A new approach to prevent skid accidents on bumpy roads

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ABSTRACT

Roads must have proper cross slopes, in order to be skid resistant. The slopes contain the drainage of rain and melt water, while superelevation/banking reduces lateral forces during cornering. Lateral forces may be detrimental on slippery surfaces, as they cause skid accidents. Extensive measurements in heavy vehicles driving on frost damaged roads in northern Sweden have revealed surprisingly high rates of roll-related lateral vibration. The exciting source is identified as large changes in cross slope within up to 25 m length, caused by pavement edge local deformation. Existing laser/inertial Profilometers accurately measure lane geometries, but no existing result index reflects this kind of damage accurately. Thus, SRA defined the new RBCSV index. The *Rut Bottom Cross Slope (RBCS)* is the slope between left and right truck wheel track bottom (3 - 4 dm wide tires with 2 m track width between contact patches). RBCS data are analyzed with so short interval that they correlate with heavy vehicle body and wheel axle roll motions. A sophisticated procedure filters out "soft" changes in RBCS, such as at correctly designed transition curves. Finally, the *undesired Variance* of RBCS is calculated in a set of filtering steps, while normalizing to the posted speed limit. In the EU Roadex III project, the new RBCSV measure was demonstrated to give alarm at skid accident black spot sections in need of edge deformation repair. RBCSV show good correlation with heavy truck lateral vibration and 0.30 % was drafted as limit value. The relevance of pavement edge deformation repair increases, as the change in climate makes slippery "black ice" more common on rough roads in the EU Northern Periphery.

Key Words: Skidding, road friction, lateral force, roll vibration, high vehicles, cross slope variance, road roughness.

1. FREQUENT SKIDDING ON BUMPY ROADS

1.1 SKIDDING IS A COMMON ACCIDENT MODE

The European northern periphery has a cold climate during the winter. In several countries, studded tyres are commonly used to increase the low friction on icy road surfaces.

Persson & Strandroth (2005) 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 winter operations standard (providing better friction) were strongly underrepresented in skid statistics.

Krafft et al (2006) compared Swedish accident outcome for cars with and without an antiskid system. They found that antiskid systems were associated with over 13 % lower risk for an accident with human injury on dry road surfaces. On slippery surfaces, antiskid systems reduce the risk by an astonishing minimum of 35 %, showing 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.

1.2 ROUGH ROADS ARE MORE HAZARDOUS

Research by Ihs et al (2002) confirms a positive correlation between general road roughness (ride vibration) and traffic accident[1] frequency (crash risk) in Sweden, as seen in Figure 1. Rough roads with an IRI[2]-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 goes very high, the crash rate increases even more than showed by the linear graphs.

The graphs at Figure 1 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.

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) 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 of a warning to the driver. Many truck accidents include an early roll tendency, but ends without a complete rollover due to corrective manoeuvres by the driver.

