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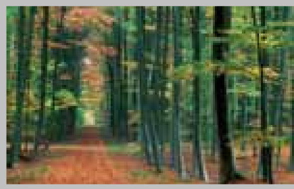

ROADEX III
NORTHERN PERIPHERY

Johan Granlund

Health Issues Raised by Poorly Maintained Road Networks

Northern European road users may be exposed to unacceptable health and safety risks, in terms of ride vibration and skid accidents. A case study has mapped such risks on the Beaver Road 331. The report demonstrates methods to efficiently prevent or reduce risks on similar roads.

Health Issues Raised by Poorly Maintained Road Networks

March 2008

Johan Granlund
Swedish Road Administration Consulting Services

PREFACE

This is a final report from Task B3 of the ROADEX III project, a technical trans-national cooperation project between The Highland Council, Forestry Commission Scotland and Comhairle Nan Eilean Siar from Scotland; The Northern Region of The Norwegian Public Roads Administration; The Northern Region of The Swedish Road Administration (SRA) and the Swedish Forest Agency; The Savo-Karjala Region of The Finnish Road Administration; the Icelandic Road Administration; and the Municipality of Sisimiut from Greenland. The lead partner in the project is The Northern Region of The Swedish Road Administration and project consultant is Roadscanners Oy from Finland. ROADEX III project Chairman is Per-Mats Öhberg from The Northern Region of The Swedish Road Administration and project manager is Ron Munro of Roadscanners Oy.

The report was prepared by Johan Granlund of SRA Consulting Services, leader of Task B3. Fredrik Lindström, Fredrik Stensson, Ylva Magnusson, Stefan Hedlöf, Erik Cuibe, Jenny Eriksson and Ulf Nilsson of SRA CS participated in the plans, measurements and analysis related to the field tests at Rd 331. Hans Johansson of SRA Central Region made very valuable contributions to the traffic safety analysis. Mats Nilsson and Anders Larsson of Brorssons Åkeri AB drove the tested timber logging truck and trailer combination. Ron Munro, manager of the ROADEX III Project, checked the project report language. Mika Pyhähuhta of Laboratorio Uleåborg designed the report layout.

The author would like to express gratitude also to the following:

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- Mr Leif Grønskov of Greenwood Engineering A/S. Thanks Leif, for your support of the reference pavement condition measurements using the accurate laser/inertial Profilograph system.
- Dr Boris Thorvald of Scania Commercial Vehicles AB. Boris, you put the finger on short step cross slope variance, truck wheel axle roll motion, related lateral forces, their impact on road polishing, road friction and, ultimately, increased skid risk. This really widened our focus!
- MSc Henrik Lindh and Dr John Aurell of Volvo 3P. Thanks both of you, for making truck dynamics more understandable!

All the good results from this research task are the fruits of successful teamwork. Should the reader find anything to the contrary, the author takes full responsibility.

Finally the author would like to thank the ROADEX III Project Partners and the Project Steering Committee for their guidance and encouragement in their work.

ROADEX III Lead Partner: The Swedish Road Administration, Northern Region, Box 809,
SE-971 25 Luleå. Project co-ordinator: Mr. Krister Palo.

CONTENTS

ABSTRACT

The EU ROADEX Project 1998 - 2007 is a trans-national roads co-operation aimed at developing ways for interactive and innovative management of low traffic volume roads throughout the cold climate regions of the Northern Periphery Area of Europe. Its goals have been to facilitate co-operation and research into the common problems of the Northern Periphery.

The overall objective for this research task was to increase the understanding for road user's health risks when riding on roads in poor condition. Better knowledge will facilitate the reduction of the risks, by means of improved pavement management, more conscious truck, bus and ambulance operations, and inspire to vehicle suspension systems improvements.

The report commences with generic descriptions of how safety and health can be affected by ride vibration, how truck suspension systems isolate and amplify vibration at various frequencies, and how pavement properties, such as cross slope, control the important forces at work.

A case study is reported from the Beaver Road 331 in northern Sweden. A heavy timber logging truck was instrumented to measure ride vibration and direction. Measurements were taken at a range of points (seat, cab, frame and wheels) and the results stored together with data on speed and interior noise. Ride vibration data from repeated rides over a 280 km long round trip from forest to coast industries was then compared with reference data on pavement condition, scanned by a laser/inertial Profilograph. Results obtained included:

- The daily exposure to Whole-Body Vibration, the A(8)-value, for timber truck drivers riding constantly on roads such as Rd 331 were unacceptably high, when compared to the health and safety Action Value in Directive 2002/44/EC.
- The truck drivers were exposed to unacceptably health risks in the back when driving at modest speed over the worst bumps, due to high spinal compression doses, S_{ed}, as per the ISO 2631-5 standard.
- A derived draft limit of 0.30 % for undesired variance in cross slope. This could be useful in pavement management to prevent roll-motion and lateral forces in road vehicles.

The case study also produced valuable spin-offs in new methods for analyzing traffic safety risks arising from incorrectly banked curves and low drainage gradients. Hospital records from accidents at Rd 331 (mainly skid accidents) were found to match road sections with high cross slope variance, curves with incorrect superelevation, transition sections with low drainage gradients, and sections with high skid risk due to low/varying Macro Texture. These serious findings call for both short and long term actions. Road agencies should use the demonstrated methods to quickly identify hazardous sites and warn road users of them. Road repair planning and practices should be improved, and funding for road repair should be increased.

An extraordinary insight after the case study is that many new roads all over the EU Northern Periphery area have skid risks inbuilt due to low drainage gradients at entrances and exits of certain curves. These risks should be eliminated by modification of road design codes, road design software, road construction practices, and improved end quality control.

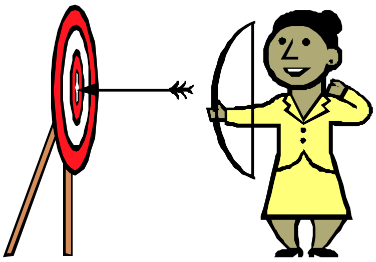
Chapter 1. THE ROADEX PROJECT IN BRIEF

The ROADEX Project is a technical co-operation between roads organisations across northern Europe that aims to share roads related information and research between the partners. The Project was started in 1998 as a 3 year pilot co-operation between the roads districts of Finnish Lapland, Troms County of Norway, the Northern Region of Sweden and The Highland Council of Scotland and was subsequently followed and extended with a second project, ROADEX II, from 2002 to 2005, and now a third project, ROADEX III, from 2006 to 2007.

The partners in ROADEX III “The Implementation Project” comprised public road administrations and forestry organizations from across the European Northern Periphery. These were The Highland Council, Forestry Commission Scotland & Comhairle Nan Eilean Siar from Scotland, The Northern Region of The Norwegian Public Roads Administration, The Northern Region of The Swedish Road Administration and the Swedish Forest Agency, The Savo-Karjala Region of The Finnish Road Administration, the Icelandic Road Administration and the Municipality of Sisimiut from Greenland.

A priority of this Project was to take the collected ROADEX knowledge out into the Partner areas and deliver it first hand to practising engineers and technicians. This was done in a series of 14 seminars across the Partner areas to a total audience of 800. Reports were translated into the 6 partner languages of Danish, Icelandic, Finnish, Greenlandic, Norwegian and Swedish as well as English. ROADEX research continued through 5 projects: measures to improve drainage performance, pavement deformation mitigation measures, health issues of poorly maintained roads, road condition management policies, and a case study of the application of ROADEX methodologies to roads in Greenland. All of the reports are available on the ROADEX website at www.roadex.org.

Chapter 2. Knowledge to find good solutions



The overall objective for the research task was to increase the understanding of the health risks to road users when travelling on poor quality roads. Better knowledge of this will facilitate risk reduction, by means of improved pavement management, more conscious truck operations, inspire to future vehicle suspension system design improvements, et cetera.

Three goals were set for the research:

- The first goal was to assess a typical truck driver's daily exposure to ride vibration, in relation to the EU Action Value, when driving on a typical Northern Periphery rural round trip route.
- The second goal was to investigate if truck drivers riding on very bumpy roads may be exposed to so intensive mechanical shock, that there is a risk for mechanical fatigue damage in the hard tissue of their spine intervertebral end plates.
- The third goal was to validate and draft limits for an indicator of undesired variance of pavement lane cross slope. Such variance excites roll motion which is especially problematic in high (heavy) vehicles. Roll vibration may not only be uncomfortable and unhealthy, but it also brings transient lateral forces that may cause skid accidents on slippery surfaces.

If the third goal was reached, it was hoped that the new pavement condition indicator could be put into daily practice by road agencies in their pavement management systems. Through this it could be possible to identify hazardous sections and have them repaired. Many roll-related skid accidents could thus be prevented and truck driver's exposure to vibration and health risk decreased.

Chapter 3. Human, vehicle and road interaction

Many readers will be able to read and appreciate the subsequent chapters, without first reading this rather long chapter. However, since the research topic covers several disciplines, it is likely that some readers may appreciate a condensed background that can bridge minor gaps of knowledge in unfamiliar disciplines. This chapter gives a brief summary on ride vibration and its effect on human beings. It also gives an introduction to heavy vehicle chassis dynamics. Finally, it shows how road geometry and condition of the pavement excite vital ride forces and vibration.

3.1 RIDE VIBRATION AND ITS EFFECT ON HUMAN BEINGS

3.1.1 General health risks associated with ride vibration

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. The risk is elevated in a broad range of driving occupations, including truck and bus drivers. Vibration exposure data indicates that current vehicles are likely to expose drivers to vibration levels in excess of the EU Action Value, as defined in directive 2002/44/EC [2]. Common control measures, such as seat suspension, are often not effective in the low frequency range where vibration energy peaks during most highway rides. A causal link has been found between back disorders, driving occupation and ride vibration. Numerous back disorders are involved, including lumbago, sciatica, generalized back pain, and intervertebral disc herniation and degeneration. Elevated risks are consistently observed after five years of exposure, see Teschke et al (1999) [1].

Whole-Body Vibration (WBV) is the term used to describe mechanical vibration and shock transmitted to the human body as a whole, usually through areas of the body (buttocks, soles of the feet and the back) in contact with a vibrating surface as seen in Figure 1. Vehicles travelling over rough surfaces expose people to periodic, random and transient ride vibration. Ride vibration contains many frequencies, occurs in several directions (bounce, pitch and roll) and changes over time. Exposure to ride vibration causes various patterns of oscillatory motions and forces within the human body; a complex, intelligent and active structure. WBV within the range 0.5 – 80 Hz cause resonance in various parts of the human body, such as the eye globes, head, spine and stomach. Thus, WBV exposure may cause[1] stressing discomfort or annoyance, influence human performance capability or present a health and safety risk (e.g. pathological damage or physiological change). The response to ride vibration varies in a confounding way; while bumps have a stressing alarm effect, the rocking motion when riding over long wave undulations results in drowsiness.

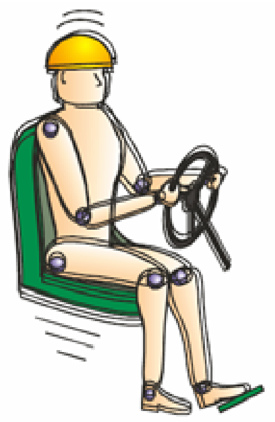


Figure 1 ***Whole-Body Vibration. From the EU Guide to good practice on WBV (2006) [24]***

Bovenzi & Hulshof (1999) [47] reviewed epidemiologic studies conducted between 1986 and 1997 on the relationship between exposure to vibration and problems in the lumbar part of the back. The review provided "*clear evidence for an increased risk for LBP disorders in occupations with exposure to WBV. Biodynamic and physiological experiments have shown that seated WBV exposure can affect the spine by mechanical overloading and excessive muscular fatigue, supporting the epidemiologic findings of a possible causal role of WBV in the development of (low) back troubles*". It is estimated that 4 - 7% of the working population in the EU are exposed to potentially harmful Whole-Body Vibration.

The National Institute for Occupational Safety and Health reports that musculoskeletal injuries, such as low back pain, vertebrogenic pain, and degenerative disk disease, account for 1 out of 5 of emergency-room-treated occupational injuries. Physical demands of many jobs make the musculoskeletal system highly vulnerable to a variety of occupational injuries and illnesses. WBV is one of the most important etiologic factors behind development of these disorders [27].

Hedberg (1991) [32] reported that the risk for certain types of cardiovascular disease in Sweden is more than three times higher for commercial drivers than for the average worker. 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

[1] A thorough guidance on evaluation of human exposure to ride vibration is given in part 1 and 5 of the international standard ISO 2631 [18] [5].

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) [33]. The increased incidence and mortality from ischemic heart disease among Swedish truck drivers has remained constant over the period 1985 – 1996, as shown by Bigert et al (2004) [26]. Hedberg & Langendoen (1989) [34] showed that amongst older commercial drivers, musculoskeletal problems and cardiovascular diseases are the primary reasons for changing their occupation.

3.1.2 Truck and bus drivers vibration exposure may exceed the EU Action Value

The European health and safety directive on physical agent vibration, 2002/44/EC [2], defines a measure A(8) for workers' 8 hour daily exposure to Whole-Body Vibration. If the A(8) exceeds the Action Value of 0.5 m/s^2, the directive demands employers to take organizational and/or technical measures to minimize the vibrations. Work tasks that bring exposures above the limit A(8) = 1.15 m/s^2 are prohibited. In Sweden the exposure limit is sharpened into 1.1 m/s^2. Since 2005, the directive minimum requirements have been implemented in all EU member state national laws. The directive is showed in Figure 2.

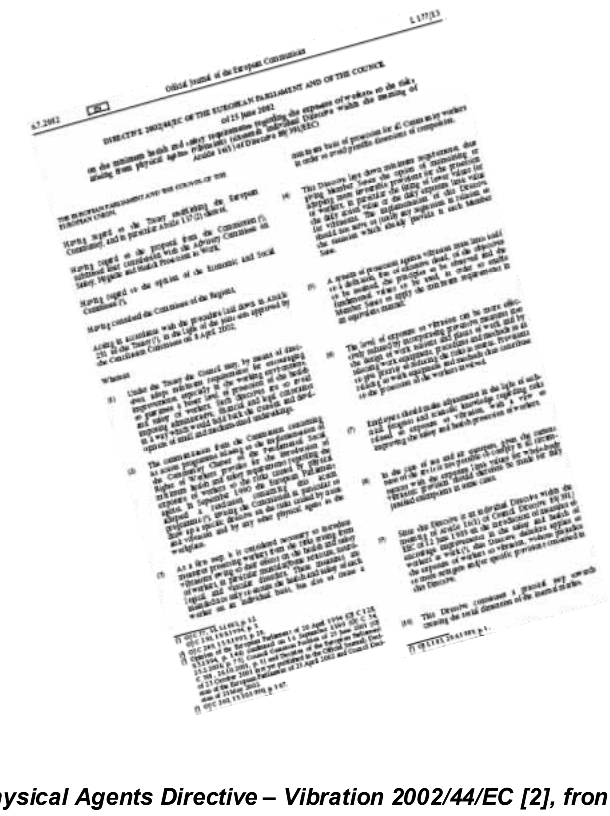


Figure 2 EU Physical Agents Directive – Vibration 2002/44/EC [2], front page

Professional drivers may be exposed to high vibration exposure and risk. The main reasons are that vibration intensity is higher in heavy vehicles (as compared to passenger cars), and the exposure time is often close to 8 hours per day. Ahlin et al (2000) [3] collated the vibration exposure of truck drivers with road roughness, vehicle type and condition, as well as with driving behaviour such as speed. Among the conclusions were that many heavy vehicle drivers in Sweden may be exposed to vibrations above the EU Action Value A(8) = 0.5 m/s^2. Within reasonable ranges, the degree of road roughness was found to have much larger impact on driver's WBV exposure, than factors such as driving speed, vehicle type and vehicle condition.

3.1.3 Bumps are of special concern to both ride quality and health

3.1.3.1 Measuring discomfort due to bumpy rides

Human exposure to occasional shock has large impact on the perceived ride quality. It is therefore very important that indicators of ride quality reflect comfort disturbance caused by shocks/bumps. Four methods to evaluate ride comfort are used all over the world today. A good overview of these is given by Els (2005) [60]. Most important is the ISO 2631-1 (1997) [18].

Spång (1997) [48] showed that the running Root-Mean-Square (RMS) of the weighted acceleration (using integration time 1 s) is a useful definition of bumpy vibration. This definition correlated very closely with annoyance perceived by a large test panel; R^2 = 92 %. The running rms method is used for transient vibration in the ISO 2631-1 standard.

For public transport, the running rms values can be compared to the (dis-)comfort scale in Table 1. This vibration comfort scale is used for people in public transport on roads, railways, in air and at sea. The level of annoyance depends on passenger expectations with regard to trip duration and the passenger's activities (e.g. reading, eating or writing) and many other factors (acoustic noise and temperature). Therefore limits are therefore not explicit, but include overlaps.

Table 1 ***Indicative comfort reactions of people in Public transportation, as per ISO 2631-1 [18]***

a_w rms		
min	**max**	**Comfort level**
> 2	> 2	***"Extremely uncomfortable"***
1,25	2,5	***"Very uncomfortable"***
0,8	1,6	***"Uncomfortable"***
0,5	1	***"Fairly uncomfortable"***
0,315	0,63	***"A little uncomfortable"***
0	0,315	***"Not uncomfortable"***

Hassan & McManus (2001) [51] showed that professional drivers perceive somewhat lower comfort disturbance for a given vibration magnitude, than seen in Table 1. Two causal factors to this finding have been identified. First, the driver can see large road obstacles and are better prepared, (their resonance-sensitive organs are protected by increased muscle tonus) when the resulting vibration comes. Secondly, the driver has a steering wheel in the hands, thus being better able to stabilize pitch and fore-aft motion of the upper body. However, there is no special comfort scale for professional drivers yet.

Further reading is given in the section "*3.1.4 Especially vulnerable road user groups*".

3.1.3.2 Measuring health risk due to bumpy rides

Sandover (1998) [4] made an review of expert opinion, stating that in general, transient vibrations with multiple shocks are much more hazardous than stationary vibration. In practice, this means that bumpy rides typically are unhealthier than ride vibration such as on a modestly wash-boarded gravel road. There are many examples demonstrating the risk from bumps, including spinal compression fractures when riding snowmobiles or military combat vehicles in rough terrain.

A method to quantify Whole-Body Vibration containing multiple shocks in relation to human health was standardized in 2004. The ISO 2631-5 [5], method uses peak vibration values to predict compression stress in the spine, and reports equivalent daily static compression dose, S_{ed}. A S_{ed} value above 0.8 MPa reflects a high health risk due to transient mechanical shocks. In contrast, a S_{ed} value below 0.5 MPa corresponds to a non-significant risk. The employer is obliged to perform a risk assessment for workers exposed to repeated mechanical shock, such as from bumpy rides. In Sweden, such assessments are, in practice, made in accordance with ISO 2631-5. Results from such assessments of professional drivers emphasize the importance of a smooth road surface to keep health risks low.

Repeated driving over bumps, resulting in transient vibration yielding a S_{ed} over 0.5 MPa, may be prohibited by the Work Environment Administration. One example is the recent prohibition, coupled with a 1 000 000 SEK (over 100 000 €) fine, against risks associated with line bus traffic over severe traffic calming speed humps on Vikingavägen (the Viking Road) and Lufthamnsvägen (the Airport Road) in Täby, Sweden. After the prohibition in the spring of 2007, the traffic on several bus routes totally stopped until each hump was repaired or totally removed, so that the S_{ed} was reduced to less than 0.5 MPa. See Brandt & Granlund (2008) [6].

Marjanen (2005) [61] studied transient vibration in 25 mobile machines for 30 hours. The results showed that the ISO 2631-5 method, based on S_{ed} value, gave a worse rating of bumpy exposures than the ISO 2631-1 method based on RMS-value. The latter is relevant for calculation of the daily vibration exposure A(8), as defined in the directive 2002/44/EC [2]. An illustrating result was an "*uncomfortable*" exposure with RMS = 0.85 m/s^2, gave a S_{ed} –value of 2.92 MPa. So while the RMS was below the exposure limit of A(8) = 1.15 m/s^2, the exposure was high above the 0.8 MPa limit for high health risk defined in ISO 2631-5.

When investigating methods applicable to tactical ground vehicles, Alem (2005) [62] found the ISO 2631-5 method to be more sensitive to cross-country terrain rides than other standards. The report mentions an anecdote on hematuria (blood in the urine) being observed in 50 % of the company, after completing a military exercise mission.

According to the ISO 2631-5 standard, the X-Y axis natural frequencies in the human spine are about 2.1 Hz. Therefore it is important that humans are not exposed to strong vibrations at frequencies around 2.1 Hz in or across the direction of travel. This should be recognized, when assessing risks associated with undesired variances in pavement cross slope, which in high vehicles can cause transient roll motion accompanied by lateral (and vertical) vibration.

Further reading is given in the following section "*3.1.4 Especially vulnerable road user groups*".

3.1.4 Especially vulnerable road user groups

Some people are especially vulnerable to vibration. Bumpy rides may be detrimental to:

- People with certain disabilities, diseases or injuries.
- Pregnant women and their unborn babies, see Armstrong et al (1988) [36] and Council Directive 92/85/EEC.
- Injured ambulance patients.

The Academy of Pediatrics (1999) [29] states, that ambulance transports may cause decreased vascular tone, manifested by unexpected decreases in blood pressure. Ride vibration may cause care equipment to come loose, cause settings to change, or produce disturbances in monitors and equipment. Furthermore, vibration may decrease the ambulance nurse's ability to perform care procedures.

Many ambulance patients report that the pain suffered during the transport as being the worst experience in their whole life. [Personal communication with Leif Leding of the Swedish Ambulance Academy].

The European trend towards fewer and more specialised hospitals is resulting in a greater percentage of ambulance transports having to cover longer distances while simultaneously administering intensive care. To manage this more, and heavier, medical equipment is required to be carried on board. As a consequence of this, modern ambulances must have a greater load capacity than before. Large vehicles, with a similar design to trucks, are needed. An effective load capacity of more than 1 tonne is common for Mobile Intensive Care Units (MICU). Ahlin et al (2000) [3] showed that ride vibration is significantly worse in large MICU ambulance vehicles, than in small Emergency Ambulance vehicles.

One of the few efficient methods to reduce ride vibration in ambulance cars, is for the driver to "read" the pavement surface condition and by risky driving avoid the worst roughness, as seen in Figure 3.

Figure 3 ***Emergency Ambulance on wrong side of Road 331, avoiding edge deformations***

3.1.5 Vibration intensities in road vehicles and mobile machinery

Most road vehicles, including modern trucks with suspended cabs, have fairly low levels of Whole-Body Vibration (WBV), given that the pavement is in good condition. Vehicles with less effective suspension, such as trucks with non-suspended cabs, may cause high WBV levels. Heavy truck vertical vibration is maximum when the truck is unloaded, while roll and lateral vibration tend to peak when the truck has full payload. Of course, the WBV exposure is very dependent on the quality of road surfaces, vehicle speeds and other factors such as how the vehicle is operated. Therefore, it is often necessary to measure the vibrations, or the road condition, in order to make an accurate risk assessment. An indicative example of vibration levels in road vehicles is given in Table 2. As can be seen from the table, the A(8) EU Action Value of 0.5 m/s^2 corresponds to a work environment being on average "fairly uncomfortable" for the full working day.

Table 2 Indicative example of Whole-Body Vibration magnitudes in road vehicles

Passenger cars	0.1 to 1 m/s^2 average for route. Up to 2 m/s^2 at bumps.
Heavy trucks	0.2 to 1.6 m/s^2 average for route. Often over 2 m/s^2 at bumps.
Reference on comfort, as per ISO 2631-1 [18]	< 0.315 m/s^2 is "not uncomfortable". > 0.5 m/s^2 is "fairly uncomfortable".
EU Action Value [2]	A(8) = 0.5 m/s^2, "average over 8 hours"

From the table, it can be seen that truck drivers are exposed to markedly higher vibration intensity than car drivers. Campbell et al (1981) [35] explained some reasons:

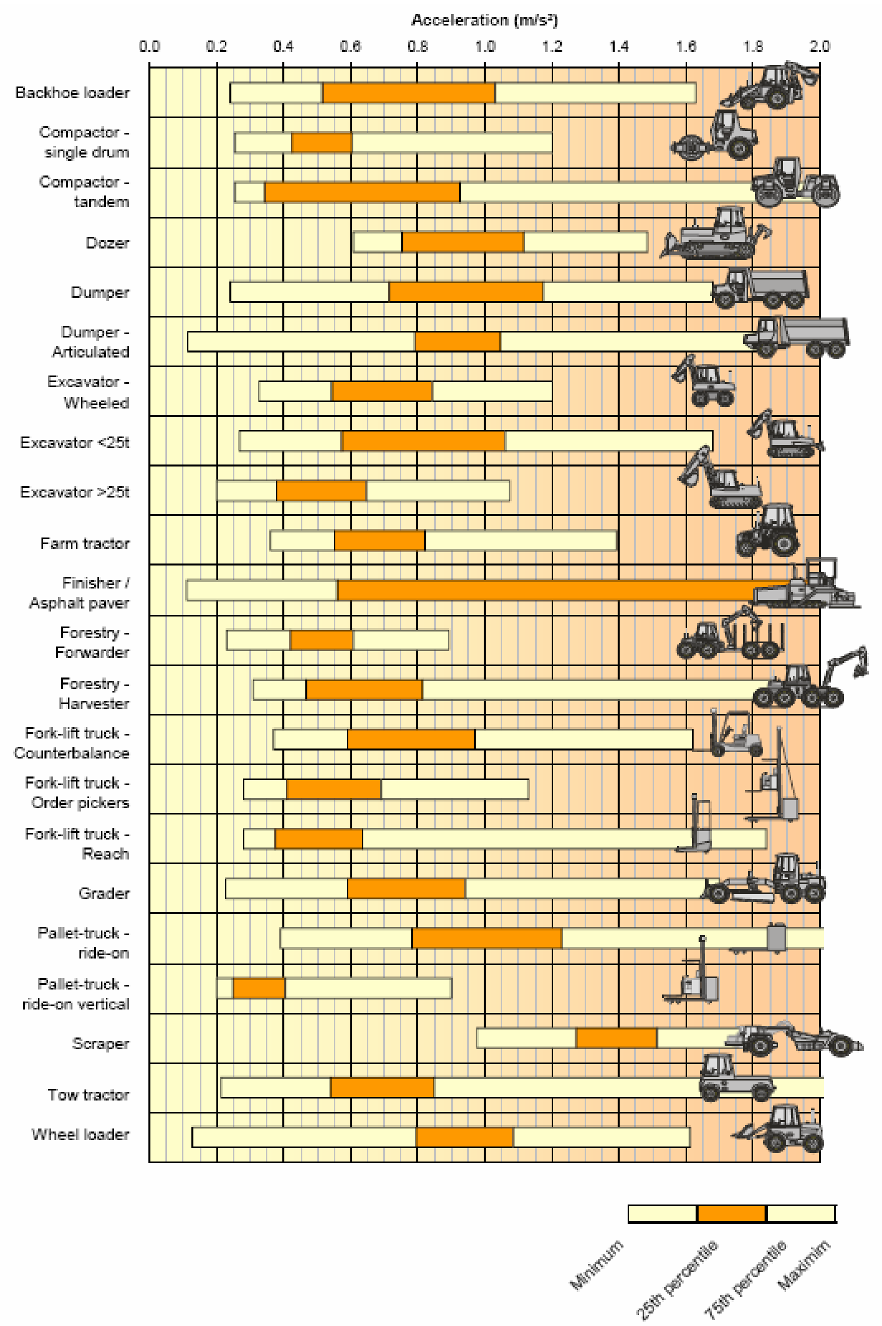
1. Driver location - namely, the truck driver is usually located at the extremities of the vehicle, rather than near its centre of gravity.
2. Trucks are more dynamically active at low frequencies of excitation, as caused by the use of articulation for manoeuvrability and frame flexibility for durability
3. Truck suspension systems possess substantial amounts of dry friction, thereby transmitting more road input to the vehicle.

The chassis suspensions on heavy vehicles are also designed for a much wider range of payload, than on passenger cars. In addition, heavy vehicles have heavier unsuspended masses (tyre, rim, brake and axles) than cars do. When the unsuspended mass hits a bump, it transfers energy to the vehicle body. A heavier mass can transfer more vibration energy than a lighter mass.

For a general comparison purpose, examples of typical vibration levels in mobile machinery used in civil engineering, forestry and industry works are given in Table 3. For machines that are often operated at considerable speed, such as graders and tractors, the highest vibration levels are usually generated in road transport mode. The table has been reproduced from the *EU*

Guide to good practice on Whole-Body Vibration [24], which gives useful guidelines to reduce risks from WBV exposure.

Table 3 ***Examples of WBV magnitudes in common mobile machinery [24]***



3.1.6 Ride vibrations have a negative effect on traffic safety

In the mid 1970's, the exposure of truck drivers to vibration was an issue raised at the federal government level in the USA, formulated as "*Do vibrations (as well as noise, toxic fumes and other factors that contribute to truck "ride quality") have a negative effect on driver health and on highway safety?*" Eventually, a five-year research programme, "*Ride Quality of Commercial Motor Vehicles and the Impact on Truck Driver Performance*", answered this question. The findings were summarised in the report *Truck Cab Vibrations and Highway Safety* [30]. This report was jointly produced by leading researchers, road authorities, vehicle manufacturers, hauliers and commercial drivers. It shows that the answer to the key question as to whether there is any correlation between cab vibrations and road safety is YES; see illustration in Figure 4. Yes, there is good reason to believe that vibrations affect drivers' health, and that vibration must be eliminated at source through effective road maintenance rather than merely dampened. The report concludes that if road network deterioration is allowed to continue, the result will be serious health and road safety problems.

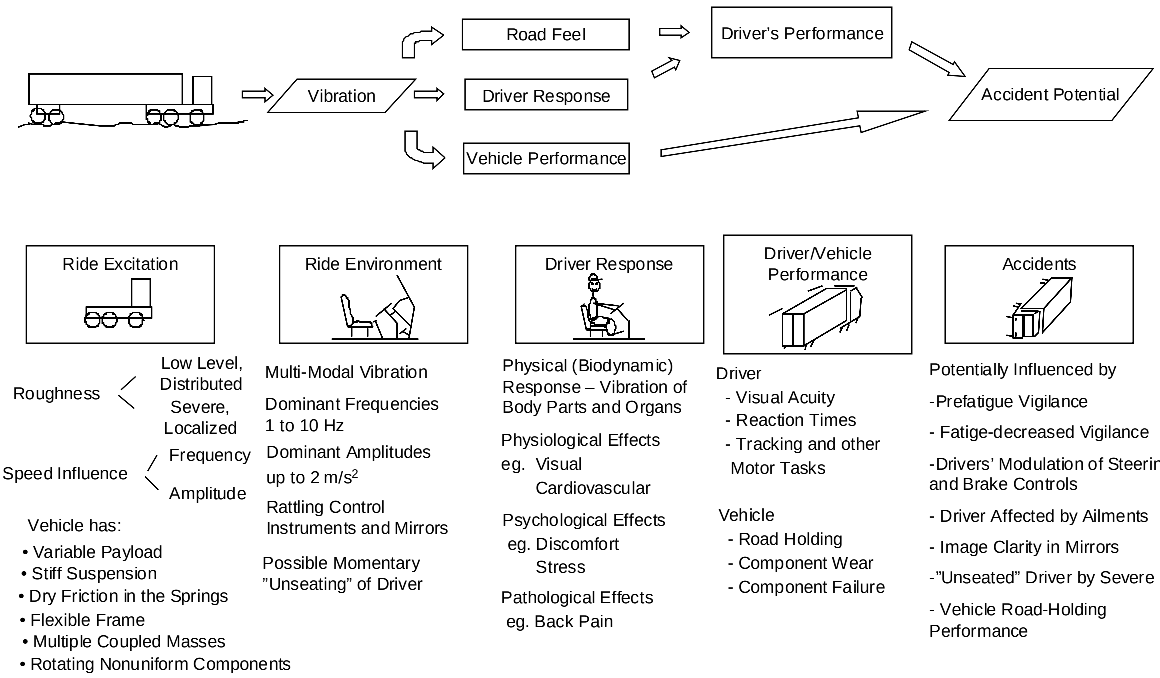


Figure 4 The primary elements in the link between truck ride vibration and safety [30].

When studying Figure 4, take note of the described driver response in terms of stress and cardiovascular effects. This associates with the research results on increased level of stress hormones and mortality from ischemic heart disease, referred in the previous section "*3.1.1 General health risks associated with ride vibration*".

The most common lethal truck accident mode is rollover. Less common modes are jack-knifing and trailer swing. Jack-knifing means the accidental folding of an articulated vehicle, similar to a pocket knife. When the prime mover skids, the trailer can push it from behind until it spins round and hits the trailer. Adverse road conditions, such as a slippery road surface, or an obstacle (i.e. curbs) hitting the rear wheels, may contribute to jack-knifing. Most truck drivers are skilful enough to correct a skid before the vehicle combination undergoes jack-knifing. Trailer swing is easier to correct. Side forces that result from cornering, operating on a crowned road, and side winds accelerate the jack-knife situation.

Research by Ihs et al (2002) [31] confirms a positive correlation between road roughness (ride vibration) and traffic accident[2] frequency (crash risk) in Sweden, see Figure 5. Rough roads with an IRI[3]-value over 3 mm/m show more than 50 % higher crash rate than smooth roads with an IRI below 0.9 mm/m. The study also showed that as roughness becomes very severe (over 10 mm/m), the crash rate increases even more than shown by the slope of the linear graphs.

The graphs at Figure 5 also show that the crash rate is much higher in the winter, than in the summer. This is due to factors such as lower road surface friction on icy roads and darker driving conditions.

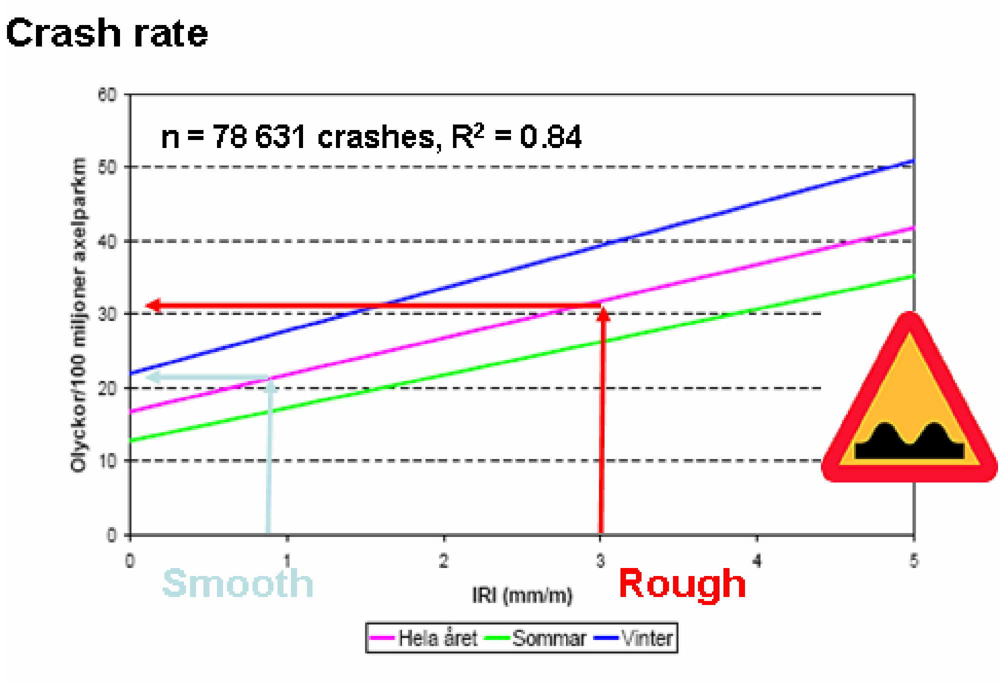


Figure 5 ***Rough roads have > 50 % higher crash rate. After Ihs et al [31]***

[2] In the study, accidents in junctions and with wild animals were excluded.
[3] IRI = International Roughness Index

3.1.7 Summarizing health and safety risks for EU Northern Periphery road users

The Swedish National Institute of Public Health has found that in Sweden, the most common types of preventable mortalities are lung cancer (death rate of 17.1), suicide (15.4) and cerebrovascular disease (11.8). Among the therapeutic treatable death causes, diabetes mellitus is worst with a death rate of 4.5. Road traffic crashes are worse, with a death rate of 4.9 on average for the whole country. However, there are large differences in the risk of being killed in a road traffic accident between different areas in Sweden. While the urban areas of Stockholm, Gothenburg and Malmoe have a Standardised Mortality Ratio (SMR) of 70 for road traffic crashes, the rural areas have a SMR of 177. This means that road users in the rural areas have 153 % higher risk in ending up in a lethal crash, as compared to road users in large cities. Of the rural counties in Sweden, Jämtland and Västernorrland have the highest SMR for road traffic crashes. In these counties, road traffic crashes are taking 39 % more lives than diabetes is [58].

This chapter has clearly showed that EU Northern Periphery road users are exposed to serious health and safety risks. Professional drivers are exposed to a very high risk for stress-related cardiovascular diseases, having three time higher rate for certain types of cardiovascular disease than other people. They are also exposed to high risk for musculoskeletal problems. All road users in the Northern Periphery are at high risk for being injured in traffic crashes on rough and poorly maintained roads. These serious findings call for responsible corrective actions. Such actions must be very well focused, since the available funds are sparse compared to the size of the Northern Periphery road networks.

3.2 AN OVERVIEW OF HEAVY TRUCKS DYNAMICS

Why do truck suspension systems isolate some vibrations very well, yet amplify others? This section will attempt to answer this type of question. The following texts are inspired by several sources, including handbooks such as the *Fundamentals of Vehicle Dynamics* [7]. The suspension performance figures come from a presentation on heavy trucks dynamics [8], and are reprinted with kind permission by MSc Henrik Lindh, supervisor on vehicle dynamics at Volvo 3P.

3.2.1 Sources of truck ride vibration

The term ride[4] vibration describes motion with frequencies from 0.5 to 25 Hz. Truck vibrations in the ride frequency range are excited by both internal and external sources. Internal sources include engine combustion pulses, power train imbalance, non-uniform wheel geometry and non-uniform tyre stiffness. External sources include pavement roughness, pavement deflection variance [9] and air pressure variance (wind load, or air bursts from fellow vehicles or reflections from road tunnel walls).

3.2.2 Influence of road roughness, vehicle factors and speed

In brief, truck cab vibrations are primarily determined by road condition, with vehicle properties being secondary, as seen in Figure 6 by Forssén (1999) [10]. Note the “0.00” effect of tyre pressure variance. This result is from tests within normal pressure level recommendations, while extremely low pressures when using Central Tyre Inflation (CTI) systems have a large effect.

