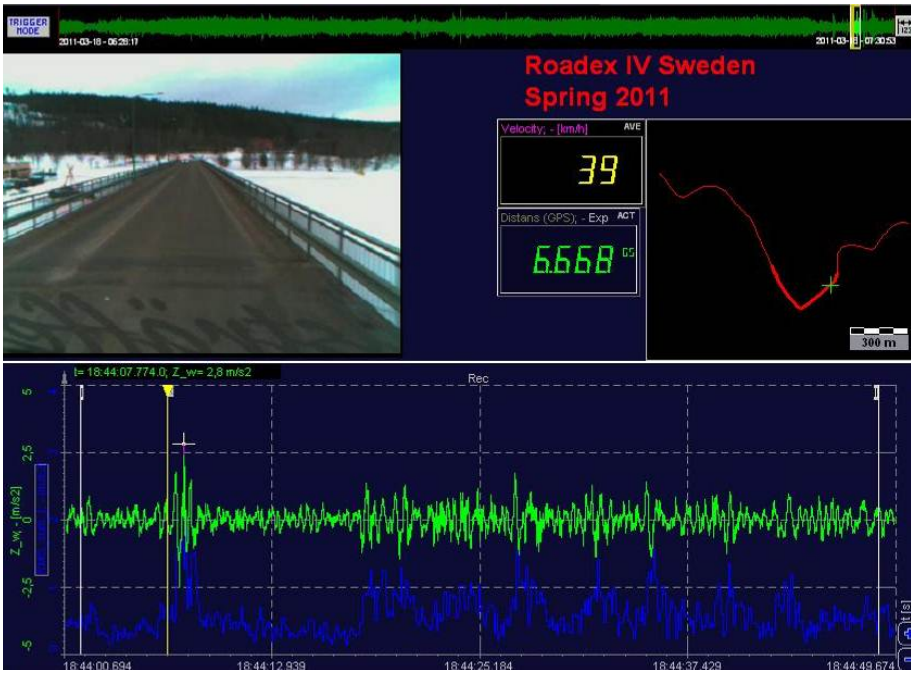

Figure 80 Shock load into the truck drivers spine when passing the bridge joint at Nämforsen

Another cause of truck ride problems at bridges is settlement in the backfill behind the abutment wall. This kind of roughness brings harm to drivers, and also damage components in the truck.

The graph in Figure 81 shows the vertical acceleration of the outer wheel of the test truck as it passed over the backfill at the bridge on Road 331 in Österforsse at 56 km/h. The acceleration peaks at 83 m/s^2, about 8 G. This kind of shock loads into the wheel assembly generates noise and cause intensive wear of many components in the vehicle.

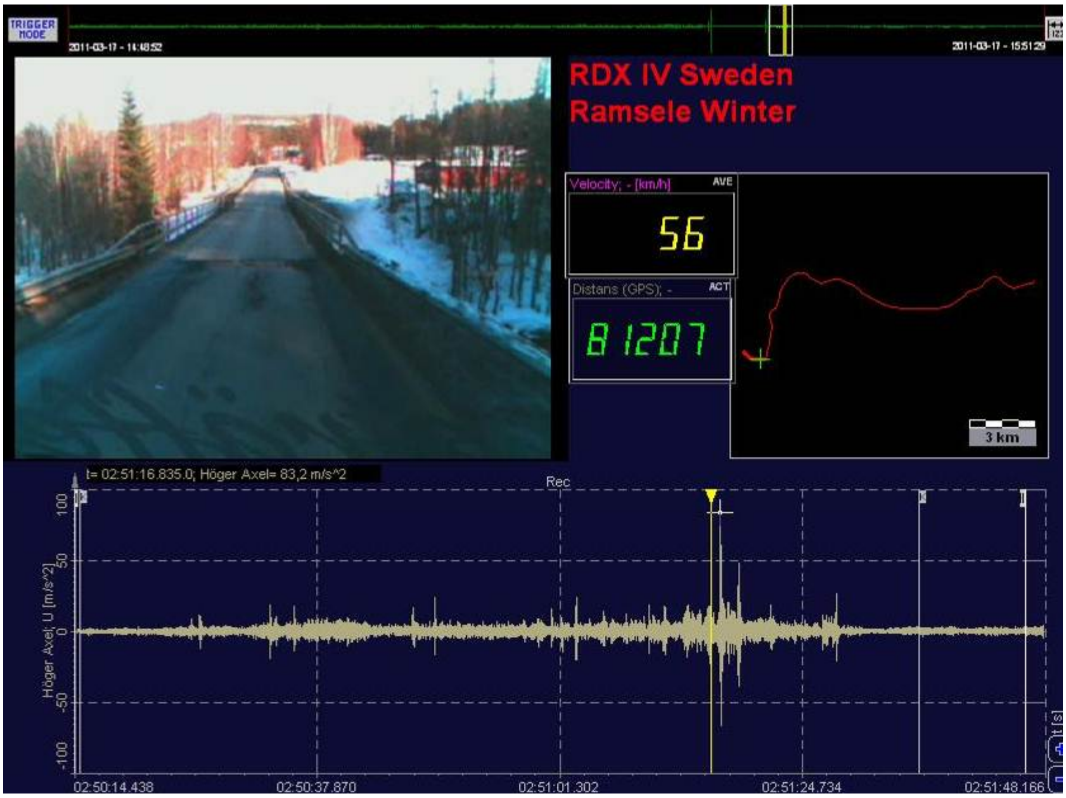

Figure 81 High acceleration of the truck wheel assembly at settlement in bridge backfill

3.5.6. Several years later: Still no warning sign at identified hazardous sites

The ROADEX III case study in 2007/2008 identified several hazardous sites (HS) on the Beaver Road 331. One of the worst HS was the edge deformation at Åkerö, reported in section 5.3.2.3 "*Rock ´n Roll at HS Åkerö*" in the ROADEX III report. In the 2007 survey, the pavement edge deformation was 69 mm deep (see Figure 82) and exposed the timber logging truck to a transient roll vibration of 5 °/s, with lateral buffeting of 2 – 3.5 m/s^2. This level of lateral buffeting could be enough to cause a half-empty tanker truck with bad suspension to have a rollover crash. The Åkerö HS was very clearly highlighted as a road safety hazard in the ROADEX III report, underlined by the fact that a photograph of the Åkerö damage included in the report revealed remains of an exploded truck tyre at the site. However, at the time of the ROADEX IV demonstration on 26th Sept 2011, the Åkerö damage had still not been repaired. In fact, there was not even a warning sign raised at the site.

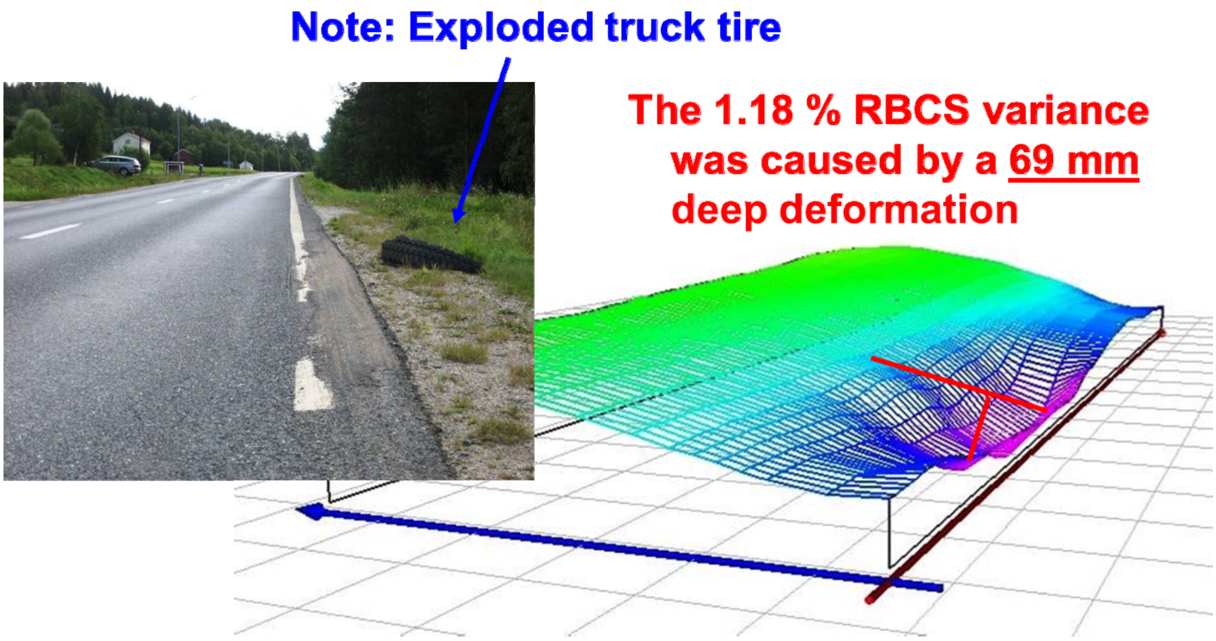

Figure 82 The Åkerö edge deformation in 2007 [Source: The ROADEX III project]

The new response measurements in the ROADEX IV demonstration showed that the driver, despite yawing to avoid the deepest part of the road damage, was exposed to 0.7 G peak vertical acceleration within fractions of a second. This is the very same intensity used as design criteria for passenger cars going at 30 km/h over traffic calming speed bumps on urban streets. The running RMS over a 1 second time window of the seat vibration measured at the edge damage in 2011 was much higher than in 2007, as shown in Figure 83.

Calculations in MatLab show that the single pass with less than a second duration over the deep road deformation in 2011 resulted in a shock load in the driver´s spine corresponding to a daily (8 hour) stress of 0.24 MPa. It will be enough with a handful of such shock loads to reach the Action Value of 0.5 MPa on a daily 8 hour basis as used by the Swedish Work Environment Authority.

It is recommended that the local road organization should re-read the report of the ROADEX III case study on Road 331 and, as soon as possible, raise the necessary warning signs and start planning for road improvement at the documented hazardous sites.