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

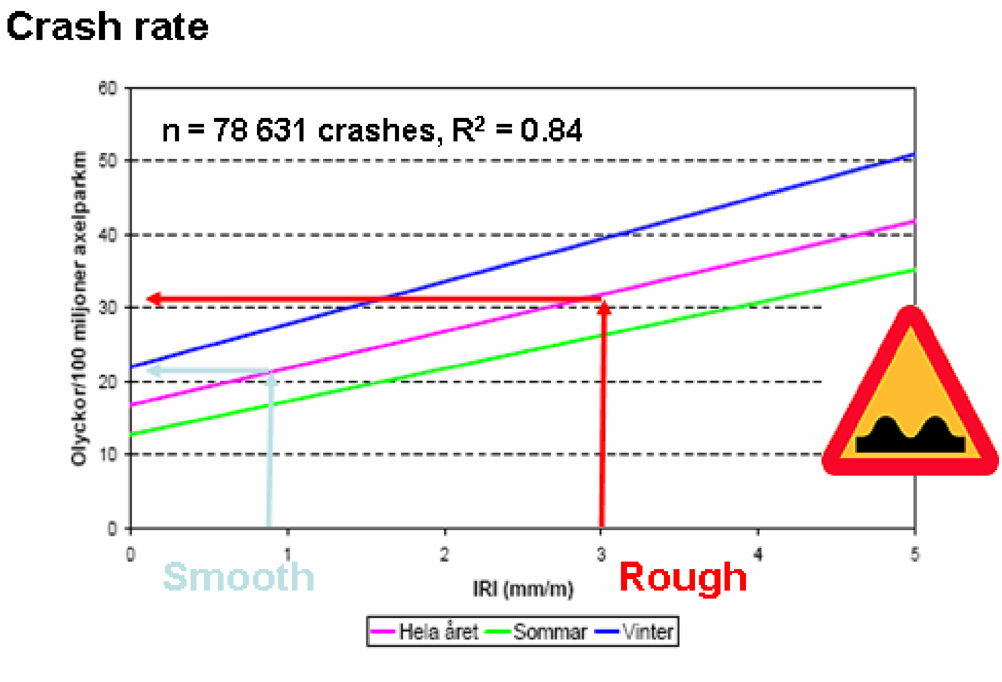

Figure 1 Rough roads have > 50 % higher crash rate. After Ihs, et al (2002)

1.2.1 Truck cab vibration decrease highway 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 (TCVHS)*” in 1982. 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 2. The TCVHS-report concluded that vibration must be eliminated at source through effective road maintenance, rather than merely dampened.

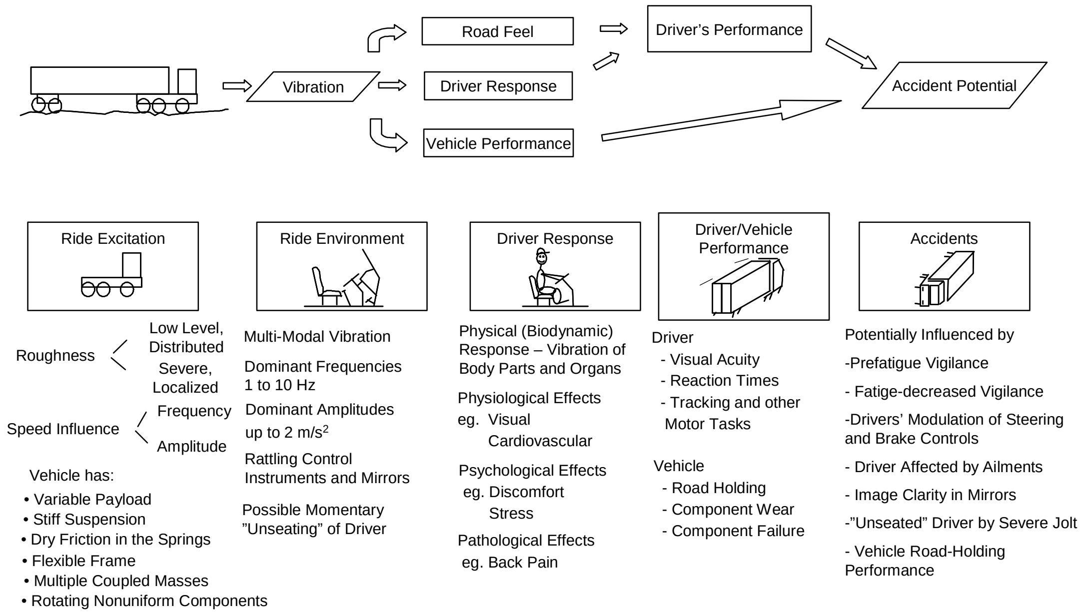

Figure 2 The primary links between truck ride vibration and safety

1.2.2 Relating ride vibration to road roughness

Road roughness has been defined as "*The deviations of a pavement surface from a true planar surface with characteristic dimensions that affect vehicle dynamics, ride quality, dynamic pavement loads, winter operations and pavement drainage, e.g., profile, transverse section, cross slope and rutting*" [ASTM, slightly adjusted at SRA].

The pavement deviations along the wheel tracks essentially excite vertical and pitch motion responses, while warping differences in elevation between the wheel tracks are the major excitation of roll and other lateral motions.

1.2.3 Roll-related lateral vibration is an underestimated problem

The road presents no lateral acceleration input to a vehicle directly, but rather, the warping elevation differences between the wheel tracks constitute a roll input that may be perceived as lateral acceleration by the driver.