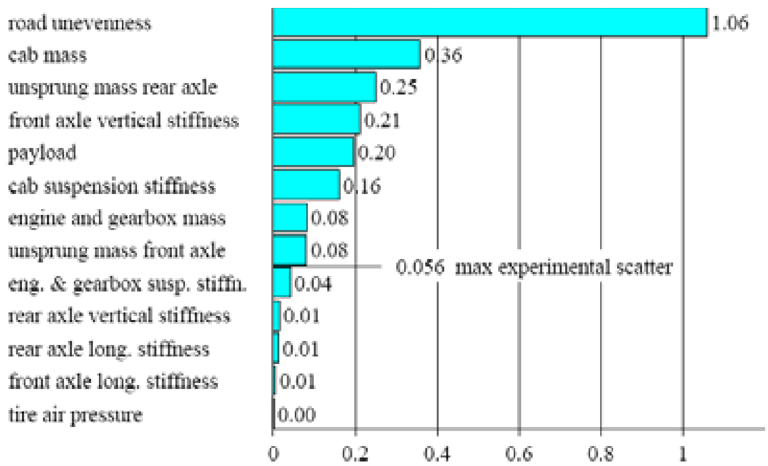


Figure 6 ***Effect of road roughness and vehicle properties on truck cab vibration [10].***

There is, in general, also a strong positive correlation between speed and vibration. At speed levels below some 30 km/h, such as in parking lots and during off-road driving at construction sites, an increase in speed by one percent will increase vibration several percent.

[4] Many vehicle engineers distinguish between RIDE as < 5 Hz and SHAKE as 5 – 25 Hz vibration.

At highway speeds however, the effect of speed on ride vibration is rather small. To reduce vibration a certain percent, it may be necessary to reduce speed twice as much. An example from a 20 km test site is given in Figure 7. A 29 % speed reduction (from 70 km/h to 50 km/h) resulted in only 18 % reduction in average vibration and 15 % reduction in maximum vibration. Also at 30 km/h, the 0.5 m/s^2 EU Action Value was exceeded. The speed limit was 90 km/h [9].

Ahlin & Granlund (2002) [11] showed in a theoretical analysis that when driving at highway speed levels, a large effect of speed change on ride vibration can only be expected when the road roughness consists of high amplitudes at long wavelengths. If there is a high degree of roughness with intermediate-length, the speed must be reduced to parking lot speed level, i.e. below 20 km/h, in order to reduce vibration significantly. If only very short wave roughness is present, the chassis vibration may in fact be reduced by increasing the driving speed. (The latter is a very rare exception however, since most rough roads also have high amplitudes at long wavelengths).

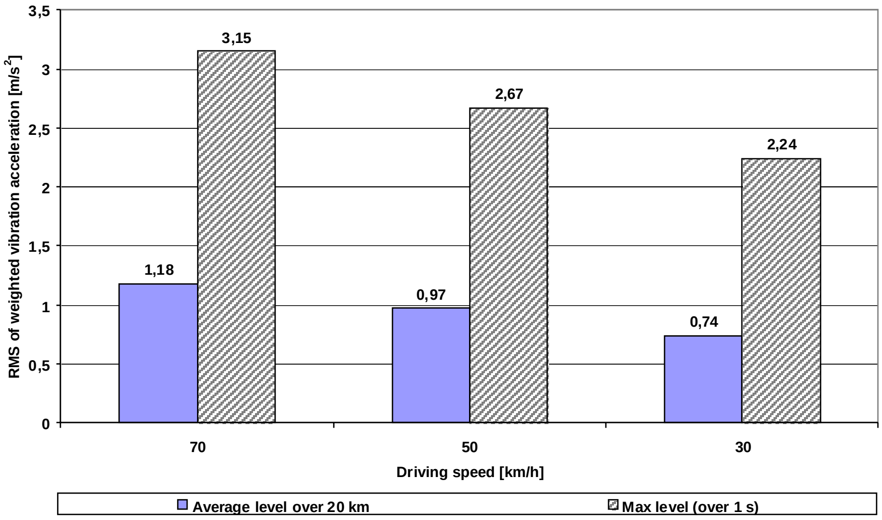


Figure 7 ***Influence of speed on seat vibration in a loaded Volvo FL12 on Rd 374, n w Storfors, Sweden***

3.2.3 Heavy trucks have several suspension systems

All highway vehicles have a suspension system designed to isolate vertical vibration from the wheels to the vehicle body. The primary functions of a chassis suspension system are to [7]:

- Provide vertical compliance so the wheels can follow uneven road surfaces, while isolating the vehicle body from the road's roughness.
- Maintain the wheels in proper steer and camber attitudes to the road surface.
- React to tyre control forces – longitudinal (acceleration and braking) forces, lateral (cornering) forces, and braking and driving torques.
- Resist chassis roll motion.
- Keep the tyres in contact with the road under minimal load variations.

Obviously, chassis suspension systems must meet many more demands - not least in a safety perspective - than to "only" isolate the cab from vibration and shock of various frequencies, directions, amplitudes and interacting histories.

A modern heavy truck has several suspension systems, as seen in Figure 8. In fact, the trucks frame may also be considered as a suspension system, with its flexural bending modes. Inside the cab, most truck driver's seats are today also equipped with a suspension system.

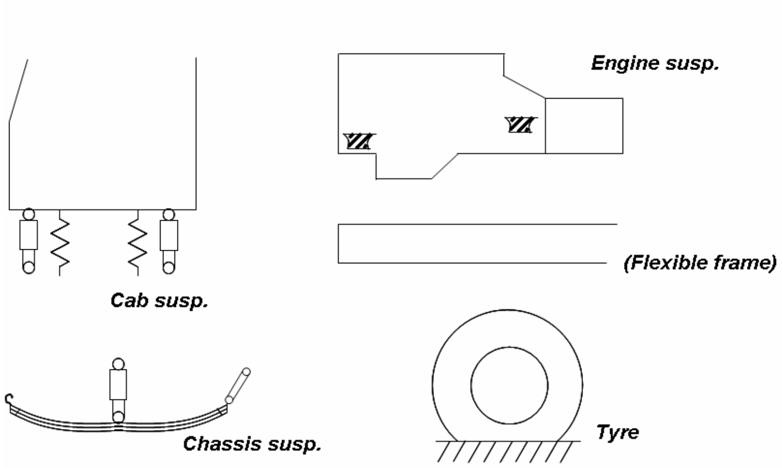
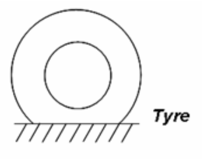


Figure 8 ***Heavy trucks have several suspension systems***

3.2.3.1 The tyre acts like a spring

Counting from the vibration main source, the road surface, the truck's first vibration filter comprises its tyre.



Due to the enveloping effect of its contact patch, the tyre smears variance in pavement Macro Texture (MaTx have waves from 0.5 to 50 mm length) and to some extent Mega Texture (MeTx have waves from 50 to 500 mm). The tyre walls also act like springs, which - under noise generation - further absorb texture variance and interact with the vertical motions of the vehicle body and unsprung masses. The tyre does not provide significant damping, with regard to the lower frequencies of ride.

The vertical vibration isolation performance of a typical truck tyre is demonstrated in Figure 9. The upper left graph shows an example of road profile spectra (tyre input), while the upper right graph shows wheel axle acceleration (tyre output). The bottom curve shows the quotient of road "acceleration"[5] and axle acceleration. This gain curve shows the tyre's isolation performance. A gain below 1 means that the system is isolating vibration, while a gain over 1 means that it is amplifying. As seen, the tyre efficiently isolates vibration with frequencies higher than some 12 Hz. At the tyre eigenfrequency of about 8 - 12 Hz, vibrations are amplified. This resonance response is known as "wheel axle hop", and contributes to wash boarding of poor dirt roads. Vibrations with low frequencies are transmitted straight through the tyre, which then follows the road profile like a rigid body.

[5] The time domain term "road acceleration" may be somewhat confusing to road engineers. It corresponds to the spatial domain term "Slope Variance" (SV). SV was a key parameter in the 1958 – 1960 AASHO Road Test [12], used as an index for short wave road roughness. In the giant AASHO Road Test, SV was found to be the most important factor behind the Public's judgement of road serviceability. In fact, the Road Test results showed that SV (road roughness) was many times more important for road users ratings, than rutting, cracking and patch repair altogether.

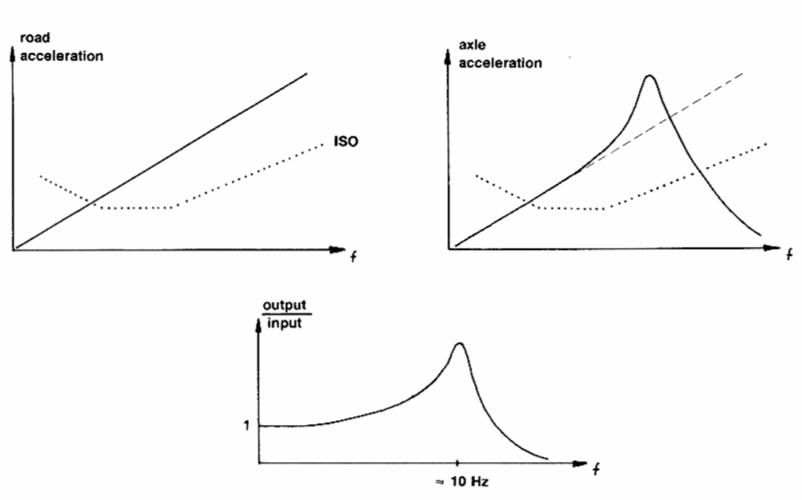


Figure 9 Input and output vertical acceleration of a truck tyre [8]

The basic relationship between roughness wavelength (λ) [unit: m], travel velocity (υ) [unit: m/s] and vertical vibration frequency (***f***) [unit: Hz] is given in Formula 1.

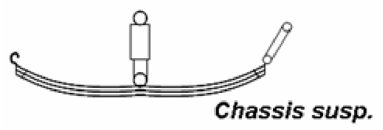
$$\lambda = \frac{v}{f}$$

Formula 1, Wavelength, Velocity and Frequency

When driving at 30 km/h (8.3 m/s), the tyre spring resonance of 8 - 12 Hz occurs on 0.7 - 1 m road roughness wavelength, as per Formula 1. At 90 km/h, tyre resonance occurs on 2 - 3 m waves.

3.2.3.2 The chassis suspension isolates the vehicle body from the wheels

Counting from the vibration main source, the road surface, the truck's second vibration filter comprises its *chassis suspension*.



The vertical vibration isolation performance of a typical truck chassis suspension is demonstrated in Figure 10. The upper left graph shows our example of wheel axle acceleration (chassis suspension input), while the upper right graph shows frame acceleration (chassis suspension output). The bottom curve shows the quotient of the axle and frame acceleration. This gain curve shows the chassis suspension's isolation performance.

The truck chassis suspension system efficiently isolates vibration with frequencies higher than some 5 - 6 Hz. Vibrations with some 2 - 4 Hz are amplified. Vibrations with low frequencies are transmitted straight through the suspension.

When driving at 30 km/h, the suspension resonance of 2 - 4 Hz occurs over road roughness with 2 - 4 m wavelength. At 90 km/h, suspension resonance occurs over 6 - 12.5 m roughness waves.

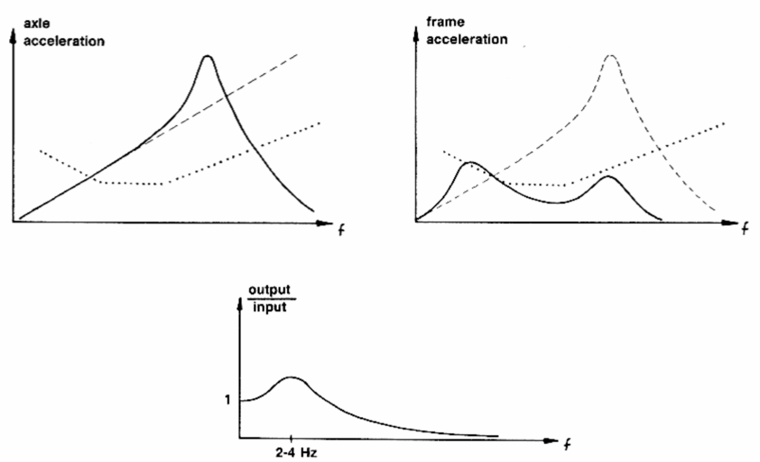


Figure 10 ***Input and output vertical acceleration of a truck chassis suspension system [8]***

Ride vibration is typically small in amplitude, involving some tenfold millimetres of suspension travel. Many truck suspension systems exhibit nonlinear properties, due to friction in struts and bushings, or interleaf friction in leaf springs. Gillespie [7] explains that for small ride motions, the effective stiffness may be three times greater than the nominal spring stiffness. Therefore some trucks may actually be more comfortable on roads with a lot of short wave roughness, than on roads without such roughness. However, this is not true for long waves and in cars.

3.2.3.3 Frame beaming

Counting from the vibration main source, the road surface, the truck's third vibration filter comprises its *frame*. It is somewhat questionable whether or not to consider the frame as a suspension system. However, its negative effect on ride is significant at *beaming* resonance frequencies.

It is customary to make heavy truck frames flexible, due to commercial demands such as low deadweight, fatigue resistance and traction in off-road conditions.

Figure 11 shows a 34 Degree-Of-Freedom truck model. Here the frame is modelled as consisting of 6 beam sections, connected with longitudinal and torsion springs and dampers (not shown). Examples of beaming are showed later, in Figure 13.

Note the integrated model of the suspended truck engine, constituting a powerful source of internal vibration with higher frequencies. The first harmonic of an engine running at 1500 rpm is at 1500 / 60 = 25 Hz, while higher order engine harmonics have higher frequencies.

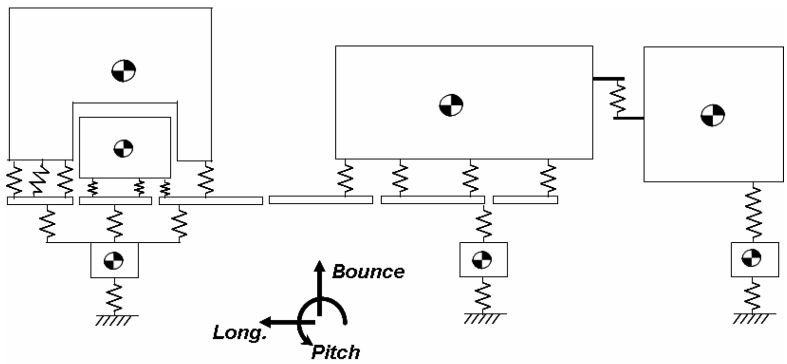
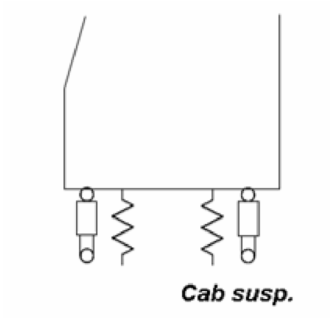


Figure 11 ***Truck model having a flexible frame [8]***

3.2.3.4 The cab is isolated from the frame

Counting from the vibration main source, the road surface, the truck's fourth vibration filter comprises its *cab suspension*.



The vertical vibration isolation performance of a typical truck cab suspension is demonstrated in Figure 12. The upper left graph shows our example of frame acceleration (cab suspension input), while the upper right graph shows cab acceleration (cab suspension output). The bottom curve shows the quotient of the frame and cab acceleration. This gain curve shows the cab suspension's isolation performance. The system efficiently isolates vibration with frequencies higher than some 3 Hz. Vibrations with some 1 - 2 Hz are amplified. When driving at 30 km/h, suspension resonance of 1 - 2 Hz occurs on road roughness with 4 - 8 m wavelength. At 90 km/h, resonance occurs over 12 - 25 m waves. Vibrations with very low frequencies are transmitted straight through the suspension.

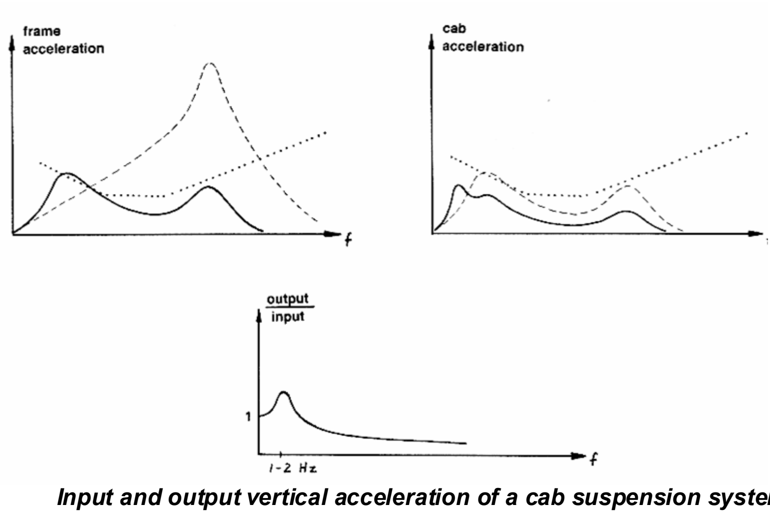


Figure 12 ***Input and output vertical acceleration of a cab suspension system [8]***

3.2.4 Net vibration in a truck cab

As seen in the above graphs, each of the suspension systems in a truck isolate vibration very efficiently. This is true for vibration with frequencies above each system's eigenfrequency. For vibration close to an eigenfrequency, resonance results in amplification instead of isolation. Resonance is seen as values above 1 in the above gain curves for each system.

For an articulated tractor-trailer truck cab, an example of net vibration content is given in Figure 13. The graph has resonance peaks at the eigenfrequencies of each suspension system.

Note that on the vertical logarithmic scale of the Figure, the cab vibration is many times more powerful at 1 - 3 Hz frequencies than at higher frequencies. For highway speeds of 50 - 90 km/h, the 1 - 3 Hz frequency range corresponds to 5 - 25 m long road unevenness wavelengths.

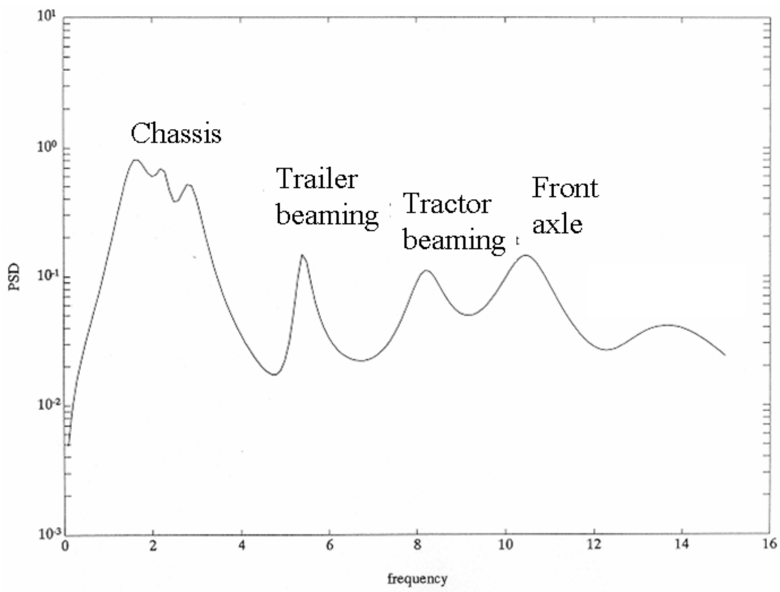


Figure 13 ***Power Spectral Density of net vibration in a truck cab [8]***

3.2.5 Seat suspension

A good seat improves the situation further, and the most efficient vibration isolating seats used in road vehicles can be found among truck driver seats.

Figure 14 shows vertical vibration data taken by Ahlin et al [3] at cab floor and at the driver's seat in a Volvo F12 6x2 timber logging truck, when travelling on National Highway 90 in Northern Sweden. By comparing the graphs, it is clear that cab floor vibration at frequencies over 3 Hz are quite efficiently isolated from the drivers buttocks by the advanced air suspended truck seat.

However, the graph for the seat pan shows highest seat vibration intensity at frequencies between 1.5 and 2.5 Hz. By comparing the graphs in Figure 14, it is clear that the expensive air suspended seat does not isolate vibration, but rather amplifies vibration, at the dominant frequencies below 3 Hz.

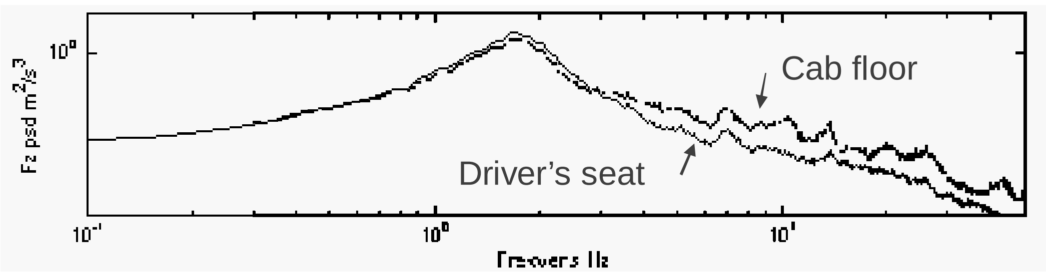


Figure 14 ***Power Spectral Density of vibration on the seat and on the floor in a truck cab [3]***

32 kilometres of the Hw 90 test section were very rough, while 5 kilometres were smooth. The root-mean-square for the weighted vertical acceleration on the seat was 0.96 m/s^2 on the 32 km very rough section of Hw 90, while the corresponding figure for the 5 km smoother section was 0.38 m/s^2. The figure 0.96 m/s^2 from the rough section is much higher than the A(8) = 0.5 m/s^2 action value for an daily eight-hour reference period, set in the health and safety directive 2002/44/EC [2]. Clearly, the ride vibration problem related to roads with similar roughness (especially long wave, as indicated from frequency content in Figure 14), is very serious. After the truck ride measurements were taken by Ahlin et al [3], the 32 km long rough section of Hw 90 was reconstructed by Swedish Road Administration.

A new and promising technology for damping in seat and cab suspension systems is based on MagnetoRheology (MR). While developed for seat suspensions, MR-technology may be more successful in large vehicle cab suspensions, where it can be used with soft springs without comprising ride and stability. LeRoy (2006) [68] claims that MR can provide both roll isolation and pitch stability.

3.2.6 Wheel axle vibration impacts on traffic safety

As a truck wheel axle is exposed to roll vibration, any arbitrary point at its outermost parts (as well as on the attached wheels) moves in lateral direction. This results in distortion to the tyre/road contact patch, making the laterally moving patch polishing the road into lower friction for following vehicles. This contact patch distortion also increases the vehicle's own need for road friction and increases its tyre wear [Personal communication with Dr Boris Thorvald, Scania Commercial Vehicles AB].

Less obvious is that when an axle is exposed to roll vibration, it also yaws. This is analyzed by Ahmadian & Ahn (2003) [28]. As a wheel moves upwards and the suspension is momentarily compressed, its toe angle changes. This results in a steering response, similar to the driver slightly turning the steering wheel. If a steering effect occurs as both wheels go up parallel, the phenomenon is called "bump steer". If it occurs as one wheel rises and the other falls (axle roll), it is called "roll steer". Solid axles generally have zero bump steer. The occurrence of roll steer is more or less inevitable, but the degree of severity differs between axle and truck models.

A soft chassis suspension may result in severe bump steer behaviour, especially by the front steering axle. In Australia, this has been identified by McFarlane & Sweatman (2003) [37] as a source of poor lane-keeping behaviour on rough road sections. Where the road width is narrow, these lateral disturbances may require the driver to increase concentration into a stress level significant for driver fatigue.

Roll vibration also results in significant vehicle fatigue damage, as discussed in a Ph D thesis by Bogsjö (2007) [22]. The research reported by Bogsjö is based on a large amount of road condition data, measured with one of SRA CS Profilographs on a set of roads including Rd 331; the road studied in this ROADEX III research task.

3.2.7 Final remarks on heavy truck dynamics

It is well known, even amongst non-specialists, that *stiffness* and *damping* are important suspension design parameters. The potential of softer suspensions as a method to reduce cab vibration has been studied by Öijer & Edlund at Volvo 3P [14]. The results show that a very soft suspension may reduce cab vibration by some 6 - 20 %, which is a clearly noticeable difference. The study also showed that after resurfacing the test road, the cab average vibration was reduced by 67 % and its peak vibration by 85 %.

When heavy trucks are exposed to roll forces at frequencies below some 3 Hz, resonance may cause the roll response to be larger than the input. There is a theoretical possibility that the truck roll eigenfrequency can be reduced, and thus the entire roll resonance, by designing the vehicle with extremely low roll stiffness (by reducing spring vertical stiffness and minimizing lateral separation of left and right springs). However, as illustrated in Figure 15, the interaction between *stiffness* and *damping* also includes a third, and less publicly recognized parameter; *spring travel (*or *deflection/displacement*). Low roll stiffness brings large roll displacements and very poor cornering performance, in terms of a major tendency to rollover in connection with fast large lateral manoeuvres such as in the famous “Moose test” (quick lane change). This is of course unacceptable from a traffic safety perspective, and therefore not suitable to implement in practice [Personal conversation with Dr John Aurell, Volvo 3P].

Figure 15 ***The dynamic triangle of stiffness, damping and spring travel [8]***

When designing single systems therefore, the vehicle manufacturer must consider the complete vehicle performance. Other requirements than vibration environment must also be considered, such as commercial aspects, stability, handling and safety.

The bottom line is:

> *If there really would have been any good quick fixes to radically improve truck drivers ride vibration environment without sacrificing other important issues like traffic safety, the large and skilled engineer teams at Volvo, Scania and other truck manufacturers would have implemented them long ago.*

3.3 RELATING RIDE FORCES TO PAVEMENT PROPERTIES

This section gives a brief summary on pavement geometry design, required to balance ride forces in curves (dynamic equilibrium), and how pavement roughness - as well as bearing capacity variance - excite heavy truck ride vibration. The texts are inspired by various road design manuals and handbooks, such as the AASHO Policy on Road Design [16].

3.3.1 Tight curves are hazardous

Tight curves are typically more hazardous than straight road sections. An example of this is seen in the map of hospital reported accidents on the section of Rd 331 shown in Figure 16. While the straight sections of the road showed no accidents, the wide curves show some, and the tight curves show several accidents. In fact, more accidents happened in the sharp "Roos curve" than at the junction with the significantly more trafficked National Highway 87. In the following sections, dynamic imbalance due to incorrectly banked curves is explained as a risk associated with tight curves. The subject of dynamic equilibrium of cornering forces was initially not considered for the project task, but serious findings during the project work made it inevitable to include it into the report.

Figure 16 ***The south exit of Roos curve in Österforsse shows unusually many accidents***

3.3.1.1 Steady cornering require dynamic equilibrium by correctly banked curves

This first part of this section analyses the ‘exciting’ lateral force acting on a cornering vehicle. Thereafter, the analysis continues with the ‘reaction’ forces needed to keep the vehicle steady in the desired curved path. When balancing these forces, the key exciting factors are vehicle (reference) speed and the road horizontal curvature, whilst the key retaining factors are lateral friction and pavement superelevation (single sided cross slope in curves).

At highway speeds on wet road surfaces, road friction is basically a function of pavement Macro Texture (MaTx) only. Thus, in slippery conditions, the cornering reaction forces depend totally on texture and the pavement superelevation. Under extremely slippery conditions, the lateral friction may drop to almost zero. One example is when driving on black ice. In such conditions, the only reaction force available to balance the ride is totally related to the pavement superelevation/cross slope.

This section ends by showing how this knowledge is used when designing superelevation in curves on new roads, and concludes that this knowledge is not yet sufficiently used in the management of curves on the existing road network.

Failure modes in accidents related to curve design and road friction

De Solminihac et al (2007) [38] have studied accident outcomes in horizontal curves, and have seen that light vehicles are more prone to run-off than are trucks, whereas the main failure condition for trucks and SUV’s is roll over.

Strandberg (1974) [53] related the truck rollover problem to the fact that many heavy vehicle combinations have poor rollover (overturning) stability. It is unusual that passenger cars rollover at lateral accelerations below 10 m/s^2. However, the rollover limit is often less than 3 - 4 m/s^2 for trucks. A half empty tanker with a bad suspension might roll below 2 m/s^2. While passenger cars require high friction and extreme skid to rollover, trucks may rollover on slippery surfaces without much warning to the driver. Strandberg also referred to numerous of investigations showing that most truck drivers use larger lateral accelerations at low speeds than at high speeds. Two of the most efficient truck design improvements to safety are utilizing maximum lateral distance between chassis suspension springs and implementing anti-roll bars. Both actions result in higher roll stiffness, thereby increasing roll vibration.

Persson & Strandroth (2005) [39] identified skidding as a common failure mode in lethal crashes on Swedish roads. During wintertime, 53 % of the lethal skid accidents occurred on thin and very slippery “black ice”. Wide roads with a high standard of winter operations did not feature to any extent in skid statistics. Krafft et al (2006) [44] compared Swedish accident outcome for cars with and without an antiskid system. They found that antiskid systems reduced the risk of accidents involving human injury by over 13 % lower on dry road surfaces. Furthermore, on slippery surfaces, antiskid systems reduced the risk by an astonishing minimum of 35 %. This shows that the efficiency of antiskid systems as safety equipment is almost as fundamental as of a seatbelt. This further confirms skidding as a common and very serious safety risk on icy low volume roads in the northern parts of EU.

The exciting lateral force

As described by Newton's second law of mechanics, cornering vehicles undergo centripetal acceleration acting toward the centre of the curvature. As seen in Formula 2, the associated lateral[6] force ***F*** is a product of vehicle mass ***m*** [kg] and squared vehicle speed ***v*** [m/s], divided by the curve radius ***R*** [m]. For a vehicle with given reference speed, the lateral force depends only of the curve radius. Smaller radii (tighter curves) yield higher lateral forces. For tight curves, even a minor increase in radius results in a large decrease of the lateral force.

$$F = \frac{m * v^2}{R}$$

Formula 2, Lateral acceleration force acting on a cornering vehicle

Figure 17 shows the factors influencing the cornering forces acting on a vehicle as described by the "Point mass model", used in road design manuals worldwide. These are the gravitational force ***G*** [N], the normal force ***N*** [N], the lateral force ***F*** [N], the side friction (demand) factor f_s [-], and tangent of the angle α corresponding to pavement superelevation/banking/cross slope [%].

The total road grip between tyre and pavement can be divided into a tangential part (braking friction, longitudinal direction) and a radial part (side friction, lateral direction). The side friction is the part of the total road grip normally utilized when cornering.

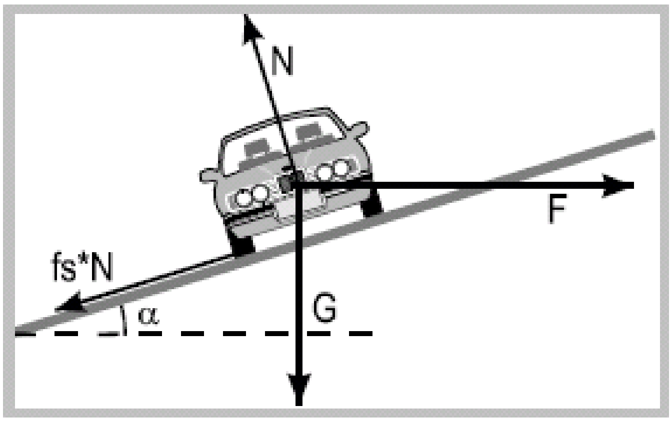


Figure 17 Vehicle cornering forces [15**]**

[6] In **Figure 17**, the centripetal force is substituted by a corresponding centrifugal force in the opposite direction. Even though people in a cornering vehicle perceive a "centrifugal force", it is fictive (not real) on the vehicle. This report follows the practice set used in many road design manuals, by referring to the (fictive) centrifugal force, rather than to the fundamentally correct centripetal force with opposite direction.

The reaction forces needed to balance the ride

If the lateral force **F** is not balanced by reaction forces, the vehicle ride will become unstable and the risk of a traffic accident (run-off, skidding and rollover) will increase. There are two reaction forces that may balance the lateral force **F**. One is the horizontal component of the normal force; **N *** sin(α). The other is the horizontal component of the side friction developed between the vehicle's tyres and the pavement surface friction force, **N** * $\mathbf{f_s}$ ***** cos (α). This can be expressed by the equation in Formula 3.

$$F = N * \sin(\alpha) + N * f_s * \cos(\alpha)$$

Formula 3, Lateral equilibrium

After division by cos (α), the equation can be written as Formula 4.

$$\frac{F}{\cos(\alpha)} = N * (\tan(\alpha) + f_s)$$

Formula 4, Lateral equilibrium (2)

After substitution with **N** = **m** * **g** (g being the gravitation constant) and with **F** as per Formula 2, the equation can be further developed as Formula 5.

$$\frac{m * v^2}{R * \cos(\alpha)} = m * g * (\tan(\alpha) + f_s)$$

Formula 5, Lateral equilibrium (3)

After elimination of **m** and recalling that cos(α) is close to 1 for small angles (from a mathematical point of view, pavement cross slopes are small angles), the equation is, with good approximation, finally expressed as Formula 6.

$$\frac{v^2}{R * g} \approx \tan(\alpha) + f_s$$

Formula 6, Lateral equilibrium (final expression)

This shows that a steady cornering is totally depending on the sum of the cross slope (banking) and the side friction factor. The correct application of banking reduces the need for side friction; while incorrect banking may instead increase the need for side friction.

Figure 18 shows the 'demand' side, the left hand side, of Formula 6 as a linear function of lateral force (Curvature[7]) for speeds of 30 to 110 km/h. A similar graph as function of curve radius is shown in Figure 19. These graphs show that slippery surfaces in very tight curves (R < 200 to 300 m) may be a challenge at low speed levels of 30 to 50 km/h also.

In very slippery conditions, when friction approaches zero, a cornering vehicle must be retained by another force other than friction. As seen in the right side of Formula 6, the only retaining factor beside friction is banking. Banking can be designed up to 5.5 % in Sweden. As friction gets low, this banking can also be decisive for safe cornering in flatter curves as can be seen by the demand values in Figure 19. Conditions that create slippery roads when cornering at highway speeds include black[8] ice, bleeding asphalt, surface contamination such as mud and sand, as well as driving with threadbare slick-worn tyres on a wet road surface.

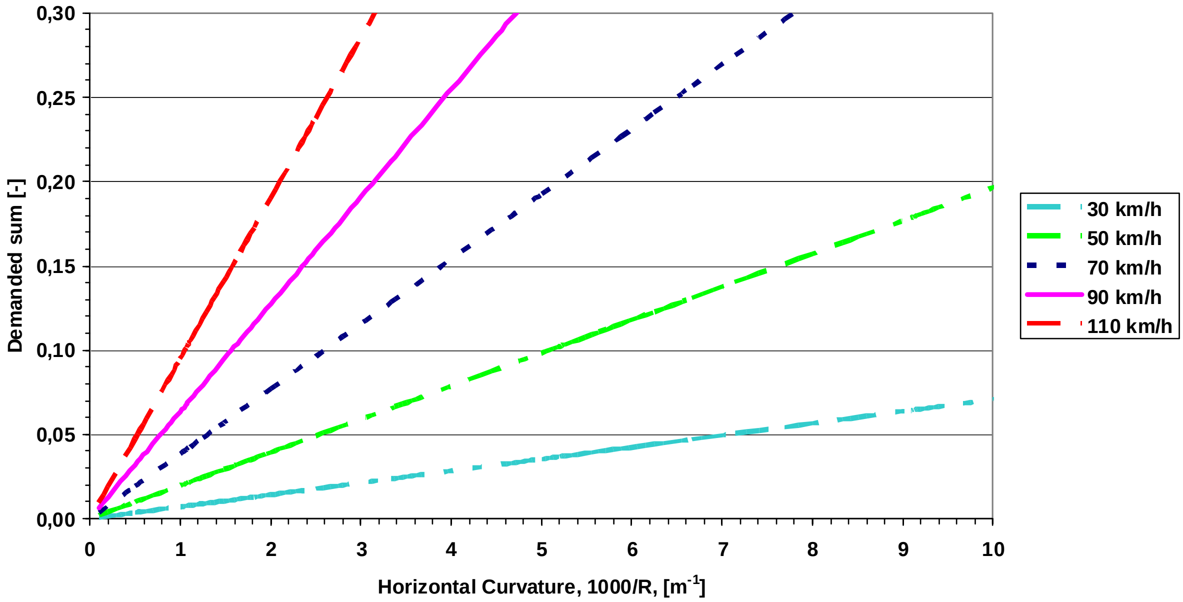


Figure 18 ***Demanded sum of superelevation and side friction to balance the cornering force***

[7] Curvature is defined as 1000/**R**, thus being directly proportional to the exciting lateral force as seen in Formula 2. Curvature also has another advantage over radius, when analyzing and reporting road alignment data. While straight sections make the radius approach +/- infinity (which is difficult to plot in a linear scale), curvature approaches 0 and is easy to plot. This is fundamental to plots as in Figure 71.

[8] Black ice, also known as "glare ice" or "clear ice," typically refers to a thin coating of glazed ice on a surface, often a roadway. While not truly black, it is transparent, allowing the usually-black asphalt/macadam roadway to be seen through it, hence the term. It is unusually slick compared to other forms of ice on roadways. It often has a matte appearance rather than the expected gloss; and often is interleaved with wet pavement, which may be identical in appearance. For this reason it is especially hazardous when driving or walking because it is both hard to see and extremely slick. [Source: Wikipedia, encyclopedia on Internet]

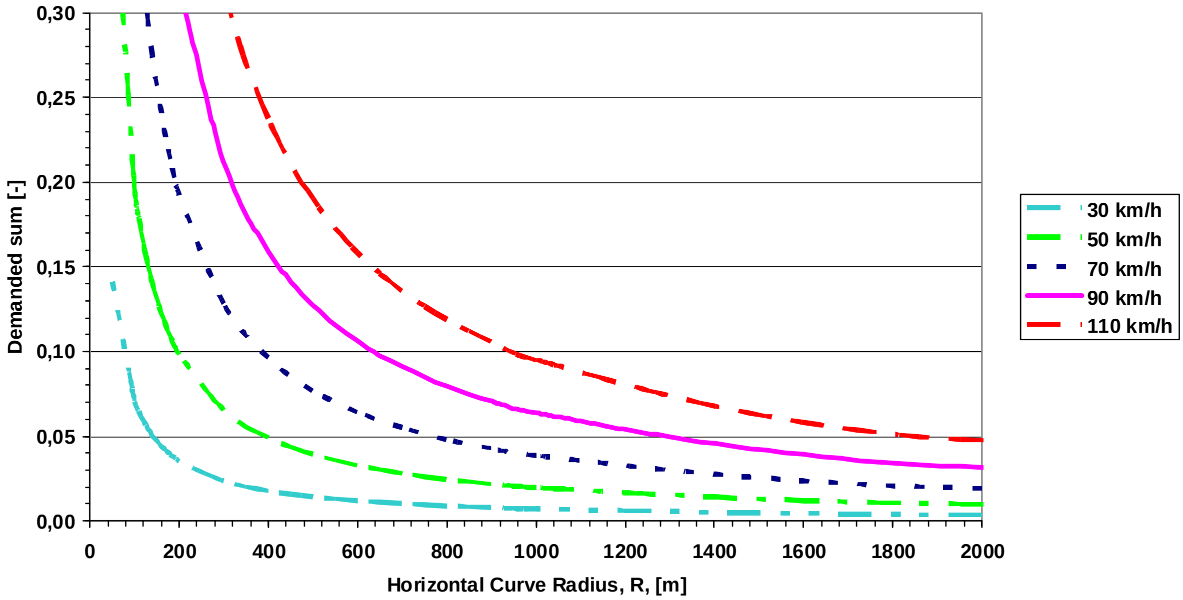


Figure 19 ***Demanded sum of superelevation and side friction to balance the cornering force***

Braking tests may not always correctly reproduce what can happen in practice. Even though adequate friction numbers are recorded in tests, cornering in under-banked curves may still end in run-off accidents under certain winter conditions. This can occur on a snow layer. Under test conditions a test tyre may be able to penetrate the snow during intensive braking, and find grip in the underlying asphalt. In practice however this may not happen as the (lower) cornering forces may be insufficient to penetrate the slippery snow layer. Under these conditions, correct banking may be the only safeguard for safe cornering.