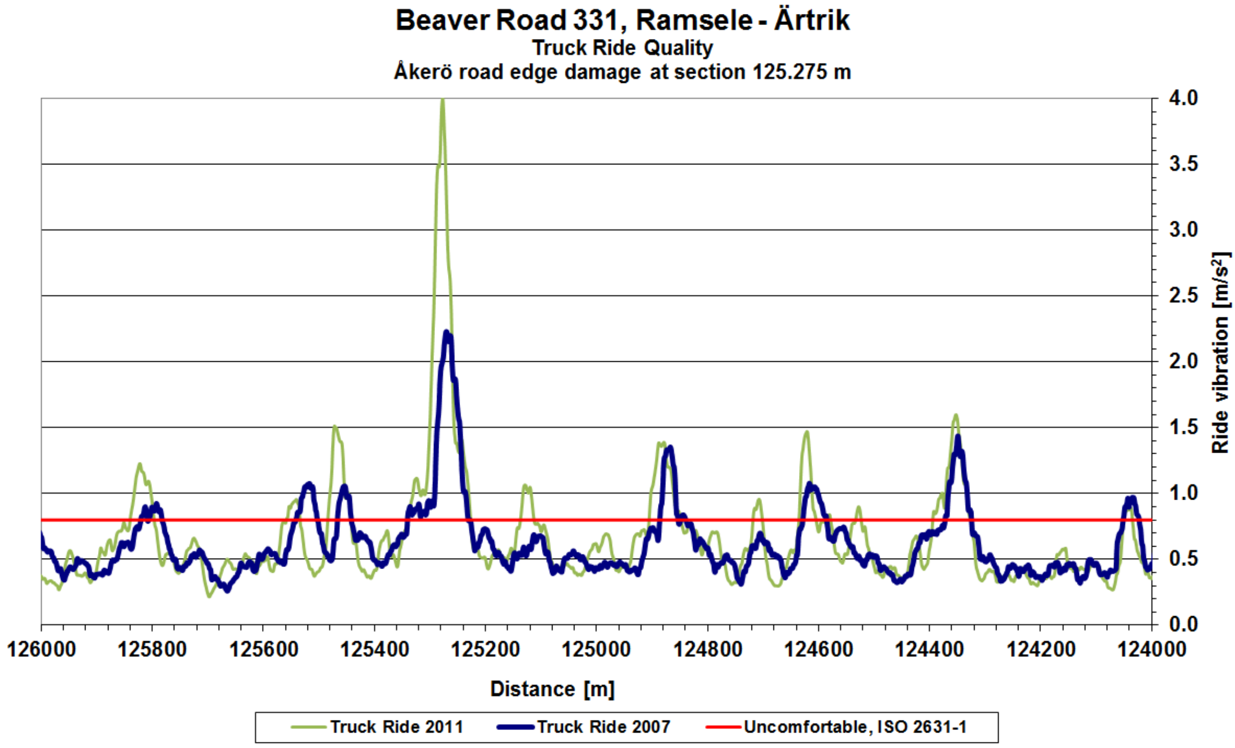

Figure 83 The seat vibration at the edge deformation in Åkerö was worse in 2011 than 2007

3.5.7. Remarkably poor quality in road repair works

The ROADEX IV main test route included a long part of Road 1035. A 5 km section of this road west of Bredbyn had previously been rated by the County Council as unacceptably hazardous for public traffic due to severe frost-related roughness and was given "heavy maintenance" during 2010/2011. The 5 km road repair work commenced with local reconstruction (excavation of frost susceptible fine-grained soil down to a frost free depth and backfill with gravel) of some local sections with extreme frost damages in the autumn 2010. In the summer of 2011 the entire 5 km section was resurfaced.

In the ROADEX IV demonstration in March 2011, the instrumented timber logging truck was, for reference purposes, followed by a passenger car with a portable laser/inertial road profiling system, as shown in the bottom left photograph in Figure 84. The GE Laser Prof System comes in a suitcase (upper photograph) and includes an advanced odometer. This wheel encoder is firmly attached with strong magnets to the bolts of the left hand non-driven wheel of the car. The encoder measures the travelled position, speed and longitudinal acceleration 20,000 times per revolution of the wheel. In order to reach this high resolution, the sophisticated sensor uses optical photoelectric scanning. This method detects even very fine lines, no more than a few microns wide, reading periodic structures known as graduations from an etched disc of glass (discs illustrated in the upper right photograph). This expensive and sensitive sensor was destroyed, see lower right photograph, at one of several extreme bumps at the reconstructed Road 1035. The story of the event is as follows:

During the 17th March 2011, some 600 km of frost-damaged rough roads had been measured by the time the truck was unloaded in Rundvik. Before the trip back to Ramsele via Road 1035, the mounting of the LaserProf System was inspected without any remarks. From Rundvik the truck and the profiling car drove on the E4 to Överhörnäs and Road 348 to Bredbyn without problem. On Road 1035 from Bredbyn there were several long-wave bumps/hollows with extreme amplitude at sections that had been reconstructed just a few months before. At one of these bumps, the powerful magnets could not keep the odometer in position, and it bounced off the car and was destroyed, see lower right photograph in Figure 84.

Figure 84 The portable LaserProf System and the odometer after being "killed" at a bump

The roughness of the "reconstructed" road sections of Road 1035, and the 3 dm "odometer killer bump" in particular, is illustrated by the recorded truck driver seat response in Figure 85. In this instance the driver was exposed to greater vibration levels than those measured in buses traversing 10 cm speedbumps in city streets, and this was just some 6 months <u>after</u> the road had been reconstructed.

Figure 85 Several high acceleration events at newly reconstructed sections of Road 1035

In the summer of 2011, the entire 5 km repair project section on Road 1035 from Bredbyn was resurfaced. However, the new road surface became unacceptably rough. The truck seat vibration during the demonstration on 26th Sept 2011 is shown in Figure 86. The average vibration intensity was 0.6 m/s^2. If the driver was to spend the whole day driving back and forth on this 5 km section, the vibration exposure would exceed the EU Action Value A(8) = 0.5 m/s^2.

Figure 86 Road 1035 still gives a rough truck ride just after resurfacing 2011

Another example of a poor result following a road repair is given in Figure 87. Despite the truck yawing to avoid the deepest part of the edge deformation in the new road surface, the truck was exposed to a transient vibration approximately 20 times higher than the average ride vibration.

Figure 87 Transient vibration at an edge deformation on a newly repaired section of Road 335

Following the ROADEX III case study on the Beaver Road 331, more than 10 km of the road between Nordankäl and Ramsele was reconstructed in 2008. Despite expensive reconstruction, this section continues to show problems. The ISO 2631 frequency weighted truck seat vibration in

2011 is shown in Figure 88. The average value was 0.46 m/s^2, just below the EU Action Value of 0.5 m/s^2.

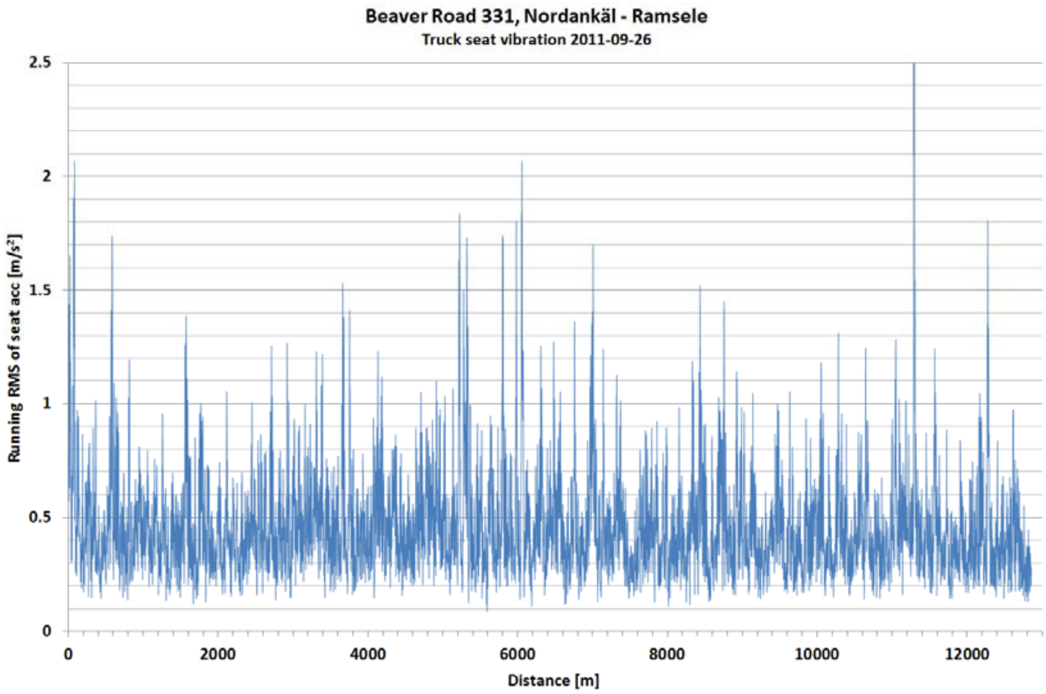

Figure 88 Average vibration 0.46 m/s^2 despite the road being reconstructed in 2008

3.5.8. Observations of hazards and various road features in Norrland

3.5.8.1. SHARP AND IMPROPERLY BANKED HORIZONTAL CURVES

As discussed in the previous section, the reconstruction of some 10 km of the Beaver Road 331 between Nordankäl and Ramsele in 2008 resulted in a poor quality road in terms of roughness. However, the reconstruction also resulted in an improperly banked curve, as seen in the measurement results in Figure 89. Despite a sharp curvature of -1.9, corresponding to a curve radius as tight as -526 m, the superelevation is only +0.6 % while the Swedish road design code requires +5.5 % (see vertical arrows in the figure). The lack of superelevation in a sharp outercurve causes a high need for side friction between tyre and road. One of the truck drivers at Brorssons had a terrible experience there in the winter of 2009. A passenger car skidded and oversteered before it gained grip again, then went straight across the road just in front of the timber truck with a gap of only a handful of metres. This “close shave” may just as well have resulted in a fatal head-on crash. With a proper cross slope, the car would have needed some 60 % less side friction, which of course would have meant a much lower risk for the skid crash.

The section Nordankäl – Ramsele also has a very sharp right hand bend, with a curvature of up to +4.7 (see red oval marking in Figure 89). This is remarkably sharp and hazardous for a 90 km/h road.

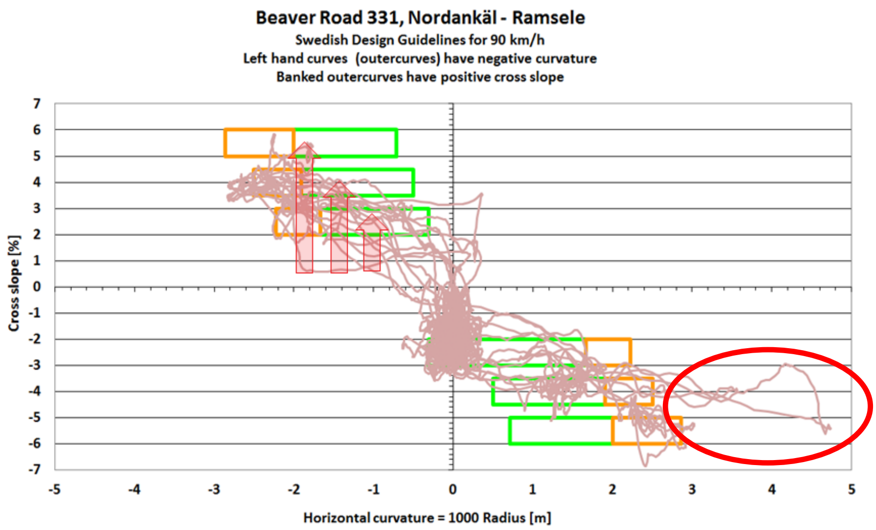

Figure 89 One outercurve became hazardous low superelevation after reconstruction 2008

The ROADEX III report by Granlund (2008) included a discussion of the improperly banked Roos curve. As seen in Figure 90, crashes have clustered there, showing that the curve is multiple times more hazardous than the average for the road. This curve was unchanged at the time of the demonstration survey in 2011. A photograph of the swaying test truck of 2011 is shown in Figure 91. As can be seen, the inner wheels almost have a lift-off due to severe weight transfer in the hazardous outercurve.