The above referred TCVHS-report (1982) found truck roll motions at normal highway speeds being generally less significant than truck vertical motions, when analyzing US highway data. Therefore the important TCVHS-report focused on pitch and vertical bounce. So have also the vast majority of all similar studies thereafter, world wide.

Since the early 2000's, roll-related lateral vibration in heavy vehicles have been highlighted in some studies. Ahlin et al (2000) found unacceptably high levels of truck cab roll vibration, and concluded that the cross slope variations on Swedish roads with badly deformed pavement edges (see Figure 3) means that these are no longer satisfactory surfaces on which to drive normal heavy vehicles. Cenek et al (2003) found that truck cab body roll, particularly when combined with cab body pitch, is of most concern to occupants of trucks.

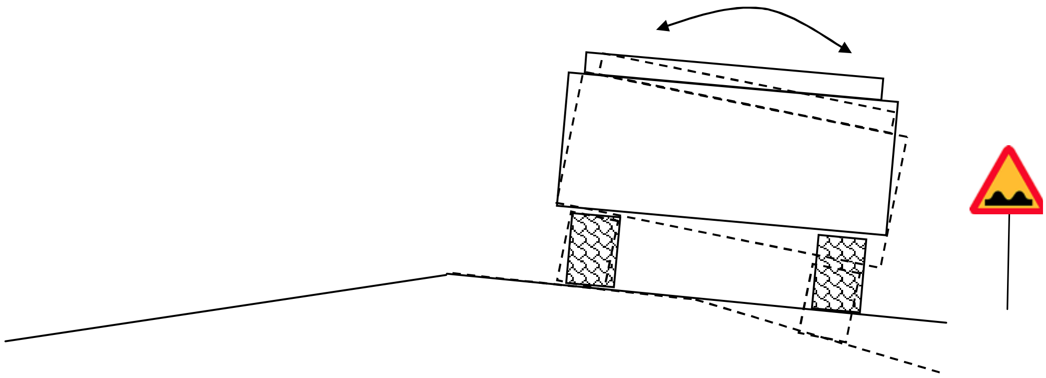

Figure 3 Pavement edge deformations excite roll vibration

Even at low levels, unexpected lateral acceleration may be hazardous when driving on a pavement covered with slippery thin black ice. If the driver believes the vehicle is skidding, he, or she, may instinctively steer towards the non-existing skid. Under such circumstances, the driver may actually cause an accident by unsuitable manoeuvre.

2. A VALID INDICATOR FOR TRUCK ROLL VIBRATION

Cenek et al (2003) defined the "Transit New Zealand Truck Ride Indicator", based on pavement condition data of Speed, lane roughness IRI, mean Grade and standard deviation of Cross Slope. These pavement condition data was averaged over 200 m sections. The product of Standard deviation of Cross Slope and √Speed was used to reflect truck cab roll vibration, and a threshold of 5 $\%*(m/s^2)^{0.5}$ was established for this product.

In 2004, the Swedish Road Administration (SRA) tested the above described NZ truck cab roll indicating product. 20 m average values of Cross Slope were taken from the Swedish Pavement Management Systems (PMS) database. The standard deviation within 200 m was calculated, and multiplied by the square root of the posted Speed limit.

The result parameter was found to give some signal at highway sections where truck cab roll vibration was high. However, much stronger alarm signal was given at the entrance and exit of the superelevation at every sharp left hand curve (Sweden has right hand traffic). These strong alarms were due to the desired change in Cross Slope, as it becomes superelevation at sharp left hand curves. While these sections give high roll (semi-static) acceleration in truck cabs, they do not necessary have high roll vibration. This showed that the non-valid NZ model often misleads road repair planning and this disappointment made SRA decide to drop the model.

In 2005, SRA started a project aiming to define a valid truck roll vibration indicator. Granlund (2006) reported the new parameter *undesired Variance of Rut Bottom Cross Slope* (RBCSV) as a suitable truck roll vibration indicator. 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 much better spatial resolution than the NZ 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 variance that relates to superelevation change at curve transitions. This is markedly notable at left[3] 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 Rut Bottom Cross Slope* (RBCSV).