Designing superelevation in curves on new road sections

The side friction factor needed to balance the lateral force in poorly banked curves can be compared with the *side friction factor used for design purpose* (set by the road agency). In order to maintain a safe margin with respect to the inevitable temporary low friction conditions such as due to snow, ice, water, bleeding asphalt and poorer than average tyres, the factor used in design must be substantially lower than the demand friction factor. The side friction factor used in Sweden for superelevation design purpose is given by Formula 7. It is also shown in Figure 20.

$$f_{s,\dim} = 0.28 * e^{-0.0096*3.6*v}$$

Formula 7, Side friction design factor in Sweden [15]

where

$f_{s,\,dim}$ = side friction factor used for design [-]
e = the natural logarithm [-]
v = design speed [m/s]

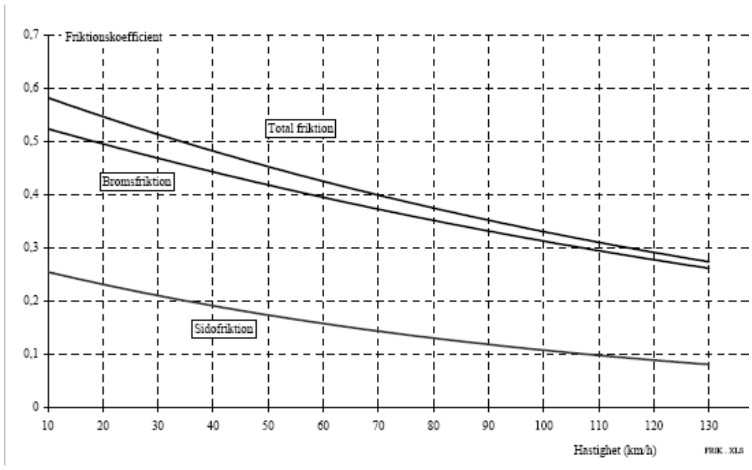
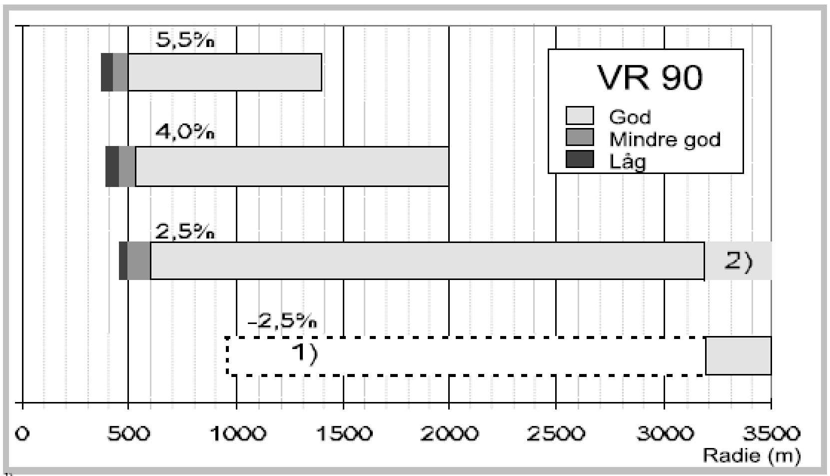


Figure 20 Swedish design values for total friction, brake friction and side friction [15]

The side friction factor used in Sweden for road design corresponds to approximately 2/3 of measured friction between good car tyres and wet asphalt pavements in good condition. Gillespie (1992) [7] reports that truck tyres generally exhibit lower friction values than cars, because of higher unit loading in the contact patch and different tread rubber compounds.

After applying the design factor, standard sheets with ideal superelevation values can be calculated for each speed limit level. The sheet for 90 km/h is given as an example in Figure 21.



1) Skevning i stora radier kan väljas om det ej medför problem med vattenavrinning i skevningsövergångarna
2) Negativ skevning kan väljas i undantagsfall vid vattenavrinningsproblem

Figure 21 Ideal ratios for superelevation at 90 km/h, as function of horizontal radius [15]

As mentioned above, superelevation design is based on analysis of the forces acting on a point-mass model. This analysis assumes that the driver will follow a perfect curved path at the design speed. This assumption can however be far from real world conditions. For example, the path travelled in practice often includes transient curvatures (and thus lateral forces) much higher than assumed, such as when changing lane when overtaking another vehicle, yawing to compensate for wind bursts, or yawing to avoid road damages such as potholes.

There is, as already stated, a margin between the side friction demand factor and the design side friction factor, but the increased accident rate experienced at many sharp curves, such as on the new expressway between Falun and Borlänge in Sweden, questions whether the current margin is large enough. It is possible that the deviations between the design model assumptions and the real world conditions, as described above, are too large to be covered by the existing margin. If so, the design of reversed superelevation, as currently allowed as per note 2 in Figure 21, should be reviewed.

Maximum values of cross slope and banking/superelevation

For snow and ice contamination, superelevation should not exceed a slope on which vehicles standing or driving slowly would slide toward the centre of the curve. In Norway, the maximum allowed value for banking in existing hairpin curves is 9.5 % [41], see Figure 22. Sliding in a section with 9.5 % banking may happen when the side friction factor is below 0.095 (9.5 %). However, the consequences of a slip incident at low speed are likely to be milder than those of skidding in high speed due to too low banking of a hairpin curve.

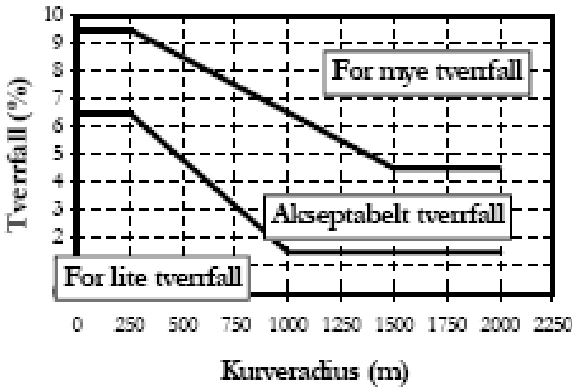


Figure 22 ***Guidelines for maintenance of banking in existing curves in Norway***

Up until now, there has been an absence of a national guideline for superelevation on existing roads in Sweden. For the design of new curves in new road sections, the maximum value is 5.5 % [15] (plus a construction tolerance of some 0.5 % [40]). This conservative Swedish road design code is however irrelevant for hairpin curves, which are inevitable in the mountainous roads in Norway. Very sharp curves also exist on old roads in Sweden however, and they often have much higher banking than 5.5 %. Values of more than 10 % are surprisingly common.

When slowly driving in a curve with higher-than-needed superelevation, the vehicle follows the desired path only when the driver steers up the slope. Since steering against the direction of the horizontal curve is unnatural to a driver, such curves may be perceived as “difficult” or uncomfortable.

When trucks and SUV’s with high centres of gravity and a soft suspension travel slowly on steep cross slopes, a large share of their weight is distributed to the down-slope tyres. If this condition becomes extreme, the vehicle may easily rollover as discussed by Strandberg (1974) [53].

Poor control of superelevation in existing curves

It appears that accumulated research and experience has resulted in reasonable design values for banking/superelevation in new curves. However, much less effort has been spent on how to manage existing curves.

The side friction factor used for design cannot be used to define a sharp limit between safe and unsafe existing roads. It can however be used to evaluate existing horizontal curve geometry (radius and banking/superelevation) against the very same “highest acceptable risk level” as applied when designing new road network sections, by using Formula 6.

As described above, the design of superelevation in new curves is based on analysis of the forces acting on a point-mass model. This analysis assumes that the driver will traverse a perfect curved path at the design speed. For existing curves on old roads, this assumption can be very unrealistic. Comprehensive surveys show that on low volume roads, operating speeds often exceed the design speed, see de Solminihac et al (2007) [38]. This is an undesired but hard fact that road managers must deal with, and not ignore. Furthermore, the geometric characteristics of old curves can seldom be described by simple parameters such as a single radius value, since the alignment can be so poor that the curvature (and thus the lateral force) varies significantly. One such example was found in Profilograph data from a Swedish National Highway, where 20 skid accidents took place in a 200 m long section of a curve, during the winter 2006/2007. On investigation, it was found that the curvature (lateral force) was doubled within fractions of a second just at the multi-crash length.

With the wide variance of real vehicle speeds in curves, there is always an unbalanced force whether the curve is superelevated or not. As discussed in the AASHO Policy on Road Design [16] unbalanced force results in tyre wall thrust, which is taken up by the friction between the tyres and the road surface. This reaction force is developed by distorting the contact area of the tyre. Keeping this distortion low, keeps the road surface from polishing and tyre wear low. These are further reasons to control and correct superelevation in existing curves.

3.3.1.2 Road factors decisive for road grip and stability on straight roads

Hydroplaning by highway vehicles is a phenomenon characterized by a complete loss of directional control. When a tyre is moving fast enough, it rides up on a film of water and thereby loses contact with the pavement. Although many vehicle, pavement and environmental factors affect the risk of hydroplaning, a rule by thumb is that hydroplaning can be expected for speeds above 70 km/h where water ponds to a depth of 4 mm or greater over a distance of 10 m or greater. Thereby, Glennon (2004) [42] states that "*hydroplaning is a function of water depth and length of the drainage flow path*".

Gallaway & Rose (1971) [25] found that the pavement water depth (above the road surface texture tops) can be calculated from:

- rainfall intensity,
- cross slope,
- length of the drainage flow path, and
- texture depth.

In addition, they defined the length of the drainage flow path as a function of:

- pavement width,
- cross slope/superelevation, and
- longitudinal gradient.

Pavement depressions (unevenness and rutting[9]) make water ponding worse, while horizontal curvature increase the exciting lateral force and thereby the demand for lateral friction. This raises the risk of skidding.

Both of the lists above include cross slope as a key factor for hydroplaning. Despite this, many road agencies do not analyze cross slopes in their road network on a routine basis!

Some 535 Swedish hydroplaning accidents have been analyzed at the macro level [31]. The results show that where cross slopes are too low, the risk of hydroplaning more than doubles; from about 26 to 54 per Mapkm[10]. Due to uncertainty in the position of the accident sites, the analysis was made using average values over as much as 500 m. This suppresses the influence of local damage on the road. If the analysis could have been carried out over shorter average lengths, i e 50 m, it is likely that even larger increases in risk could have been identified, as cross slopes become too low.

The design value used in Sweden for cross slopes on new straight sections is -2.5 % on roads with hot mix pavements, and -3 % on pavements with surface dressing as the only bound layer

[9] In the EU Northern Periphery, rutting is not only caused by compaction of the pavement, but also by surface abrasion due to the use of studded tyres in the winter. One exception is the Highlands of Scotland, where studded tyres are not common and surface friction has instead been handled by using surface dressing pavements.

[10] The unit Mapkm (million axlepairkilometer) describes traffic work.

[40]. These design values for new roads have been set with an allowance for future settlements. When repaving old roads, where settlements are likely to have stopped, a slightly smaller CS of -2 % may be a beneficial target. A CS of -2 % is sufficient for a good water flow, and makes driving in windy conditions easier. Occupants can also sit more upright and comfortable than with larger cross slope. These latter aspects are especially important in providing a sound work environment for professional drivers.

3.3.2 Relating poor ride to pavement condition

This section starts with a short review of opinions of EU Northern Periphery road users. Then it describes how ride vibration is affected by many factors, such as road conditions, vehicle properties and driving behaviour (including driving speed). Of these, road condition is by far the most decisive for in-vehicle vibration. Various types of road defects cause various ride vibration problems. Examples of these are long wave unevenness, undesired cross slope variance, roughness, megatexture, potholes and other local damages, particularly deflection variance in weak pavements under heavy vehicles as shown by Granlund et al (2005) [9]. The section ends with a description of how to measure ride quality on dirt roads.

3.3.2.1 EU NP professional road users perspective on ride conditions

Opinions of professional road users on road service levels in test areas across the EU Northern Periphery was mapped by Saarenketo & Saari (2004) [49] in the ROADEX II Project. 330 questionnaires were issued, and with a satisfying response rate of 45 % the result was 147 answers. The answers showed that roughness was a major problem for the forest industry; 70 % of timber transporters stated that uneven roads were their main problem. Also over 50 % of respondents in the construction and public industries suffered from severe problems due to roughness. Truck drivers stated that the worst sections had bumps at culverts, located at the bottom of a valley with steep hills adjacent to the low point culvert. This situation required them to slow their truck down to almost zero, in order to prevent vibration damage, and once the bump was crossed, it did not have enough momentum to climb the next gradient. The drivers also reported much higher fuel consumption on rough roads. Many problems were reported to be related to weak pavement shoulders, poor road alignment and poor bearing capacity. A significant share of the drivers gave poor traffic safety ratings, due to factors such as poor winter condition (maintenance), bad cross slope, uneven frost heave bumps, poor road alignment and lack of crash barriers in curves on high embankments.

The truck drivers questioned also reported continual stress when driving on some long routes (including National Highways) that the road agency believed to be in good condition for driving. This happened when unexpected poor road conditions made the perceived maximum safe speed drop far below the planned speed. The result was a conflict within the driver, between making a delayed delivery and causing a major traffic safety risk. Such a conflict caused high stress to the truck driver. Typical sources of this kind of problem are frost related roughness and delayed snow removal. The latter allows snow to be compacted and leads to the development of deep tracks and ruts. Wet snow freezes into ice in the lanes and these ice ruts then remain for a long time. This type of slippery rut can be difficult to remove with a truck mounted snow plough and typically they must be scraped off (costly) with a slow-moving heavy grader. Severe cases may even require many repeated runs with the grader.

3.3.2.2 Roll vibration is excited by undesired variance of Rut Bottom Cross Slope

The Swedish Road Administration has been laser-scanning the surface condition of their road network since the 1980's and importing the data into the SRA Pavement Management System (PMS). On-going evaluations by Johan Lang of SRA show that the average condition of rutting and roughness on the Swedish highway road network is quite constant, despite gradually increased intervals between repaving actions and large yearly increases in traffic. One reason for this important success is the increasingly systematic use of laser-scanned condition data by the local pavement engineers [Personal communication with Mats Wendel, SRA Head Office].

The condition parameters most commonly used in PMS so far, are Rut Depth and International Roughness Index (IRI). These parameters do not work well on road sections with edge damages although these can cause excessive roll motion to high (heavy) vehicles. Therefore, the SRA Central Region has in the strategic regional plan for 2004 - 2015 pointed out an urgent need for a "Roll vibration indicator" as a new pavement condition parameter [20].

At the national level, the SRA's action plan for traffic safety 2004 - 2015 has identified that "*Pavement edge deformations are perceived as very uncomfortable by all road user groups, especially drivers of (high) heavy trucks*" [23]. This confirms the need of a pavement condition parameter to address this kind of distress properly.

A potentially suitable roll vibration indicator has been defined "down under". As reported by Bowler et al (2001) [45], Transit New Zealand (TNZ) has carried out excellent customer focused work in the award winning *Truck Ride Improvement Initiative*. This included a two-stage research process that started with a programme of qualitative research that looked at the specific concerns of truck drivers. This was followed by a second research stage where the truck drivers were asked to quantify their concerns. The results of the first stage were used build a list of concerns that were prioritised by the drivers. Before the final ranking, the truck drivers were informed on the relative costs for each type of improvement.

After some adjustments for willingness to pay, the 300 truck drivers' top priorities were:

1. Build more passing lanes.
2. Repair surface undulations and settlements.
3. Straighten out too sharp corners.
4. Repair incorrectly banked corners.
5. Improve road alignment and evenness at bridges; i. e. repair settlement on the approaches to bridges.
6. Build wider shoulders.
7. Correct vertical alignments; take away dips and rises which block visibility.
8. Build wider bridges.
9. Build longer passing lanes.

Findings from the TNZ "market investigation" was then used in a technological project, defining how to detect road sections where unevenness significantly impacted on truck ride and handling. Cenek et al (2003) [43] presented this project, where the focus included long wave undulations and roll caused by roughness warping between wheel-paths. The outcome is that TNZ now has an awareness of the need to focus on those sections of the highway network that are of priority to truckers, and on the repair of these. The results also provided justification for questioning current road management practices and funding allocations, which are not delivering the types of state highway improvements that professional customers require. TNZ found that cab body roll, particularly when combined with cab body pitch, was of most concern to occupants of trucks. This is an important finding, as existing road roughness parameters used for pavement management purposes (i e IRI) have their emphasis on vertical vibration, not on rotation. The threshold value for uncomfortable truck ride, related to rotational response (pitch and roll), was found to be 4.0 to 4.5 °/s. A complex Truck Ride Index was developed from this. It is based on existing 20 m average values of cross slope, curvature and other parameters available in TNZ's pavement management system. Since 2001, Transit New Zealand has been given an additional road funding of NZ$3 million annually that has been specifically allocated to the repair of critical sections for truck ride.

In 2004, the SRA tested the truck cab roll component from TNZ's complex Truck Ride Index using data from road Y 953 in the SRA Central Region. The results were disappointing however. The potential roll vibration indicator gave much higher alarms at entrances and exits of normal left hand curves, than at critical sections with severe edge deformations and roll problems. This was seen as a defect in the system, since it could lead to a waste of road repair funding. At a result of this, SRA decided to define a new roll vibration indicator in-house. The new indicator is based on road profile data, laser scanned at 16 kHz in the bottom of the truck wheel paths (left and right) and reported in steps no longer than 1 m. This revised indicator offers 20 times better spatial resolution than the TNZ roll indicator. From the data recovered, the Rut Bottom Cross Slope (RBCS) is calculated. At this point a crucial filtering procedure is applied, to remove the very long wave slope variances that relate to superelevation change at curve transitions. This is markedly notable at left[11] hand curves. Depending on road section width and reference speed, such desired change in cross slope takes place over some 40 - 200 m. These transitions smoothly tilt the truck cab roll angle from one side to the other without producing roll-mode vibration. The vital filter is calibrated with the road's reference speed, thereby normalizing the filtering to typical heavy truck roll vibration eigenfrequencies. In the next step, undesired variances in the RBCS are calculated. This is done in two parallel runs. One run calculates the variance over "short sections", addressing the excitation of the axle roll of the truck wheel. The other run calculates the variance over "long sections", addressing the excitation of the truck chassis/cab roll. Finally, the maximum of these two variances is reported as the undesired variance of RBCS. See Granlund (2006) [21] for details.

One of the three goals in the present ROADEX III project research task, is to draft a limit for the new "undesired Rut Bottom Cross Slope Variance" parameter defined at SRA. *Should the limit be 0.25 %, 0.50 % or what? Should there be different values in curved vs. straight sections, in long curves vs. short curves, and in wide vs. narrow sections?*

[11] In the UK and other countries with left hand traffic, this applies to right hand curves instead.

3.3.2.3 Frost related bumps and potholes are worst

The ROADEX II professional road user interviews [49] showed that uneven frost bumps and potholes were considered to be some the worst damage types on paved roads. These short and high/deep local damages can cause mechanical shock that can result in damage to vehicle, cargo and/or vehicle occupants. As can be seen in the following clause, the traditional use of long report intervals is one of the main reasons why road agencies have not be able to focus on local damages, despite using sophisticated laser/inertial profilometers.

3.3.2.4 Road condition data must be analyzed over relevant report intervals

An important issue when discussing road condition in relation to drive comfort as well as health and safety, are the properties of the used road statistics used; i e the report interval. By tradition, rutting and roughness values have been described as mean values over long sections such as 20 m, 100 m, 400 m, 1000 m, whole roads or even whole road networks.

Since roughness is defined as a deviation from a planar surface, it is of course less relevant to analyze the mean value, than some kind of estimate of the worst deviations. Figure 23 shows values from a variety of report intervals, ranging from 1 dm to 400 m, from an analysis of a very rough road in the SRA Northern Region. The result shows that local bumps were 20 - 30 times worse than the average IRI value of 3.8 mm/m, giving peak IRI-values of 80 - 130 mm/m. This is comparable to, or actually worse than, many 10 cm high traffic calming speed bumps on urban streets. At the worst sections of this 90 km/h road, heavy trucks almost bounce off the road at speeds over 30 km/h. Despite this, roads with IRI lower than 4 mm/m are not reported in the SRA annual report as a severe problem. This is may be true for roads with low roughness variance, but definitely not for roads with severe local damages with IRI > 80 mm/m!

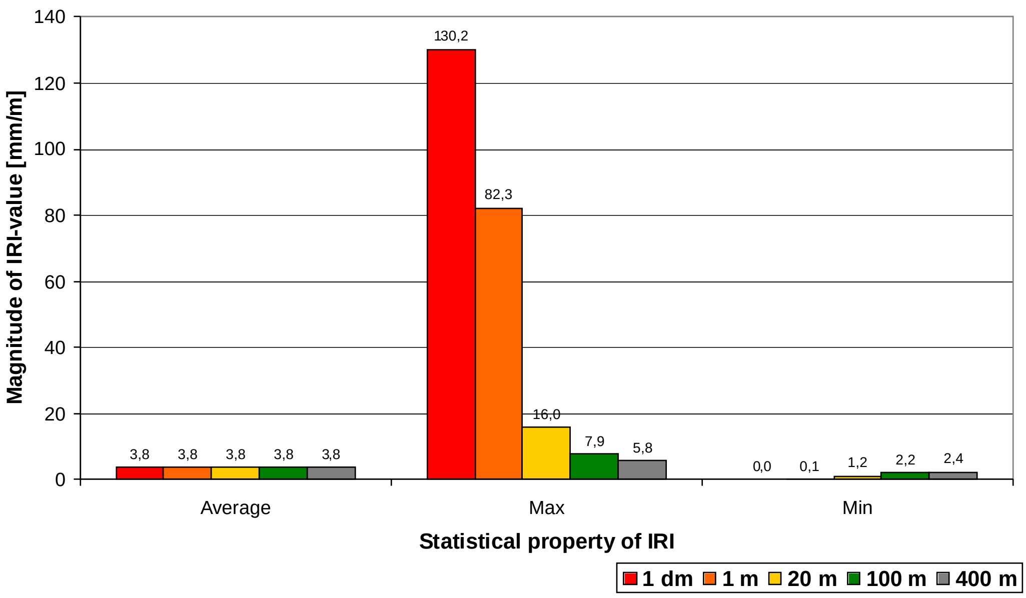


Figure 23 ***Surface roughness IRI for 6.5 km of Rd 374 Vitvattnet – Storfors, 2002***

As illustrated above in Figure 23, roughness variance is extremely high at local bumps. Thus averaging over distances much longer than the bump itself (often about 1 m), such as with IRI_{20} or IRI_{100}, disguises the variance. This averaging eliminates the ability to identify those bumpy sections that heavy vehicle operators consider intolerable. A better parameter could be the 95'th percentile, such as is used when mapping vibration emission from roads and railways to nearby dwellings. Another option could be to report a parameter related to the variance in data, together with a mean value. By reporting the mean value, together with the "two sigma" limit (corresponding to the 95'th percentile), a better picture is given of the worst sections.

3.3.2.5 Heavy vehicles suffer from soft spots in weak pavements

Heavy vehicles perceive not only the static surface roughness, but also a dynamic roughness component when the pavement has "soft spots". Pavement deflection is typically less than two millimetres under a moving heavy vehicle. This magnitude seems negligible, being comparable with road wearing course texture. The texture however, is smoothened by the tyre's "enveloping effect". Ride comfort is associated with vibration acceleration and vibration velocity, rather than vibration displacement. (This makes sense; otherwise a stiff sports car would be considered more comfortable than a soft luxury car when riding on bumpy roads). Vehicle vertical vibration acceleration is associated with road roughness profile slope variance, rather than roughness profile height. So, even if a pavement deflection under heavy vehicles, with few exceptions, would not be larger than about one or two millimetres, significant vehicle vibration acceleration could occur at soft spots where the deflection profile varies rapidly in terms of large slope variance. The importance of soft spots is confirmed by the Australian coal mining industry, where they are recognized by handbook *Bad Vibrations* [50] as an important source of ride vibration in transport vehicles.

Ahlin et al (2000) [3] made an unexpected observation when comparing road roughness with ride vibration in ambulances and heavy trucks. When surface roughness drops to zero, significant seat vibration remains in heavy trucks while vibration drops to almost zero in ambulance cars. In the trucks, the threshold of the weighted vibration acceleration was found to be as high as 0.2 m/s^2 rms. This value is to be compared with the Action Value of 0.5 m/s^2 rms over 8 hours, stated in directive 2002/44/EC. Clearly, other factors other than road surface roughness can bring as much as 0.2/0.5 = 40 % of the allowed truck seat vibration. Soft spots in the pavement are believed to be a causal factor behind such vibration; Forssén (2001) [10] discusses road deflection variance as an important but hard-to-grip property. Granlund et al (2005) [9] measured and compared truck wheel vibration with theoretical wheel vibration calculated from road surface roughness (assuming a perfectly stiff road profile) on 80 km of roads in Sweden. The hypothesis was that large differences between measured and calculated vibration indicates possible soft spot locations along the road. The study found a correlation between soft spot indications recorded in the truck and reference data on pavement bearing capacity properties, such as subgrade stiffness module, pavement thickness, frost fatigue damage, and overall bearing capacity index. These findings give further support to the theory that significant amounts of heavy vehicle vibration arise from soft spots in weak pavements.

3.3.2.6 Measuring ride quality on very low volume dirt roads and winter roads

Many road agencies measure the condition of paved roads with laser[12]/inertial profilometers, as with the Profilograph used in the case study of this project. The advanced and expensive Profilograph can report a wide variety of condition parameters, including longitudinal roughness in terms of IRI-value and other indices, such as rutting, cross slope and texture. Very low volume roads do not however require such demanding accuracy and can be measured with cheaper instruments. It may in fact be impossible to make relevant condition measurements with a laser/inertial profilometer on very poor condition dirt roads or icy winter roads.

A relatively cheap measurement method available is to ask road users about their perceived ride quality; the so-called “no cost instrument”. By using a comfort scale, such as in Table 1, “backwards”, it is possible to estimate the vibration intensity and use it as a condition rating. An obvious problem however is how to distinguish between transient shock at bumps and average vibration by roughness.

A somewhat more expensive system can be based on vehicle seat mounted vibration sensors; the “medium cost instrument”. Two examples are the CVK Health Vib (see Figure 24) and the Bruel & Kjaer Human Vibration Measurement Kit (see Figure 25). A more advanced state-of-the-art example is the Dewetron Stream Machine, used in the case study and presented later in this report. The price of such instruments ranges from a few thousand €, up to some thirty thousand €. Then there are costs of extra sensors such as odometer, GPS, video and others. There have been experiments trying to measure road condition with accelerometers that have been mounted to wheel axles. One obvious drawback is that such a system does not yield results comparable with either the ISO 2631 comfort scale, or the EU Action Value for professional drivers WBV exposure.

Using a cheap instrument however is no guarantee of a cheap measurement. A full measurement process includes activities such as data collection, transfer, storage, backup, analysis, quality control and distribution to users. There are also costs for client system infrastructure, user education, and much more. So a low total cost may depend more on smart purchase behaviour, than on cheap sampling with low precision (subjective comfort rating) and limited outcome.

“Cheap” sampling can have drawbacks for road managers, particularly those who purchase road maintenance based on road condition. If road users start to give biased ratings in order to achieve “above standard” conditions, such measurements may become very expensive in a road maintenance contract context. Alternatively, if the vast majority road users see a particular bump and always brake for it, the vibration will be reduced and an on-board logger will not trigger an alarm. In this case the bump will not be repaired. Such bumps however may come as a hazardous surprise to foreign road users not familiar with the road.

[12] The sensor recording the height above the pavement may be of another type other than a laser sensor; i e an ultrasonic sensor. However, laser sensors have proved to be able to better fulfil the high accuracy and high environment demands associated with road profiling. A current trend in the road profiling industry is to scrap cheaper sensors and replace them with rugged “road edition” laser sensors.

Figure 24 The CVK Health Vib system

Figure 25 Brűel & Kjaer Human Vibration Measurement Kit 4447

Chapter 4. Case study on the Beaver Road 331

Figure 26 ***The southern entrance to the Beaver Road 331***

Rd 331 is a 170 km long regional route in Sweden, connecting the rural forest area in eastern Jämtland County and western Västernorrland, with the heavily industrialized coast at the east of Västernorrland County as seen on the map in Figure 27.

Rd 331's Annual Average Day Traffic (AADT) ranges from 350 to 2000 vehicles per day.

Rd 331 is a main supply road for timber transports servicing the paper mills in the Sundsvall area, such as SCA's factories in Tunadal, Östrand and Ortviken. Thus, the share of heavy trucks is very high, from 12 to 19 %. Most of the trucks have three axles and a trailer; the average number of axles per recorded truck is as high as 4.8. The timber transports on Rd 331 are also expected to increase by another 150 000 m^3/year. This is due to a redirection of timber from the Sollefteå area, which up until now has been transported to Utansjö Bruk (being shut down), north of Härnösand.

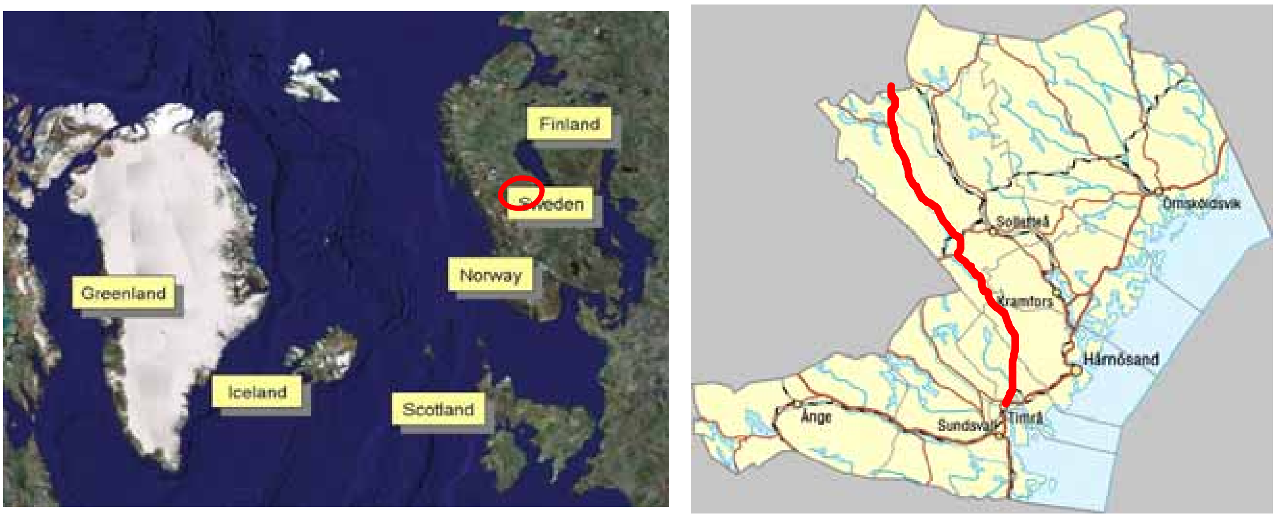


Figure 27 Swedish Beaver Road 331 connects the forest area with the industrialized coast

Connecting National Highway 87 in Viksmon to the Coast, Rd 331 also is a link on the ambulance route between the local hospital in Sollefteå and the region hospital in Sundsvall. Among the most sick or severely injured patients, some are in need of specialized care not available in Sollefteå. These patients, often very vulnerable, are transported on this road to Sundsvall.
The speed limit alternates between 90 and 70 km/h, with a drop to 50 km/h in some villages.

Rd 331 is considered a normal road, while SRA have thousands of kilometres of roads in similar condition and use. Therefore results of this case study are therefore not unique, but relevant to a large proportion of the road network.

In the SRA Road Data Bank (RDB), Rd 331 starts at the Coast and its distance is measured towards Jämtland. In this study, however, most of the analyses have been made in the direction of the timber transportation. This direction is opposed to the RDB distance direction. For this reason, most of the data graphs presented have the distance markings in the reverse direction.

Rd 331 suffers from many and severe traffic accidents. In 2005, seven people were killed in road traffic accidents on the road network in Västernorrland County. Three of them died on Rd 331. A map over police reported serious accident black spots on Rd 331 is showed in Figure 28. The site with highest accident rate in Västernorrland County is the Hazardous Site Stavreviken, “HS Stavreviken”, at the southern exit of Rd 331. The map has been created by Hans Johansson, traffic safety officer at SRA Central Region.

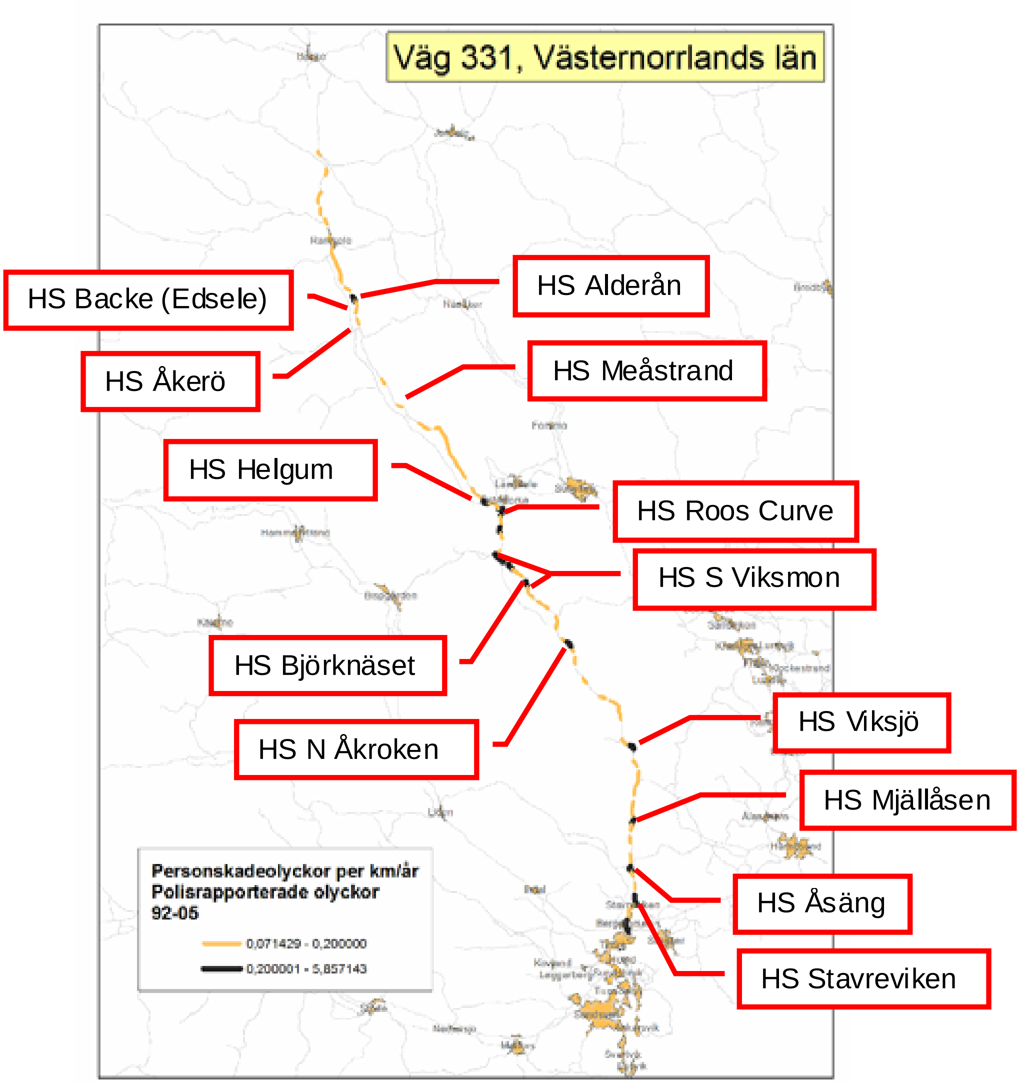


Figure 28 ***Accident black spots at the Beaver Road 331, <u>not</u> normalized to AADT (Individual Risk)***

4.1 TRUCK TEST PARTNER - BRORSSONS ÅKERI AB

Brorssons Åkeri AB was founded in the mid 1940's, at the end of World War II. During the eras of water power plant construction from 1940 to 1960, the company was heavily employed transporting soil, gravel and other material to the construction sites. After the end of the era, the transport markets changed and for the last twenty years timber logging has been Brorssons' core business.

The company operates 14 timber logging trucks, each with a large trailer. The trucks are loaded by separate cranes (see Figure 29), to minimize the dead weight of the vehicle and maximize payload. Each truck runs Monday to Friday in two shifts resulting in 18 hours per day. On Fridays, only an 8 hour shift is used. Normally each truck daily drives 4 round trips of some 2 x 140 km on the Beaver Road 331, depending on which forest the timber is to be picked up from. The annual mileage per truck is 200 000 km. All trucks and trailers are exchanged at 3 to 4 years of age.

Figure 29 Logging timber from forest to the coastal industries

The company's vehicles are seldom involved in traffic accidents, other than some low speed trailer incidents on narrow, steep and slippery forest roads. As a result, the company has a modest insurance cost for the truck fleet. However, the drivers are very uncomfortable with seeing foreign road users suffer from accidents at "Hazardous Sites". The drivers think that many of these accidents could have been prevented. The drivers have requested road improvements including increased width of the narrow, high and steep road banking from Viksmon to Stavre, straightening the Roos Curve and some other sharp curves, repair of incorrectly banked curves, repair of edge deformations and bumps at culverts, more frequent and higher quality resurfacing, and intensified winter road maintenance such as frequent removal of ice-ruts with a heavy grader. These requests have been raised by professional drivers riding an astonishing total of 2 800 000 vehicle km/year on Rd 331.