Figure 90 Crashes have clustered at the improperly banked Roos curve

Figure 91 The “Roos curve” on Road 331 between Österforsse and Helgum

A graph from the ROADEX III report by Granlund (2008) is repeated here in Figure 92. This figure shows that the Roos outercurve needs to be banked up from -1 % cross slope up to the maximum allowed superelevation +5.5 % (see vertical red arrow in the figure). Today, up to +7 % superelevation is allowed when improving old sharp bends in Sweden.

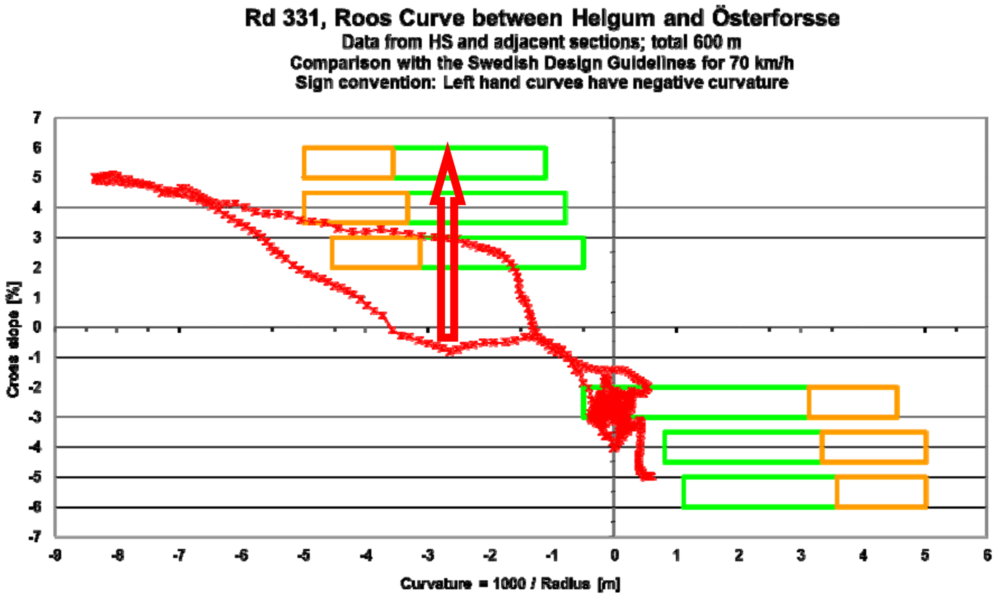

Figure 92 Profilograph data from the improperly banked, sharp Roos Curve

As seen in the results from the case study in Norway, the same circumstance is also quite common with banked innercurves on the E6 in Northern Norway. Banked innercurves are very hazardous, as they tend to "push the vehicle over into the oncoming traffic". This kind of road hazard is quite rare in Sweden. Instead, the main problem with innercurves in Sweden is excessive negative cross slope, which may be nice for over-speeding traffic but can give a problem for unskilled and insecure drivers at low speed on slippery roads. It is far from natural to have to turn the steering wheel counter clockwise in order to take a right hand bend. However, innercurves do not need to be banked into superelevation in order to be hazardous. It is in fact often enough to have too little (negative) cross slope to make an innercurve dangerous. One example of this is given from a section of the Beaver Road 331, as seen in the photo in Figure 93 and the corresponding plot of road curvature and cross slope data in Figure 94. The photograph shows that the trailer rear inner wheels almost have a lift off (caused by weight transfer to the outer wheels). Note that the photograph is taken at a roll angle from a trailing car at speed in the sharp curve, as can be realized from the lack of vertical alignment of the trees in the background of the picture. As seen in the plot below the photograph, the negative cross slope in this sharp curve at Mo should be increased from current 3.5 to 4.5 %, to (at least) 5.5 % in order to better comply with the Swedish road design code for cross slope of innercurves.

Figure 93 Unusual hazard: Insufficient crossfall of <u>INNER</u>-curve at Road 331 at Mo

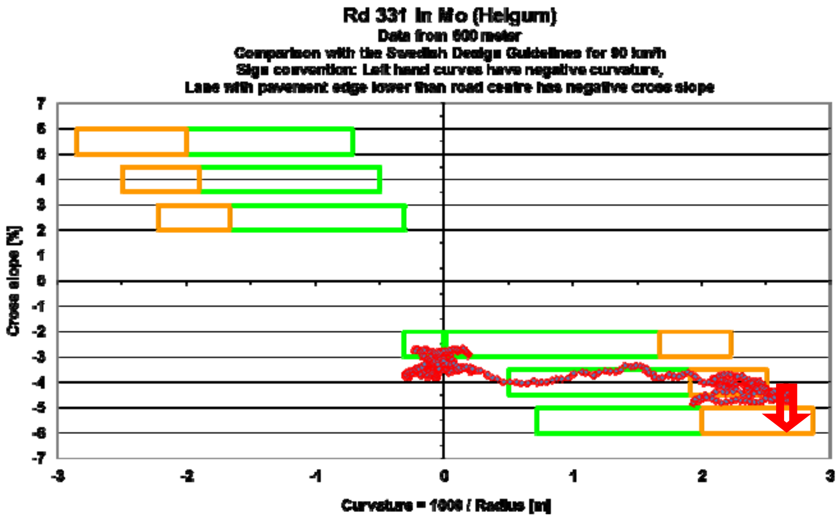

Figure 94 Profilograph data from the sharp and too flat innercurve at Mo

4. RELATING RIDE TO ROAD STANDARD

Most national public road administrations worldwide are surveying the condition of roads in their road network, with respect to criteria such as Road durability, Winter operations, Noise, Debris, Mobility, Road safety, Ride Quality, Wear and Tear and Energy Consumption. See the headers of the vertical columns in Figure 95.

Each criterion is affected by several road properties, as seen in the horizontal rows of the figure. Longitudinal roughness causes ride vibration. Due to its large impact on criteria such as Road durability, Mobility, Road safety, Ride quality, Wear and tear as well as Fuel consumption, the by far most important is the longitudinal roughness having most red-marked cells in Figure 95. When considering normal conditions, megatexture (waves 50 – 500 mm), friction between tyre and road, macrotexture (waves 0.5 – 50 mm), edge deformation, water pooling and bearing capacity are secondary in importance. Rut depth[11], crack index and other parameters are third in importance; having mainly yellow, green or even white (no importance) marked cells in Figure 95.

For road safety and ride quality, the focus aspects of this report, the most important road properties are longitudinal roughness, megatexture, edge deformation, water pooling and friction. Cross slope has been given a low rank in the matrix. If it had been combined with horizontal curvature and speed limit as well as longitudinal grade, or together with the mentioned properties been transformed into “Need for side friction” and “Drainage gradient”, it would surely been top ranked for road safety (as reflected in road design manuals world-wide).

		Criteria										
									Wear and tear			
		Road durability	Winter operations	Noise	Debris	Mobility	Road Safety	Ride Quality	Vehicle	Tyre	Goods	Fuel consumption
Road property	Bearing capacity	3				3						
	Surface stiffness			1								2
	Longitudinal roughness	3	2	2	1	3	3	3	3	2	3	3
	Megatexture	2	2	3	1	2	2	3	3	2	3	3
	Macrotexture	2	2	3	1		2	1	1	3		3
	Cross slope	2			1	1	2	1	1	1		1
	Edge slump	3	2	1		3	3	3	2	1	2	1
	Rut depth	3	2	1	2	2	2	2	1	1	1	1
	Water pooling	1	1	1	3	2	3	2				1
	Friction		3	1		3	3	2		3		3
	Retroreflection					2	2	2				

	Importance
Large	3
	2
	1
Small	0

Figure 95 Influence of road properties on road durability, safety, road user costs etc [After VTI]

[11] Rut depth in Norway is measured (or rather: calculated) by a fundamentally different definition than in countries following the “wire method” defined in the EN 13036 standard. The Norwegian definition can give very high “rut depth” values for roads with a convex-shaped cross section, and for newly laid asphalt layers without any ruts at all. This may lead to serious confusion, both in road contracts and in research.

4.1. COMPARING VEHICLE DRIVER VIBRATION TO IRI-VALUES

The overall single most important road property of the matrix in Figure 95 is longitudinal road roughness. There are several available scales for road roughness. The most used scale globally is the International Roughness Index, IRI. This index is calculated with a computer-based "quarter car model" as illustrated in Figure 96. IRI was defined by the World Bank in 1986 and describes the vertical motion between the suspended vehicle body and the unsuspended wheel mass, when driving at the reference speed 80 km/h. When calculating IRI, a set of reference parameters for stiffness, damping and mass are used. These parameters define the "Golden car" used for the IRI-calculation. See Ahlin & Granlund (2002) for details.

IRI may be computed from road profile data achieved by various methods, including static rod and level. However road profile sampling must be made at maximum 3 dm long steps (see ASTM E 1364) and with very high vertical accuracy. For practical reasons, road condition measurements are normally made with mobile high-speed laser/inertial profilometers as per the ASTM E 950 standard.

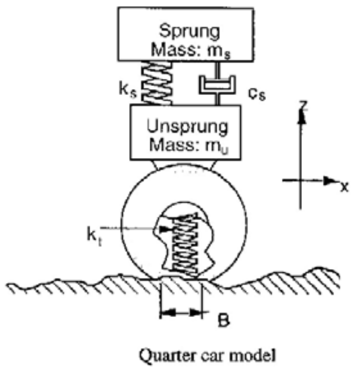

Figure 96 Quarter car model used for calculation of IRI

Since many road agencies are measuring and managing the condition of their road network based on the IRI-scale, it is relevant to relate truck drivers' exposure from whole-body vibration (WBV) to IRI-values / road quality. The following sections report on relationships between WBV and IRI established in some previous studies as well as in ROADEX IV.

4.1.1. Previous studies relating vehicle drivers WBV to IRI-values

4.1.1.1. PASSENGER CAR DRIVER VIBRATION

Mucka & Granlund (2012) made a review of reports from studies of relations between ride vibration in passenger cars and road roughness on the IRI-scale. Most studies have resulted in linear relationships as per Equation 1.

Equation 1 Vehicle seat or cab floor vibration a_w as function of IRI-values

$$a_w\ [\mathrm{m/s^2}] = a + b * \mathrm{IRI}\ [\mathrm{mm/m}]$$

The review of car studies showed ranges for the intercept "a" of $0 < a < 0.0768$ and for the slope factor "b" of $0.0665 < b < 0.27$. Most studies had a coefficient of determination R^2 better than 0.90, a high value which indicates that IRI is a relatively good indicator of ride quality in passenger cars.