2.1 DRAFTING A RBCSV LIMIT

One of the goals in the ROADEX III project, was 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?* This paper gives a condensed report on the results. Details can be found in a comprehensive report by Granlund (2008).

3. CASE STUDY ON 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 4.
Rd 331's Annual Average Day Traffic (AADT) ranges from 350 to 2000 vehicles per day. The share of heavy trucks is very high, as Rd 331 is a main supply road for timber transports servicing the paper mills in the Sundsvall area. The speed limit alternates between 90 and 70 km/h, with a drop to 50 km/h in some villages.

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

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 4. Many of the accidents involve skidding.

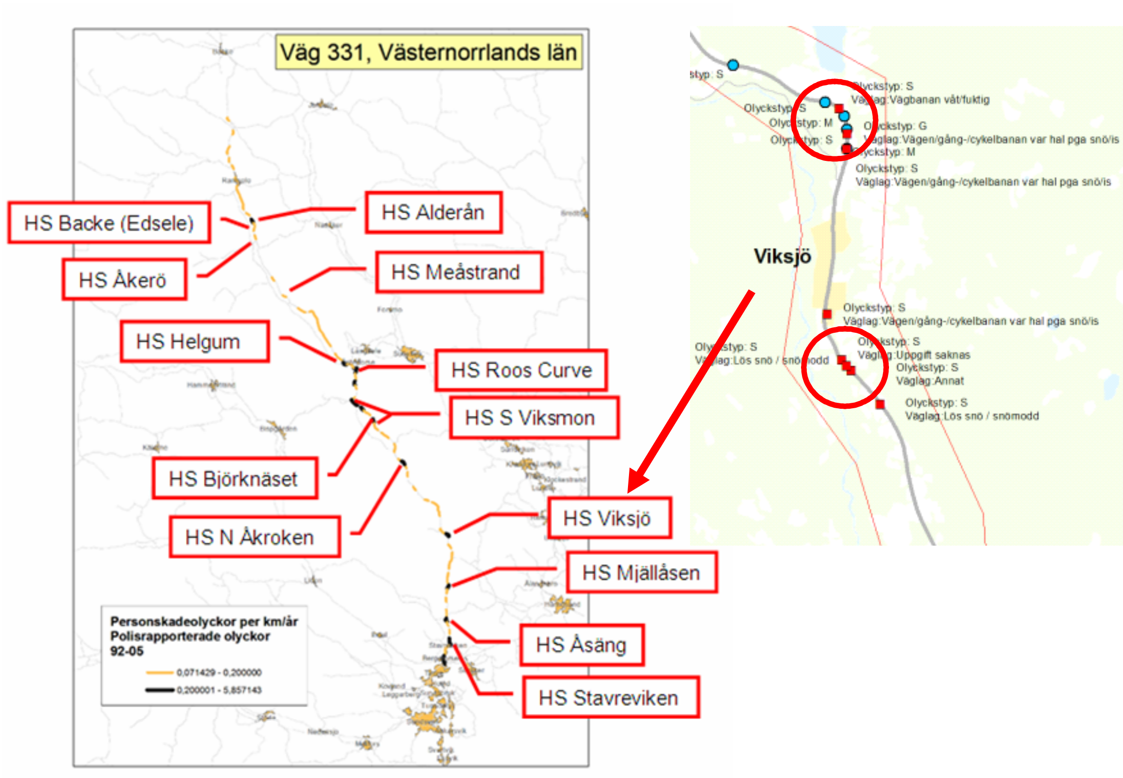

Figure 4 Accident black spots at the Beaver Road 331

3.1 COMPREHENSIVE RIDE AND ROAD CONDITION MEASUREMENTS

3.1.1 A Scania R480 164 G 6x4 was used as test truck

The truck ride tests were made in cooperation with Brorssons Åkeri AB in Ramsele. The company operates 14 timber logging trucks, each with a large trailer. Each truck runs Monday to Friday in two shifts. Normally each truck daily drives 4 round trips of some 2 * 140 km on the Beaver Road 331. The company's drivers are together doing some 2 800 000 vehicle km/year on Rd 331; they know every section of Rd 331 very well.