4.2 A SCANIA R480 164 G 6X4 WAS USED AS TEST TRUCK

The test truck (licence registration number WPT 493) was three years old, and had a mileage of 609 000 km. The instrumentation was carried out on Sunday 26th of August, 2007.

Figure 30 ***A damper bush was broken, but this was not perceived under normal driving***

When demounting one of the truck's front wheels, see Figure 30, it was found that the damper bush was broken. None of the two experienced professional drivers, Mats Jonsson and Anders Larsson, had noticed anything unusual during their daily driving work. The truck had been at the Scania Workshop for service just the week before and had to be driven back for the necessary repair work on Monday morning, before the ROADEX main test. Measurements were carried out on this journey for reference purposes only.

The gross vehicle weight of the test vehicle combination was 60 tonnes with a full payload. The dead weight was some 19 tonnes. Measurements were taken under normal working conditions; hauling timber from the forest to the coast, and then driving back unloaded. If nothing else is stated, the data in the graphs presented are recorded with the vehicle combination fully loaded and travelling to the coast.

The drivers were instructed to drive as they would normally do, with one exception. They were asked to remain in the wheel tracks, and not to avoid driving over local road damages. (In normal driving, they can avoid some bumps unless there are oncoming or overtaking vehicles).

4.3 TEN ROUNDTRIPS OF 280 KM WERE RECORDED

A total of ten 2 x 140 = 280 km round trips from the Ramsele forests to the coast were recorded, in order to investigate the precision in truck ride measurements. One trip also included the most northwest 30 km section from Backe to Ramsele.

The round trips were carried out from Monday 27th to Thursday 30th of August 2007. Many of the measurement trips were undertaken in rainy weather and on wet roads.

Driving a timber logging truck is extremely busy. In the forests, the truck drivers get a short break while the timber is loaded by a large separate crane as seen in Figure 29. At the coastal delivery points, there are almost no natural pauses at all. The huge Svetruck log stackers with their 8.2 m^2 grapple need only single grips to unload each of the three timber piles on the truck and trailer combination. The driving shifts change at 14.00. This is done without even a few minutes common break for a cup of coffee together.

The detailed analysis focused on a series of Hazardous Sites (HS) identified from truck driver interviews, from pavement condition data and from crash statistics in the Swedish national road traffic accident database STRADA.

4.4 COMPREHENSIVE RIDE AND ROAD CONDITION MEASUREMENTS

4.4.1 Truck ride measured by accelerometers and a combined GPS/inertial unit

Truck ride vibration was measured with a Dewetron Stream Machine system, owned by SRA Consulting Services (SRA CS). This system carries out real time calculations of health risk, as defined in the recent ISO 2631-5 (2004) standard [5]. The system, and the connected accelerometers, satisfies the comprehensive accuracy demands set out in the EN ISO 8041 instrumentation standard [17]. The accelerometers were located at several points of the truck to record motion in multiple directions (see Figure 31 for definitions and Figure 32 for photos of mounting):

- Left and right front axles, z-axis, 5 kHz
- Left and right side of the frame, above the front axle, z-axis, 5 kHz
- The pan of the air-suspended drivers seat, xyz-axes, 5 kHz

Both drivers weighed around 90 kg.

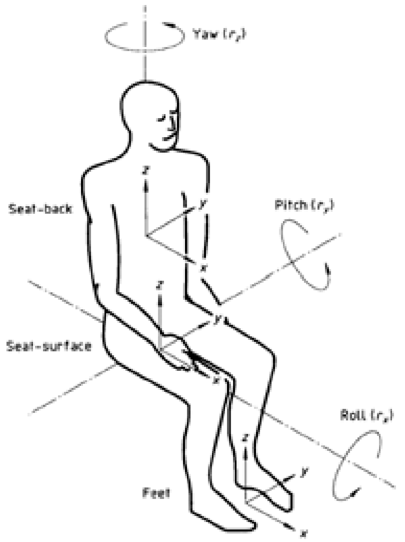


Figure 31 Basicentric axes of the human body in seated position [18]

Figure 32 Left: Accelerometers at axle and frame, Right: Seat pad with 3-axis sensor

The vehicle speed during the tests was recorded with a GPS/inertial unit, updating speed values at 100 Hz. This corresponds to measuring every second dm of the ride at 80 km/h. This data was also used to calculate the distance position with a fair accuracy.

A digital video camera recorded front view “Right-Of-Way” (ROW) from the truck cab. Noise < 5 kHz was recorded with a microphone.

One of the main tasks of the test was to study roll vibration of the truck cab. For this purpose, an OxTS RT 3050 100 Hz GPS/inertial unit was used, see Figure 33. This unit recorded the motion of the cab in all 6 axes; xyz translation, as well as rotation in yaw, roll and pitch. The accuracy and resolution was so good, that the system was able to pick up a change in elevation of 1 mm between the left and right truck tyres road contact patch. The RT 3050 was mounted on a carbon-reinforced RT Strut, with very high torsion stiffness, seen in Figure 34.

Figure 33 The OxTS RT3050 GPS/Inertial unit, used for 6-axis ride measurement

Figure 34 The RT 3050 mounted on a RT Strut in the truck cab

4.4.2 Passenger car ride measurement

For reference purpose, vibration was also measured on the driver seat in the new Ford Mondeo passenger car seen in Figure 35. The driver’s weight was about 90 kg. The car was driven just below the speed limit, with a minimum of speed variance.

Figure 35 ***Reference driver seat vibration measurements in a new Ford Mondeo***

4.4.3 Laser/inertial reference measurement of pavement condition

In this case study, the road alignment, the 3-D geometry of the pavement lanes and the surface texture of the road were scanned with one of SRA CS's advanced laser/inertial Profilographs, as shown in Figure 36. These Profilographs are used for routine survey of the condition of paved public roads, airfields, test tracks et cetera. The resolution of the system is 0.1 mm (texture 0.01 mm). The accuracy expressed in terms of precision and trueness, is within fractions of a millimetre under normal operation conditions, as certified by third party. The Profilograph allows accurate inertial compensated measurements to be gathered whilst driving at speeds up to 165 km/h, although speeds of 15 to 90 km/h are more normally used in highway surveys.

Figure 36 SRA CS's laser/inertial Profilograph P45 [Photo: Mats Landerberg]

The Profilograph is equipped with a 2.5 m wide rut bar, as seen in Figure 37. The rut bar is equipped with 16 kHz lasers scanning the road surface's shape relative to a large scale inertial plane. The two outermost lasers on each side are angled outwards, giving rise to a total scanned lane width of 3.2 m. Three of the lasers sample at 64 kHz, taking accurate measurements of the road surface texture. One scans the left wheel path, one the right, while the last texture laser scans between the wheel paths.

Figure 37 ***The Profilograph with its 2.5 m wide rut bar, scanning a 3.2 m wide lane cross section***

Chapter 5. Expected results are confirmed

5.1 UNACCEPTABLY HIGH WHOLE-BODY VIBRATION AND SHOCK

5.1.1 Daily vibration exposure exceeds the EU Action Value

It is impossible to define a long term representative daily vibration exposure to 2 decimal places for professional truck drivers. An obvious reason, for Brorssons drivers at least, is that they pick up timber at various places. Every week they drive not only Rd 331 between the coast and Ramsele, but also other connecting local and forest roads in the Ramsele area. They drive at different speeds on roads with varying roughness. The result is various vibration intensities. Given this complexity, a set of calculations have had to be made in order to consider the various driving routes. This analysis has been carried out using the Vibration Doses Calculator, available on the UK Health and Safety Executive's website[13]. Normal shifts with roundtrips from forest to coast, resulted in A(8) values from 0.65 m/s^2 and higher. Some of the forest roads outside Ramsele were very rough, but since speed was low and the driving times on them were similarly low, their contribution to the total daily exposure was lower than the main partial exposure from the long round trips on Rd 331 between Ramsele and the coast. Figure 38 shows the resulting A(8) of 0.76 m/s^2 for an 8 h shift example, including simulation of pauses with zero vibration. Figure 39 shows an example of calculation details.

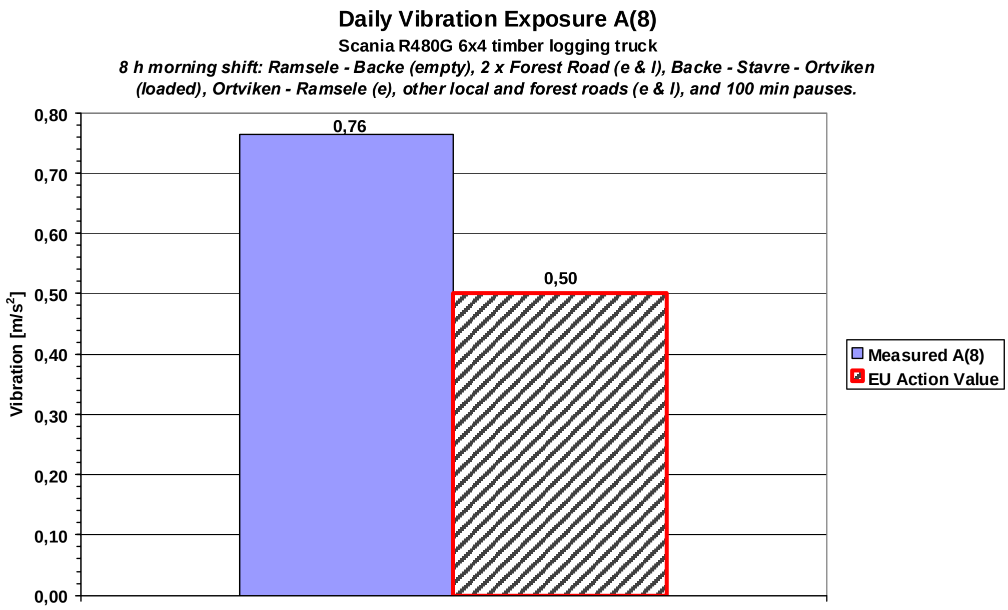


Figure 38 ***The drivers daily exposure to vibration exceeds the EU Action Value***

[13] Internet: www.hse.gov.uk/vibration/calculator.htm

		Vibration intensity m/s²	Exposure time hours	Exposure time minutes	Partial exposure m/s²
Ramsele - Backe	Empty	1,66	0	25	0,382
Backe - Ramsele	Loaded	1,32	0	28	0,316
Ramsele-Österforsse	Loaded	0,54	0	43	0,160
Österforsse - Viksmon	Loaded	0,66	0	7	0,080
Viksmon - Stavre	Loaded	0,66	0	56	0,226
Stavre - Tunadal	Loaded	0,44	0	9	0,061
Tunadal - Stavre	Empty	0,56	0	9	0,076
Stavre - Viksmon	Empty	0,83	0	56	0,285
Viksmon - Österforsse	Empty	0,83	0	7	0,100
Österforsse - Ramsele	Empty	0,58	0	40	0,168
Forest Road	Empty	0,80	0	22	0,172
Forest Road	Loaded	0,64	0	22	0,137
Misc roads, average intensity	E & L	0,79	0	58	0,276
Pause, non-driving time		0,00	0	100	0,000
		Daily exposure value, m/s² A(8)			0,76

Figure 39 Vibration Dosis Calculator spreadsheet, calculating A(8) for an example route

In accordance with the ISO 2631-1 standard, the seat vibration was measured in three directions; x (fore-aft), y (lateral) and z (vertical). The measured vibration was high in all these three axes. The EU vibration directive states that the daily exposure value A(8) shall be calculated from only the axis with highest vibration. Furthermore, the values for lateral (y) and fore-aft (x) vibration shall be multiplied by 1.4, since vibration in these directions are considered to be unhealthier[14] than vertical vibration (z). On “normal” roads, the vertical axis typically has highest vibration. However, on some sections of 331, the lateral axis had the highest vibration (after multiplication with the 1.4 factor).

All the daily exposures calculated were significantly above the EU Action Value of A(8) = 0.5 m/s^2. This finding is very serious. The law now calls for the employer, Brorssons Åkeri AB, to take necessary technical and/or organizational actions to minimize the driver’s exposure to vibration. In fact, all companies with similar trucking operations and conditions to Brorssons (long and bumpy driving) are obliged by the law to make a relevant risk assessment of the drivers’ vibration exposure.

[14] The factor 1.4 is only used for health risk assessment. For comfort, the factor is 1 which means no extra weighting.

5.1.2 Some of the worst bumps gave spinal compression stress S_{ed} over 0.5 MPa

Transient vibration (mechanical shock) may cause high compression stress in the spine. This health risk is presented in the section “3.1.3 Bumps are of special concern to both ride quality and health”.

The worst bumps in the current tests were located on small roads, such as on the road to the Sawmill in Graninge. When driven at low speeds of about 40 km/h, these bumps exposed the truck driver to spinal compression stress S_{ed} over 0.5 MPa. This stress level corresponds to a health risk, as per ISO 2631-5 [5].

Also on the “main road”, Rd 331, truck drivers drove over many bumps that excited significant transient vibration. The first bump the drivers faced in the morning was only 400 m from Brorssons garage at the western exit from Ramsele. As seen in Figure 40, the bump was so deep, that it had rubber marks made by retracted, non-rotating, truck bogie tyres, similar to the marks seen in landing zones on airfield runways. This bump was due to settlement at an old culvert and had been present for many years.

Figure 40 ***Bump due to settlement at an old culvert in Ramsele, RDB section 141/336 km***

Rd 331 had not only severe bumps due to old culverts, in some sections there were even worse bumps at newly reconstructed culverts. One example was in Gammelmo, 7 km south of Ramsele. A photograph of this site can be seen in Figure 41. The section in Gammelmo is similar to one of the most stressing driving conditions perceived by EU NP professional drivers: "*Truck drivers stated that the worst sections have bumps at culverts, located at the bottom of a valley".*

Figure 41 Bumpy newly reconstructed culvert in Gammelmo, RDB section133/000 km

When driving at normal highway speed over this new culvert, the driver was exposed to "very uncomfortable" transient vibration, as seen in Figure 42.

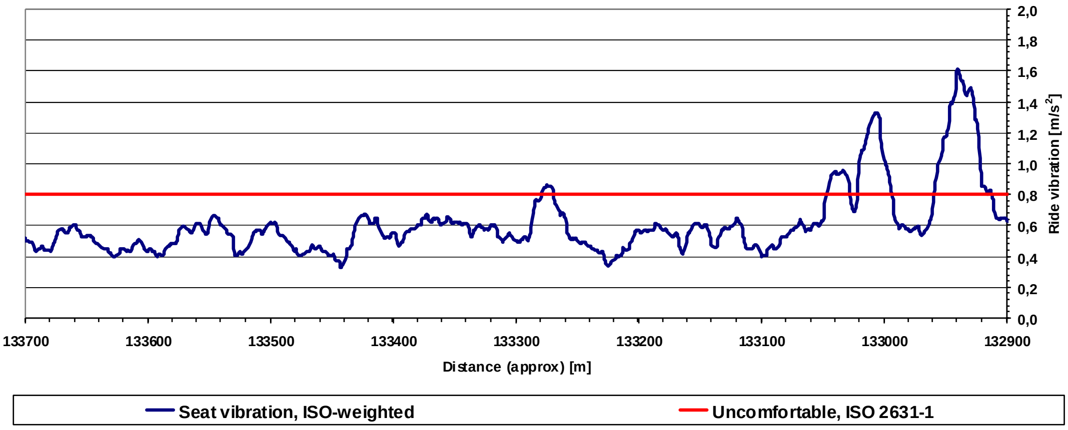


Figure 42 Very uncomfortable truck seat vibration when driving over the new culvert in Gammelmo

The cause of the transient vibration in the driver's seat can be seen in the following 3D laser scan from the Profilograph. Figure 43 shows a 20 m long and 57 mm deep hollow in the newly paved asphalt over the culvert. The culvert had been reconstructed just a couple of months before the test in August 2007.

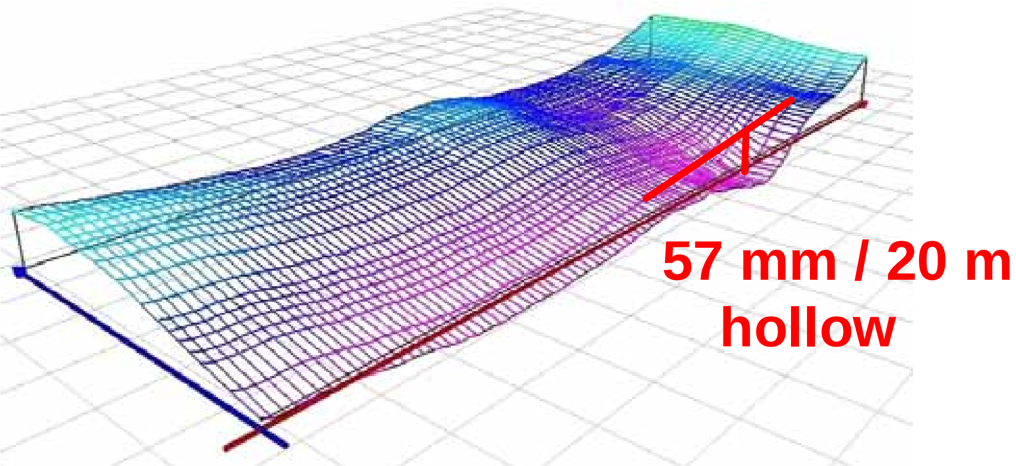


Figure 43 ***3D laser scan of settlement at reconstructed culvert in Gammelmo***

An example of a series of extremely annoying bumps was found 5 km south from Edsele. At this location there were three very bumpy culverts in a row within 200 m. When these culverts were crossed by a heavy truck travelling at around 80 km/h, the result was repeated transient seat vibration. The in-truck measurements recorded powerful shocks in the vertical, pitch and fore-aft directions at all three bumps, as seen in Figure 44. The first bump is indicated by skid marks from truck tyres, as seen on the Right-Of-Way video in the figure.

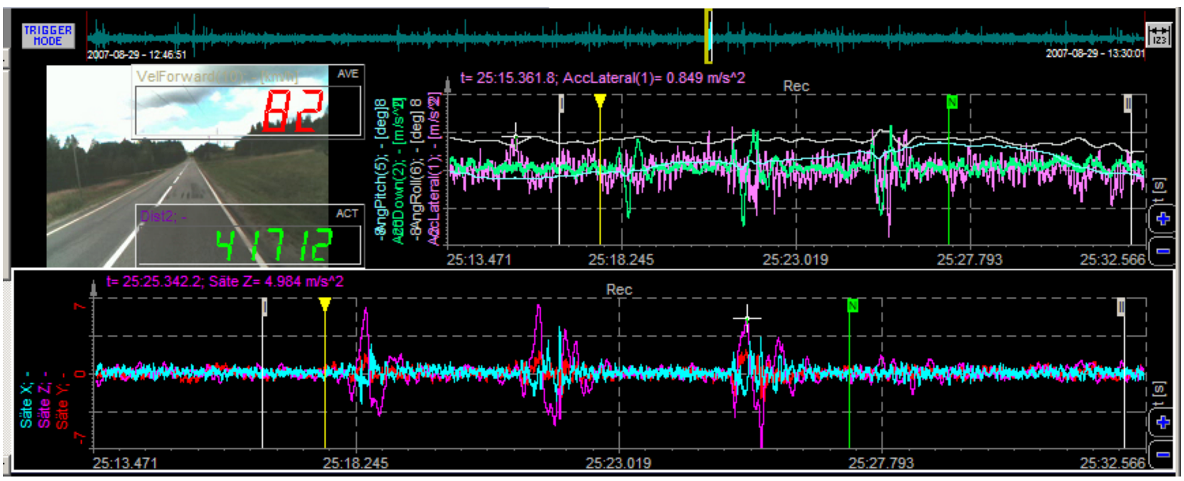


Figure 44 ***Three bumpy culverts within 200 m, RDB section 117/200 km***

Two of the three bumps at RDB 117/200 km are shown below in a 113 m long 3D laser scan in Figure 45, taken by the Profilograph. The driving direction is from the left to the right of the graph. These bumps were up to 50 mm deep; a magnitude comparable to the suspension compression stroke of a normal road vehicle. With such a bump there is a high risk for the suspension to hit its bump stops, causing a non-linear shock. Obviously this kind of severe road obstacle can be hazardous when driving at highway speeds.

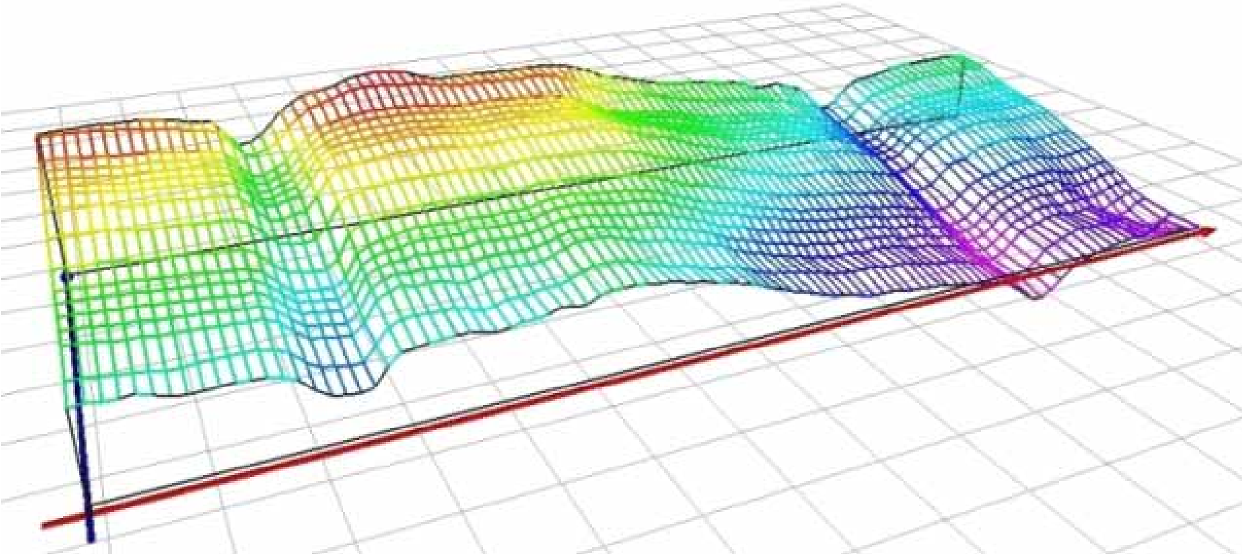


Figure 45 ***3D laser scans of two bumpy adjacent culverts, RDB section 117/200 km***

5.1.2.1 One of the worst bumps was found on the guest section of National Highway 87

On the short section between Viksmon and Österforsse, Rd 331 is a "guest road" on Hw 87. It was surprising to see that this National Highway section gave as high truck seat vibration intensity as the long section Stavre - Viksmon on Rd 331, see spreadsheet in Figure 39. However, the worst roughness on the short Hw 87 section could be reduced very efficiently. This can be accomplished at low cost, by the repair of the bumps at a high banking over the culvert about 1 km north of Viksmon. Profilograph data in Figure 46 shows a large bump with an IRI_{20} = 6.4 mm/m just above the culvert, and another bump with IRI_{20} = 7.6 mm/m at the poorly finished asphalt joint, just one hundred meter later.

An IRI_{20} of 7.6 mm/m is comparable to the IRI measured with a Profilograph on the 1 dm high speed bump in front of Umeå Plaza Hotel. At that bump, Mrs Gunhild Högberg from Örnsköldsvik was severely injured by a spinal compression fracture, when riding with her husband at low speed in their campervan.

As seen in Figure 46, the section on Hw 87 reminds of one of the most stressing driving conditions perceived by EU Northern Periphery professional drivers: "*Truck drivers stated that the worst sections have bumps at culverts, located at the bottom of a valley*" [49].

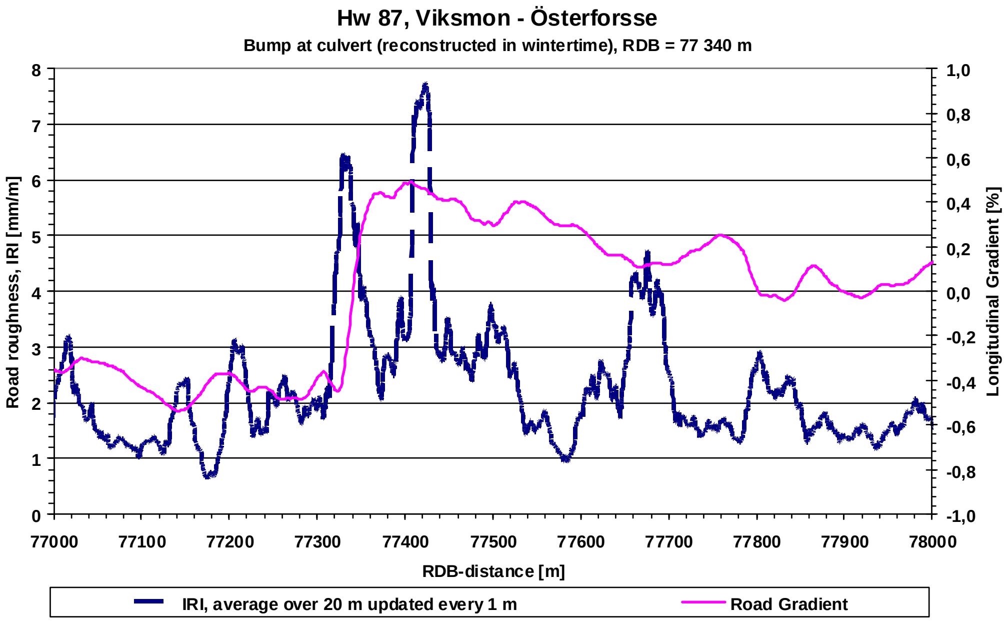


Figure 46 ***Bump at culvert in the bottom of a valley, where grade change from downhill to uphill at 0 %***

The culvert beneath the high banking on Hw 87 was undermined in the winter of 2003 and an emergency reconstruction was carried out to make the road serviceable again. The emergency repair was done at temperatures below zero; therefore good compaction at optimum moisture content was impossible. The present roughness is obviously not acceptable in the long-term perspective, as can be seen in the results. This kind of winter repair must to be finished by a second phase in summertime, after the inevitable settlements have happened. The poor winter-paved asphalt should then be milled off, the base watered and compacted thoroughly, unevenness smoothened and finally repaved with new asphalt. The smoothness over such reconstructed culverts should be systematically monitored for two years, and repeated repaving actions ordered if needed.

5.1.2.2 Bumpy joints at the bridge over Fax River in Helgum

Transient vibration can also be caused by bumpy bridge joints. A 3D laser scan from Hazardous Site Helgum is seen in Figure 47. The joints on both sides of the bridge are tenfold times rougher than the SRA tolerance. When timber logging trucks pass the > 4 cm bumps, snow and mud fall off the vehicles, contaminating the road and requiring intensified ploughing.

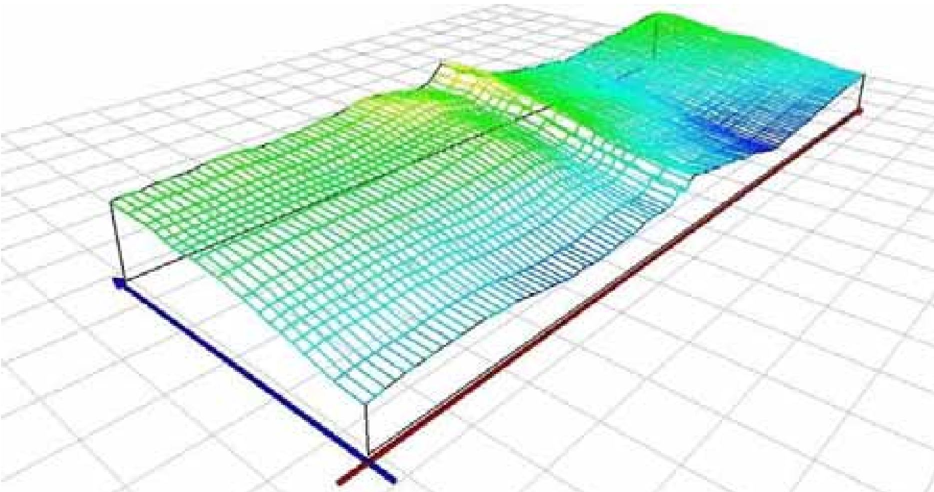
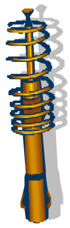


Figure 47 ***3D laser scan of a bumpy joint at the bridge over the Fax River at HS Helgum***

5.2 THE TRUCK SUSPENSION SYSTEMS PERFORMED VERY WELL



The measurements recorded during the tests permitted the performance of the vertical suspension systems of the Scania test truck to be evaluated. Figure 48 present's data from a 13 minute ride at 78 km/h over 17 km of Rd 331, southbound from the junction with National Highway 87 in Viksmon. The vertical vibration intensities recorded are plotted over frequency, using a log-log scale. This figure does not represent response functions, so a similar figure from another road section will differ somewhat, depending on the properties of the particular road profile.

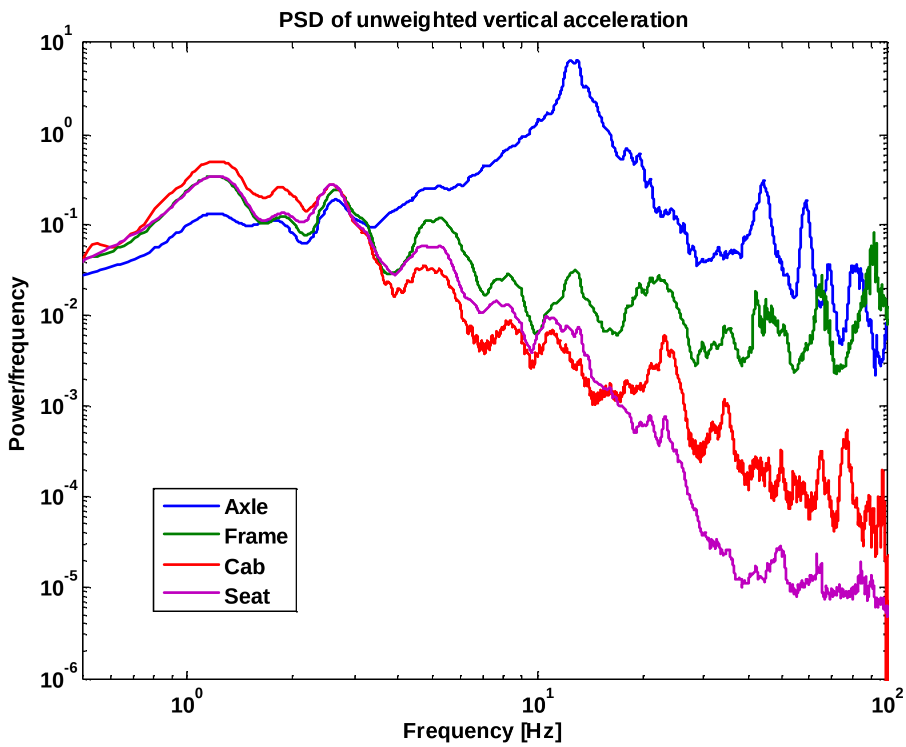


Figure 48 ***Power Spectral Density of vertical acceleration in the trucks suspension systems***

5.2.1 The wheel axle had much 11 Hz vibration from 2 m wave roughness

The blue trace at the top of Figure 48 shows the vibration recorded at the wheel axle. There is a wide vibration maximum at about 11 Hz, and high clear resonance peaks at about 45 Hz, 60 Hz and wide maximums below 2.7 Hz. The lack of a clear peak at the 11 Hz maximum may be due to superposition of several peaks. One such peak is the wheel axle parallel hop resonance; another is the wheel axle tramp (roll) resonance. The 45 Hz peak may be related to the tyre's 1st eccentric modal resonance. As the wheel is close to the vibration source (the road), Formula 1 can be accurately used to relate the 11 Hz frequency with maximum intensity to road roughness with wavelengths of 2 m. The other peaks relate to 0.37 m, 0.5 m and 8 m. The intensity at the 45 Hz vibration peak is equal, or below, the intensities from 6.5 to 20 Hz. This bandwidth corresponds to a road roughness ranging from 1.1 to 3.3 m. This waveband, 1.1 to 3.3 m, is obviously perceived by the truck wheel axle as the worst roughness in the road section.

5.2.2 The frame had much 1.2 Hz vibration from 18 m wave roughness

The green trace, second from the top, shows the vibration recorded at the truck frame. The maximum is at some 1.2 Hz, with more intense vibration than at the wheel axle. This amplification is likely to be due to resonance in the chassis suspension system, and relates to road profile waves with some 18 m length. The second peak is at about 2.7 Hz, and a third at 5 Hz. These peaks relate to 8 m and 4.3 m. The highest intensities are seen from 0.7 Hz up to 3 Hz. This shows that the truck frame perceived the waveband from 7 to 31 m as the worst unevenness in the road section.

5.2.3 The cab suspension system gave good isolation at high frequencies

The red trace, third from the top in Figure 48, shows the vibration in the truck cab[15]. Just as in the frame, the maximum is at 1.2 Hz, and is related to road profile waves with some 18 m length. At frequencies above 4 Hz, the cab vibration is much lower than the frame vibration. Below some 2.7 Hz, the cab suspension system amplifies the frame vibration. Similar to the frame, the truck cab perceived the waveband from 7 to 31 m as the worst unevenness in the road section.

5.2.4 The seat suspension isolated high frequency vibration further

The purple trace, at the bottom, shows the vibration on the truck seat. Just as in the cab and in the frame, the maximum is at about 1.2 Hz. The seat suspension isolates vibration over some 16 Hz very well, as it is designed to. At frequencies between 4 and 16 Hz, vibration from the cab seems to be amplified, getting higher on the seat pan. However, the RT 3050 truck cab reference sensor was not mounted under the driver seat, but between the two seats. Therefore data from the cab (input) and the seat pan (output) must be compared with care.

[15] The cab vibration data are measured with the OxTS RT 3000 system, sampling at "only" 100 Hz. This cause some aliasing errors at high frequencies, so with respect to the sampling theorem, cab vibration data at frequencies above 50 Hz are not reliable. These data are of no practical importance for the research objectives in this case study.

5.2.5 Altogether, the truck suspension systems gave excellent vibration isolation

The vibration "transmissibility" from the wheel axle to the driver seat is shown in Figure 49. An amplification (gain) of "1" means "what comes in, gets out"; neither isolation, nor amplification.

At frequencies over 10 Hz, the truck suspension systems have together isolated more than 99 % of the wheel axle vibration from reaching the driver seat. This is of course an excellent performance. Vibration at frequencies from 3 to 10 Hz has been isolated with efficiency from 0 up to 99 % as the frequency increases. At the "slow" frequencies below 3 Hz, amplification makes the driver seat vibration reach up to 2.5 times the wheel axle vibration.

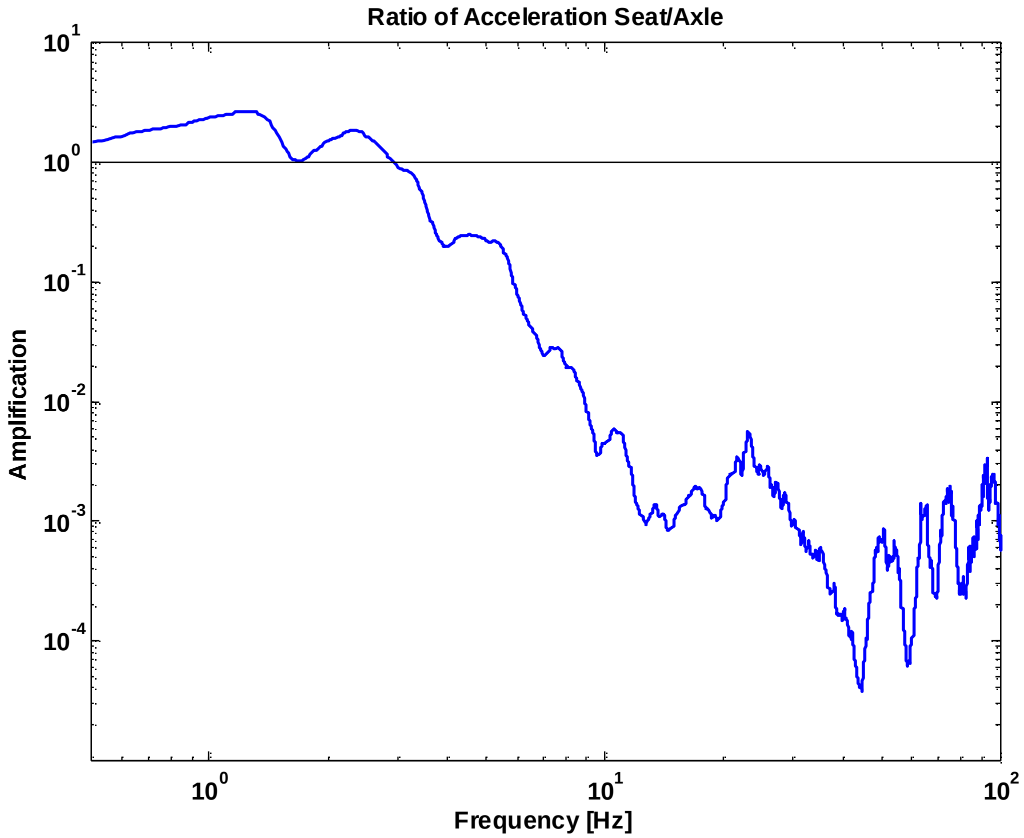


Figure 49 ***Gain of vibration from wheel axle to driver seat***

5.2.5.1 The first problem is low frequency vibration, due to long wave road unevenness

As seen above, the worst ride vibrations are from 0.7 to 3 Hz, at 78 km/h related to road unevenness within a waveband of 7 to 31 m.

When calculating the drivers exposure to WBV, seat vertical vibration at frequencies below 2 Hz are weighted (reduced) by a factor 0.5 or smaller, as per the W_k filter in ISO 2631-1 [18].

Despite this 50 % reduction by the frequency-weighting, very high intensities still remain at frequencies between 0.7 and 3 Hz.

For the 17 km section south of Viksmon, the root-mean-square (RMS) "averaged" value for the weighted xyz vector was 0.86 m/s^2. This rates the 13 minute ride "uncomfortable" on average, as per the ISO 2631-1 comfort scale in Table 1.