Ahlin and Granlund (2002) derived the physical relationship between IRI and cab floor vertical acceleration in the "Golden car" reference model for the IRI computation. The derived relationship in Equation 2 concerns the vehicle model´s "driving speed" *v* and the waviness w of the road profile elevation. Typical values for waviness are 1.6 < w < 2.4. For v = 80 km/h and w = 2, the slope factor “b” equals 0.16. The intercept a-value was 0 (zero). Note that this study did not include the effect of megatexture waves, which is a likely cause to why the intercept was a = 0.

Equation 2 Golden car cab floor vibration a_w as function of IRI-values

$$a_w\ [m/s^2] = 0.16 * (v/80)^{((n-1)/2)} * IRI\ [mm/m]$$

4.1.1.2. DRIVER VIBRATION IN HEAVY TRUCKS WITH TRAILERS

Ahlin et al (2000) measured seat vibration (as per the ISO 2631 standard) in timber logging trucks and collated the drivers’ vibration exposure at 75 km/h to road roughness on the IRI-scale. The collation was carried out using a linear relationship as per Equation 1.

Exploratory data analysis (EDA) showed that there were greater variances in seat vibration at road roughness levels above IRI = 3 mm/m. This may be explained by the fact that while modest road roughness is difficult to see, severe road damages are more visible. Hence most truck drivers try to avoid traversing the worst roughness by changing the truck´s lateral position on the carriageway (even to the extent of driving on the wrong side of the road), and by braking to lower the speed in order to reduce vibration. Another explanation is that rough road sections with IRI > 3 mm/m cause much more rotational vibration in roll and pitch modes, with associated lateral and fore-aft vibration.

Regardless of the exact reason why there is a breakpoint for WBV (x, y, z vector) at IRI = 3 mm/m, the EDA led to the conclusion that different regression analysis had to be made for IRI above and below 3 mm/m. Results from Ahlin et al (2000) are given in Equation 3, Equation 4 and Figure 97.

Equation 3 Seat vibration (weighted x,y,z vector) in a truck with a trailer at IRI < 3 mm/m

$$WBV\ [m/s^2] = 0.18 + 0.30 * IRI\ [mm/m]$$

Equation 4 Seat vibration (weighted x,y,z vector) in a truck with a trailer at IRI > 3 mm/m

$$WBV\ [m/s^2] = 0.35 + 0.22 * IRI\ [mm/m]$$

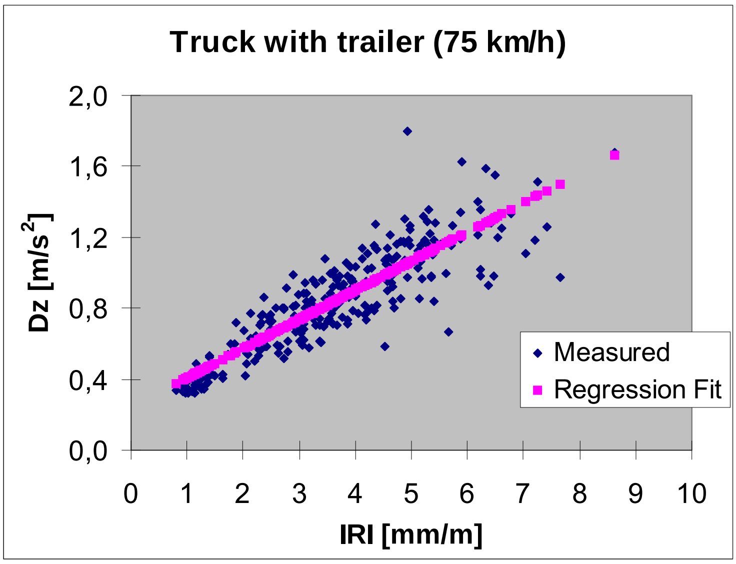

Figure 97 Truck drivers WBV (vertical direction only) as function of IRI. From Ahlin et al (2000).

Note that according to Equation 3, and assuming an 8 hour daily driving time, the truck drivers exposure to WBV exceeded the EU Action Value of A(8) = 0.5 m/s^2 with as little as an IRI slightly above 1 mm/m. Roads with IRI = 1 mm/m are considered by typical passenger car occupants to be in good condition and give a very smooth ride. Note also that a significant part of the truck seat vibration is related the equations´ a-term (the intercept), rather than to the b-term (the slope factor) associated with road roughness reflected by the IRI-scale. With the a-value being as high as 0.18 (not to mention the 0.35 in Equation 4), the intercept makes a great proportion of the EU Action value = 0.5 m/s^2. If the intercept can be lowered, a higher IRI-value (rougher roads) can be accepted without exceeding the EU Action Value for truck driver´s exposure to whole-body vibration during the truck operation.

Experience from several other studies show that the factors a & b in Equation 1 vary between road sections and between trucks. Typical ranges are for the intercept "a" of $0.1 < a < 0.35$ and for the slope factor "b" of $0.2 < b < 0.3$. Bad roads and bad trucks results in higher factors.

A very important question is
-Why does the seat vibrate significantly despite no road roughness being present? Why isn´t the intercept a = 0 (zero) at IRI=0?

Recalling the previous section, it was shown by Ahlin & Granlund (2002) that a = 0 for the idealized "Golden car". When studying real cars however, the intercept ranged up to a = 0.08 for passenger cars. This may possibly be explained by the fact that IRI does not reflect megatexture waves < 0.5 m at all, while megatexture causes vibration in cars. Hence tendencies of washboarding, ravelling and pothole formations may be present and cause ride vibration despite low IRI-values in both cars and heavy trucks.

For heavy trucks, there are several other possible explanations why the intercept is not at zero:

- On weak roads, especially during the spring thaw period, "soft spots" in the road can give high variance in pavement deflection under a heavy truck wheel (as indicated by falling weight deflectometer testing of pavements). This causes ride vibration but is not measured by IRI, as IRI is calculated assuming a 100 % stiff road profile.
- Truck wheels may suffer from severe unbalance, caused by geometric and stiffness eccentricity. While wheel unbalance is more or less impossible to become unaware of in any modern passenger car, the resulting vibration in a heavy truck may be masked by other vibration and may hence not be easily discovered.
- Truck frames are flexible compared to stiff car bodies. Long wave road unevenness may cause vibration due to "frame beaming", while IRI is not sensitive to these long waves.
- The truck engine´s powerful combustion pulses may not be efficiently isolated from the frame, cab and driver seat.

4.1.2. Relating truck driver WBV to IRI-values in the current ROADEX IV study

Data from two adjacent sections of road 331 recorded in the very same truck at constant speed are presented in Figure 98. While the slope factor b is similar for both road sections (0.25 á 0.26), the intercept a-factor differs by a factor close to 2 (0.12 versus 0.21). This indicates a large difference in road properties. The section with IRI of 1.0 to 1.5 mm/m and intercept a-factor 0.21 had been fairly recently resurfaced, but has probably low and varying pavement stiffness due to being built on a subgrade of soft soil.

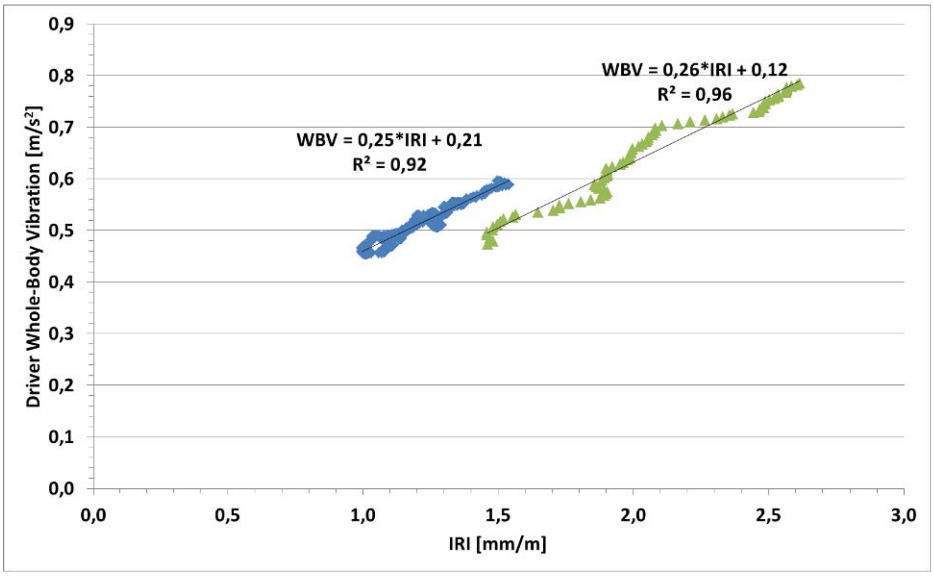

Figure 98 Truck drivers WBV (weighted x,y,z vector) as function of IRI. Current ROADEX IV study.

4.1.2.1. USING IRI TO ESTIMATE TRUCK RIDE VIBRATION

This section offers an example on how to use IRI to estimate truck ride vibration, based on the background in previous sections in this chapter. The road section example is from Hw 21 in Finland, heading Northbound for Kilpisjärvi. Data in the Finnish PMS show that this section had IRI = 1.81 mm/m. The example vehicle is a grocery truck. It is of a comfortable premium model, but old and worn. To reflect this, ”low mid-range” values for a & b-factors have been inserted into Equation 1, resulting in WBV ≈ 0.18 + 0.23 * IRI, i.e. WBV ≈ 0.18 + 0.23 x 1.81 = 0.60 m/s^2.

In reality, ROADEX IV measured the truck driver WBV to be 0.58 m/s^2 for this case, so the estimate was very close the measured value. The author of this report is convinced that *with a fair selection of a & b when using Equation 1, IRI can give WBV typically within some 15 %[12].*

The final step in assessing the daily A(8) vibration exposure is to use the UK HSE A(8)-calculator[13] to normalise the WBV-value to daily driving hours.

[12]For truck speed far below 80 km/h, IRI may overestimate ride vibration at rather long waves. This makes it unsuitable to use IRI for estimating truck ride quality at undulating secondary/tertiary low speed roads.
[13] UK HSE Vibration Calculator on Internet 2012-05-15: http://www.hse.gov.uk/vibration/wbv/

4.1.2.2. USING THE EU ACTION VALUE TO IDENTIFY ROAD ROUGHNESS LIMITS

An overall objective for road management should be to keep pavements in such good condition that it is possible to operate normal trucks over normal working days behind the steering wheel, and still keep the A(8) under the EU Action Value 0.5 m/s^2.

Many road agencies have limits for road roughness on the IRI-scale in their pavement management. In most (all?) cases, these limits have been set with respect to passenger car drivers comfort, and not with respect to the working environment of professional truck drivers. This has led to a serious overestimation of acceptable road roughness, as shown below.