The truck used for the tests is seen in Figure 5. It was three years old, and had a mileage of 609 000 km.

Figure 5 The tests were made in a Scania R480 truck

3.1.2 Truck ride measurements

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. This unit recorded the cabs motion 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 truck tyres road contact patch. The RT 3050 was mounted on a carbon-reinforced RT Strut, with very high torsion stiffness, seen in Figure 6. The RT 3050 also logged the truck's speed, with an update every second dm during an 80 km/h ride. The speed data was used to calculate the distance position with a fair accuracy.

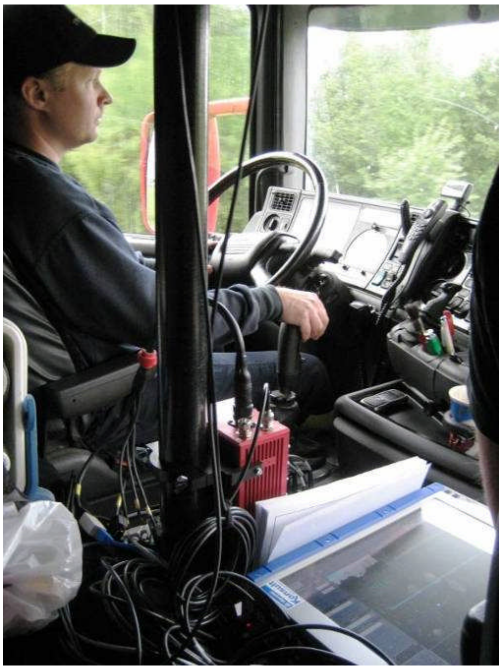

Figure 6 The RT 3050 mounted on a RT Strut in the truck cab

3.1.3 Laser/inertial reference measurement of pavement condition

The road alignment and the 3-D geometry of the pavement lanes were scanned with one of SRA CS's advanced laser/inertial Profilographs, as shown in Figure 7. 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 normal traffic speeds.

Figure 7 SRA CS's laser/inertial Profilograph P45 [Photo: Mats Landerberg]

The Profilograph is equipped with a 2.5 m wide rut bar. The rut bar is equipped with seventeen pieces of 16 - 64 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.

4. CORRELATING PROFILE AND TRUCK ROLL DATA

4.1 RBCS SHOW GOOD FIT TO TRUCK ROLL ANGLE

Pavement Rut Bottom Cross Slope (RBCS) show a good fit with the dynamic roll angle in the Scania R480 truck cab, as seen in data from Hazardous Site Backe (Edsele) in Figure 8.