5.2.5.2 The second problem is the intense lateral vibration

Calculation of the 13 minute ride's contribution to the daily exposure A(8) is based on the single axis having highest RMS. This was the z-axis, which had 0.59 m/s^2. When analyzing health risk, lateral vibration must be multiplied by a factor 1.4 [2]. After this operation, the y-axis had almost as much vibration as the z-axis; 0.54 m/s^2. This is remarkably high, compared to the vertical vibration. "Off-roads" such as Rd 331 calls for a new approach to truck suspension systems. It is obviously not enough to isolate vertical vibration; there is also a need to prevent or isolate lateral vibration as well.

5.2.5.3 The third problem is the transient bumps

The worst bump in the 17 km long section southbound from Viksmon, gave a maximum transient vibration value of 2.44 m/s^2 along the XYZ vector (MTVVV). This value, calculated after integration over 1 second, corresponds to an "extremely uncomfortable" ride on the ISO 2631-1 comfort scale in Table 1.

5.2.6 The broken truck suspension bush had no significant effect

The first truck test run was made without a bush on one damper in the chassis suspension system, as seen in the photographs in Figure 30. Before the main test runs, the bush was replaced at a Scania workshop. The truck driver's seat vibration has been compared with and without the bush for the first 30 km section southbound from Ramsele. The results show that the vertical (z-axis) vibration was 3.3 % higher with the bush in place. This is within the reproducibility noise level, so it should not be taken as a working bush makes seat vibration worse. Rather, the results show that the effect of the damper is low. However the truck chassis suspension system provides much of its damping by other means than the "damper" component.

5.2.7 The lateral vibration was 124 % higher in the truck than in the car

The average xyz vibration on the Scania truck driver's seat was 83 % higher than the vibration on driver's seat in the Ford Mondeo (see photograph in Figure 35), when comparing data from Viksmon and 17 km towards Viksjö. While the truck ride was "uncomfortable", the 0.47 m/s^2 car ride was only "a little uncomfortable" as per the ISO comfort scale in Table 1. While the worst bump was "very uncomfortable" (MTVVV = 1.48 m/s^2) in the car, the worst bump was "extremely uncomfortable" (2.44 m/s^2) in the truck. These findings confirm the indicative preferences given in Table 2.

As expected, the high Scania truck was more prone to RBCSV, since it showed 124 % higher average lateral (y-axis) vibration than the lower Ford Mondeo passenger car. The ratio between truck and car was 34 % higher on lateral vibration (y-axis) than on vertical vibration (z-axis). This further confirm that deformed pavement edges are a much larger problem to truck drivers than to car drivers, (including Councillors and road agency officers in their comfortable duty cars).

5.2.6 Rd 331 can't be efficiently repaired by traditional asphalt overlay

The vibration intensity of a truck wheel axle can be very high, from 0.7 to 3 Hz in Figure 48. At 78 km/h, these frequencies correspond to road roughness with waves ranging from 7 to 31 m. The peak vibration in the frame, cab and seat occurs at 1.2 Hz, which corresponds to road profile waves of approximately 18 m lengths.

These truck responses show a ride problem that is related to long wave unevenness in the road. This finding is confirmed when analyzing the same road profiles scanned by the laser/inertial Profilograph. A typical road profile example from the 17 km section is given in Figure 50. It records up to 60 mm deep hollows in wavelengths of over 30 metres.

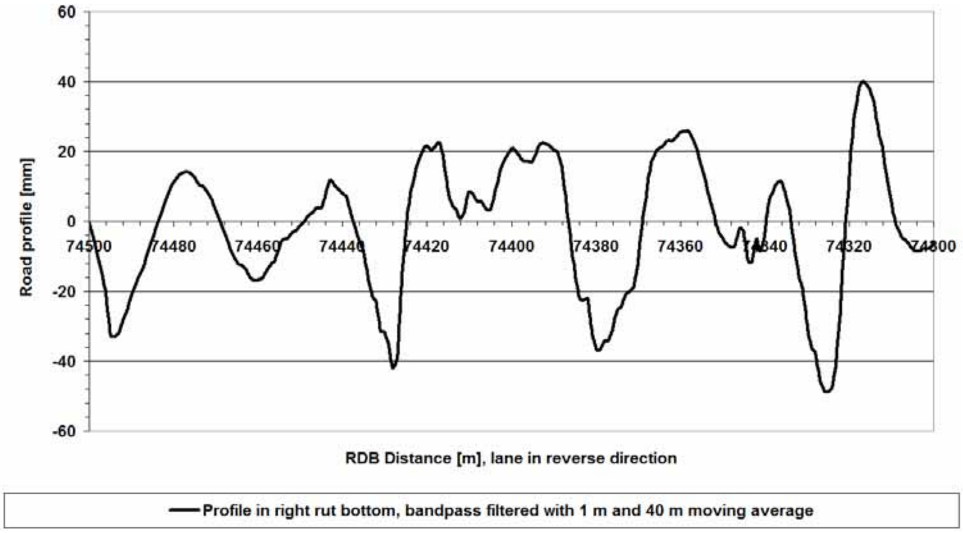


Figure 50 ***Rd 331 Viksmon - Viksjö: Unevenness with high amplitudes at up to over 30 m long waves***

The SRA Central Region plans to carry out a traditional asphalt overlay for this road section in 2008. However, its steep 7 - 31 m waves are obviously too long to be efficiently repaired by a simple asphalt overlay. These waves are so long that the paving equipment will simply ride along them, only raising the unevenness by the thickness of the new asphalt mat. To produce a good solution, the road machines must be effectively controlled and forced to make the necessary changes to the unevenness, as the present defects are much longer than the machines themselves. It can be claimed that these waves can be repaired by subjective spot fillings before paving the mat. However, this ad-hoc method is unable to make the alterations necessary without using an excessive amount of costly asphalt. A proper and cost-effective repair of this road requires an accurate measurement of the road 3D-geometry, and a careful (computer aided) rehabilitation design at each 5 m section. The benefits in terms of the reduced low frequency ride vibration of this type of road repair method are presented in detail by Granlund & Lindström (2004) [13]. Another alternative is a more costly “total pavement reconstruction”. Unless one of these two methods is used, much of the low frequency vibration is likely to remain for heavy vehicles after the road repair has been carried out.

5.3 GOOD FIT BETWEEN PROFILOGRAPH DATA AND TRUCK RIDE

5.3.1 Precision of repeated truck ride

There are of course variances between truck rides on a given road section. The reproducibility for the seat vibration between two runs with truck driver A and a third run with driver B is shown in Figure 51. The graphs are not perfectly synchronized in distance, due to slightly different lateral position in curves et cetera. Despite being instructed to follow the ruts, it appears that one of the drivers may have been more active in steering to avoid driving over bumps. This is very human, since it is easy to revert to periods of 'normal driving behaviour' during test driving over a number of days. The graphs show clear differences between good and poor road sections, even though the variance in a given section can be significant. It will be recalled that similar variances were seen when comparing truck ride data with the reference road profile data from the Profilograph. However, by filtering data from repeated truck runs, variance can be reduced.

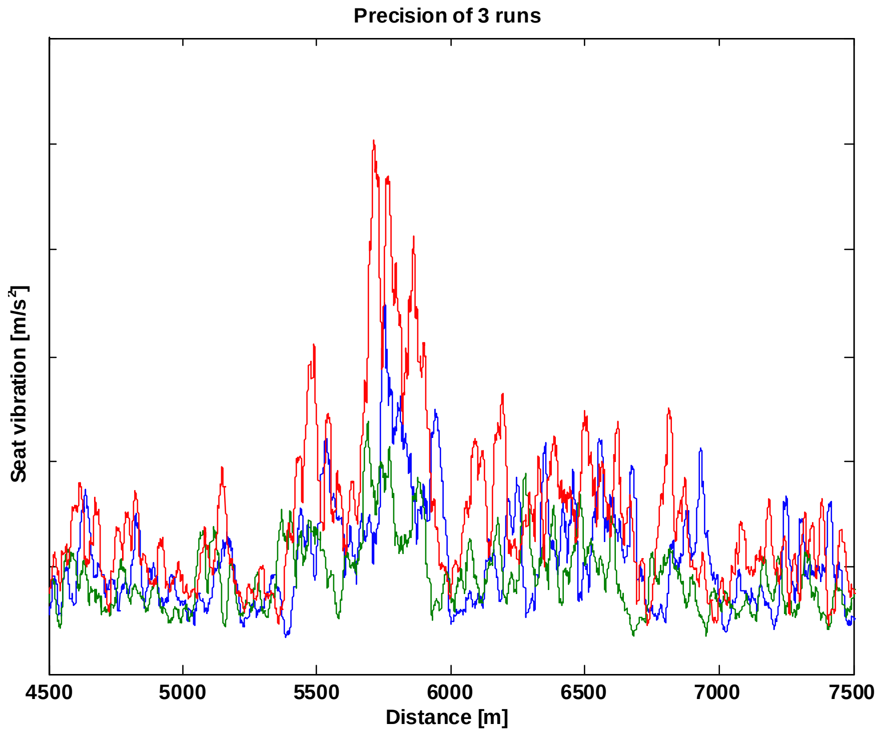


Figure 51 ***Reproducibility in truck driver seat vibration between three runs at HS S Viksmon***

5.3.2 Profilograph data is a proven reference to vertical ride vibration

Previous research has shown a very good fit between pavement roughness, as measured by a Profilograph, and vertical ride vibration in heavy trucks. However, in road sections with very poor bearing capacity this fit may drop significantly, as shown by Ahlin et al (2004) [19], due to soft spots in the pavement affecting the roughness experienced through the truck tyres.

Profilograph data is frequently used in advanced studies on vehicle ride vibration. One example is seen in the Ph D thesis on heavy truck fatigue damage by Bogsjö (2007) [22], based on data from Rd 331 and other Northern Periphery roads. Another study of Profilograph data from Rd 331 is reported in the Masters thesis on ambulance car ride quality by Nilsson (2004) [69].

5.3.3 Profilograph data emerge a good reference to truck roll angle and rate

5.3.2.1 RBCS show good fit to truck roll angle

In this project, an important issue is truck roll vibration and its relation to undesired variance of the Rut Bottom Cross Slope (RBCS) of the pavement. The case study on Rd 331 included Profilograph measurement of pavement RBCS, as well as measurement of the dynamic roll angle of the Scania R480 truck cab. Comparisons of the two types of data show a good fit, as seen at Hazardous Site Backe (Edsele) in Figure 52. This confirms the value of Profilograph data as a reference input for calculations into the dynamic roll motion of trucks.

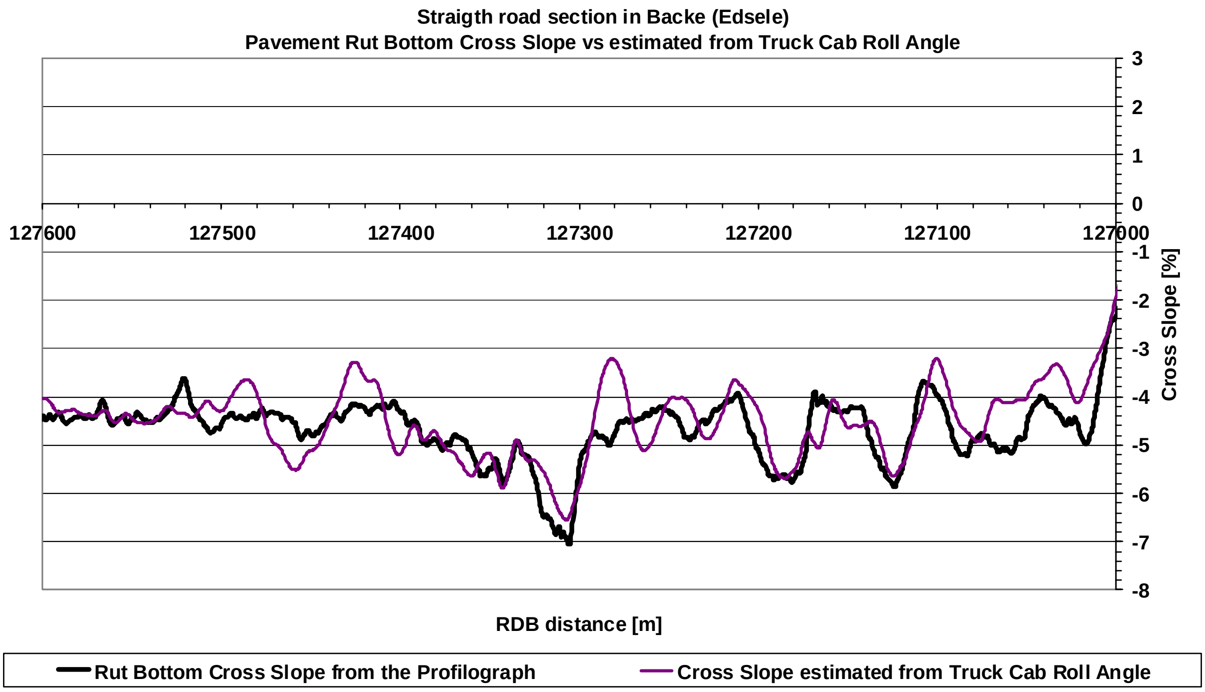


Figure 52 Good fit between pavement Cross Slope and Truck Cab Roll Angle

5.3.2.2 Rock ´n Roll at HS Backe (Edsele)

Figure 53 shows a photograph of the truck, warping as it enters a section of severe long-wave edge deformation at RDB distance 127/325 km. The truck's large roll angle should be particularly noted. Also noteworthy are the different roll angles of the truck and the trailer, as well as the different yaw angles.

Figure 53 HS Backe (Edsele): Warping truck and trailer at RDB distance 127/325 km

A cut screen-print from the onboard Dewetron system is given in Figure 54. The recordings were captured synchronized with photographs taken from the roadside as in Figure 53 above. The forward facing video in Figure 54 actually shows the exterior photographer standing beside the road. The white undulating top trace shows the variance of the truck cab roll angle, recorded by the OxTS RT 3050 unit. The peak rate of the change in roll angle at the Hazardous Site at Backe (Edsele) was over 3 °/s. In the case of the test vehicle, a roll angle of 1 ° corresponds to a 35 mm vertical displacement between the left and right tyres.

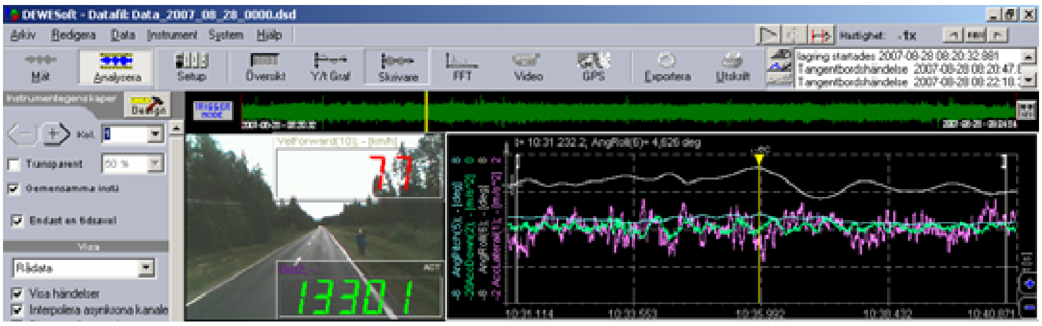


Figure 54 HS Backe (Edsele): ROW video and some of the recorded truck ride data

Section 127/325 km was rated as “*very uncomfortable*” and “*hazardous*” by the truck drivers. The vector of roll and pitch rates peaked at 4.48 °/s. This touches the threshold used in New Zealand, as presented in section “*3.3.2.2 Roll vibration is excited by undesired variance of Rut Bottom Cross Slope*”. The section’s RBCSV peaked at 0.47 %.

Excessive Cross Slope in straight road sections is an ergonomic problem

The cross slope (CS) magnitude is remarkable at the Hazardous Site at Backe (Edsele). The section has values ranging between -4 % and -7 %, see Figure 52, despite the design value for straight roads being -2.5 %. The maximum value allowed for CS when designing extremely sharp curves in Sweden is +/-5.5 %. Obviously this straight section has too much CS. Excessive CS contributes to a poor work environment for professional drivers as they have to sit in an awkward side sloping position to counteract the adverse CS, causing the spine to be twisted, while also being exposed to high ride vibration.

Response data are not good reference to road management

It may seem that truck response data could be useful in pavement management systems. However, this type of road condition data depends on many dynamic parameters, such as speed and lateral position. Therefore response data from commercial trucks or other vehicles could give poor estimates of pavement parameters such as cross slope. This is obvious at RDB section 127/300 km in Backe (Edsele), where the truck roll response differs by almost 2 percent, compared to the pavement cross slope, as seen in Figure 52. This difference is many times larger than the tolerance limit applied on quality certified road condition data used in normal pavement management systems.

5.3.2.3 Rock ´n Roll at HS Åkerö

The HS Åkerö pavement edge damage is seen on photo in Figure 55. Take note of the exploded truck tyre to the right! Traditional optical photographs do not reflect unevenness very well. A better way of visualizing unevenness is to use a 3D laser scan. This highlights all of the unevenness features. A Profilograph scan of the HS Åkerö damage can be seen in Figure 56. The deformation at this site was found to be 69 mm deep.

A cut screen-print from the onboard Dewetron Stream Machine system is reproduced for HS Åkerö in Figure 57. The white undulating top trace shows the variance of the truck cab roll angle. The RT 3050 had registered a peak rate for the roll angle of 6.8 °/s. The lateral acceleration measured in the truck cab was 2.0 m/s^2, and it was 75 % higher (3.5 m/s^2) at the driver's seat pan. The latter confirms that current seat suspension systems are unable to isolate lateral vibration as they have been designed primarily to isolate vertical vibration. These seats appear to actually amplify the problem, in fact, with lateral jolts at low frequencies. The HS Åkerö section was rated as "very uncomfortable" and "hazardous" by the truck drivers.

The cross slope magnitude is also remarkable at the straight road section at Hazardous Site Åkerö. Recalling that the design recommendation for cross slope was -2.5 %, this section has values ranging between -3 % and -6 %. The peak CS exceeds the maximum banking of +/-5.5 % allowed when designing the sharpest curves in Sweden.

Figure 55 ***Pavement edge deformation at HS Åkerö. Take note of the exploded truck tyre!***

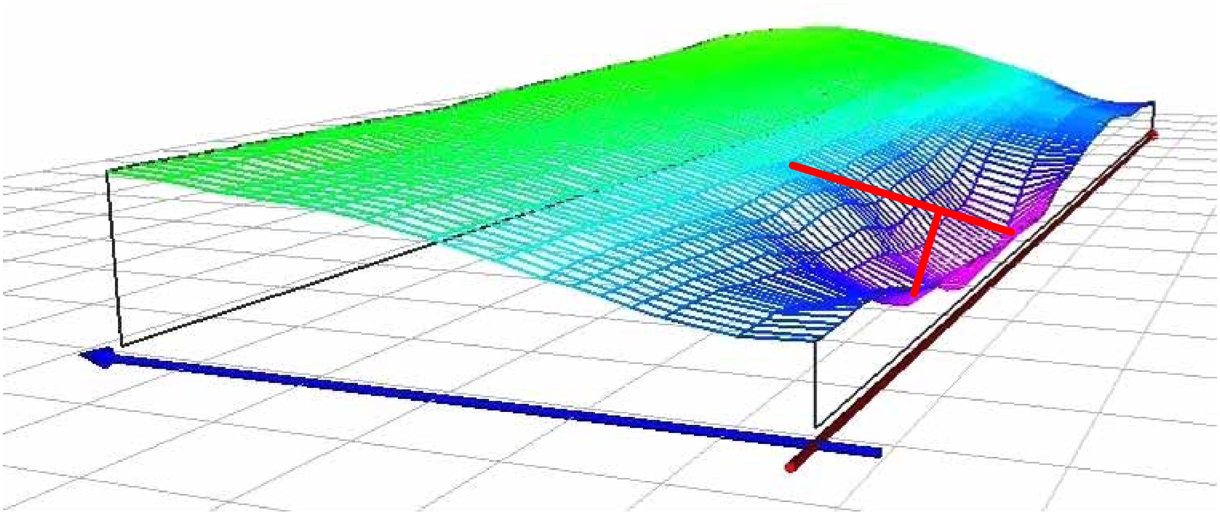


Figure 56 Profilograph 3D plot of the HS Åkerö 69 mm deep edge deformation

Figure 57 HS Åkerö: ROW video and some of the recorded truck ride data

As stated above, an important issue for this research was the relationship between undesired variance of the Rut Bottom Cross Slope (RBCS) of the pavement and the truck roll vibration. In the previous section, a good fit was found between RBCS and truck cab roll angle. The variance of cab roll angle is a measure of the cab's roll vibration. Further analysis confirms a good fit between variance of the roll angle and variance of the RBCS (RBCSV), as can be seen in data from HS Åkerö in Figure 58.

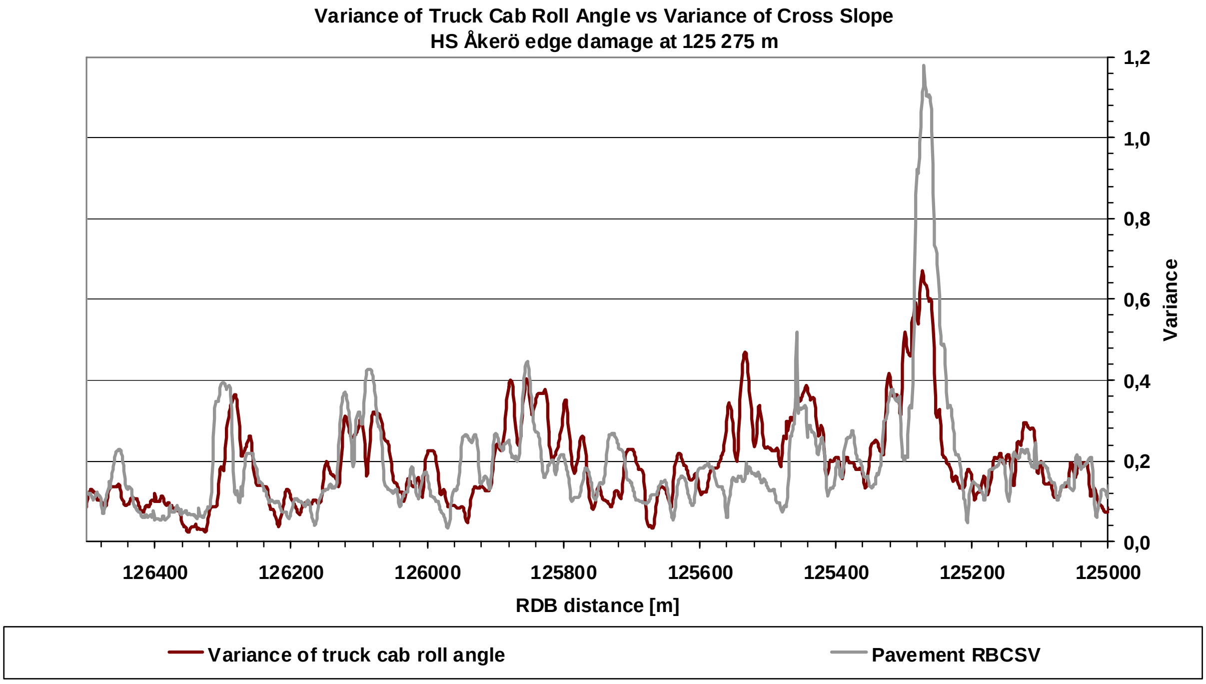


Figure 58 Good fit between Variance of RBCS and Variance of Truck Cab Roll Angle

The RBCSV parameter has been designed to identify those sections with cross slope variance that cause roll vibration in the suspended masses (body, cab and payload) of heavy trucks, as well as in the wheel axle [21]. As a result of this multi-purpose requirement, one should not look for a perfect match between RBCSV and the roll vibration of the cab. There can be significant variances between reproduced truck rides, as seen in Figure 51. With this in mind, the match seen in Figure 58 seems good for the intended purpose of the RBCSV parameter.

5.3.2.4 Warping RBCS at Hazardous Site N Åkroken

The Hazardous Site north of Åkroken shows an unusually high accident number, as seen in Figure 28. This site also show extremely high RBCSV; 1.04 %. This is ten times the "noise level" of 0.1 %, as seen in Figure 59. This clear alarm is caused by a warping change in cross slope from -4 % to -7.5 % and then back to -4 %. The net change of 2.5 % cross slope corresponds to a change of 5 cm in elevation between left and right wheel track, as they are spaced 200 cm; 0.025 * 200 = 5 cm.

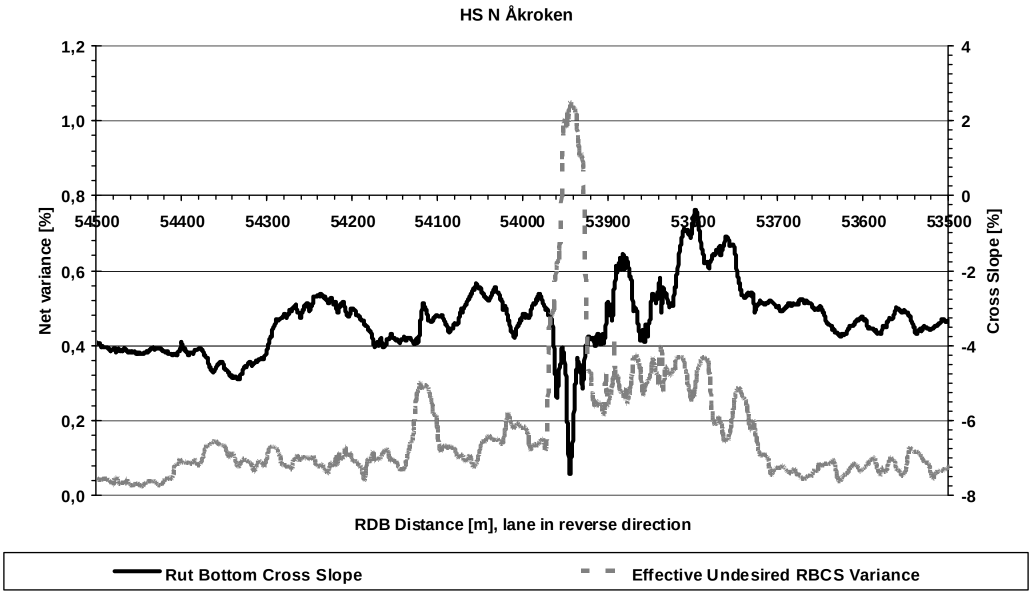


Figure 59 ***High RBCSV indicate severe pavement edge deformation at HS N Åkroken***

5.3.2.5 Warping RBCS at Hazardous Site Meåstrand

In contrast the Hazardous Site at Meåstrand "only" shows a slightly increased accident number. However, the truck drivers report this to be one of the most dangerous sites. The modest consistency between driver opinion and accident black spot map, may be explained by the fact that this site has low traffic intensity. This calls for an "Individual Risk" mapping, where accident number is divided by traffic intensity AADT as described by Ogden & Daly [64]. However, such an analysis requires further resources not available within this project which has its focus on health issues rather than traffic safety.

HS Meåstrand shows a high degree of warping RBCSV; 0.95 %. This is almost ten times the "noise level" of 0.1 %, as seen in Figure 60. This clear "alarm" is caused by a warping change in cross slope from -2.9 % to -5.2 % and then back to -3.0 %. The net change of 2.3 % cross slope corresponds to a change of about 4.6 cm in elevation between left and right wheel track, as they are spaced 2 m. A photo of a truck yawing to avoid this pavement edge is showed in Figure 61. Take note of how the painted road marking line reflects the lateral component of the pavement's deformation. Also take note of the glare of the asphalt repair in the outer wheel track. Friction aspects on this kind of single track patch repair will be further discussed later in the report.

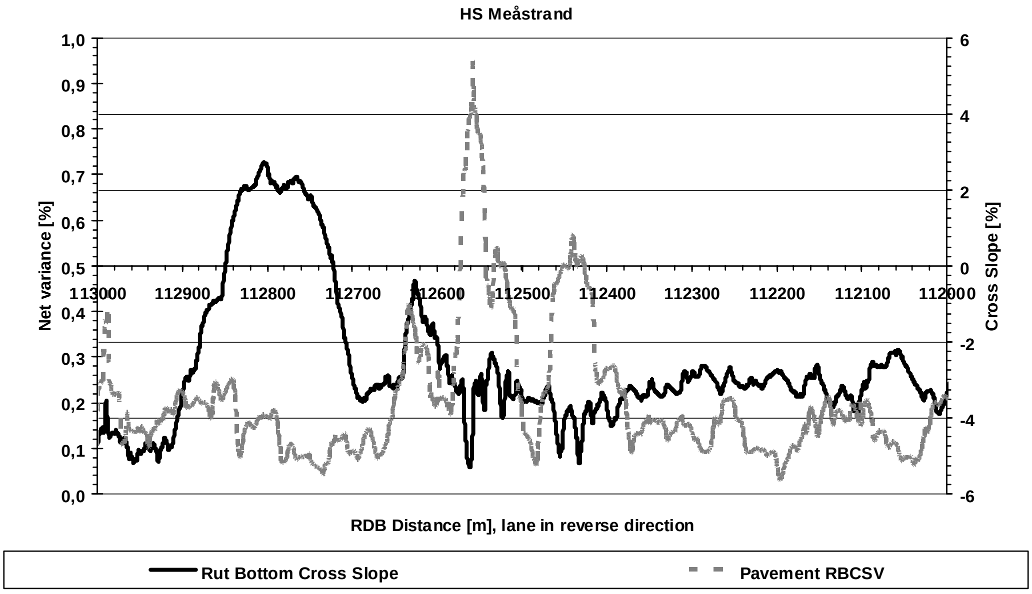


Figure 60 High RBCSV indicate severe pavement edge deformation at HS Meåstrand

Figure 61 ***Severe pavement edge deformation at HS Meåstrand***

5.3.2.6 Warping RBCS at Hazardous Site Alderån

HS Alderån shows an unusually high accident number, as seen in Figure 28. This site also shows several peaks with RBCSV up to 0.55 %. This is over five times the "noise level" of 0.1 %, as seen in Figure 62.

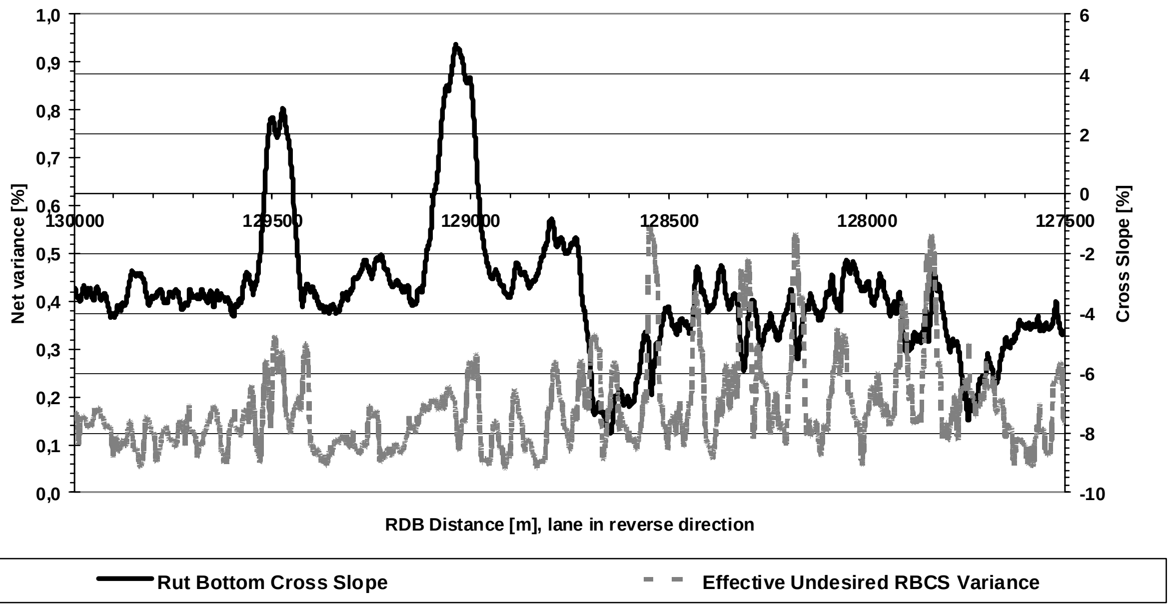


Figure 62 High RBCSV indicate warping pavement edge deformation at HS Alderån

HS Alderån also has other problematic features. It is a sharp right hand curve at the foot of a long and steep hill. In the curve, the cross slope is worse than -8 %. This is a very large slope, especially when appearing just after a long grade. Furthermore, the cross slope transition lengths are too short. On top of all of this, the pavement Mega Texture (MeTx) is unacceptably high in the curves´ outer wheel path.

MeTx is longer than Macro Texture, but shorter than roughness. These short waves range from 5 up to 50 cm. High MeTx causes distortion in the tyre/road contact patch, thus being a source of friction problems. MeTx is also a significant source of annoying interior and exterior noise. At HS Alderån, the MeTx peaked at 0.9 mm, being 4.5 times the normal "noise level" of 0.2 mm.

5.3.2.7 Warping RBCS at Hazardous Site Åsäng

HS Åsäng shows an unusually high accident number, as seen in Figure 28. A photo of a recent truck skid accident can be seen in Figure 63. The Police reported the friction to be zero, due to polishing. The truck driver said that the truck responded neither to steering, nor to braking, at the exit of the left hand curve.

Figure 63 ***Truck skid accident in Åsäng, 2007-02-22 [Photo: Torbjörn Elverheim, ST]***

This site also shows several peaks with RBCSV up to 0.49 %. This is over five times the "noise level" of 0.1 %, as seen in Figure 64.

There are three transient RBCSV peaks in Figure 64, at distances of 11/450, 11/435 and 11/403 km. Such peaks relate to short wave CS variance, which excite wheel axle tramp. This rolling motion of the axle results in lateral tyre displacements polishing the road, as discussed in section "*3.2.6 Wheel axle vibration impacts on traffic safety*". The Police observation on the road being polished into low friction give support to the theory of RBCSV causing low friction due to polishing.

As mentioned, Figure 64 shows three transient RBCSV peaks between 11/450 and 11/403 km. These transients increase the RBCSV by some 0.1 %, and correspond to about 1 % change in RBCS as seen in the graphs. In other terms, the transients correspond to 0.01 x 200 = 2 cm warping in profile elevation in one of the rut bottoms. Such warps are characteristic for steps at the start and end of poorly made 2 cm thick pavement repair patches. Macro Texture results (not shown here) also indicate likely starts and stops of patch work at the sections distance 11/450, 11/435 and 11/403 km. Furthermore, the MaTx was remarkably low, down to 0.2 mm at the patch indications. A benchmark minimum value is 0.6 mm MaTx for acceptable wet friction when braking at highway speeds. As seen on the photograph in Figure 63, the ice rut bottoms showed some asphalt, so the low MaTx may possibly have contributed to the observed low friction.

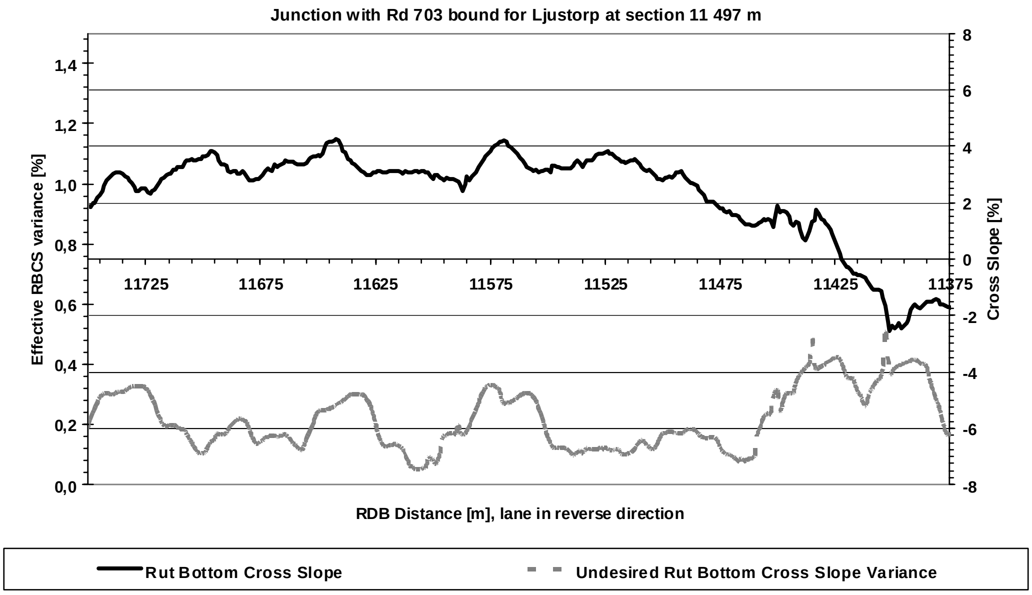


Figure 64 ***High RBCSV indicate warping pavement edge deformation at HS Åsäng***

The photograph in Figure 63 was taken at about section 11/400 km, and the skidding may have occurred just at the peak RBCSV in section 11/435 km. There is also another indication of the accident being related to the pavement condition. This is discussed in the section on insufficient Drainage Gradient.

5.3.2.8 Warping RBCS at Hazardous Site Mjällåsen

HS Mjällåsen shows an unusually high accident number, as seen in Figure 28. It has a long curve with varying curvature. In this curve, there are sections with excessive CS; up to 8.23 % negative CS. An ideal CS for dynamic cornering balance with respect to current curvature is -4 % in this section.

This site also shows several RBCSV peaks up to 0.85 %. This is more than eight times the “noise level” of 0.1 %. This clear “alarm” is caused by a warping change in cross slope from -3.3 % to -0.8 % and then back to -3.9 %. The net change of up to 3 % cross slope corresponds to a change of 6 cm in elevation between left and right wheel track, as they are spaced 2 m. The RBCS trace down to -0.8 % indicates that the pavement centre, rather than the edge, has collapsed. If this is the case, this road section could have serious bearing capacity problems. Such problems should be considered when planning repair of the road section. If only a simple surface repair is done, the road will most likely deteriorate in very short time.