The discomfort scale in the ISO 2631-1 standard says that vibration is clearly "uncomfortable" at 0.8 m/s^2. As seen in previous sections, the vehicle vibration response to road roughness (the b-factor in Equation 1) for the reference "Golden car" is 0.16 at 80 km/h. With an intercept of a = 0, road roughness can be as high as IRI = 5.0 mm/m before WBV corresponds to the "uncomfortable" WBV = 0.8 m/s^2 in normal cars.

When changing focus from car drivers comfort to truck drivers working environment and the A(8)-concept implemented in Directive 2002/44/EC, a first step is to account for the truck driver's one hour of breaks with zero vibration.

Equation 5 Assessing the daily vibration exposure **[AFS 2005:15 Vibrationer / Directive 2002/44/EC]**

$$A(8) = A(T) * \sqrt{\frac{T}{8}}$$

The effect of reducing driving time from 8 to 7 hours in Equation 5 is rather small. This is because A(8) is affected by exposure time only in a "root" relationship, and is affected by vibration intensity in a linear relationship. Using the UK HSE A(8)-calculator it is easy to compute that the acceptable A(8) = 0.50 m/s^2 at 8 vibration exposure hours daily, corresponds to 0.53 m/s^2 after reducing the exposure time T to 7 hrs/day. The increase in allowed vibration was only 0.03 m/s^2 or 6 %, despite a reduction of driving hours T by 12.5 %.

Inserting the "low mid-range" values of "a" = 0.18 and "b" = 0.23 into Equation 1 and solving for WBV < 0.53, the result is IRI < 1.52 mm/m.

By changing focus from car comfort to healthy and safe professional heavy truck operation, the acceptable road roughness drops from being about 5 mm/m[14] to some 1.5 mm/m!

Of course IRI < 1.52 mm/m is a target difficult to reach without a massive increase on road maintenance funding. Thus two relevant questions are:

1. Is the EU Action Value of A(8) = 0.5 m/s^2 really justified?
2. What else can be done to comply with the Action Value, besides shortening the interval between asphalt overlays to prevent high IRI-values?

The first question is simple to answer; -Yes, the Action Value of 0.5 m/s^2 is justified! Even without reference to scientific knowledge reviews, it is enough to realize that WBV = 0.5 m/s^2 corresponds to "fairly uncomfortable" as per the ISO 2631-1 standard. You do not need to be expert on how stress affects human health, in order to realize that negative health effects are likely in the long term among many of those who are working in an environment that is "fairly uncomfortable" on the average during the whole working day, year after year.

[14] An example is STA Pavement Management standard 2011, available in Swedish on Internet (2012-06-30): http://publikationswebbutik.vv.se/upload/6636/2012_074_Underhallsstandard_belagd_vag_2011.pdf

The second question calls for more complex but also innovative answers. Truck seat vibration can be lowered by many actions besides shortening the interval between asphalt overlays:

- Increasing pavement stiffness and decreasing pavement deflection variance ("dynamic road roughness"). This can be achieved by better pavement bearing capacity management and ultimately pavement reinforcement.
- Improving the initial asphalt smoothness and eliminating long wave unevenness by using modern laser-based technologies for management of pavement geometry (crossfall and profile) when resurfacing roads.
- Reducing initial asphalt megatexture; 50 – 500 mm waves.
- Improving the truck by equipping it with the best available seat and other technical solutions, such as a tyre pressure control system or counteract balancing beads (or similar products) for best possible and continuous balance of the wheel ends.

By combining the above bulleted actions, the road roughness can be allowed to go higher than IRI = 1.52 mm/m also at roads with truck operating speed of 80 km/h.

4.2. LATERAL BUFFETING – A SEVERE CRASH RISK

Road warpiness is a serious traffic safety problem for vehicles with a high Centre-of-Gravity (CoG), especially on slippery icy roads. At sections where the lanes cross slope oscillates within a spatial "window" of up to some 25 m length, vehicles can be exposed to roll vibration (both wheel axles and vehicle body) and roll-related lateral buffeting.

An example of a road section with severe warpiness on Road 956 in Finnish Lapland is shown in Figure 99. The weak and deformed pavement edge seen in the upper photograph has been repaired, but has settled even more after the repair. The result is a strong transient roll and lateral vibration in the ROADEX IV test truck, as seen in the screen dump below. High transient roll vibration / roll-related lateral vibration were measured in all ROADEX IV demonstration projects. This confirms that lateral buffeting is an issue in Scotland, Finland, Norway as well as Sweden.

Figure 99 Pavement edge deformation is a common cause of road warpiness

Lateral buffeting on icy roads may trigger the vehicle to skid. The lateral buffeting in other cases can fool the driver that there is a skid, requiring a quick response with evasive manoeuvring (against a non-existing skid) occasionally thereby initiating a real skid. See the photograph taken by Niklas Thunborg in Figure 100 for a tragic example that occurred 20th October 2010 on extremely slick thin black ice at a Hazardous Site with remarkably high road warpiness identified in the ROADEX III project.

Figure 100 A fatal skid crash on "black ice" at a section of Rd 331 with RBCSV >> 0.3 %

A new pavement condition parameter Rut Bottom Cross Slope Variance (RBCSV) was defined[15] in Sweden in 2006, aiming to identify road sections with severe road warpiness, causing truck cab roll vibration and related lateral buffeting. The ROADEX III project validated the RBCSV-parameter and drafted a limit value of max acceptable RBCSV = 0.3 % or 3.0 BAC.

In ROADEX IV the RBCSV-parameter has been further evaluated. Data on truck cab roll vibration has been collated with data on pavement RBCSV from Road 331 in Sweden in Figure 101. The road had severe pavement edge damages at about section 112,250 m, which are clearly detected by both the truck roll sensor and by the RBCSV parameter. Truck cab roll vibration has also been collated with data on pavement rut depth (Figure 102) and with road roughness IRI (Figure 103). As seen by comparing these figures, pavement RBCSV is a good predictor of truck cab roll vibration as opposed to both the rut depth and the IRI parameters.

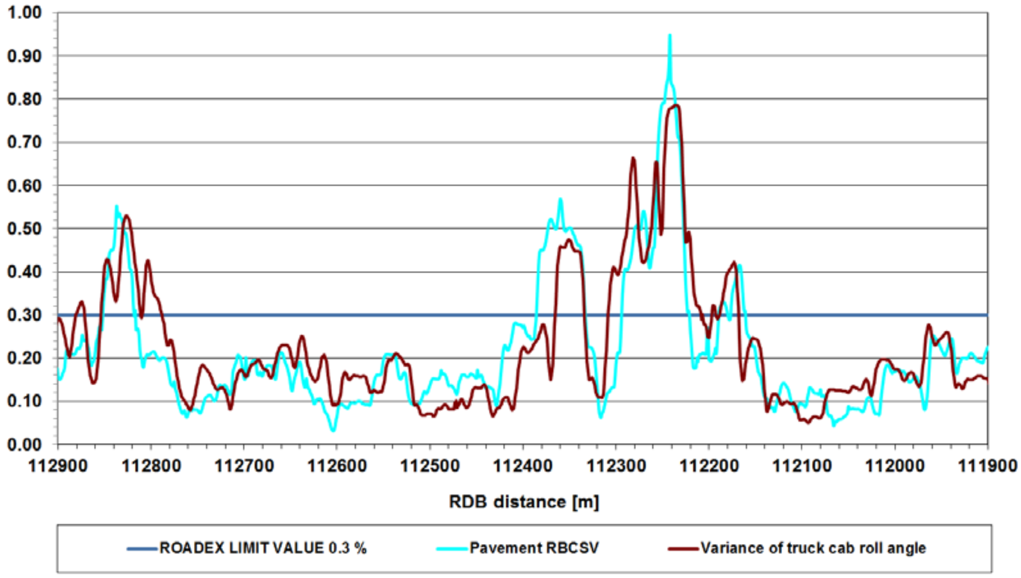

Figure 101 Collations of Truck Cab Roll Vibration and Pavement RBCSV

15 The RBCSV algorithm is presented in English in the paper by Granlund (2010).

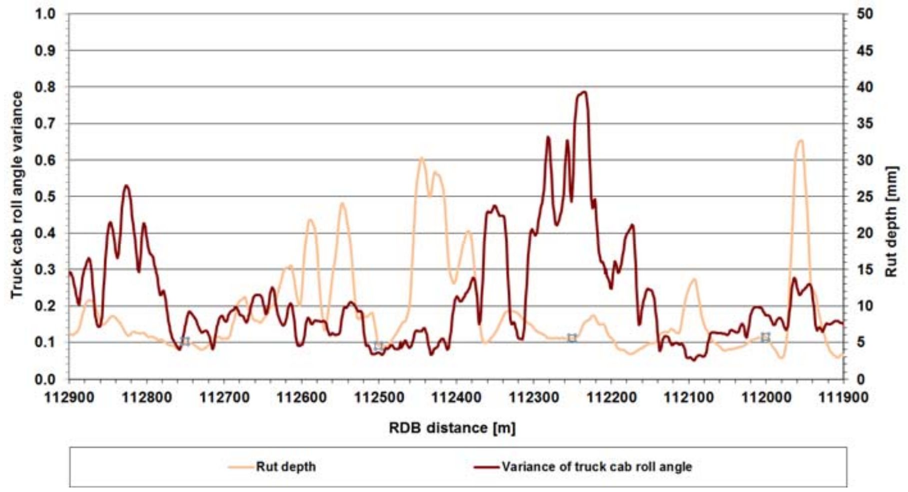

Figure 102 Collations of Truck Cab Roll Vibration and Pavement Rut Depth

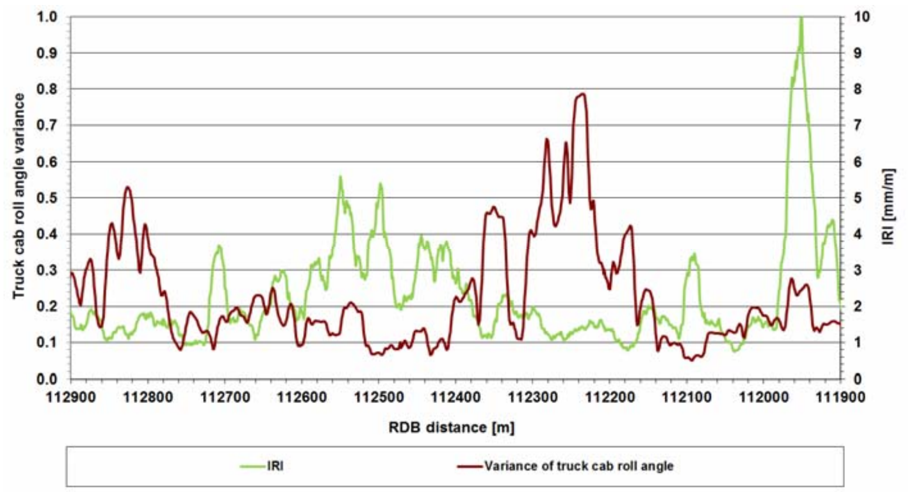

Figure 103 Collations of Truck Cab Roll Vibration and Road Roughness on the IRI-scale

Due to a phenomenon called *rearward amplification*, the highest lateral acceleration is typically seen at the end of the trailer [Hurtig 2010]. Hence it can be argued that an indicator of road warpiness should be designed to match trailer end lateral vibration, rather than truck cab vibration. However, the amount of rearward amplification is greatly affected by truck and trailer properties, and these properties are subject to vehicle regulations. In order to not over-tune the road warpiness indicator to a certain type of truck and trailer combination, as well as keeping maximum correlation to truck drivers' exposure to ride vibration, the concept of keeping the RBCSV-parameter designed to match cab vibration is justified.