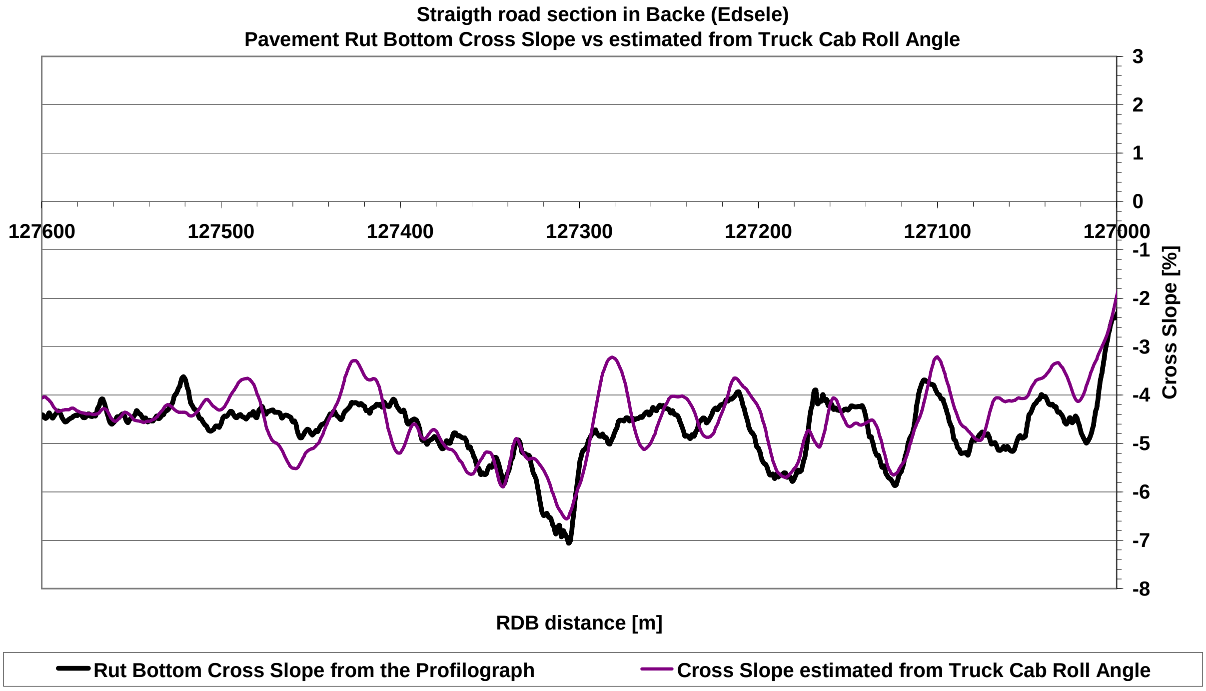

Figure 8 Good fit between pavement Cross Slope and Truck Cab Roll Angle

4.1.1 RBCSV show good fit to truck roll vibration

The Hazardous Site (HS) Åkerö pavement edge damage is seen on photo in Figure 9. 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 10. The deformation at this site was found to be 69 mm deep.

Figure 9 Edge deformation at HS Åkerö. Take note of the exploded truck tyre!

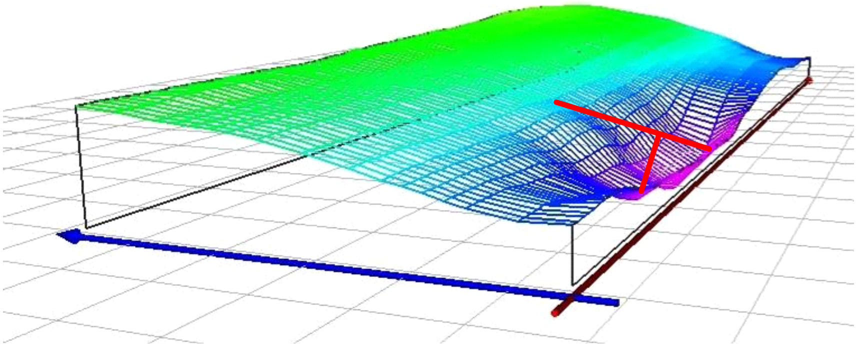

Figure 10 Profilograph 3D plot of the HS Åkerö 69 mm deep edge deformation

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 11.

Granlund (2006) designed the RBCSV parameter to identify sections with such cross slope variance that cause roll vibration in the suspended masses (body, cab and pay-load) of heavy trucks, as well as in the wheel axle. As a result of this multipurpose, one should not look for a perfect match between RBCSV and the roll vibration in the cab only. Furthermore, there are also significant variances between reproduced truck rides. With this in mind, the match seen in Figure 11 seems good for the intended purpose of the RBCSV parameter.