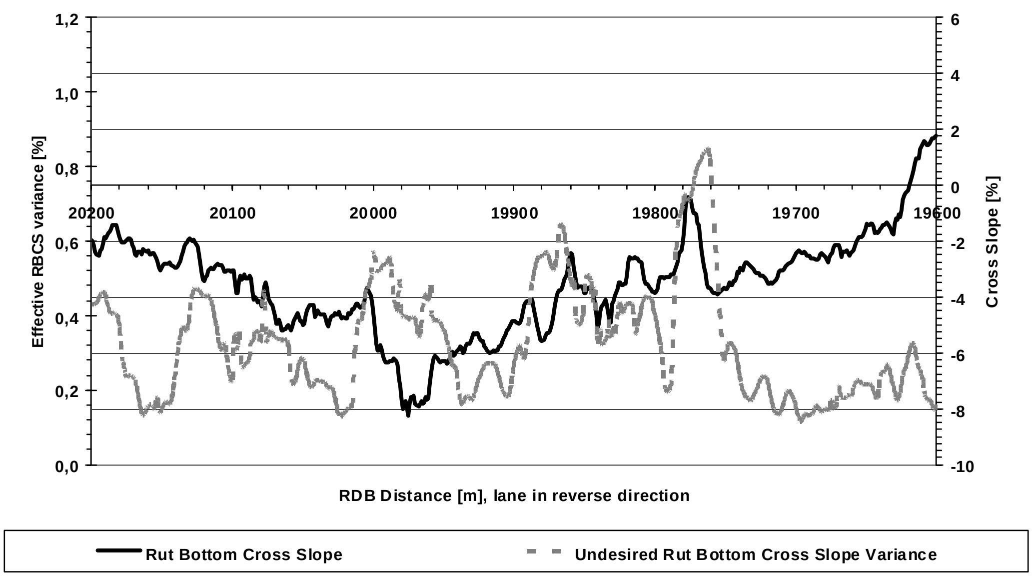


Figure 65 High RBCSV indicate warping pavement deformation at HS Mjällåsen

5.3.2.9 RBCS is a more accurate pavement parameter than Lane Regression CS

There are many ways to define/measure the Cross Slope (CS) of a pavement lane. Since 1997, the Swedish Road Administration's Pavement Management System (PMS) has measured CS by the "regression method". This uses the 17 laser measurement spots on the Profilograph distributed over a width of 3.2 m. In the regression method, data from the whole 3.2 m wide cross section are used to calculate the CS. In sections with severe edge deformation, the regression method may report significant smaller slopes than perceived between the left and right wheels of a truck. One example is found at HS Åkerö, in the section showing severe edge damage at RDB distance 125/275 km. As can be seen in Figure 66, the lane regression CS differs one unit from the 6 % truck cab roll angle; a relative difference of 1/6 = 17 %. In 2006, the SRA defined Rut Bottom Cross Slope (RBCS) as a parameter focusing on pavement slopes as perceived as a priority by drivers of heavy trucks [21]. Figure 66 shows a good fit between lane regression CS and the new RBCS parameter, except at the pavement damage in section 125/275 km, where the RBCS matches the truck roll angle much better. The difference between these two measures of cross slope can be large at sections with severe edge deformations in the shape of a basin, where a "wall" of displaced material is raised outside the outermost wheel as seen in Figure 55 and Figure 56. This kind of damage has a great effect on truck ride and RBCS must therefore be considered to be the most accurate road-user oriented parameter of the two.

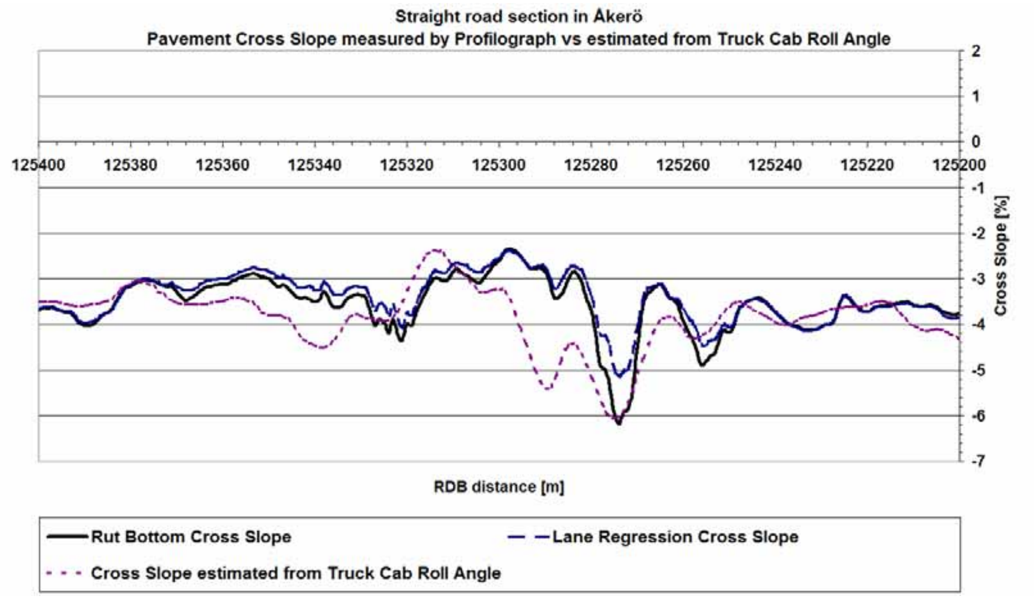


Figure 66 ***RBCS is a better estimate of truck roll angle, than Lane Regression CS is***

5.3.3 Road edge deformation may excite as much lateral vibration as a curve

Lateral acceleration is commonly recognized as a key parameter for vehicle driving stability, and thus for traffic safety. This is especially relevant on slippery surfaces, where the lateral friction forces are small. When a vehicle changes its roll angle quickly, the roll motion is accompanied by a lateral acceleration. An example from HS Åkerö is given in Figure 67. This shows a left hand curve (curvature -1.6) at distance 126/200 km, reflected by the change of sign in cross slope as it becomes superelevation through the curve. The graph for "Running Root-Mean-Square of Truck Cab Lateral Acceleration" shows a semi-static level of 0.78 m/s^2 through the curve. This can be compared to the value of 0.66 m/s^2 for lateral RMS acceleration recorded on the section of straight road with severe edge damage at HS Åkerö, section 125/275 km. In this latter section, the peak lateral acceleration was -1.37 m/s^2, whilst the peak lateral acceleration in the curve at 126/200 km was only -0.94 m/s^2.

The HS Åkerö example clearly shows that severely deformed pavement edges are a serious safety hazard, as they may result in lateral acceleration forces comparable to the lateral forces experienced when travelling a horizontal curve.

The grey trace in Figure 67 shows that the pavement RBCSV parameter was registering approximately 0.1 % through the curve, where the cab lateral acceleration was fairly constant with low vibration. However as intended, the parameter quickly gives a clear alarm of 1.18 % (being over 6 times larger than the 0.1 to 0.2 % noise level) when it enters the HS Åkerö section of pavement edge damage. This example also shows that the RBCSV parameter does not give "false alarm" due to normal superelevation transitions at left hand curves, where the truck cab roll angle smoothly tilts from side to side.

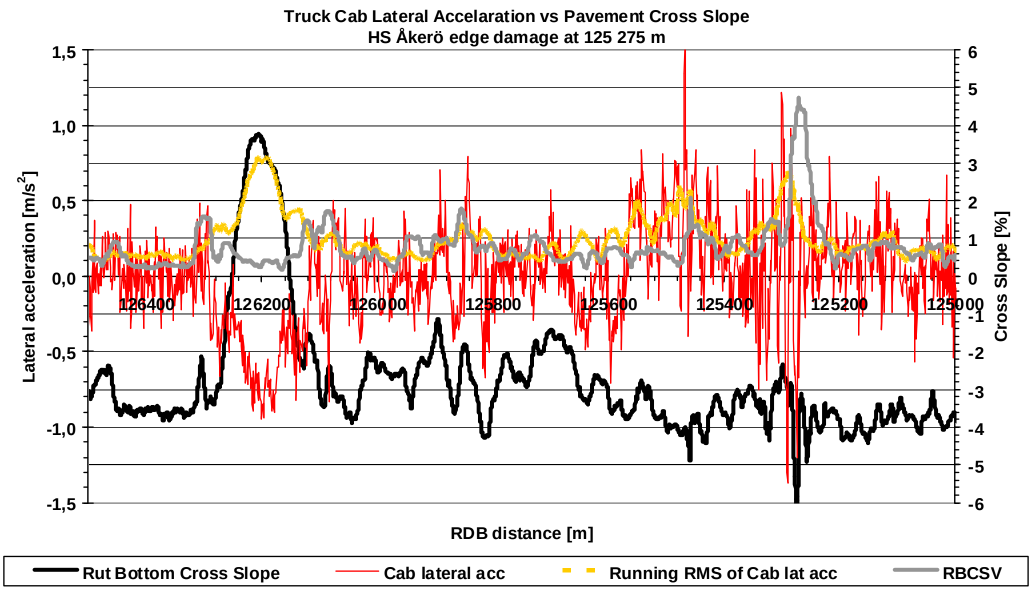


Figure 67 Edge damages may excite as much lateral acceleration as a horizontal curve do

5.4 DRAFTING A "WARPING LIMIT" FOR RBCSV

One goal in this project was to draft limit values for maximum warping between the road profile in left and right wheel track; the 'undesired variance' of the pavement's Rut Bottom Cross Slope (RBCS). For this task, it is important to understand typical distributions of warping on road sections in "normal" and in bad condition.

The 26.5 km section from Östergraninge down to Viksjö is a "quite normal old road". Compared to the Hazardous Sites *N Åkroken* and *N Viksjö* (see the black spot map in Figure 28), it shows a modest accident record. The distribution of Rut Bottom Cross Slope Variance (RBCSV) values on this section is shown in Figure 68.

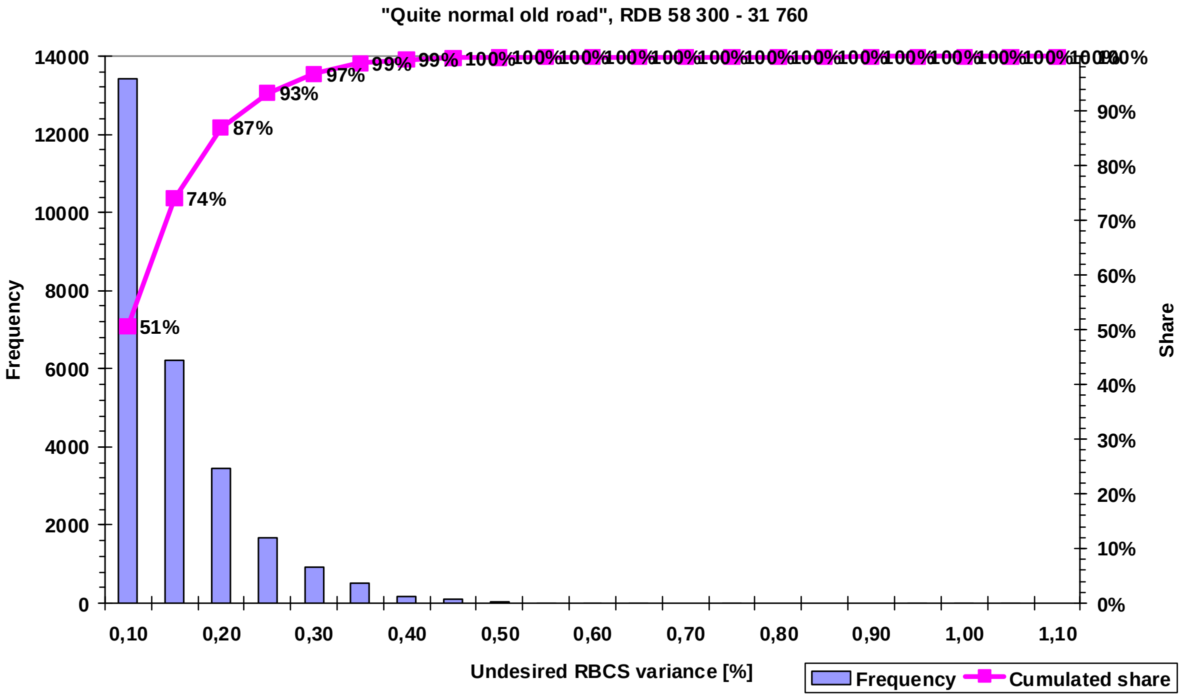


Figure 68 ***RBCSV distribution at a "normal" old road, Östergraninge - Viksjö***

The 17 km from the junction with Hw 87 in Viksmon, and down southeast to Östergraninge, is a rough section with severe pavement edge deformations, resulting in intense lateral vibration in the truck cab. An unusually large number of traffic accidents have taken place on this section, including the HS Björknäset, as seen on the black spot map in Figure 28. The distribution of Rut Bottom Cross Slope Variance (RBCSV) values on this section is shown in Figure 69.

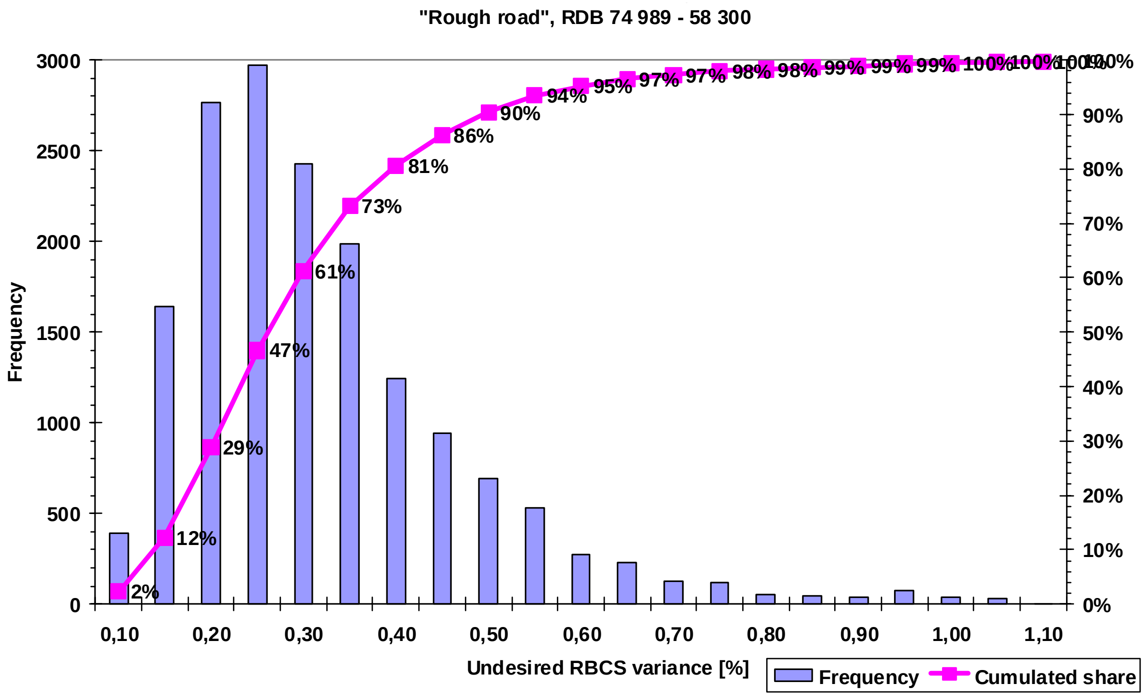


Figure 69 ***RBCSV distribution at the rough road section S Viksmon – Östergraninge***

Sample results of collation of Profilograph data, truck ride data and truck driver perception of comfort and safety are given in earlier report sections. These results show that a RBCSV of 0.4 % is too high as a limit value. On the other hand, 0.1 % RBCSV corresponds to the "background noise" on old roads, and is obviously too low to be a limit value. A reasonable limit could be somewhere between 0.2 % and 0.3 % RBCSV. The graph in Figure 68 shows that 3/100 of the old road length exceeds 0.30 % RBCSV, while 13/100 of the road length exceeds 0.20 % RBCSV. Since it is important to focus road repair to a limited fraction of the road network, a reasonable draft limit value could therefore be 0.30 % RBCSV.

On the rough road, 0.30 % RBCSV is exceeded on 39/100 of the length, as seen in Figure 69. Again, 0.30 % RBCSV is exceeded on 3/100 of the length of the old road Östergraninge - Viksjö, which include some Hazardous Sites. This shows that 0.30 % RBCSV can be a good draft limit value.

A statistical analysis of the data from the section from Ramsele to Ärtrik shows that 0.3 % RBCSV gave approximately 2.0 °/s roll rate in the test truck at the normal operation speeds on this road section.

Chapter 6. Spin-off results on traffic safety

A map of accident black spots on Rd 331 is shown in Figure 28 and data recording intense truck vibration and high road roughness values have been presented above for a number of the Hazardous Sites involved. These findings support the theory that a causal relationship between pavement damages and traffic accident risk.

When taking ride measurements in the high truck, the SRA CS team clearly perceived unexpected high lateral forces in many curves. This indicated that the curves may be incorrectly banked. This suspicion was further enhanced by complaints from truck drivers. As a consequence of this it was decided to make some analysis of the dynamic equilibrium of cornering forces due to road alignment in the curves. For many curves (and straight sections as well), the analysis resulted in some alarming results as seen below.

A refined analysis method was demonstrated to quickly show if a curve is correctly banked or not. The results confirm that many curves on the Beaver Road 331 are incorrectly banked and thereby hazardous.

Data clearly show an overrepresentation of incorrect banking in left[16] hand curves. The causal reason has been analyzed and explained.

Several left hand curves include sections where cross slope is 0 (zero) %. These have also been investigated with respect to Drainage Gradient (DG), the resultant vector to cross slope and longitudinal grade. The results show that, on roads with modest grades, the vast majority of left hand curves have spots with unacceptably low DG at their entrance and/or exit, resulting in a high skid risk due to water ponding. Analysis on new sections on other roads confirms that this is a ubiquitous problem in road design.

Finally, analysis shows that the spot repair of pavements, in one wheel track only, may cause hazardous split friction when braking hard at high speed (emergency baking) in wet weather conditions.

[16] Sweden has right hand traffic; in the UK the problems are focused into right hand curves instead.

6.1 EFFICIENT ANALYSIS OF INCORRECTLY BANKED CURVES

6.1.1 Ideal ratios of cross slope and horizontal curve radius

As seen in section "*3.3.1 Tight curves are hazardous*", road agencies worldwide have defined ideal ratios for cross slope versus horizontal curve radius, in order to create a dynamic balance to the lateral cornering force. An example of ideal ratios at the reference speed 90 km/h used in Sweden is given in Figure 21.

It is not practical to relate cross slope (CS) to radius (**R**) when analyzing data from real roads, including straight sections of roads where **R** approaches infinity and becomes difficult to plot. Curvature, defined as 1000/**R**, is a more practical parameter for real roads since it approaches 0 (easy to plot) on straight sections. Furthermore, curvature is directly proportional to the lateral cornering force. Therefore, the ideal CS to **R** ratios in Figure 21 has been plotted as CS to Curvature in Figure 70. The green boxes in the figure correspond to a high standard of road alignment, whereas the orange boxes correspond to a moderate to low standard. These boxes include +/- 0.5 % tolerance limits, as implied by (complex) tolerance demands stated in the Swedish road construction code [40]. The sign convention in Sweden is illustrated by a two lane road cross section to the left in the figure. Sweden has right hand traffic, so the focus is on the right hand lane. In straight road sections, the correct cross slope is -2.5 % (-3 % for roads with cold non-mixed pavements) and curvature is 0. In right hand curves, the absolute value of cross slope (banking/superelevation) should be increased where the curvature is high (radius low); the most extreme design value is -5.5 %.

With +/- 0.5 % tolerance, the most extreme box goes from -6 % to -5 % CS. Significant left hand curves (> 0.3 % negative curvature) call for the cross slope to be tilted to the other side, thereby changing the CS sign. Corresponding sharp right hand curves, the most extreme box for left hand curves goes from + 5 to + 6 %. The CS transition between -2.5 % and +2.5 % should at roads with 90 km/h reference speed be carried out at negative curvature smaller than 0.3, corresponding to a radius wider than -3200 m.

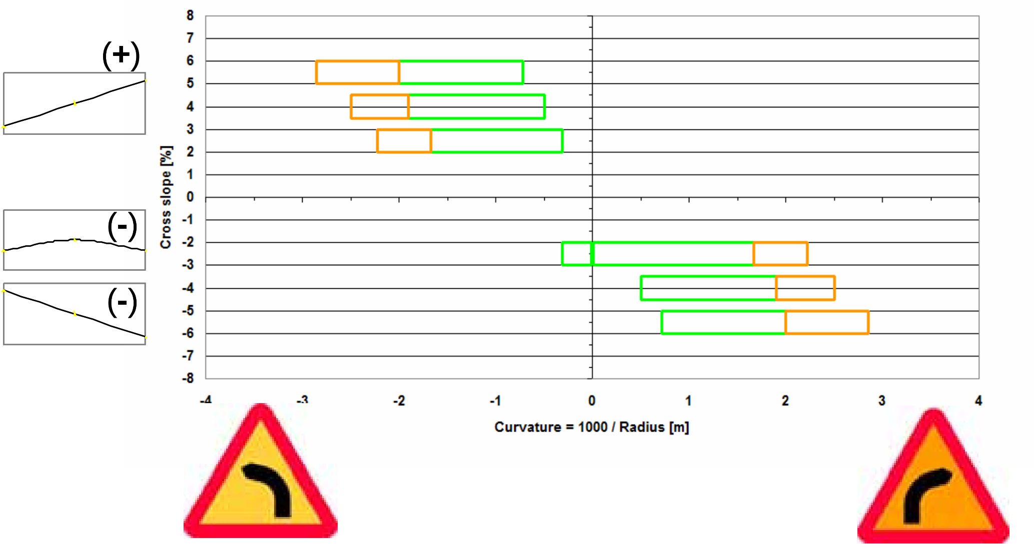


Figure 70 *Ideal Ratios between Cross Slope and Curvature at 90 km/h reference speed. After [15]*

6.1.2 Reference patterns of fair alignment on real roads

In Figure 71, 12300 values from a reconstructed section of Hw 90 are plotted. Each point represents the average value for 1 m road section, in total 12.3 km. This plot gives a reference to patterns created by fair ratios between cross slope and curvature on real roads.

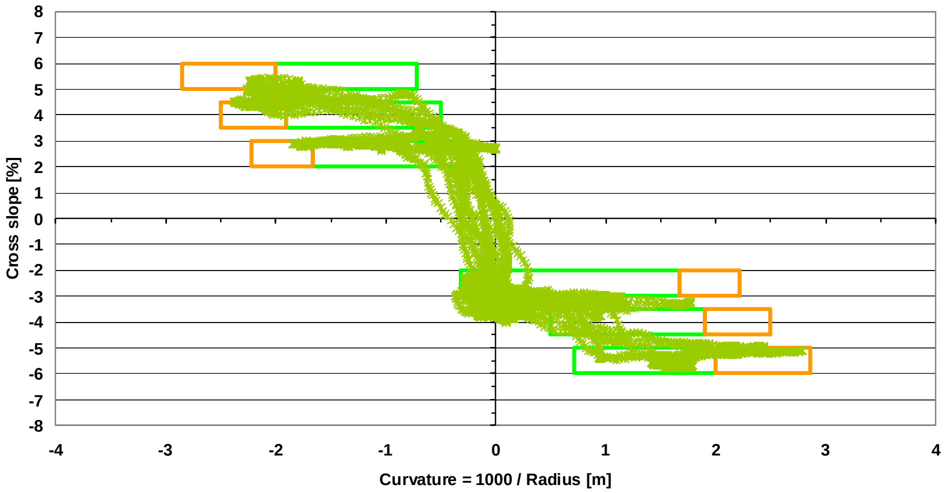


Figure 71 New Hw 90: Reference ratios between CS and Curvature, 90 km/h reference speed

It is easy to identify a handful of reference road alignment "families" in the plot, as seen in Figure 72. Straight sections are marked "1", low cross slope (CS) in wide right curves "2", high CS in sharp right curves "3", low superelevation in wide left curves "4", high superelevation in sharp right curves "5" and cross slope transitions to/from left curves "6".

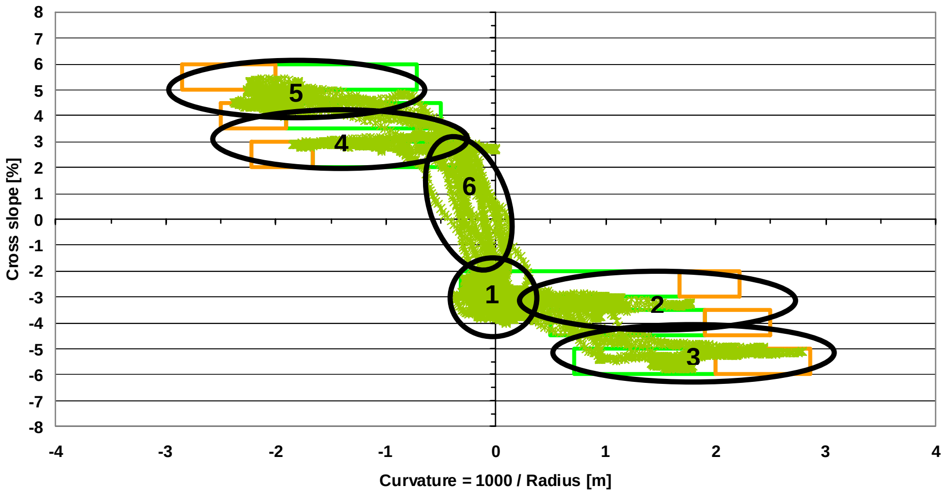


Figure 72 Identifying reference road alignment families

6.1.3 Incorrectly banked curves on Rd 331

If the road alignment data does coincide with the fair road alignment reference families, the road section is likely uncomfortable and possibly hazardous at the reference speed.

Data from 12.3 kilometres of the old Beaver Road 331 (Ramsele - Edsele) are compared with data from new Hw 90 in Figure 73. In this plot, several uncomfortable and hazardous families of road alignment data can be identified. Note that the Curvature axis has been widened, to make it possible to plot data from the sharp curves on Rd 331.

Straight sections with excessive Cross Slope (CS) are marked “7” in Figure 73. These sections include CS greater than the permissible banked sharp curve allowed in Sweden. These cause an uncomfortable ride. They are also a health risk, since they force the driver’s spine into an awkward twisted position making it much more susceptible to Whole-Body Vibration. These sections are also hazardous when overtaking another vehicle, as the large difference in CS between the two lanes causes large lateral vibrations if the overtaking is done with a quick lateral manoeuvre. On the section Nordankäl - Backe, a straight section had CS down to - 8.5 % (not shown here).

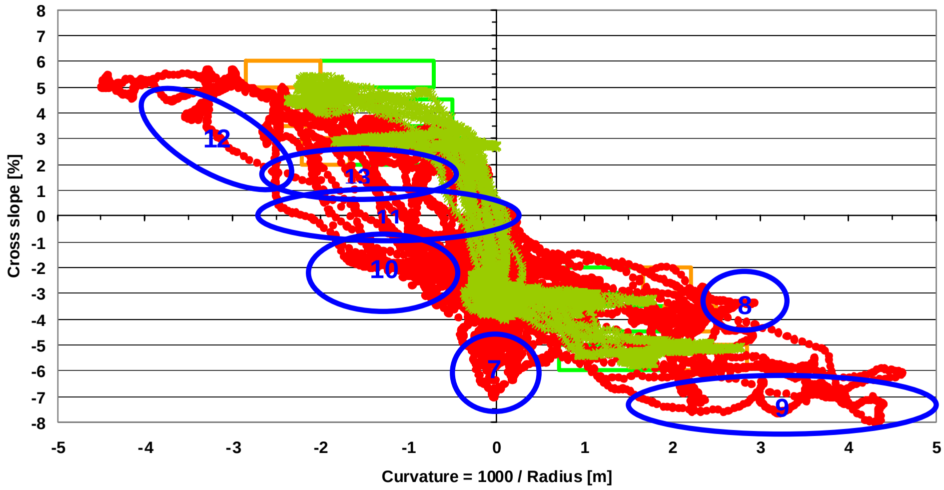


Figure 73 ***Comparison of data from old Rd 331 and new Hw 90***

Wide right hand curves with too little negative CS are marked “8” in Figure 73. These curves contribute to skid accidents as they do not generate sufficient lateral support to reach a dynamic balance when cornering in slippery conditions.

Sharp right hand curves with high negative CS are marked “9”. These curves contribute to slip accidents in vehicles driving at lower speeds than the reference speed.

Left hand curves where the banking is tilted to the wrong side are marked “10”. These are of course extremely hazardous, as it is difficult to avoid skidding in slippery conditions. For heavy vehicles, the risk for rollover accidents is obvious.

Sections with close to 0 (zero) % CS are marked “11”. With few exceptions, these are entrances or exits of left hand curves. Unless these sections happen to be in a longitudinal grade, they will also have a Drainage Gradient close to zero. This will cause water to pond, and the road will often develop local (surprising) ice spots in cold weather. These bring unacceptably high skid risk, so these sections should be checked for Drainage Gradient. This type of analysis is done in the next section of this report.

Left hand curves with too little CS are marked “12”. These curves contribute to skid accidents, as they do not generate enough lateral support to reach a dynamic balance when cornering in slippery conditions. It is noticeable that almost none of the left hand curves have excessive positive CS.

The family marked “13” can be described as “poorly synchronized CS transitions”. This family includes sections where CS transitions take place at a curve radius sharper than - 3200 m (Curvature -0.3). In practice, these are sections where the curve has started, but the superelevation is applied later in the curve. Or even worse; in curves where positive superelevation suddenly becomes negative CS before the curve is finished. This kind of road feature can come as a dangerous surprise to road users, unfamiliar with local hazards. The data families “10” to “12” may also include poorly synchronized transitions.

Figure 73 also includes families of unacceptably sharp left and right curves on Rd 331. When these curves are evaluated against the acceptable risk level stated by the SRA Road Design Manual [15], many are even too sharp at the lower reference speeds of 70 and 50 km/h. As per the Tylösand declaration (see section “*7.2 The Tylösand Declaration*”), SRA must as soon as possible make sure that all of these curves gets warning signs, and should start planning for straighten them out.

It is interesting to see that Figure 73 is non-symmetric. It shows that hazards are more common in left hand curves, than in right hand curves.

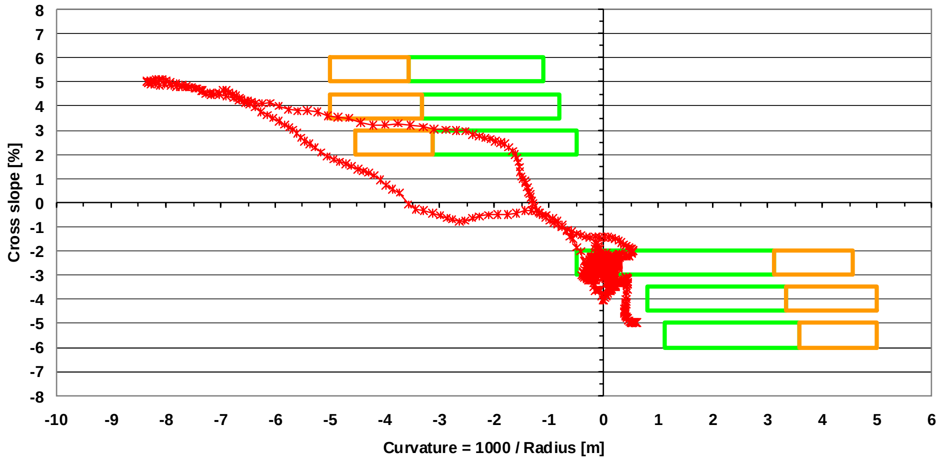


Figure 74 ***Poor road alignment cause dynamic imbalance at the Hazardous Site Roos Curve***

The Roos Curve in Österforsse is extremely hazardous, as can be seen in the hospital record plot in Figure 16. Today, the speed limit is 70 km/h through the curve. When analyzing ratios between CS and Curvature for Roos Curve in Figure 74, the data can be classified into several of the above defined hazardous families of road alignment. This non-uniform horizontal curve includes a minimum "radius" of about - 120 m, as Curvatures reach - 8.32. These extreme Curvatures cause very high lateral forces. Considering the curve's CS, and a lateral friction factor of less than 0.1 for slippery conditions, the maximum safe speed is definitely lower than 50 km/h as per the graphs in Figure 18. The posted speed limit is therefore more than 40 % higher than the safe maximum speed. Obviously, it is extremely important to maintain high road surface friction in this curve. It is recommended that this curve should be straightened out, or at least should have the banking very carefully redesigned, as soon as possible. (Each point in Figure 74 corresponds to an average value over 1 m; the plot includes 500 m).

There are two Hazardous Sites (HS) at Viksjö; one just north of the village and the other just south of Viksjö, as seen in the hospital record plot in Figure 75.

The HS south of Viksjö shows three fatal heavy truck accidents at exactly the same location. In the flat village of Viksjö the speed limit is 50 km/h. At the south exit, the limit is raised to 70 km/h. The road makes a short and sharp left hand curve, as it begins a long and steep downhill grade. Then it makes a wide right hand curve, followed by a short but very sharp left hand curve. This third curve also ends the grade, and the road goes over a bridge at the bottom of the valley. In the grade, truck drivers have lost control of their vehicles. At the exit of the third curve, each of the trucks have missed the bridge and made a large hole in the - obviously undersized - crash barrier. All of these lethal rides ended with a 20 m long and 12 m deep jump into the rift.

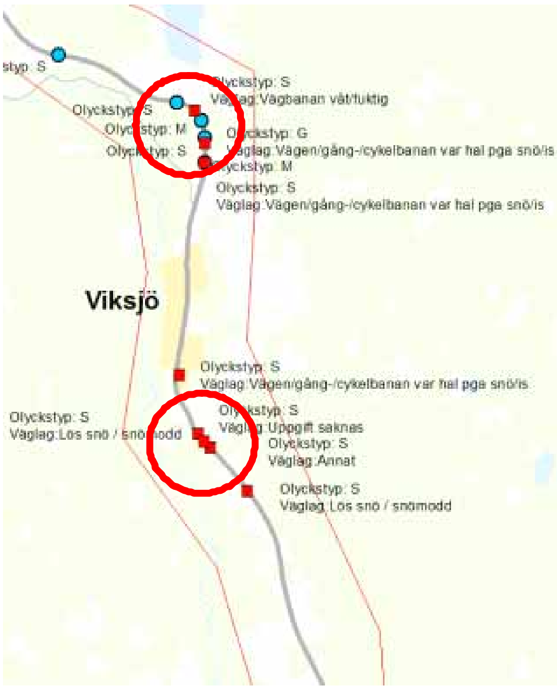


Figure 75 ***Hospital record plot from HS N Viksjö and HS S Viksjö [Hans Johansson, SRA]***

Figure 76 ***HS S Viksjö: Truck crash in Oct 2005 [Photo: High Coast Rescue Dept]***

When analyzing ratios between CS and Curvature for HS S Viksjö in Figure 77, the data can be classified into several of the above defined hazardous families of road alignment. The non-uniform horizontal curves include a minimum “radius” of about -150 m, as Curvatures reach -6.77. These extreme Curvatures cause very high lateral forces. Considering the curve’s CS, and a lateral friction factor below 0.1 for slippery conditions, the maximum safe speed is about 50 km/h as per the graphs in Figure 18. The posted speed limit is 40 % higher.

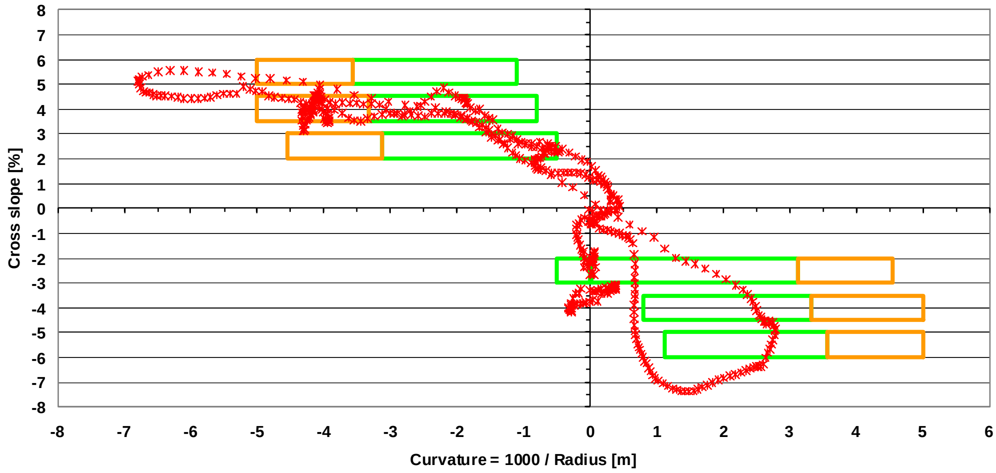


Figure 77 ***Poor road alignment cause dynamic imbalance at the Hazardous Site S Viksjö***

6.2 IDENTIFYING HIGH SKID RISK DUE TO WATER PONDING

Where the "Drainage Gradient" of a non-permeable road surface is lower than 0.5 %, water will not run off and water pools can be formed in wet weather. Water ponding, such as seen in Figure 78, increase the skid accident risk.

Figure 78 Water ponding at a CS transition section [Photo from the UK road network survey]

Road design manuals worldwide recognize the risk for water ponding and demand a minimum Drainage Gradient of 0.5 %.

From a mathematical point of view, Drainage Gradient (DG) is the resultant of the Cross Slope (CS) and longitudinal Gradient (G) of road surface, as illustrated in Figure 79 and defined by Formula 8.

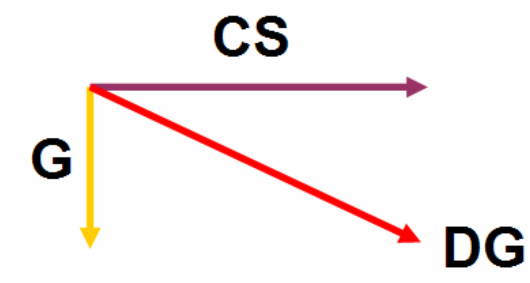


Figure 79 Drainage Gradient is resultant of Cross Slope and longitudinal Gradient

$$DG = \sqrt{CS^2 + G^2}$$

Formula 8, Calculation of Drainage Gradient

Straight roads are generally designed with 1 to 3 % negative CS. Curves are designed with a superelevation up to +/-5.5 % (Sweden), +/-7 % (UK), +/-9.5 % (Norway, maintenance of existing roads).

With more than +/-0.5 % CS, the DG should never drop below the minimum limit of 0.5 %. Neither straight sections, nor curves, have less than +/-0.5 % CS. So in what type of road sections could DG become insufficient? The Swedish road design manual [15] does not include guidance on this important question. The UK road design manual [54] gives a clue on the topic:

”-*Care must be taken to ensure that a minimum longitudinal gradient of at least 0.5 % is maintained wherever superelevation is to be applied or reversed*”.

So, critical sections are the transitions where superelevation starts or stops between straight sections and curves. As shown later in this section, the critical sections are further limited to left[17] hand curves, where CS change direction and sign as they pass through 0 (zero) %.

An important question is: ”-*How can unacceptably low DG be avoided at entrances and exits of left hand curves in flat terrain*?” Again, the Swedish road design manual does not give guidance, while the UK manual does:

”-*In flatter areas, the vertical alignment should be manipulated by the introduction of vertical curvature simply to achieve adequate surface water drainage*”.