4.3. SEVERE FROST RELATED ROUGHNESS

This ROADEX IV project measured and compared truck ride vibration during summer and winter condition in Sweden. The winter condition included mixed impacts of a corrugated ice layer on some “late winter” inland road sections, and of uneven frost heave action at “early spring” roads, see Figure 104.

The measurements were made in the same truck in both winter and summer, and comparison was made on the very same route. This 438 km “main route” started with the loaded truck and trailer at Brorssons truck garage in Ramsele, a journey to the Rundvik Sawmill were the timber was unloaded, and finally back to Ramsele again. During the winter, the truck average speed was for safety reasons 7 km/h slower than during the summer measurements.

Figure 104 The winter conditions included driving on corrugated ice layers and uneven frost heaves

The resulting daily vibration exposure A(8) values were:

- Winter, severe frost A(8) = 0.91 m/s^2 (68 km/h)
- Summer, no frost A(8) = 0.66 m/s^2 (75 km/h)

The truck drivers´ daily vibration was +39 % during the winter, despite a 10 % slower speed.

The problem with additional road roughness / ride vibration during winter conditions is present also in Northern Finland and Northern Norway. The Norwegian Public Roads Administration has started to include data on wintertime road roughness in their Pavement Management System database “Rosita”. For a 10 km long section on European Highway 6, the measurements show a +17 % increase in road roughness in the winter compared to in the summer as seen in Table 14.

Table 14 Road roughness at E6 Fauske – Trondheim section 17/000 – 27/000 km

IRI [mm/m]		Measurement date	
		2011-08-25	2012-04-19
Average value		2.4	2.8

It is clear from this that additional winter roughness should be reflected in strategies for road condition surveys in the Scandinavian part of the EU Northern Periphery. The road network condition / rideability needs to be measured also when the roads are frozen and covered with an ice layer.

4.4. CORRUGATION IN THE ICE LAYER CAUSE NOISE AND VIBRATION

The Swedish Ambulance service reported[16] in December 2011 that they had to avoid driving ambulance transports on National Highway 90 north of Sollefteå, due to unhealthy interior noise for both patients and staff. Noise measurements showed average sound pressure of 100 dB(A) with peaks up to 120 dB(A), and both patients and staff needed earmuffs to prevent permanent hearing damages. The noise source was extreme corrugation in the thick ice layer covering the highway. The upper left photograph in **Figure 105** was taken several days after the corrugations had been smoothed with a heavy grader.

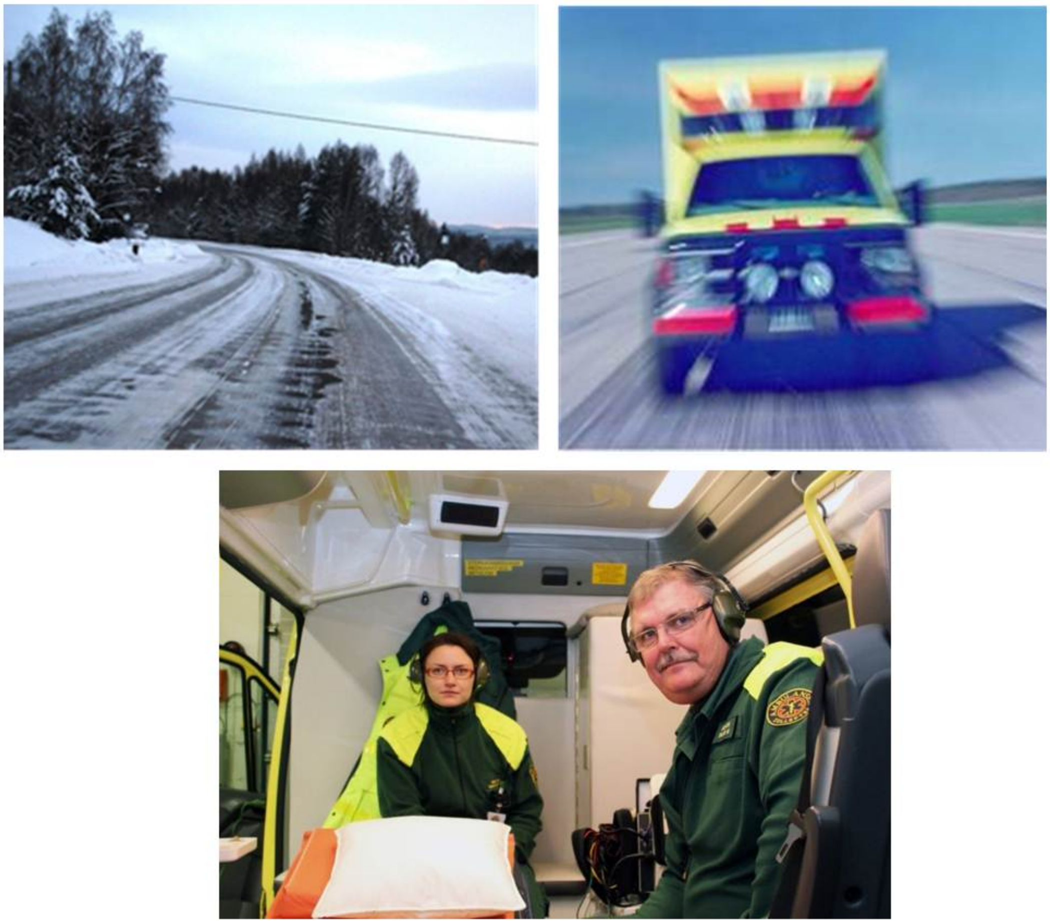

Figure 105 Corrugated ice caused noise in ambulances [Photo: S Engblom, Wiman Amb., J Granlund]

In this project, interior noise was measured in a modern Ford Galaxy family car in good condition while driving at 90 km/h on the corrugated ice layer, but only AFTER it had been graded. Reference measurements in the Ford Galaxy car were made at 90 km/h on small roads with a non-corrugated ice layer. These resulted in noise pressures of about 65 dB(A). The measurements on the graded Highway 90 revealed noise pressures with an average over 75 dB(A) and peaks above 100 dB(A). The EU work environment regulation calls for earmuffs at a noise level of 75 dB(A). Clearly not only ambulance car occupants needed earmuffs before the ice layer was graded, but also normal passenger car occupants.

Since the graded ice layer was still not smooth enough to be considered as acceptable (with respect to the 75 dB noise), the graded corrugations were inspected. The sections generating highest peak noise had 3-4 dm wavelengths and amplitudes up to 1.5 cm (after grading), as seen in Figure 106.

[16] Internet 2012-06-30: http://allehanda.se/start/solleftea/1.4224782-ambulans-undviker-riksvag-90

Figure 106 Remaining corrugations; note grooves created by the grader **[Photo: J Granlund]**

According to the Swedish Transport Administration´s specification for winter maintenance standard, roughness in thick ice layers shall be measured as deviations from a 60 cm long straight edge. Roughness, "ojämnhet" in Swedish, is allowed to have amplitude of up to 1.5 cm, see Figure 107.

Ojämnhet

Ojämnheter i tjock is eller packad snö ska mätas med en 60 cm lång rätskiva. Detta gäller såväl längs som tvärs vägen, samt vid anslutande statlig väg.

Rätskivan ska vila mellan två ojämnheter eller mellan en ojämnhet och vägytan varefter mätning sker vinkelrätt mot rätskivan.

Krav vid uppehållsväder och när åtgärdstid efter nederbörd löpt ut.

Sektions-element	Vägytetemperatur			Ojämnhet cm
	varmare än -6°C friktionstal	-6°C till -12°C friktionstal	kallare än-12°C friktionstal	
Körfält	snö/isfritt	0,35	0,25	1,5
Vägren	0,25	0,25	0,25	1,5
Sidoanläggning	0,25	0,25	0,25	1,5

Figure 107 STA spec for roughness of ice-covered roads

The STA specification has been in use for over a decade and experience has proved it to be relevant for ice-ruts and for singular roughness. However graded corrugations with less than the allowed 1.5 cm amplitude also resulted in over +10 dB noise, which is not acceptable. This shows a need for an additional roughness specification to include corrugations that cause resonance in normal car wheel suspension systems. Additional research is needed to establish a reasonable specification on corrugations. This is relevant for both ice-covered roads and for dirt-roads as well.

5. TPC-SYSTEMS REDUCE SHAKE VIBRATION

5.1. TPCS REDUCE RIDE VIBRATION

One of the tasks for ROADEX IV was to evaluate the effectiveness of a Tyre Pressure Control System (TPCS) on vibration isolation from road roughness to the truck driver's seat.

Truck tyre standard inflation pressures are required to be set high enough to comply with maximum load, maximum speed and the worst road condition. Thereby the tyres are normally over-inflated during many operations, such as when driving with low or no payload, as well as at low speed. Hence a normal timber logging truck may be operating with suboptimal settings, and thus experiencing excessive ride vibration, during up to 65 % of the driving cycle [Munro & McCulloch].

The upper left photographs in Figure 108 show that the tyre footprint can be increased by use of a TPCS. With a larger footprint, the tyre has better enveloping effect on the road megatexture (waves with 50 – 500 mm length). A significantly lowered tyre pressure also reduces the stiffness of the tyre carcass, especially its walls. This affects the eigenfrequency and further contributes to improved ride quality at low speed on mega-textured surfaces on potholed or stony dirt-roads and on corrugated ice layers.

Figure 108 TPCS isolates the driver from mega-textured roads **[Photo: J Granlund & P Granlund]**

The first ROADEX IV experience from studying TPCS in Scotland was very tangible. When measuring on the Loch Arkaig dirt-road with TPCS in low pressure, the truck ride was quite harsh. But when measuring with high pressure, the truck cab shook so hard that the measurement computer fell on to the floor!

Numeric results confirm a great effect from the TPCS on truck driver´s ride quality. During the full South Laggan round-trip, including both A82 + several km of dirt-road, the A(8) was 0.80 m/s^2, with high tyre pressure for the whole round-trip. The same round-trip but with low pressure except when driving at highway speed with full payload resulted in A(8) = 0.66 m/s^2; a reduction of some 17 %! However, the driver´s exposure to vibration was still over the EU Action Value of 0.5 m/s^2.