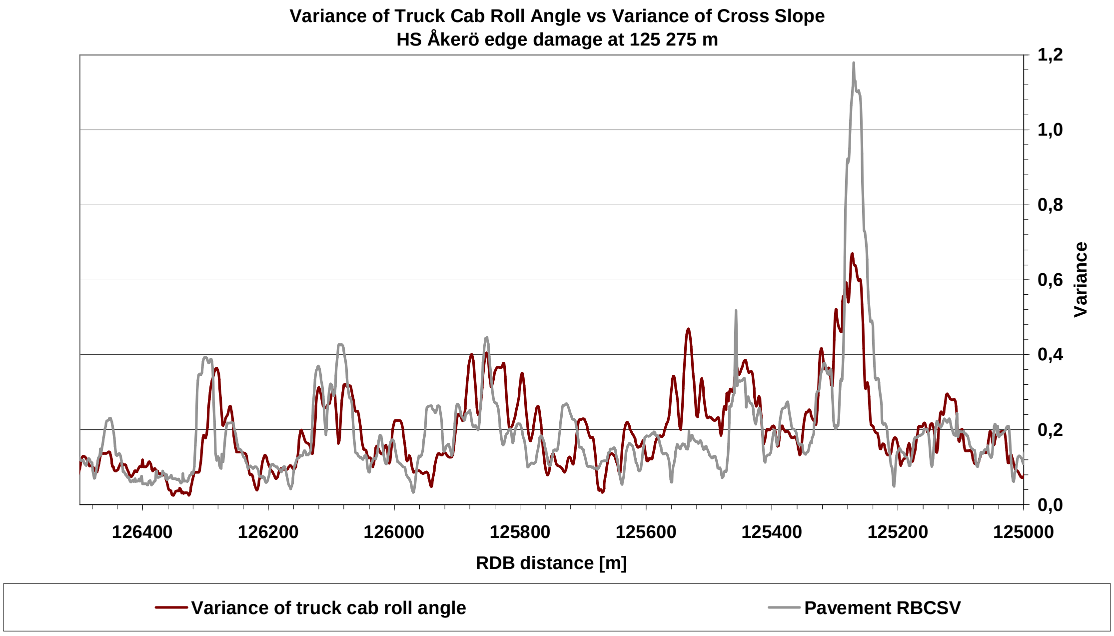

Figure 11 Good fit between RBCSV and Variance of Truck Cab Roll Angle

4.1.2 Edge deformations excite much 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 with a lateral acceleration. Again, data from HS Åkerö is given as an example in Figure 12. 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 12 shows that the pavement RBCSV parameter is registering approximately 0.1 % through the curve where the cab lateral acceleration is rather constant with low vibration. However as intended, it quickly gives a clear alarm of 1.18 % (being over 6 times larger than the 0.1 á 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.

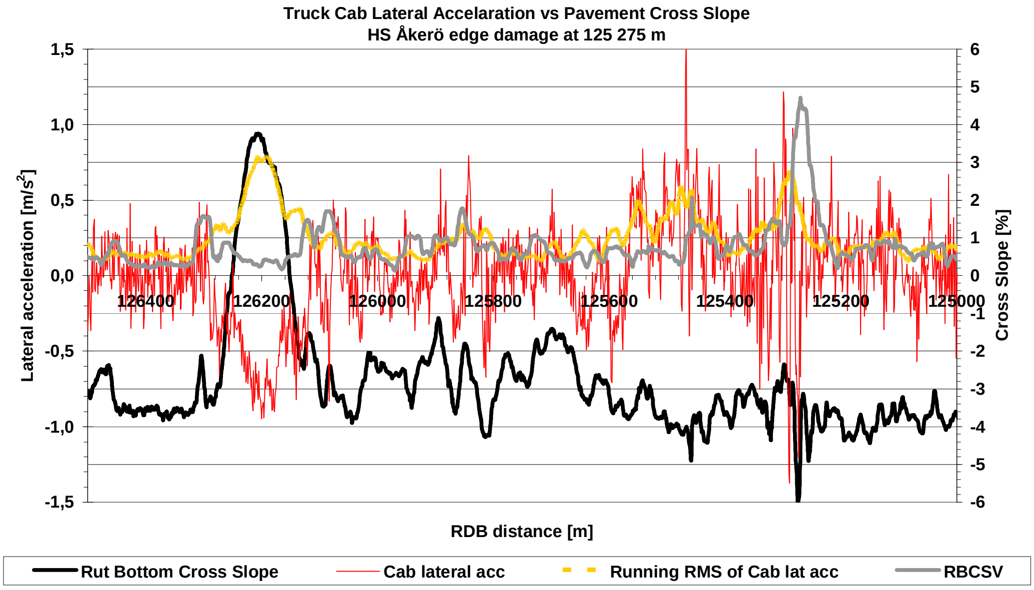

Figure 12 Edge damages may excite as much lateral acceleration as a curve

4.2 DRAFTING A LIMIT FOR WARPING RBCS

Sample results after collation of Profilograph data, truck ride data and truck driver perception of comfort and safety show that 0.4 % undesired Variance of RBCS is a too high limit value. One example is the Backe (Edsele) section, rated by the truck drivers rated as "*very uncomfortable*" and "*hazardous*". The section's RBCSV peaked at 0.47 %. This, and similar findings at other Hazardous Sites at Rd 331, justifies a significantly lower limit value.