The solution presented in the UK manual, is to construct local vertical curves so there are at least 0.5 % longitudinal Gradient in the sections where CS is close to 0 % as it changes sign. To create a 0.5 % slope over 50 m length, an elevation of 0.25 m is required. This is a reasonable

[17] In the UK the opposite is true; *to right hand curves.* This is due to the left hand driving in the UK.

design option when building a new road, where profiling is made by local material such as gravel and rock fill or by cut section. It is important to use smooth gradient changes, so the ride doesn't get bumpy at highway speeds.

There is also another solution. Where there is a grade before the left hand curve starts, the CS can be moved into this grade. Thereby the CS can make a transition from -2 % to +2 % long before the left hand curve starts. One drawback with this method is that a longer road section will have somewhat longer drainage path, thereby also a slightly larger water film depth.

A third option is to minimize the length of road where the CS is close to 0 %. This can be done by varying the "tilt rate". The transition from i.e. -2 % to -0.5 % can have a low tilt rate, from -0.5 to +0.5 % a higher tilt rate, and from +0.5 % to +5.5 % the tilt rate is slow again. Road sections designed with this method should be checked to ensure that it does not excite significant roll vibration.

A fourth option to reduce water ponding and thereby the skid risk, is to construct a permeable pavement in the sections where DG is low.

6.2.1 Low Drainage Gradient gave an unacceptable skid risk at HS N Viksjö

The northern HS at Viksjö shows an unusually high number of accidents leading to hospital care, as seen in Figure 75. The curve is sharp and induces high lateral cornering forces; the curvature reaches -5.12 (radius tighter than 200 m). Despite this fact, the maximum allowed superelevation of 5.5 % has not been utilized, as the curve only has about 4 % in the northbound direction. Furthermore, it has a warping Rut Bottom Cross Slope Variance of 0.54 %, which is significantly above the above proposed "warping limit" of 0.30 % RBCSV. In addition to these features, at the southern entrance of the curve, the Drainage Gradient is below the 0.5 % minimum limit value on a long section as shown in Figure 80.

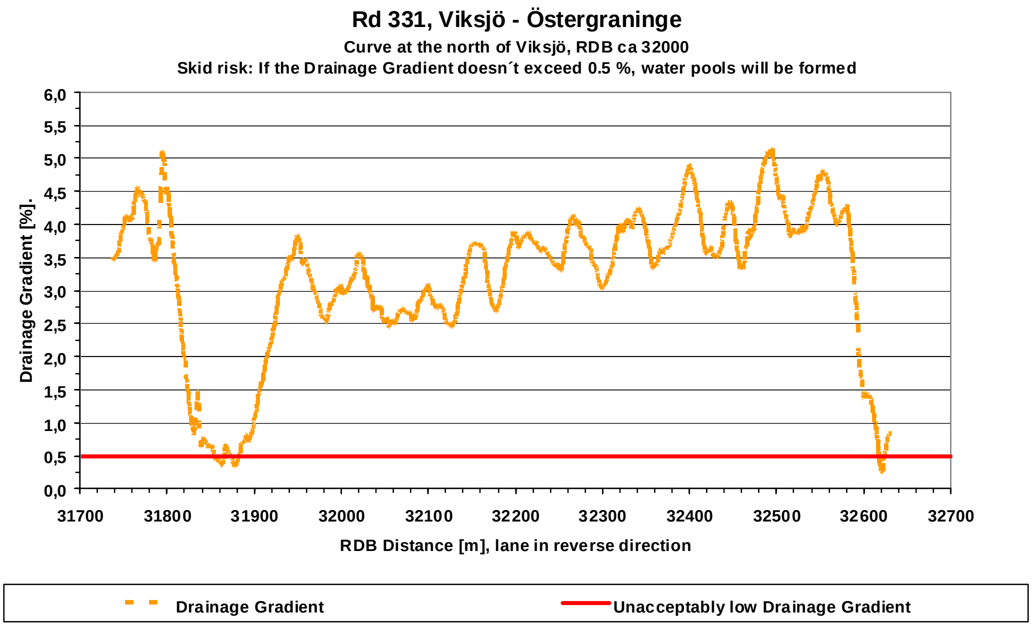


Figure 80 ***Extreme skid risk due to low Drainage Gradient at entrance of the left curve at HS N Viksjö***

6.2.2 Low Drainage Gradient gave unacceptable skid risk at HS S Viksjö

Figure 76 shows a photograph of a truck accident in front of the bridge at southern Hazardous Site in Viksjö. As previously presented, this site has poorly banked curve and a low Drainage Gradient at the exit of the sharp left hand curve (in front of the bridge), as seen in Figure 81.

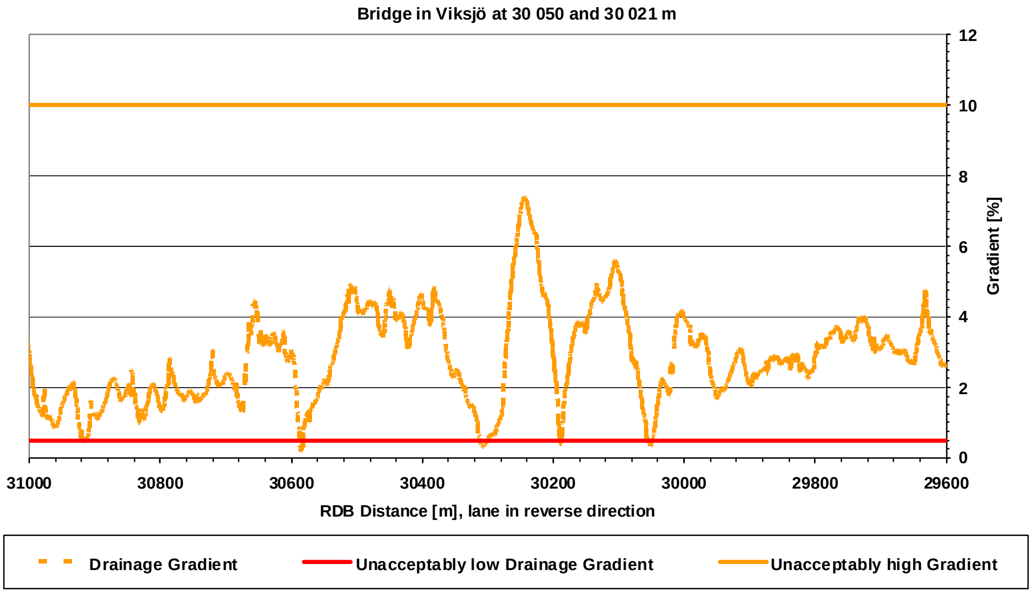


Figure 81 ***High skid risk due to low Drainage Gradient before the bridge at HS S Viksjö***

6.2.3 Extreme skid risk at HS Björknäset

Hazardous Site Björknäset shows an unusually high accident number, as seen in Figure 28. At this site, the Drainage Gradient is low for hundreds of metres, see Figure 82. This causes water ponding and the formation of ice during the winter, bringing extremely high skid risks. This hazardous geometry may be explained by the road section being very weak so the pavement has collapsed totally.

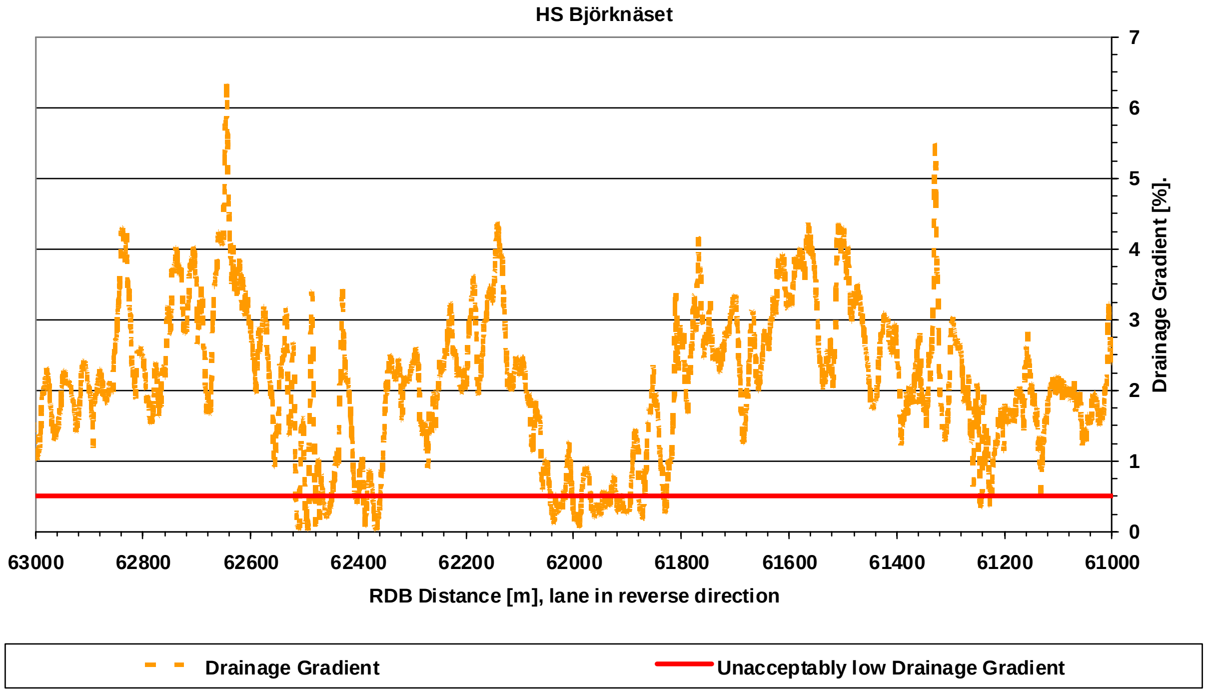


Figure 82 ***Skid risk due to low Drainage Gradient over hundreds of metres at HS Björknäset***

6.2.4 Extreme skid risk at HS Helgum

Hazardous Site Helgum shows an unusually high accident number, as seen in Figure 28. At this site, the Drainage Gradient is unacceptably low for hundreds of metres, see Figure 83. This causes water ponding and the formation of slippery ice during the winter, bringing extremely high skid risks. Another problem is excessive Cross Slope (CS). In the junction with Rd 950 at RDB distance 86/422 km, Rd 331 makes a curve with CS up to + 6.3 %. In this 70 km/h section, a CS of + 2.5 % is sufficient with respect to current curvature, as per the Swedish road design code. As seen in accident records, many vehicles turning in the junction with Rd 950 are skidding.

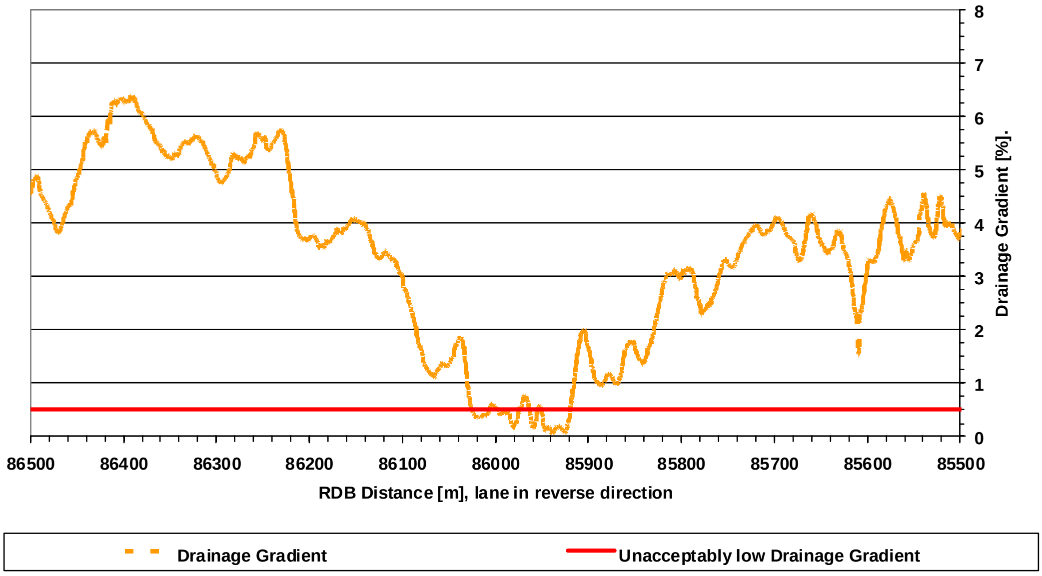


Figure 83 ***Extreme skid risk due to low Drainage Gradient on one hundred meter at HS Helgum***

6.2.4 Skid risk at HS Åsäng

Hazardous Site Åsäng shows an unusually high accident number, as seen in Figure 28. As shown in a previous section, the pavement on this site is significantly deformed. Just before the section of the crash photograph in Figure 63 (taken at RDB section about 11/400 km), the Drainage Gradient is very low as seen in Figure 84.

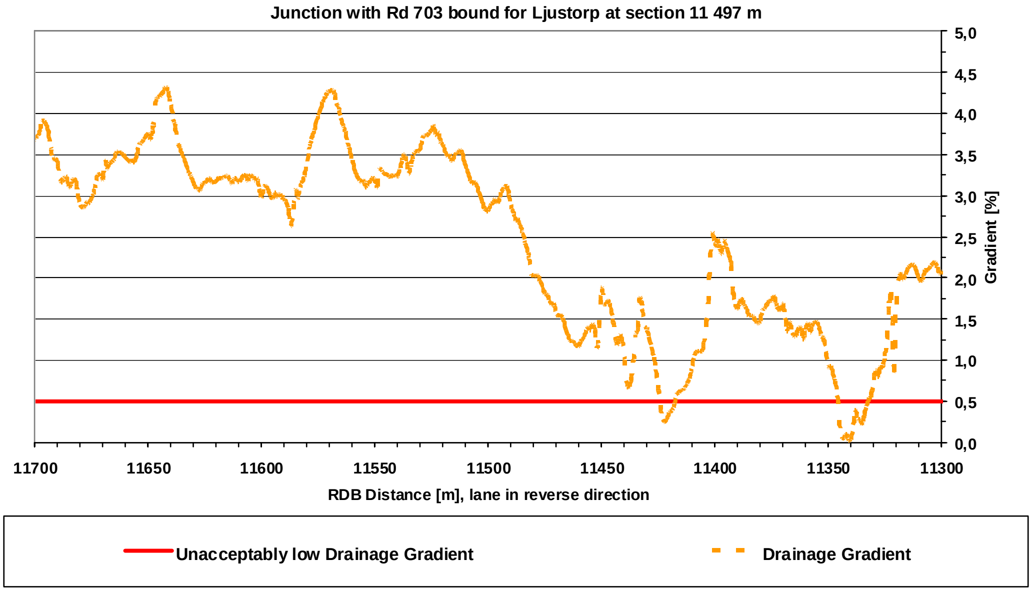


Figure 84 *Unacceptably high skid risk due to too low Drainage Gradient at HS Åsäng*

6.2.5 Many areas with unacceptable skid risk from Ramsele to Åkerö

South of Ramsele, there is a 18.5 km long road section that, despite low traffic volume, shows an increased accident number, as seen in Figure 28. This section has a lot of skid risk areas with insufficient Drainage Gradients, as seen in Figure 81.

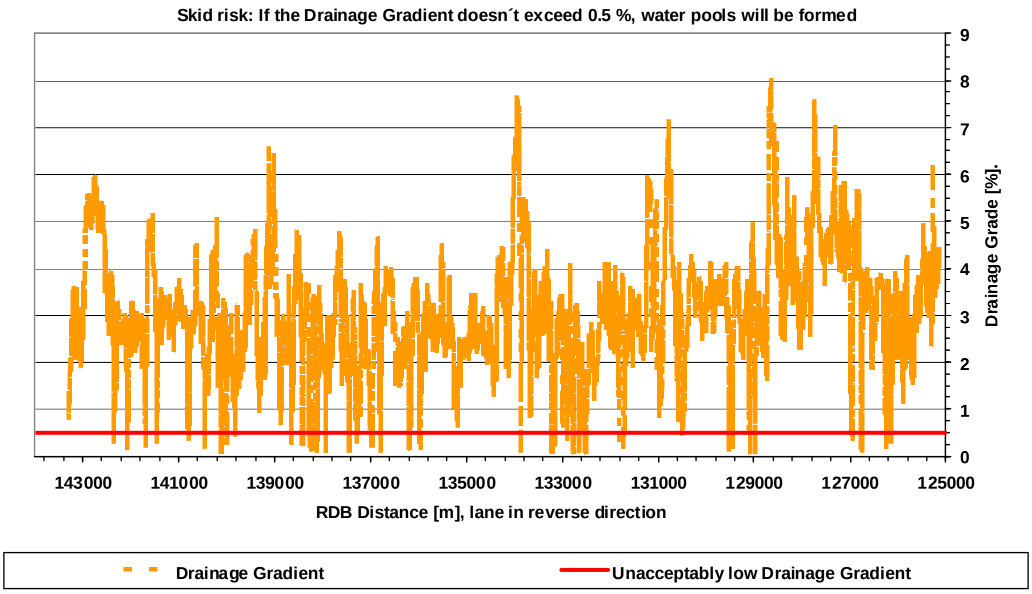


Figure 85 Many sections between Ramsele and Åkerö show unacceptably low Drainage Gradient

6.2.6 Also new roads have skid risk areas due to too low Drainage Gradients

For reference purposes, Drainage Gradient (DG) was calculated for a 12.3 km new section on Hw 90 north of Sollefteå. This section had been reconstructed totally, after the study by Ahlin et al (2000) [3]. However, the resulting DG plot was surprising and gave some very valuable knowledge. As seen in Figure 86, the new road section has 12 skid risk areas; one per km. The black Curvature trace clearly shows that all skid risk areas are located at the entrances or exits of left hand curves (having negative curvature). No skid risk areas can be seen at right hand curves or on straight sections. Tests on data from highways and expressways in various parts of Sweden demonstrate that this new knowledge on skid risk hot spots has a generic application.

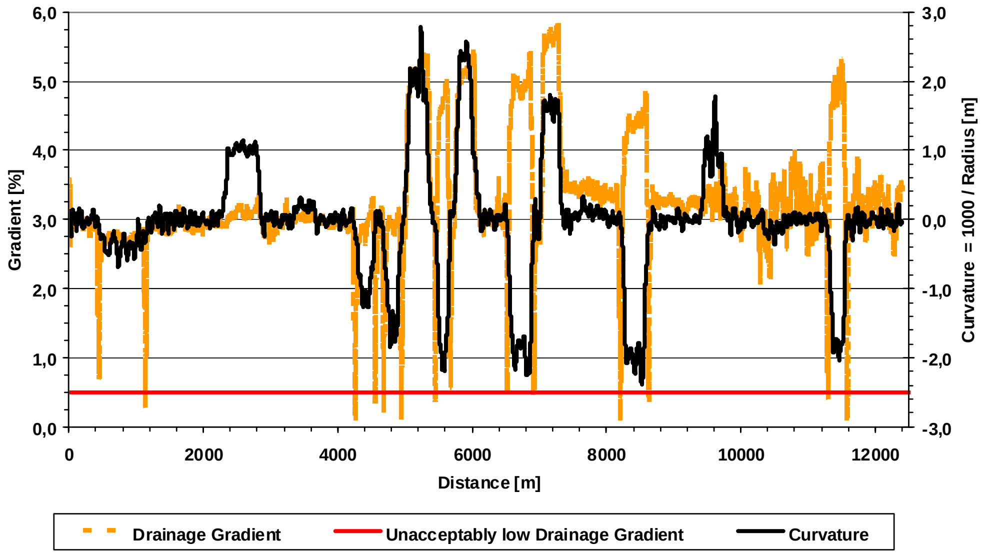


Figure 86 *The new section on Hw 90 has unacceptable skid risk at left hand curves*

6.3 FRICTION ISSUES DUE TO LOW OR VARIED MACROTEXTURE

6.3.1 Low wet friction at the extremely Hazardous Site Stavreviken

The spot with most skid accidents in the Västernorrland County is HS Stavreviken. Numerous skid accidents take place there every year. In one week there were three accidents. In southbound direction, the road makes a long and steep downhill grade, finished by a hairpin curve over a railway. The skidding incidents take place at the end of the grade, at about RDB section 5/380 km, just before the hairpin curve begins. Most skidding vehicles crash within a zone of 10 metres length. The SRA Central Region is planning to solve the troubles with HS Stavreviken by building a 2.1 km new road and railway bridge section at a cost of about 3 M€ [71].

Mahone (1975) [55] showed that the friction in hard emergency braking at highway speeds on wet road surfaces is mainly determined by the surface Macro Texture (MaTx). At HS Stavreviken, all vehicles must brake hard to keep speed low in the grade. Many vehicles brake with significant tyre slip, thereby polishing the road surface. In Figure 87, Macro Texture values from left and right wheel track are reported from HS Stavreviken. As seen by the graphs, the values seldom exceed the benchmark minimum level of 0.6 mm.

A low cost action to increase the Macro Texture and reduce the skid risk in wet conditions could be a double surface dressing. There are also extremely skid resistant special surfacings available. One such surfacing, based on steel slag, is currently being tested in Dalarna County within the SRA Central Region [66]. A pair of speed-activated “Your speed” displays could be beneficial at the top of the grade. If initial speeds were lowered, the need for braking in the grade would be much less.

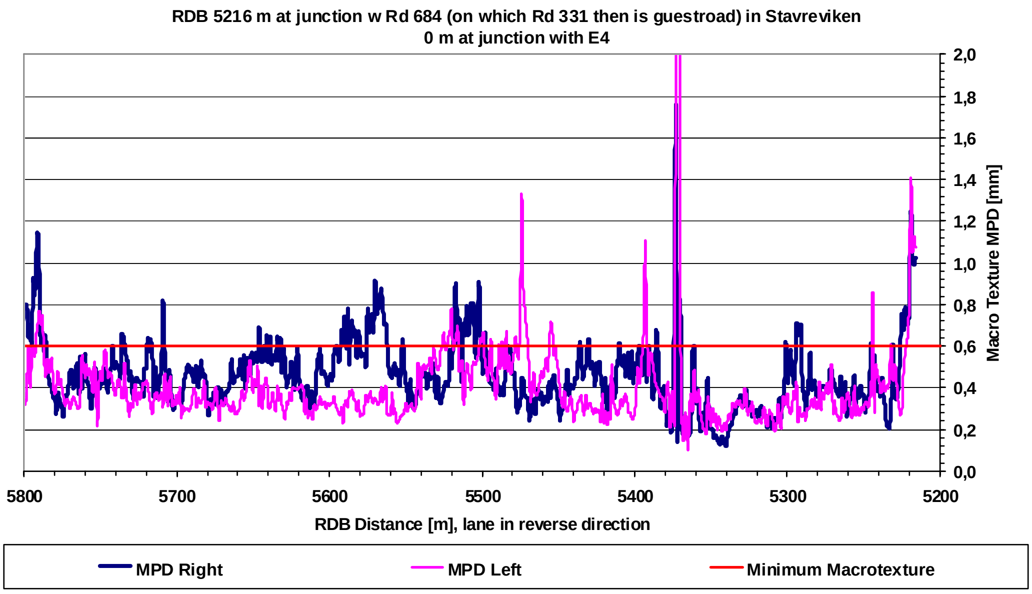


Figure 87 *Insufficient Macro Texture at HS Stavreviken*

6.3.2 Hazardous Split Friction due to patch repair in one wheel track only

Split Friction (SF) is an extremely hazardous condition, known to cause instability phenomena such as jack-knife and trailer swing when braking hard with heavy vehicle combinations [33]. SF happens when the friction is much lower in one wheel track than in the other. SF may be difficult to recognize when cruising or braking normally. However, it is detrimental when (emergency-) braking hard. When doing so, the vehicle rotates over the wheel track offering high friction. ABS-brakes reduce the instability problem, but at the price of a longer braking distance. An extreme example of SF is ice in one track and bare asphalt in the other.

SF may occur after a patch repair in one wheel track only. Such a repair can result in large differences in colour, as well as in MaTx, between the wheel tracks. This can create very high SF condition, especially in mornings after a night with temperatures slightly below 0 °C. When this happens the road surface can become covered with thin ice. As the sun rise, its radiation is absorbed by the black bitumen-rich patches so the ice on these thaws quicker than the greyish old asphalt in the non-patched track. When braking hard on such split friction surface, the result may be a skid into the ditch or over to the opposite side of the road.

A photograph from HS Meåstrand is shown in Figure 61; take note of the glare slick patch repair in the right wheel track. Profilograph results for the site's MaTx are showed in Figure 88. The right side vertical scale is for MaTx, while the left is for the turquoise Split Friction risk indication trace. SF risk indication is defined as difference in MaTx in the wheel tracks, divided by the lowest MaTx of the two tracks. While there are several sections with low MaTx in the right wheel track, there are fewer sections with high SF risk. The most hazardous section is at 125/770 km.

On investigation, Split Friction due to asphalt patch repair has been identified as a likely causal factor behind five skid accidents within two weeks after patch repair at a curve on Hw 61 in Värmland, Sweden.

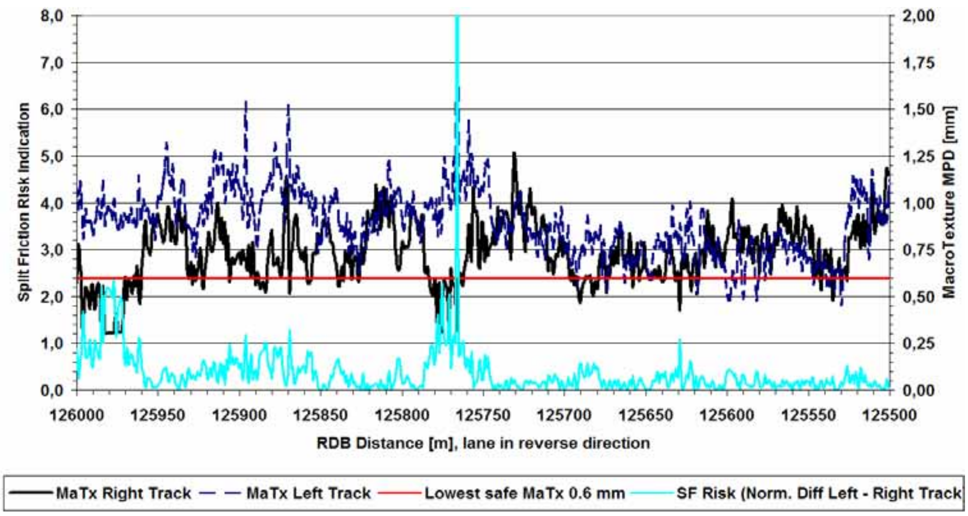


Figure 88 ***Macrotexture values indicating low and split friction (due to patch repair in only one track)***

Chapter 7. Ethical aspects on safety issues

7.1 VISION ZERO FOR ROAD SAFETY

"Vision Zero" is the basis for all modern road safety work in Sweden. The approach was ratified by the Swedish Parliament in 1997, and has resulted in changes to road safety policy and the work undertaken.

Since *Vision Zero* was established in Sweden, fewer people have been killed on roads. Now the ideas behind *Vision Zero* have also had an international breakthrough.

Vision Zero is an image of a future in which no one will be killed or serious injured. It is both an attitude to life and a strategy for making a safe road transport system. Road safety in the spirit of *Vision Zero* means that roads, streets and vehicles must be much more adapted to human capacity and tolerance.

The responsibility for safety is shared between those who design, and those who use the road transport system.

7.2 THE TYLÖSAND DECLARATION

The Tylösand Declaration lays down the principal rights of citizens for road traffic safety. These rights serve to protect them from the loss of life and health caused by road traffic. They rest on the general assumption that no road user wishes to harm either himself or herself or any other fellow human being, whatever the circumstances under which they are using the roads.

The Declaration was signed at the annual conference in Tylösand 2007, by Jörg Beckmann (Executive Manager of European Transport Safety Council), Åsa Torstensson (Sweden's Minister on Infrastructure), Ingemar Skogö (Director-General of Swedish Road Administration), together with other decision makers and experts within Europe as well as from other continents.

The Declaration includes five articles:

1. Everyone has the right to use roads and streets without threats to life or health.

2. Everyone has the right to safe and sustainable mobility: safety and sustainability in road transport should complement each other.

3. Everyone has the right to use the road transport system without unintentionally imposing any threats to life or health on others.

4. Everyone has the right to information about safety problems and the level of safety of any component, product, action or service within the road transport system.

5. Everyone has the right to expect systematic and continuous improvement in safety: <u>any stakeholder within the road transport system has the obligation to undertake corrective actions following the detection of any safety hazard that can be reduced or removed</u>.

7.3 PRIORITIZING VARIOUS ROAD SAFETY IMPROVEMENTS

It is well known, that one, or several, of the following factors are involved in the vast majority of traffic accidents:

1. Drugs, including alcohol, narcotics et c.
2. High speed.
3. Not using a seat belt.
4. Suicide.

Thus, it is rational that most road safety improvement actions should be focused on reducing the above human factors, mainly no 1 - 3.

However, acting rationally does not always mean the same as acting ethically.

The above listed factors have much in common: most road users are aware of risks associated with factors listed; they have personal control over each of the factors; and, finally, road users[18] have decided to expose themselves to the risks. Taken all together, this means that road users should be able to take large responsibility for these risks.

Below is a list of other factors involved in traffic accidents. These also have much in common: many road users are unaware of them and/or their association with risk; it is difficult for road users to exercise control over the associated risks; road users have generally not decided to expose themselves to the risks. Taken all together, this makes it difficult for the road user to take responsibility for this second list of risks. However, a fourth common feature is that the road

[18] An exception is the second party, suffering from actions by the causal individual. One example is an "innocent" driver crashing due to a drunk driver over-speeding at the wrong side of the road.

agency <u>is</u> able to exercise control over all of the factors. The control option makes it obligatory for road agencies to take responsibility for the risks listed below:

1. Longitudinal or lateral roughness, causing ride vibration related phenomena such as driver fatigue, bump steer and loss of friction due to weight transfer.
2. Bumps, without a warning sign.
3. Poorly banked curves, not giving relevant lateral support for cornering vehicles.
4. Pavement local areas with too low drainage gradient, where slippery water puddles ponds and in the winter freeze to ice spots.
5. Split friction between left and right wheel tracks during (hard) emergency braking from high speed and on a wet (thin ice) surface, caused by different texture after spot repair in only one wheel path.

Considering the above discussion on the individual's responsibilities versus the road agency's responsibilities, it may actually appear more ethical to spend road agency funding on road repair, rather than on rational campaigns aimed at reducing drunk driving, over speeding and reminding to buckle up. It seems important to discuss this balance further, both in- and outside road agencies.

Chapter 8. Serious and useful findings

8.1 RIDE VIBRATION SHALL BE PREVENTED AT THE SOURCE

The Rd 331 case study has shown that many professional truck drivers are likely to be exposed to a daily vibration exceeding the EU Action Value A(8) = 0.5 m/s^2. Timber hauliers like Brorssons Åkeri AB are now obliged, by law, to carry out a risk assessment and implement organizational and/or technical actions to minimize the driver´s vibration exposure. These actions will bring significant costs to hauliers and their customers in the forest industry.

Why is truck ride vibration a problem at all? Shouldn't vehicle manufacturers be able to isolate all ride vibration? Road managers are likely to ask these kinds of questions, and more, after reading the daily vibration exposure results from this research project.

The answer is that if feasible technological solutions were at hand, they would already be a success on the market. The vehicle industry, unlike the average road agency, spends very large resources on product development and their engineers work hard to continually develop new solutions and improvements to overcome perceived problems. However these organisations work within many constraints, such as commercial aspects, handling and stability. The net effect of their improvements to vibration in vehicles is therefore typically small, when compared to the potential improvements by road repair. A good example of this can be seen in the case study, where the truck driver seat vibration did not change after a missing chassis suspension damper bush had been replaced (see section *5.2.6 The broken truck suspension bush had no significant effect*).

The SRA has thousands of kilometres of roads in a condition similar to Beaver Road 331, used for the case study. Thousands of kilometres of roads are likely to be in a similar condition also across the ROADEX partner areas. The truck response recorded on Rd 331 includes very high roll vibrations at frequencies below 5 Hz. The *Handbook of Vehicle - Road Interaction* [52], states that roll motions at frequencies under 5 Hz are not common when driving heavy trucks on roads with "normal" roughness and at normal speeds. This implies that roads in this kind of condition should be considered as non-compatible with normal heavy vehicles.

Article 5.1 in directive 2002/44/EC states: "*Taking account of technical progress and of the availability of measures to control the risk at source, the risks arising from exposure to mechanical vibration shall be eliminated at their source or reduced to a minimum*".

A similar conclusion was made in the five-year US research program "*Ride Quality of Commercial Motor Vehicles and the Impact on Truck Driver Performance*", performed by leading researchers, road authorities, vehicle manufacturers, hauliers and commercial drivers; *Vibration*

<u>must be eliminated at source through effective road maintenance</u> rather than merely dampened. See section "*3.1.6 Ride vibrations have a negative effect on traffic safety*".

8.1.1 Long wave unevenness require improved road repair methods

The case study showed that low frequency, below 3 Hz, truck ride vibration is a serious problem. Low frequency vibration is difficult to reduce, both in today's vehicle fleet and with all currently demonstrated truck suspension solutions.

Because of this road managers should pay particular attention to the prevention, and repair, of those forms of road damage that cause low frequency ride vibration. Vibration at 0.5 - 3 Hz frequencies relates to road unevenness with 5 - 40 m long wavelength. Asphalt pavers cannot repair such long wave uneveness efficiently, since the paver only "rides along" in waves longer than the paver itself. Repair of long wave unevenness requires a more advanced approach than seen in many current road maintenance practices. Milling machines and asphalt pavers must therefore be "forced" by machine control systems to follow a carefully engineered repair design. This type of solution relies on two prerequisites:

1. A carefully engineered (computer aided) design of the geometric asphalt repair works.
2. Asphalt pavers being operated with a suitable machine control system, such as used when repaving airfield runways.

Current standard road repair practice cannot repair long wave unevenness efficiently.

8.1.2 Excessive Cross Slope is an ergonomic problem

Based on the testing carried out in the current trials it appears likely that many professional truck drivers in the Northern Periphery of Europe are being exposed to higher health risks than truck drivers in central Europe. Not only is the ride vibration level high, but many truck drivers in the Northern Periphery may also be sitting in an awkward side sloping position due to excessive pavement cross slope (CS) on straight road sections. In the case study on Rd 331, many straight road sections had a CS that exceeded the maximum superelevation/banking allowed in the tightest horizontal curves. This excessive side slope causes the spine to be twisted, which is not only uncomfortable, but also makes the back more susceptible to Whole-Body Vibration exposure. Excessive CS has not been reported as a systematic problem in central Europe.

8.2 BUMPS ARE MOST UNHEALTHY

Transient vibration (shock) is much more detrimental to health than stationary vibration. Many bumps give shocks that can be compared to those recorded on city bus drivers' seats when they driving at 30 - 50 km/h over traffic calming speed bumps with 1 dm height. The worst bumps in the current tests were located on small roads, such as on the road to the Sawmill in Graninge. These bumps, when driven at low speeds of about 40 km/h, exposed the truck driver to spinal compression stress S_{ed} of over 0.5 MPa. This stress level corresponds to health risk. Also on the "main road" Rd 331, truck drivers drove over many bumps that excited significant transient vibration. These bumps were due to settlement at old culverts, poorly reconstructed culverts and settlements at bridge joints.

8.3 ROLL VIBRATION REQUIRE SPECIAL FOCUS

Many of the Hazardous Sites in the case study were found to have local severe pavement edge damages, characterized by high Rut Bottom Cross Slope Variance (RBCSV).

Repair of these pavement damages will minimize lateral vibration in trucks. (Truck suspension systems cannot isolate such vibration). This kind of road repair will bring better health and safety to professional truck and bus drivers. It will also improve safety for fellow road users, due to the reduced risk of collision with skidding trucks.

Road damages resulting in high variance of Rut Bottom Cross Slope (RBCSV) has been identified as a critical factor behind truck rollover accidents by the group analysing lethal crashes in the Central Region of Norway. Repeated lethal crashes (2005, 2006) have occurred in an “eggshaped” curve at Smalåsen on road E6, where a culvert bump reduced the Cross Slope in a section where the curve is tightened (and the lateral force increased). Deformed pavements have also been found to be a cause in accidents, as the deformations affect the driving stability of the vehicles. Deformations have been found very hazardous to cars with low profile tyres, motorcycle traffic and at slippery road conditions [72] [Personal communication with Mr Bård Øien, head of the crash investigation group in Central Norway].

8.3.1 Lateral vibration

Lateral acceleration is commonly recognized as a key parameter for vehicle driving stability, and thus for traffic safety. This is especially relevant on slippery surfaces, where the lateral friction forces are small. When a vehicle changes its roll angle quickly, the roll motion is accompanied by lateral acceleration. Results from the case study show that severely deformed pavement edges are a serious safety hazard, as they may result in lateral acceleration forces comparable to the lateral forces experienced when travelling around a horizontal curve.

The high lateral vibration seen in the case study raises a question whether it is sufficient to have truck suspension systems that deal with vertical vibration alone. There seems also to be a similar need to prevent and/or isolate lateral vibration. This is a significant challenge to truck and seat designers, since the conflicts with traffic safety are obvious. Any additional isolation systems to the present provision will however increase the deadweight of the vehicle and thus reduce the payload that can be carried, thereby increasing the number of trucks necessary to meet a given transport need. The development of new efficient solutions will cost money, and new components also bring new costs. The net effects of this is that new systems for isolation of lateral vibration are likely to be accompanied by increased transport costs, and increased number of trucks on the roads.

The conclusion is that the cross slope variations on badly deformed EU Northern Periphery roads makes them incompatible surfaces on which to drive normal heavy vehicles. Such road sections should be repaired as soon as possible.

8.3.1.1 Tramp-related polishing creates extremely slick areas

Road roughness with short (0.7 - 3 m) wavelengths causes truck tyre resonance. Roughness with these short wavelengths often has a low coherence between the left and right wheel track. This means, for example, that the left track may have a short bump whilst the right track may be flat, or even have a depression. This can result in the wheel axle starting to roll, accompanied by lateral forces and an oscillating motion between road and tyre. Such “tramp-motion” gives a polishing effect which, after accumulated truck passes, can make the road extremely slippery. Short wavelength road roughness is therefore a road safety issue that should be controlled and kept below safe levels. This kind of road roughness can be repaired by a simple asphalt overlay.

8.3.2 The change in climate calls for increased repair of RBCS damages

Change in climate is likely to make freezing and thawing more frequent in the Northern Scandinavia. Data from year 1961 - 1990 (left) can be compared with a computer modelled scenario for 2071 - 2100 (right) in Figure 89. The result shows that the number of days with temperature shifts of around 0 °C will increase.