The TPCS-study in Sweden was made on a very long round-trip mainly on paved state highways. With full tyre pressure during the whole route, the A(8) was 0.91 m/s^2 with an average speed of 68 km/h. With reduced tyre pressure at a significant share of the route, A(8) was lower at 0.86 m/s^2 on a higher average speed of 73 km/h. Despite +7 % increased speed, driver vibration was reduced by 7 % which is impressive good. Still though, the vibration was far too high to be acceptable.

5.2. TPCS PREVENTS DRIVING WITH UNDER-INFLATED TYRES

Maintaining correct tyre pressure is crucial to achieve optimum tyre performance with minimal energy consumption and impact on the environment. With correct tyre inflation pressure, the driver can experience good comfort, while the tyre and vehicle durability is maximized. Tyre deflection (the tread and sidewall flexing where the tread comes into contact with the road) remain as originally designed and excessive sidewall flexing and tread squirm is avoided. Heat build-up is prevented and rolling resistance kept low. Proper tyre inflation pressure also stabilizes the overall tyre structure, blending the tyre response, traction and handling.

An over-inflated tyre is stiff, while the size of its footprint in contact with the road is reduced. If a vehicle's tyres are over-inflated, they could be damaged more easily when running over potholes or foreign objects on the road. Higher inflated tyres cannot isolate the road´s megatexture well, causing a harsh ride.

An under-inflated tyre loses its shape and becomes too flat while in contact with the road. Lower inflation pressure will allow the tyre to deflect more. This can however build up internal heat, increasing the rolling resistance and causing a reduction in fuel economy. The vehicle can also experience a significant loss of steering precision and cornering stability.

Tyre pressure must be checked with a quality air gauge, as the pressure cannot be accurately estimated through visual inspection. In both of the ROADEX demonstration projects on test trucks with traditional tyre solutions (Finland and Norway), the lack of realistic access to the tyre air valves on pair-mounted wheels on both the drive axle and on the bogie axle was noted. These and similar trucks suffer high risk for poor tyre pressure management and hence high risk to be operated unintentionally under-inflated.

With a TPCS mounted, such as on the test trucks in Scotland and Sweden, the risk for operating under-inflated is minimized.

However, the TPCS test truck in Sweden suffered from a serious problem. In the mid 1990´s, a new technology for heavy vehicle tyre balancing was introduced. With this technology, an absorbent balancing powder is placed directly inside truck and bus tyres. Due to the powder´s ability to re-distribute itself when the vehicle is in motion, it provides maximum tyre and wheel balance at all times, during the entire lifetime of the tyre. This technology is routinely used on standard truck tyres in the Västernorrland region and unfortunately the tyre workshop erroneously applied it also to the tyres on the TPCS-equipped truck. The result was that the TPCS air valves clogged with the powder, thereby obstructing the TPCS to deflate the tyres at normal pace, until the tyres and the TPCS got cleansed. Obviously there is a need to implement means (warning signs, introduce a check for TPCS at the tyre workshops) to prevent this kind of problem in the future.

6. CONCLUSIONS

The ROADEX IV demonstration projects in Finland, Scotland, Norway and Sweden had the overall objective to reproduce the ROADEX III case study from the Beaver Road 331 in Sweden (2008):

1. Measuring truck drivers daily vibration exposure and comparing the A(8)-values to the Action Value 0.5 m/s^2 in 2002/44/EC.
2. Measuring spine compression stress, S_{ed}, caused by jolts at severe bumps and comparing the values to the 0.5 MPa stress limit in ISO 2631-5 (used as Action Value in Sweden).
3. Relating truck roll & lateral buffeting in heavy trucks with high Centre-of-Gravity to laser-scanned non-uniform deformation at the pavement edge (the latter quantified by the pavement condition parameter “Rut Bottom Cross Slope Variance”).

A high repeatability was confirmed between similar truck round trips, when using the ROADEX method to assess truck drivers’ daily vibration exposure A(8).

Results from the first task, concerning the A(8), are summarized in Figure 109. The only measured A(8) below 0.5 m/s^2 was for European Highway E6 in Norway. However, that measurement was taken under best possible conditions. After adjustment to average conditions, the A(8) for E6 in Northern Norway is also expected to exceed the EU Action Value 0.5 m/s^2.

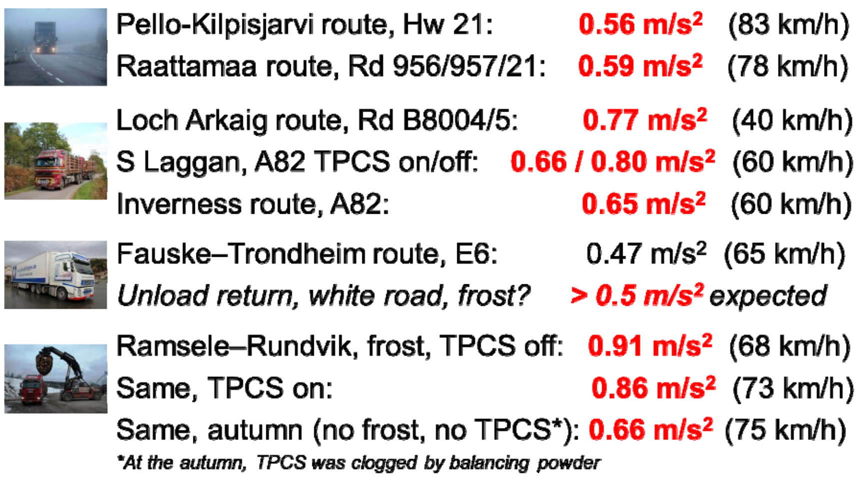

Figure 109 Daily vibration exposure A(8) exceeds EU Action Value 0.5 m/s^2

Results from the second task are summarized in Figure 110. The drivers of timber logging trucks both in Scotland and in Sweden were exposed to unhealthy spinal compression stress.

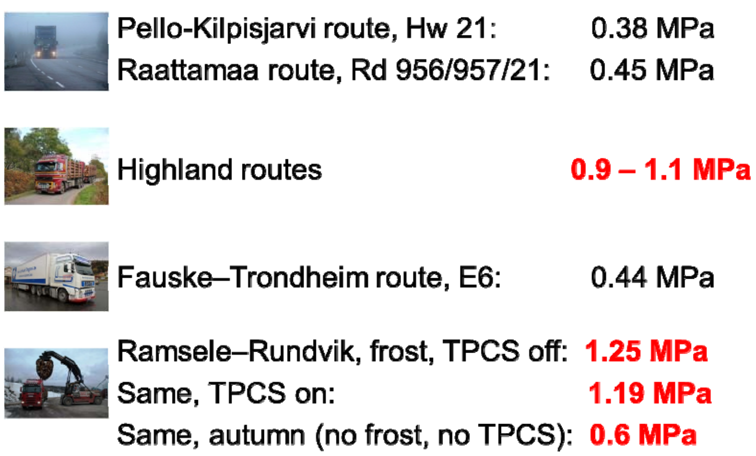

Figure 110 Timber truck drivers had high spinal compression stress S_{ed}

Measurement results confirmed that roll vibration and roll-related lateral buffeting in heavy trucks is an issue in Scotland, Finland, and Norway, as well as in Sweden. The traditional road condition parameters of “Rut Depth” and “IRI” were showed to have poor correlation with truck cab lateral buffeting. The pavement condition parameter “Rut Bottom Cross Slope Variance” (RBCSV) defined in 2006 was again shown to be a good indicator of “road warpiness” and to truck lateral buffeting.

This project did not reach the goal *to implement the use of the Rut Bottom Cross Slope Variance (RBCSV) parameter in the Partner areas.* A reason for this was that Profilometer data from network surveys in Norway and Scotland was not available in the step length of 1 m required for calculating the RBCSV parameter. The RBCSV parameter has been tested with good results in both Finland (by the consulting company Destia OY that carries out the network condition survey, see Hurtig 2010) and by Vectura in several projects in Sweden. The research institute VTI is currently making an in-depth evaluation of the RBCSV parameter as indicator of road warpiness. Preliminary results from VTI are that the RBCSV show high correlation with both pavement edge deformation and with vehicle roll vibration.

This ROADEX IV project showed that there is a need to define a new measure and establish associated limit values for corrugation in both ice layers and in dirt-roads. Current specifications deal only with rutting and with singular roughness. The Swedish specification could not be used to penalize corrugations that made National Highway 90 unusable for normal transports (incl ambulance) due to extreme interior noise.

An overall objective for road management should be to keep pavements in such good condition that it is possible to operate normal trucks at normal working days behind the steering wheel, and still keep A(8) under the EU Action Value 0.5 m/s^2.

Many road agencies have limits for road roughness on the IRI-scale. In most (all?) cases, these limits have been set with respect to passenger car drivers comfort and not with respect to the working environment of professional truck drivers. This has led to a serious overestimation of acceptable road roughness. By changing the focus from car comfort to a healthy and safe heavy truck operation, the acceptable road roughness drops from being about 5 mm/m[17] to some 1.5 - 2 mm/m. This report discusses several means of lowering truck seat vibration besides shortening the interval between asphalt overlays, for example improved balancing of truck wheel ends with “balancing powder”.

Winter conditions in the Northern Periphery include extremely uneven frost heaves and severe corrugation in the ice layers covering non-salted[18] roads. The project results show that these conditions can make the ride vibration significantly worse than during summer conditions. Hence assessment of Northern Periphery truck drivers’ exposure to daily vibration at work must be adjusted for difference in summer and winter.

Road network condition surveys with laser profilers are currently made only in summer time. The above finding shows that such condition assessments can seriously underestimate the winter season problems with road roughness. The road condition assessment procedures of the ROADEX Partners Norway, Sweden and Finland (maybe also Iceland?) therefore need to be reviewed.

A secondary research objective concerned mapping the benefits of tyre pressure control systems, regarding vibration transfer from tyre footprint to driving seat. One research goal was to quantify the transfer as function of vibration frequency (roughness wavelength x speed) from data recorded

[17] An example is STA Pavement Management standard 2011, available in Swedish on Internet (2012-06-30): http://publikationswebbutik.vv.se/upload/6636/2012_074_Underhallsstandard_belagd_vag_2011.pdf

[18] Road salt is used as de-icing agent in order to increase road friction and traction. At temperatures below about -9 á -13 °C however, the salt resin re-freezes and can create an extremely slick road surface and hence increase instead of decrease the skid risk.

in Sweden. This goal could not be met for several reasons. In the summer test, the test truck TPCS air valves became clogged, so the system was not useable. In the winter test, the portable laser profiler was damaged at an extreme bump at a road section that had been reconstructed 6 months previously.

The report from the ROADEX III case study 2007/2008 on road 331 in Sweden included identification of about a dozen very hazardous sites. These have not been addressed at the date of this report, neither have warning signs been raised at these hazardous sites.

Similarly a number of actions need to be taken to address defective practices highlighted in the study. Examples include, bumpy “steps” at bridge joints and at transversal joints at asphalt patch repair, extreme roughness in the first winter following reconstruction of frost damaged road sections, new resurfacings exceeding the EU Action Value for an 8 hour daily truck ride, etc. Current practices in some geographical areas are not yet acceptable with respect to the health and safety of professional truck drivers.

There is a need to foster a renewed spirit in road professionals and a focus on sustainable road management. The historic background of underfunding of rural roads over the years, and the resultant backlogs of work, may be dispiriting. However, focused engineers can still make large difference in assuring that Northern road networks continue to remain valid for the challenges ahead.

7. RECOMMENDATIONS

Current limits for road roughness on the IRI-scale have been set with respect to passenger car drivers´ comfort and not with respect to the working environment of professional truck drivers. This focus needs to be changed, from car comfort, to healthy and safe heavy truck operation. This calls for much smoother roads.

In addition, several other means to lower truck seat vibration also need to be implemented, for example improving the balancing of truck wheel ends with “balancing powder” or installing a TPCS. The effectiveness of the proposed actions should be further investigated.

Roll vibration and roll-related lateral buffeting in heavy trucks is an issue in Scotland, Finland, and Norway as well as in Sweden. The pavement condition parameter “Rut Bottom Cross Slope Variance” has again been validated as a relevant measure of road warpiness and should be considered for implementation in all Partner areas.

Truck cab transient lateral acceleration may exceed the 5 m/s^2 (0.5 g) lateral acceleration to be considered when latching loads on road vehicles, as per the IMO/ILO/UN ECE Guidelines for cargo securing, when passing over pavement edge damages at 70 - 80 km/h. The latching guidelines may need a review because of this.

Pavement edge damages worse than RBCSV 0.30 % should be repaired ASAP, with a warning sign raised until the road repair is completed. Truck operators should also educate their drivers to drive slowly at this kind of pavement damage.

Investigations of truck crashes do not always include competent analysis of the role of road properties. This is in fact true also in many investigations of fatal crashes. Given this context, the new RBCSV road condition parameter could be a useful tool to identify of road damages that may have contributed to a rollover crash.

The assessment of Northern Periphery truck drivers’ exposure to daily vibration at work, and road network condition surveys, must be adjusted for difference in summer and winter.

There is an urgent need to establish a new measure and associated limit values for corrugation in paved roads with ice layers and in dirt-roads.

Several of the root causes to high vibration are man-made. Actions need to be taken to assure that road repairs are effective and not worse than before. It is recommended the road condition (alignment, slopes and surface condition) should always be measured by a certified inspector after the completion of any major road-repair works using an approved ASTM E950 “Class 1” road profiler.

Transversal edges of new asphalt overlays should not be placed “layer-on-layer” with the old asphalt, but cut down into the same elevation as the surface of the old asphalt. This will require the use of a small milling machine. Such machines are available on the market, but not always implemented in highway pavement maintenance.

Long wave unevenness is difficult to repair with a traditional asphalt overlay, since the paver tends to only go “roller-coasting” in the up to more than 30 m long waves. A sustainable solution contains careful filling in the hollows and preferably also gentle milling on the ridges, before resurfacing. Preferably this procedure should be done after laser-scanning the undulations, computer aided design of the undulation repair, and computer aided manufacturing of the milling works. The final resurfacing should preferably not be done with computer aid, with respect to the complexity of controlling the paving plants floating screed.

Improperly banked horizontal curves are a common traffic safety problem in the Northern Periphery. A method for easy detection of hazardous flat outercurves as well as banked innercurves has been demonstrated in this report. It is recommended that this is implemented by all ROADEX Partners with road management responsibility, as well as by investigators of rollover or other instability road vehicle crashes.

8. ACCURACY AND UNCERTAINTY

The repeatability of A(8)-assessment using Vecturas portable vibration measurement system was demonstrated in three runs between Corpach and South Laggan in Scotland, with very good likeness (almost to the second decimal) between the runs, see Figure 40. The reproducibility was also surprisingly good when comparing results between the measured data from the Beaver Road 331 between Ramsele and Ärtrik at the Åkerö edge damage recorded in ROADEX III (2007) respectively in ROADEX IV (2011), see Figure 83.

Some measurement data files were found to be damaged due to severe mechanical shocks as described in the report. Those data were discarded and not used when preparing this report.

9. REFERENCES

- Directive 2002/44/EC on The minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (vibration). The European Parliament and the Council.
  Internet 2010-01-30: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2002:177:0013:0019:EN:PDF
- Granlund, J. (2008). Health Issues Raised by Poorly Maintained Road Networks. The ROADEX III project.
  Internet 2010-01-30: http://www.roadex.org/Publications/docs-RIII-EN/Health%20Issues%20-%20RIII.pdf
  Videolecture 2010-01-31: http://videolectures.net/surf08_grandlund_rhirt/
- Westerling, R. (2008). *Åtgärdbar dödlighet som en indikator i den folkhälsopolitiska uppföljningen. (Avoidable mortality as an indicator in the evaluation of public health politics)*. Statens folkhälsoinstitut, Rapport 2008:03.
  Internet 2010-01-30: http://www.fhi.se/PageFiles/3122/Atgardbar_dod_webb_0802.pdf
- Teschke, K., Nicol, A-M., Davies, H. & Ju, S. (1999). *Whole Body Vibration and Back Disorders Among Motor Vehicle Drivers and Heavy Equipment Operators: A Review of the Scientific Evidence.* Report to Workers' Compensation Board of British Columbia.
  Internet 2010-01-30: http://www.cher.ubc.ca/PDFs/WBV_Report.pdf
- Systematiska kunskapsöversikter: *2. Exponering för helkroppsvibrationer och uppkomst av ländryggssjuklighet.* Arbete & Hälsa Report 2012:46
- *Arbete och helkroppsvibrationer – hälsorisker.* Arbetsmiljöverket. Rapport 2011:8
- Arnberg, P. & Åström, G. (1979). *Vägojämnheters inverkan på bilförares prestation och trötthet. Statens Väg- och Trafikinstitut,* Rapport 181.
- Gillespie, T.D., Segel, L., Ervin, R.D., Schneider, L.W. & Campbell, K.L. (1982). *Truck Cab Vibrations and Highway Safety.* Highway Safety Research Institute, University of Michigan. FHWA report RD-82/093.
- Hedberg, G.E., et al. (1993). *Risk indicators of ischemic heart disease among male professional drivers in Sweden*. Scand. J Work Environ Health, Vol 19, p 326-333.
- Bigert, C. Klerdal, K., Hammar, N., Hallqvist, J. & Gustavsson, P. (2004). *Time trends in the incidence of myocardial infarction among professional drivers in Stockholm 1977-96*. Occup Environ Med; Vol 61, p 987 - 991. Internet 2010-01-30: http://oem.bmj.com/content/61/12/987.abstract
- McFarlane, S. & Sweatman, P.F. (2003). *Investigation into the Specification of Heavy Trucks and Consequent Effect on Truck Dynamics and Drivers: Final Report.* Roaduser International Pty Ltd.
- Saarenketo, T. & Saari, J. (2004). *User perspective to ROADEX II test area's road network service level.* The ROADEX II project.
  Internet 2010-01-30: http://www.roadex.org/Publications/docs-RII-EN/1_1%20User%20Perspective_l.pdf
- Bray, A., Bronstein, A.M., Green, D.A., Gresty, M. A. & Golding, J. F. (2006). *Tachypnea and hypocapnia are induced by 'buffeting' in vehicles.* Clin Auton Res, 16:281–285.
- EN 14253+A1 (2007). *Mechanical vibration – Measurement and calculation of occupational exposure to whole-body vibration with reference to health – Practical guidance.* European Standard.
- *European Best Practice Guidelines on Cargo Securing for Road Transport.* European Commission Directorate – General for Energy and Transport.
  Internet 2012-04-15: http://ec.europa.eu/transport/road_safety/vehicles/doc/cargo_securing_guidelines_en.pdf
- Högfors, C. (2001). *Snabba accelerationers inverkan på gods under transport*.
  Internet 2012-04-18: http://mariterm.se/download/Rapporter/Snabba_accelerationers_inverkan.pdf
- *Rutevise utredninger for riksvegnettet, Riksvegrute 7, E6 Trondheim - Fauske med tilknytninger*. (2011). Statens Vegvesen, Norway.
  Internet 2012-05-15: http://www.vegvesen.no/_attachment/263397/binary/467332
- Tom, G.K.J. (1995). *Accidents on Spiral Transition Curves*. ITE Journal.
- Berglund, A. (2009). *Tjäle – en litteraturstudie med särskilt focus på tjällossning*. Luleå Tekniska Universitet. Internet 2012-05-15 http://pure.ltu.se/portal/files/3333867/Tjale_Litteraturstudie.pdf
- Ahlin, K., Granlund, J. & Lundström, R. (2000). *Whole-Body Vibration When Riding on Rough Roads – A Shocking Study.* Swedish Road Administration, Vol. 31E. Internet 2012-05-30: http://publikationswebbutik.vv.se/upload/3054/2000_31E_Whole_body_vibrations_when_riding_on_rough_roads.zip
- Ferguson, R., Prem, H., Ramsay, E. & McLean, J. (2000). *A Road Profile Based Truck Ride Index (TRI)*. Austroads Inc., Australia. Internet 2012-05-30:

http://www.rahiran.ir/data/reports/australia/heavy_vehicle/a%20road%20profile%20based%20truck%20ride%20index/377_AP-R177.pdf

- Mucka, P. & Granlund, J. (2012). *Is the Road Quality Still Better?* Journal of Transportation Engineering, Vol. 138, No. 12. Internet 2012-06-30: http://dx.doi.org/10.1061/(ASCE)TE.1943-5436.0000460
- Ahlin, K., and Granlund, J. (2002). *Relating road roughness and vehicle speeds to human whole body vibration and exposure limits.* Int. J. Pavement Eng., 3(4), 207–216.
- Granlund, J. (2010). *Reducing Health and Safety Risks on Poorly Maintained Rural Roads*. 11´th International Heavy Vehicle Transport Technology Symposium, Melbourne, Australia.
- Hurtig, E. (2010). *Raskaan kaluston kallistelun voimakkuuden arvioiminen tienpinnan profiilista.* MSc thesis. Aalto University School of Science and Technology, Finland.
The thesis in English summary on Internet 2012-04-15: http://tierakennusmestari.com/lehdet/Hurtig.pdf
- Munro, R. & McCulloch, F. (2008). *Tyre Pressure Control on Timber Haulage Vehicles*. The ROADEX III project.
Internet 2012-05-30: http://www.roadex.org/uploads/publications/docs-RIII-EN/TPCS%20Trial%20-%20RIII.pdf

- Hurtig, E. (2010). *Raskaan kaluston kallistelun voimakkuuden arvioiminen tienpinnan profiilista.* MSc thesis. Aalto University School of Science and Technology, Finland.
The thesis in English summary on Internet 2012-04-15: http://tierakennusmestari.com/lehdet/Hurtig.pdf

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- 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
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