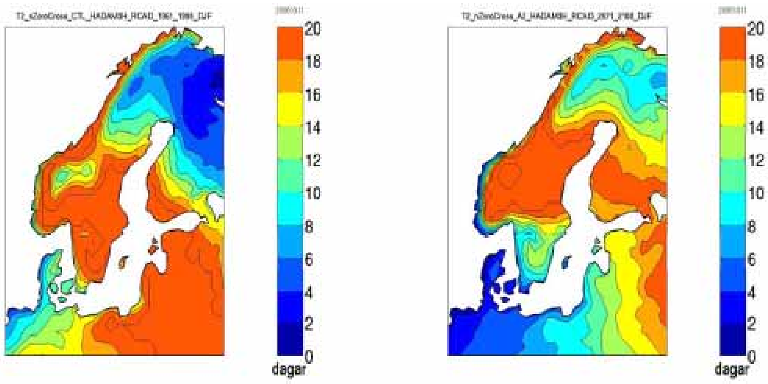


Figure 89 ***Freezing and thawing Dec - Jan; increased number of times temperature passes zero [46].***

Slippery “black ice” occurs more frequently at temperature shifts of around 0 °C, than at very cold temperatures. Thus, extremely slippery conditions will become more and more common on the rough roads in the Northern Scandinavia.

The <u>combination</u> of slippery surfaces and pavement edge damages results in lateral forces and can be very dangerous. Thus, the need for repairing Rut Bottom Cross Slope Variances (RBCSV) will increase as climate change continues.

A relevant example is the strong increase in road crashes in the High Coast Ådalen (Sollefteå, Kramfors and Härnösand) in SRA Central Region, as seen in Figure 90. In the period from 1 January to 10 March, the number of crashes has increased from 18 to 23 during the 10 year period 1998 - 2007. Given the mean value of 23 in the past ten years and considering the natural variance of this statistic (the standard deviation over the past ten years was 3.7 crashes), there was over 95 % probability of less than 31 crashes in 2008. However, the 2008 outcome was 42 crashes. This is an increase by 109 %, as compared to the ten years before. The Rescue Leader had reported poorly maintained roads as a causal factor behind more than

50 % of the crashes in 2008, while 25 % also involved deep ice ruts. The High Coast Rescue Department also see a clear relation to the extreme and unsteady climate. Most crashes were single car accidents. Most of these took place on straight road sections in daytime, and many of the crashed cars were driven by women. [Personal communication with Peter Carlstedt, Head of High Coast Rescue Department] [73].

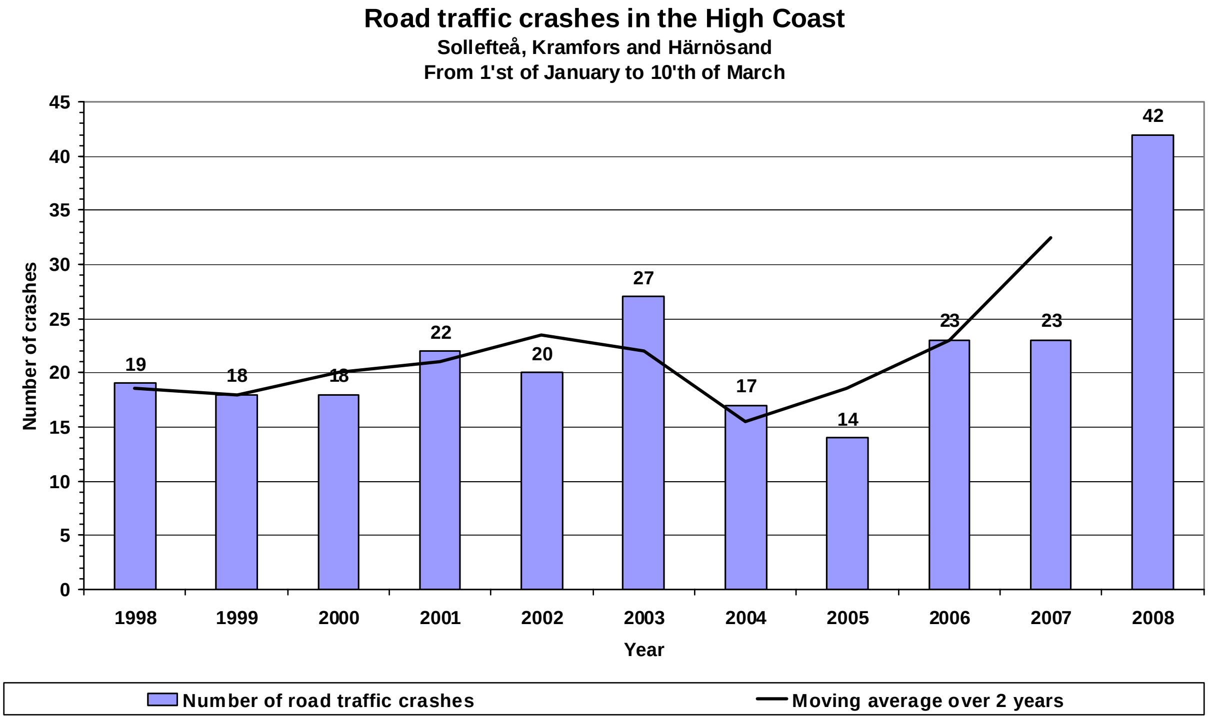


Figure 90 ***A strong trend of increased road traffic crashes***

8.4 SOME ROADS ARE MORE HAZARDOUS – NOW WE KNOW WHY

The objectives for this project focused on health issues but the work also gave valuable spin offs in safety issues. From the overall accident records, it is obvious that there is still a long way to go before “Vision Zero” can be reached. The findings in this study however show that there is great potential to reduce accidents by make existing road surfaces safer.

Antiskid systems in cars were recently recognised to be as important pieces of safety equipment as seatbelts [44]. This confirms skidding to be a common and very serious safety risk. Seatbelts are accepted as being a very successful safety aid, yet society still continues its efforts to prevent traffic accidents. In the same way, society should not rely on antiskid systems as the sole solution to skid problems. Greater efforts should still be made to make road surfaces more skid resistant. After all, a vehicle’s braking distance is much shorter on a skid resistant surface, than in a similar vehicle with antiskid system braking on a slippery surface.

Technological advances in the future vehicle fleet are likely to make large improvements to traffic accident outcomes. However these solutions are also likely to require even better friction than current road surfaces are offering, in order to make use of the full safety improvement potential. Obviously, it is time to start making the road network more skid resistant!

8.4.1 Incorrect banking cause dynamic imbalance in curves

Many of the Hazardous Sites in the case study were found to have incorrectly banked curves, causing dynamic imbalance when cornering.

The case study demonstrated that plots of Cross Slope (CS) versus Curvature can be useful tools when analyzing dynamic balance in curves, using similar safety margins to those employed in designing new roads. Groups of data, “families”, with safe and comfortable road alignments in such plots were identified in Figure 72. Data outside these families are from sections with incorrect Cross Slope / Superelevation.

8.4.1.1 Evaluating / redesigning old roads is different from designing new roads

When designing new roads, specified CS values are used; i.e. 2.5 %, 4 % and 5.5 %. When evaluating or repaving old roads however using such fixed values has a poor cost-benefit return as it can be very costly to modify existing CS. For modest Curvatures (absolute values ranging from 1 to 3 for a reference speed of 70 km/h), the magnitude of CS between 2.5 % and 5.5 % are of low to moderate importance for safety as well as for comfort. However, it is very important that the CS does not vary to the extent that high vehicles start to roll, as measured by the new RBCSV parameter.

The red dots in Figure 91 are inside the tolerance box for the design of new 70 km/h roads, whereas the green stars are outside the box. The green stars however represent a road section offering a safer and more comfortable ride, than a section represented by the red dots.

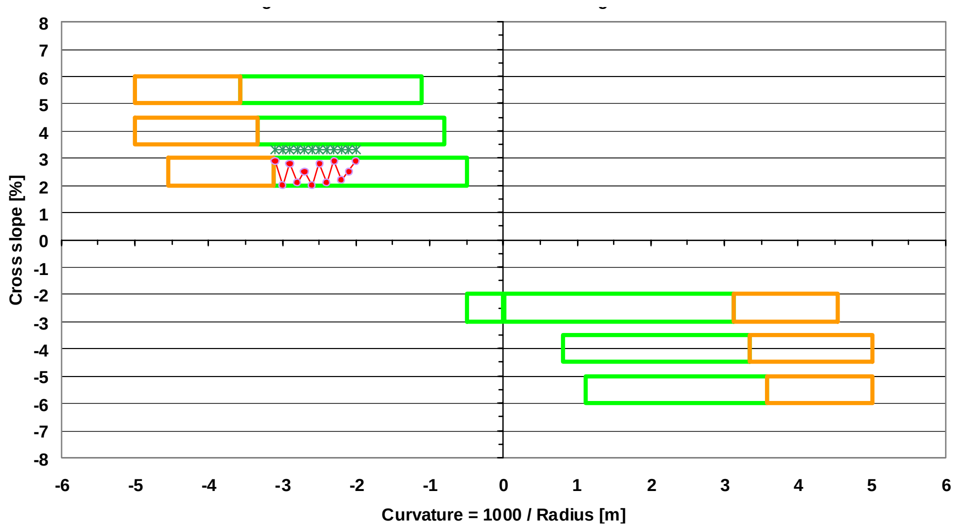


Figure 91 *What is worse on an old road: CS outside tolerance boxes, or high RBCS variance?*

8.4.2 Large hydroplaning risk at left hand curves, also at new roads

Where the road surface Drainage Gradient (DG) is lower than 0.5 %, water will not run off the road and water pools will be formed in wet weather. Water ponding, such as seen in Figure 78, increases the risk of skidding accidents.

Many of the Hazardous Sites in the case study were found to have DG lower than the 0.5 % lower limit used in road design manuals worldwide. The case study demonstrated that entrances and exits of left hand curves are hot spots for a low DG. The reason of this was explained.

A further finding was that even new roads had been designed with very low DG at many left hand curves, thereby creating an unacceptable skid risk.

Low DG was found to correlate somewhat with pavement deformation in terms of high RBCSV and high IRI (the details have not been shown in this report). This indicates that water on the road, and by implication within the pavement itself, can hasten permanent deformation. Keeping DG sufficient is therefore a prequisite for keeping the service life time costs to manageable levels. Insufficient DG can bring unneccesary road agency costs through deformation.

8.5 LOW AND VARYING MACRO TEXTURE CAUSE SKID ACCIDENTS

The location with most skid accidents in the Västernorrland County road network is HS Stavreviken on Rd 331. Numerous skid accidents take place there every year; in some cases several accidents take place over a few days! Macro Texture values from HS Stavreviken are generally below the minimum level of 0.6 mm. A low cost action to reduce the skid risk at the site could be to make the road surface more skid resistant. A surface dressing can often give a very good effect in terms of increased friction factor. The texture of the existing aggregate may also be rejuvenated by ultra-high pressure water cutting, as investigated by Pidwerbesky & Waters (2008) [63]. However, the most efficient action is to prevent polishing, by careful selection of polish-resistant aggregates for those sections with high polishing energy, i.e. tight corners, downhill end of grades, roundabouts, and junctions et cetera. Using steel slag as asphalt aggregate could also be one cost effective solution [66] [67].

Split Friction (SF) is an extremely hazardous condition, when the friction is much lower in one wheel track than in the other. SF may be difficult to recognize when cruising or braking normally. However, it can be detrimental when braking hard in an emergency. When doing so, the vehicle tends to rotate over the wheel track offering high friction. SF may occur after a patch repair in one wheel track only. The case study demonstrated the use of a new Split Friction risk indication parameter, based on Macro Texture data from the laser/inertial Profilograph.

8.5.1 Double surface dressings have better Mega Texture

It is well known that double surface dressings give off less noise than single surface dressings [65]. However, there is a myth that the noise difference is due to the lower Macro Texture on double surface dressings. The true causal factor is that the double surface dressings have less Mega Texture (MeTx) than single surface dressings. Lower MeTx levels result in reduced interior and exterior noise, due to reduced tyre vibration. The reduced tyre vibrations are also likely to reduce Hand-Arm Vibration to vehicle operators and improve friction. These benefits of double surface dressings are not generally recognized yet, but they are likely to become more apparent with the increasing use of pavement texture analyses.

8.6 RETHINK CULVERT WORKS

The case study showed that culverts can be critical locations for bumps, giving poor ride quality and health damage to the spine. There are three problems. First, current culvert repair practices can be poor resulting in centimetre-deep initial unevenness immediately after repair. Secondly, poorly compacted backfill may add settlement of several cm within a couple of years. Third, culverts have been found to collapse at a fraction of the design age. This brings unacceptable costs to taxpayers.

8.6.1 Poor culvert construction practice

A 6 cm deep hollow appeared immediately after constructing a new culvert on Rd 331 in Gammelmo. The cause of this initial bump is likely to be found in poor construction work, rather than in deficiencies in the road culvert installation code. It is most unlikely that such a large settlement could occur in an established road embankment unless the construction work (material selection, compaction et cetera) was poor.

8.6.2 Poor culvert-related road surface maintenance management

There is a need for an improved maintenance regime for culverts. Many culverts on the Beaver Road 331 collapsed during the winter, making the repair even more difficult. “Everybody” knows that there will be settlement when a culvert is constructed or repaired, due to difficulties in the compaction of the thick backfill, differences in material properties, etc. The case study shows however that the resulting bumps due to such settlements are totally unacceptable for road users, in terms of comfort, health and traffic safety. There a clear need for robust management of bumps at culverts. Road users can probably be expected to cope with a culvert bump for a few months. However, it is a modest demand that culverts should be inspected for road roughness, in the first and the second year after reconstruction, so that repair of any local roughness can be carried out in a timely fashion where necessary. It is recommended that a culvert repair should always be followed by systematic roughness inspection and additional road repair where necessary.

8.5.3 Water-piping in permeable culvert foundation beds

Culverts manufactured with Portland Cement Concrete (PCC) are usually manufactured for a design life of up to 100 years. It is therefore surprising that so many apparently sound concrete culverts need to be reconstructed within only 5 - 20 years after their installation. As seen on Rd 331, a common failure mode is a full collapse, caused by water piping in the soil below the culvert. This shows a need for a revision of the culvert design code. Can water really be expected to flow within a culvert, when the culvert itself is founded on a permeable gravel bed at the bottom of the culvert ditch in low-permeable soil (so water can pipe its way beneath the culvert), as seen in Figure 92. Should not the foundation need to be made low-permeable? These are questions that culvert experts should consider.

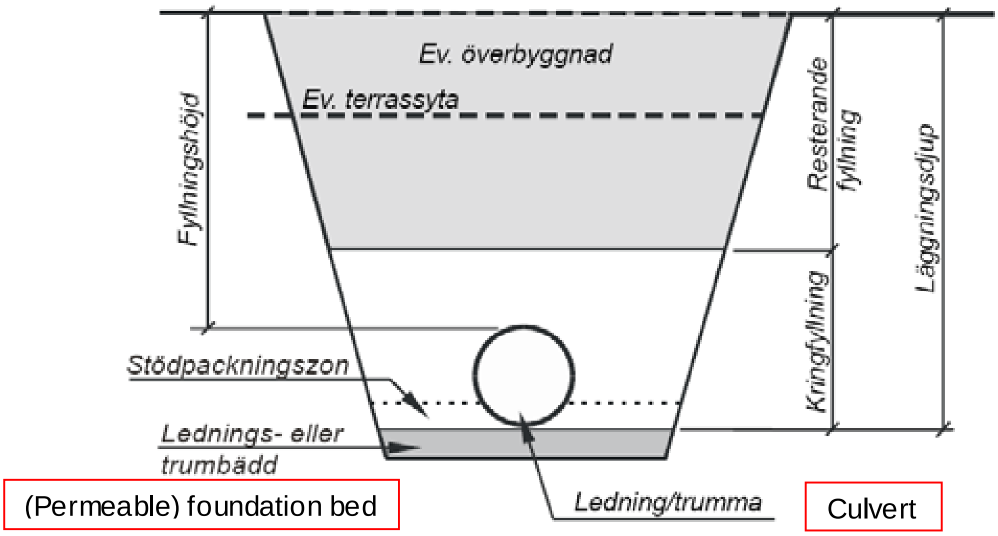


Figure 92 Section of a culvert on its permeable foundation bed [40]

Chapter 9. How to use the new insight

This chapter sets out recommendations for stakeholders across in Northern Periphery, from vehicle manufacturers to road agencies, based on the project results. It is hoped that these will be accepted in a constructive fashion, improving the present situation for the benefit of all.

9.1 HAULIERS MUST MONITOR DRIVERS WBV EXPOSURE

The daily exposure value A(8) for Whole-Body Vibration (WBV) must be determined for truck drivers. The value should be representative of year round operations and measurements should include driving during winter. In good winter conditions, the road can be smoother than in the summer. Conversely poor winter condition, through poor road maintenance, can result in significantly higher ride vibration. The A(8) value will therefore be depending on the road maintenance standard, both in summer (pavement condition) and in winter (snow ploughing). A further factor to be considered is vibration when driving on road sections under reconstruction.

Discussions should be held with the owners of local roads in poor condition, such as the access road to the Graninge Sawmill, regarding the condition of the road. If the worst bumps on the Graninge access road are not repaired, it may be necessary to close the road to heavy trucks.

Where alternative routes are possible, a longer route with lower roughness / vibration could be an option. An example in the case study is the smoother route on Hw 87 - Hw 86. This route could be used instead of the rougher, but shorter, Rd 331. An important question that arises here is "*Who is prepared to pay for the additional costs for the longer route*"? How can competing truck hauliers be equally treated?

An efficient tool to reduce WBV on roads with excessive shortwave roughness is tyre pressure control or Central Tyre Inflation (CTI) systems. (CTI cannot isolate long waves). Using CTI it is possible for the driver to change the pressures in the tyres of the vehicle while driving, and this has proven to reduce WBV by 8 % on four test roads in central Sweden.

In the case study, a chassis suspension damper bush was out of order, as seen in Figure 30, without anyone being aware of the problem. This lack of detection indicates a need for improved vibration control in vehicles in truck fleets.

Hauliers in the Northern Periphery are recommended to use special winter tyres. Brorssons Åkeri AB use the new Michelin XFN+ winter tyre on the steer axle, offering 10 % better side friction against the road surface and 5 % shorter braking distance.

9.2 DEVELOPING USEFUL NEW VEHICLE TECHNOLOGY

On-board vibration loggers could be useful for hauliers, especially as they are obliged by law to assess the risks to their drivers from vibration exposure. One problem with seat pan mounted automatic logging systems is that the driver's ingress and egress may cause data artefacts (false "shocks", resulting in unacceptably high S_{ed} values), as discussed by Mansfield & Newell (2004) [59]. A more robust solution could be to have the vibration sensor at the cab floor, and calibrate it to predict seat pan vibration. This may require a calibration that takes account of the driver's weight, and should be further investigated. The vibration logger could also be managed by a condition stating that vehicle speed must exceed a specified minimum, e.g. 5 km/h, before vibration data is stored.

As seen in the case study, many EU Northern Periphery roads give high lateral vibration. Currently heavy vehicles are not so good in isolating lateral vibration. Increased efforts on preventing and isolating lateral vibration could therefore be beneficial. The potential use of MagnetoRheology (MR) technology in trucks should be further investigated. However it is important not to implement solutions that increase bounce, when decreasing roll.

There is a need for a declaration of a vehicle's vibration emission value to be made, so that drivers can be in a position to request the most appropriate truck to be purchased. A generalized test is defined in the EN 1032 standard [57].

Road profile data from laser/inertial profilometers can be used to develop even better trucks in the future. At the date of writing, Profilograph data from Rd 331 is being used in a road simulator hydraulic test rig at Volvo 3P. Figure 93 shows a photograph from a simulation of a very rough road, causing bounce vibration as seen by the photographed truck vertical "traces". The simulation shown was of obviously made on a road without pavement edge damage, otherwise roll traces would have been seen as well. Severely damaged road sections, such as at HS Åkerö on Rd 331, may require road simulators to have larger hydraulic ranges than the current versions.

Figure 93 ***Truck ride vibration tests in a hydraulic road simulator [Photo: Volvo 3P]***

9.3 IMPROVING ROAD TRAFFIC CRASH INVESTIGATIONS

A wise man said: "*When investigating road traffic crashes, it is important to define a clear objective. Investigators trying to identify who to blame, tend to search after deviant behaviour. Investigators trying to understand normal road users need for better technology and infrastructure, tend to search after repeated patterns*". Which of these strategies has the best potential to support improvements into a safer future road transport system?

As seen in the case study results, each of the Hazardous Sites at Rd 331 show remarkable properties in the laser/inertial Profilograph road condition measurement. With exception of crashes with obvious causes, such as suicides, crash investigators should study pavement profilometer data on a routine basis.

Key safety parameters should include Cross Slope (CS) by magnitude and undesired variance (RBCSV), dynamic imbalance due to suboptimal combinations of CS and Curvature in incorrectly banked curves, high Curvature (lateral force), insufficient Drainage Gradient (hot spots at left hand curves and at deformed pavement sections), excessive Mega Texture (MeTx), insufficient Macro Texture (MaTx) and heterogeneous MaTx causing Split Friction. It is recommended that all of these parameters should be analyzed in road safety ratings, such as in the Euro Road Assessment Programme.

The work of improving road network safety could gain much from being benchmarked with aviation safety work. Before using an airfield for international air traffic, the facility administrator must demonstrate that the runway surface provides the minimum required level of safety, as defined by the International Civil Aviation Organization. Today, aircraft seldom crash due to deficiencies in the runway condition.

In Norway, all lanes of all paved highways are profiled annually in both directions. In Sweden, only one lane in one direction is monitored at least every fifth year. One consequence of this lesser measurement strategy is that when a serious crash occurs, it is often necessary to carry out extra profilometer measurements to obtain sufficient accurate data for the investigation. It is not possible to take laser/inertial measurements on icy roads or at temperatures below 0 °C.

9.4 IMPROVED ROAD MANAGEMENT

It should be a top priority within a road agency to recognise the importance of good road condition to comfortable, stress-free, healthy and safe road use.

A key factor in the reduction of professional drivers' daily exposure to vibration A(8) is the effective reduction of road roughness. This calls for a good focus in the selection of road repair sections, the planning of repair methods, the performing repair work, and in the end control.

The profilometer data held in a road agency's Pavement Management System (PMS) is a powerful tool for the management of paved roads, and its use should be encouraged and developed. Special training courses in the application of data would be beneficial, as would interregional, and international, benchmarking between road agencies local offices.

As seen in the case study, much of the truck ride problem relates to long wave unevenness and pavement edge deformations. The new Rut Bottom Cross Slope Variance (RBCSV) parameter should be implemented immediately in PMS. Effective repair of long wave unevenness and RBCSV is a new target for the road maintenance sector, requiring new methods. Detailed drawings should be made per 5 m section, showing target values for asphalt overlay thickness (including depth of grinding, if milling machines are to be used) and redesigned Cross Slope. A computer aided method for this is already in practice for high volume roads. This method should also be used on low and medium volume roads. Asphalt machines should be equipped with machine control systems, so they can perform the designed repair work effectively. Such systems are in use on airfield runways and high volume roads. The time has come to implement similar solutions on low and medium volume roads as well.

Why does such a large proportion of the road length in Sweden have severe pavement edge deformations as a result of weak road shoulders? Perhaps the design of pavement edge/shoulders should be reviewed. Is the quality of the road materials too poor? Are the road structure layers too thin? Could the reason be insufficient shoulder width and/or too steep embankment? These questions need to be answered. The deformed pavement edge at HS Meåstrand on Rd 331 in Figure 61 does not compare favourably with the stable Danish road edge design shown in Figure 94.

Figure 94 ***A Danish stabile pavement edge with paved shoulder and a wide grass verge***

The SRA Northern Region has been using laser/inertial profilometry in the control of roughness of new pavements for almost 10 years. Their experience is that the technology can result in much smoother new pavements without raising the price of paving. The outcome is lower ride vibration, longer pavement service life, and thereby lower road lifetime costs.

Good road maintenance practice could be encouraged by giving an award to the "smoothest resurfacing project of the year". This is already an accepted practice in Norway, but not in Sweden. Such an award would gain extra attention and status, if sponsored by stakeholders using the road, such as a truck haulage association.

Good practice amongst contractors could also be encouraged by openly reporting profilometer measurement results after surfacing operations, possibly accompanied by a comment from the project manager on any gap between target and outcome.

In the Northern Periphery the daily vibration exposure A(8) can be affected by winter maintenance operations. Poor snow ploughing response times can result in the formation of ice roughness on the surface of the road, which can cause intense vibration in the vehicle. Such vibrations can also cause interior noise. Professional drivers are exposed to many stress factors, including vibration and noise. Stress can also occur in the internal conflict in a driver when he, or she, has to decide whether to reduce vehicle speed to match poor road conditions, and thereby delay a delivery, or continue to try to meet the schedule, possibly as an accident risk. As presented in this report, researchers suspect the prevalence of increased stress hormones in the blood to be the cause of the strongly increased prevalence of myocardial infarction among the drivers. Therefore it is important to reduce as many stressors as is possible. Some types of stress can be reduced by good information on the route conditions, but the prevention of poor road conditions should not be underestimated.

A special concern is transient vibration/shock at bumps. A special program should focus on repair and prevention of bump hot spots, such as at culverts (see section *8.6 Rethink culvert works*), bridge joints, frost related deformations and potholes.

Roughness after culvert repair should be carefully monitored for the following three years. Culverts requiring emergency repairs during the winter should be revisited in the first summer.

A significant share of the road network is repaired each summer. Road roughness can be extreme during road repairs, and this can contribute to high vibration exposure A(8) to truck drivers. It is therefore important to try to restrict road repair section length and maximum roughness levels during reconstruction works.

It could be cost-efficient to make a special contract for bridge joint roughness repair. This could permit the successful contractor to assemble a team of specialists to repair the settlements at low cost in the spring, ahead of the main paving season.

Transient wheel vibration can be caused by poor joints in patch repairs. The case study shows several examples of some 2 cm high joints, causing wheel axle bounce and tramp-related polishing resulting in very low friction. It is recommended that no patching should be carried out without 2 cm deep edge grinding, to enable a proper joint with the adjacent road surface. Only very local patches such at potholes should be exceptions from such a practice. Preparatory edge grinding should be carried out at the repair of bumps at culverts and of pavement edge deformations. An example of small size grinding machines now available on the market is shown in Figure 95.

Figure 95 ***A small asphalt grinder [Photo: Tobias Edberg, SRA Production]***

Double surface dressings should be considered in preference to single surface dressings as they have less Mega Texture (MeTx).

Maximum limits for MeTx should be implemented as soon as possible.

The current standards for laser/inertial road condition profilometry of newly laid pavements should be revised. The Swedish profilometry standard “VVMB 116” does not require reporting of key safety parameters such as Curvature (plots of Cross Slope vs. Curvature), Longitudinal Gradient (to be combined with CS, when calculating Drainage Gradient), Rut Bottom Cross Slope Variance, Mega Texture and Macro Texture.

Pavement condition data should be stored in 1 m steps, rather than the present 20 m steps, or longer, used by the national road administrations in the Northern Periphery. Should it be required, this new style of data can be readily re-calculated as a “running 20 m” value for comparison with old 20 m data. Such results are still “20 m values”, directly comparable with existing data, limits and preferences. However, “running 20 m” values with a 1 m update step length are much better in reflecting local bumps, than traditional 20 m values with a 20 m update step length are.

Road workers can be exposed to unacceptable Whole-Body Vibration (WBV). Typical examples of these are drivers of snow ploughing trucks and operators of asphalt paving machines, as indicated in Table 2. Road agencies should start to measure WBV for these workers. In Sweden, drivers of contracted snow-ploughing trucks have filed complaints in respect of newly milled rumble strips in the centre of many roads. These are alleged to cause work related health problems due to their excessive ride vibration and noise.

The Tylösand Declaration states that road administrators are obliged to identify Hazardous Sites (HS) quickly, warn road users, and make appropriate repairs.

The proper identification of Hazardous Sites on low volume roads is an important issue. The case study demonstrates that there is a strong correlation between accident black spots and poor road condition. However, many of the worst pavement damages were in the section Backe - Ramsele which does not show any major black spots. The reason for this is the very low traffic volume on the section. It has an AADT of less than 350 vehicles per day. Obviously there is an urgent need to use the “Individual Risk” approach for low volume road networks. In this approach, it is not enough to analyze the number of accidents; the numbers must also be normalized to (divided by) the AADT figure. The Individual Risk approach is promoted by road user organizations, such as the Royal Automobile Club of Victoria, as it increases the likelihood of identifying very Hazardous Sites on low volume roads [64].

One drawback with the Individual Risk approach is that the low numbers involved make the assessment more susceptible to randomness. A way to increase the accident numbers, and thereby reduce the influence of risk, is to include data from registers of insurance companies. These registers hold more data than databases such as STRADA in Sweden where only Police and Hospital reported crashes are registered.

Another method to identify Hazardous Sites is to analyze road condition data from laser/inertial profilometers, see the previous section for examples of key safety parameters. The collation of accident data from STRADA versus Profilograph data shows a valuable potential that should be further explored. However, in the case study many examples were found of poorly positioned crash records in STRADA, including lethal crashes such as at HS S Viksjö. A separate project should seek to improve the quality of such crash record positions. It is also important to develop and refine generalized relationships between road condition and accident risk, such as in Figure 5.

A further option is to ask road users to identify their perceptions of hazardous sites. Focus groups, incorporating regular road users such as Brorssons Åkeri AB on Rd 331, may be a good tool for this. In Finland, the Internet-based “Street Channel” / KatuKanava [56] is used to map road user opinions. Improved customer focus by roads management may also bring better road user satisfaction.

There is a need for better standardization in setting up warning signs on roads. At present there are no objective limits for erecting a bump warning sign. Such a limit should be defined with respect to road condition data from profilometers as well as a subjective decision on “need”. Similarly, there should be objective limits for when to warn for high Curvature (lateral force), rutting, incorrectly banked curves, and skid risk due to too low, or varying, Macro Texture. There should also be limits on the length of road section that can have a Drainage Gradient below 0.5 m, before a warning should be given. It is impossible to sign for all of such flat areas, as they currently exist at almost every left hand curve (right hand curve in the UK).

It is not enough however to identify Hazardous Sites and put up additional warning signs. The road network needs to be more skid resistant and less unhealthy, by focusing actions at the identified hot spots. This requires a long-term program, with significant funding. Such a program could benefit of a benchmarking with Transit New Zealand's Truck Ride Improvement Initiative, running with a 3M$ annual budget since 2001.

Cross Slope (CS) is identified as a key factor for skidding and its modification requires substantial amounts of road material, and consequently substantial funding. For these reasons it is recommended that CS should also be analyzed on a road network level. The new RBCSV parameter is suitable for such a purpose as it is easy to interpret. A higher RBCS value shows a higher need for road repair and greater funding.

A slightly more difficult analysis is that of dynamic imbalance due to the ratio of CS to Curvature, the "incorrectly banked curves" in the report. Further research should seek methods to quantify the problems with incorrect banking at the road network level. This is important, as the reconstruction of slopes in existing curves requires significant quantities of road materials and thus significantly larger funding than traditional overlays of ruts and short wave roughness. Plots, as Figure 73, should be employed in the programming, planning and detailed design of the repair, as well as in the quality control of finished work.

An easy-to-use parameter is the Drainage Gradient (DG). This is a key safety parameter as demonstrated in the case study and should exceed 0.5 % to avoid water ponding problems. Road agencies with DG in their databases will find it easy to identify those sections that have DG below the safety limit 0.5 %.

Suitable software can identify road sections with insufficient DG from existing databases and during a typical search it can also be possible to identify other flat sections requiring rehabilitation. Examples of the latter type can be found at the HS Björknäset and the HS Helgum. Repair of such weak sections should be designed by support of bearing capacity testing with a falling weight deflectometer.

Road agencies should require their road designers to report the designed DG, especially at entrances and exits of left hand curves (UK: right hand curves). Consultants and Contractors should face high penalties if their work results in Drainage Gradients that are too low.

The limit of 0.5 % DG is tight, and requires high measurement accuracy. DG is calculated from Cross Slope and Longitudinal Gradient. It is possible to report both of these parameters from most laser/inertial profilometers on the market. However, most profilometers do not measure the road's Longitudinal Gradient. Rather they only measure the gradient of the profilometer vehicle body. The grade of the vehicle and the road grade often differ significantly, especially when the profilometer vehicle accelerates or brakes. When this occurs the difference can be very large. The vehicle grade can also change in response to changes in wind load, the level of fuel in the fuel tank, and other changes in load. The SRA CS Profilograph used in the case study has an accurate system for road grade measurement, taking into account the vehicles own pitch angle in relation to the road. Without such a system, profilometer reported grades/Drainage Gradients might not be sufficiently accurate to be useful in analyzing the risk for skid accidents. This should be considered when purchasing road condition measurements.

The allocation of existing road maintenance funding should be reviewed. The repair of pavement deformation with high RBCSV in the Northern Periphery costs more than overlays of rough, but much more planar, surfaces in the southern areas. Repair of incorrectly banked curves and insufficient Drainage Gradient require even more funding, as significant quantities of road materials are needed. Such road repairs are one-time investments, since slopes, once created, do not normally change significantly over time.

There should be an extra focus on maintaining high road surface friction in sharp and incorrectly banked curves and at the downhill part of long and steep grades. This can be done by increasing the use of high friction surfacings and intensified winter maintenance.

The failure mode at HS S Viksjö shows that the barrier may be undersized. In three lethal crashes, heavy trucks have made a big hole in the standard crash barrier. There is therefore an acute need for crash barriers to have the capacity to retain heavy vehicle combinations with up to 60 tonne gross vehicle weight (GVW). There are plans to increase the max GVW to 80 - 88 tonnes in Sweden. Such plans should be reconsidered on those road networks that do not have crash barriers with the relevant heavy truck capacity.

Measurements of Split Friction risk potential should be carried out on road sections with new patch repairs, such as the repair seen in Figure 61. The friction numbers should be measured in both the left and right wheel track, focusing on the difference between them.

Profilometer results should be systematically used in traffic safety inspections and analysis. Left hand curves (Right hand curves in the UK) are hot spots for hazardous road alignment errors., Only one lane in one direction is currently monitored in Sweden in accordance with the road surface profilometry strategy of the SRA. This lane is scanned at least every fifth year. One of the net effects of this strategy is that the PMS does not include relevant data for 50 % of the left hand curves on the network (important geometrical parameters may be totally different in the opposed directions). Temporary changes should be made in the measurement strategy, aiming to result in having relevant geometrical data from every lane within three years from now.

A consequence of a limited road condition measurement strategy is that, in the event of a serious having to be investigated, it may be necessary to carry out additional profilometer measurements to obtain sufficiently accurate data for the investigation. Such non-scheduled measurements are more expensive than systematically planned measurements.

When planning actions to improve safety at road sections suffering from many skid accidents on wet pavement or thin ice, such as HS Stavreviken, resurfacing with high friction double surface dressings should be tried before planning to build expensive new road sections. Speed monitoring displays could reduce skid accidents at such sites.

As recommended by the group analysing lethal crashes in Norway's Central Region, the time tolerance for removing wet snow (which is risky as snow, and later, after forming ice ruts) should be reduced. Furthermore, the contractor performing daily road maintenance should be paid for making extraordinary friction improvement actions when weather conditions become extreme [72].

9.5 ROAD DESIGN POLICY IMPROVEMENTS

Left hand curves should be identified as hot spot sections for insufficient Drainage Gradient (DG) in road design manuals (right hand curves in the UK).

The minimum limit on DG should be raised. The present design limit of 0.5 % should be redefined as a rare exception, as it is too close to the normal deviations in road construction works (about 0.5 % is allowed Cross Slope deviation in the Swedish ATB VÄG road construction manual). In practice, this means that a "properly designed" section of road may end up with an insufficient DG if the construction on site is only just inside the tolerance limits. Considering the need for a reasonable production tolerance, the normal design limit needs to be raised, up to about 1 %.

The RBCSV concept should be implemented in manuals for redesign of existing roads.

Low-permeable material should be considered for culvert foundations.

9.6 WORK TO BE CONTINUED (IN ROADEX IV?)

This project suggests a draft limit value of 0.30 % for undesired Variance of the pavement's Rut Bottom Cross Slope (RBCS). Further work should draft differentiated RBCSV limit values, depending on road/lane width, curvature and length of curve. It should be noted that the RBCSV is normalized to a user defined reference speed. Therefore the same limit value can be used for 50 km/h roads as for 90 km/h roads.

How common are the road damages found on Rd 331 on roads in the Northern Periphery partner area?

The comfort scale in ISO 2631 is relevant for people in public transportation and there are indications that professional drivers may have a somewhat higher comfort tolerance. Should a special comfort scale be developed for professional drivers?

A scale and a limit value should be drafted for short road roughness that causes tramp-related polishing and thus extremely low friction. Mega Texture could be used as one parameter, but 0.5 - 2.5 m roughness could also be addressed.

The relation between speed and vertical truck seat vibration is fairly well known. But the relation between speed and roll/lateral vibration should be further explored. (However, there are no indications on a larger speed dependence on roll, as compared to vertical bounce).

The correlation of road surface texture and truck interior noise should be mapped.

Whole-Body Vibration, Hand-Arm Vibration as well as interior noise should also be measured when driving heavy vehicles on winter roads with ice ruts accompanied by high Mega texture on the ice edges.

The effect of changing winter road maintenance standards on ride vibration should be investigated.

The impact of general road roughness should be mapped against the ability to perform efficient snow ploughing in winter.

Why does such a large proportion of the road length have severe pavement edge deformations? The design of pavement edge/shoulders could be reviewed. Is the quality of the road materials too poor? Are the road structure layers too thin? Could the reason be insufficient shoulder width and/or too steep embankment?

A method to quantify the problems with incorrect banking at the road network level could be developed. Such a method could be drafted from an analysis of plots such as Figure 73.

Chapter 10. Further reading

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Comfort, comfort my people, says your God.

A voice of one calling in the desert;

-Prepare the way for the Lord, make straight paths for him. Every valley shall be filled in, every mountain and hill made low. The crooked roads shall become straight, the rough ways smooth.

The path of the righteous is level; O upright One, you make the way of the righteous smooth. And all mankind will see God's salvation.

[Isaiah 26:7, Isaiah 40:1,3-5, Luke 3:5]

ROADEX III PUBLICATIONS

Developing Drainage Guidelines for Maintenance Contracts

Tyre Pressure Control on Timber Haulage Vehicles

Understanding Low-Volume Pavement Response to Heavy Traffic Loading

Health Issues Raised by Poorly Maintained Road Networks

Road condition management policies for low volume roads – tests and development of proposals

Policies for Forest Roads – Some Proposals

Road Construction in Greenland - The Greenlandic Case