A statistical analysis was made for data from two long sections of Rd 331, south of Viksmon. The first section from Viksmon to Östergraninge is 17 km long and in rough condition. Large parts of this section show accident black spots (see Figure 4), and the entire section will be resurfaced during 2008. The second 26.5 km section from Östergraninge down to Viksjö is a "quite normal old road". Beside the Hazardous Sites *N Åkroken* and *N Viksjö* (see the black spot map in Figure 4), it shows a modest accident record.

The graph in Figure 13 shows that 0.1 % RBCSV corresponds to the background noise on the "normal" old road", and is obviously a too low limit value.

A reasonable limit could be somewhere between 0.2 % and 0.3 % RBCSV. The graph in Figure 13 shows that 3/100 of the old road length exceeds 0.3 %, while 13/100 of the road length exceeds 0.2 % RBCSV. Since it is important to focus road repair to a limited fraction of the road network, a reasonable draft limit value could be 0.3 % RBCSV. The graph in Figure 14 shows that 0.3 % RBCSV is exceeded on 39/100 of the 17 km long rough road section. Again, 0.3 % RBCSV is exceeded on 3/100 of the length of the old road Östergraninge - Viksjö, which include some Hazardous Sites. This show that 0.30 % RBCSV can be a good draft limit value.

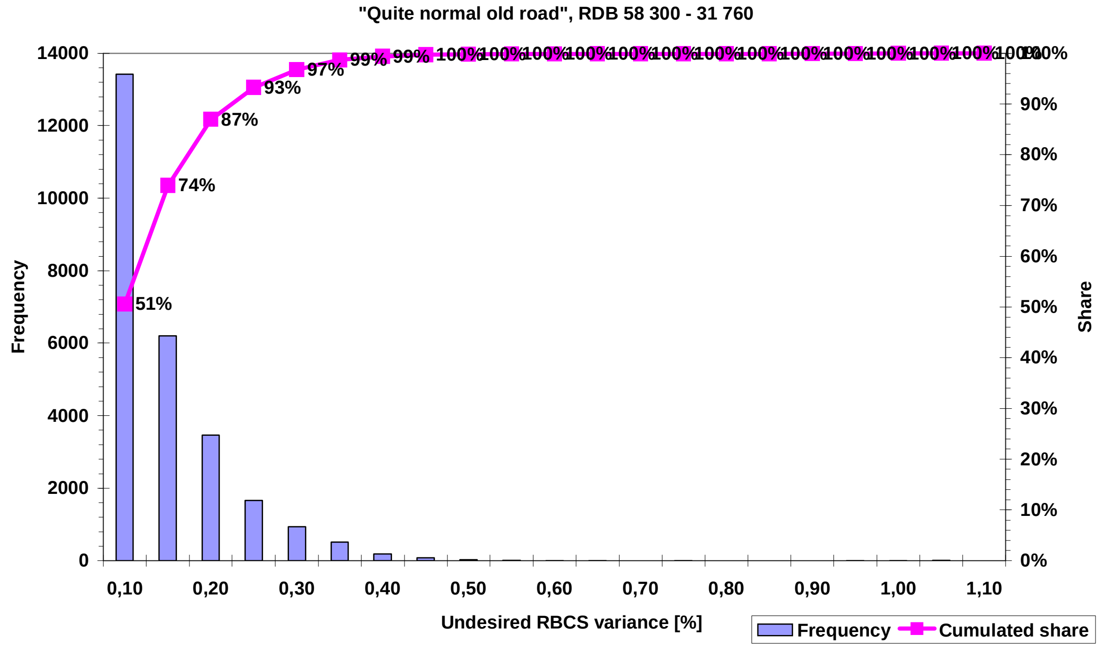

Figure 13 RBCSV distribution at a "normal" old road, Östergraninge - Viksjö

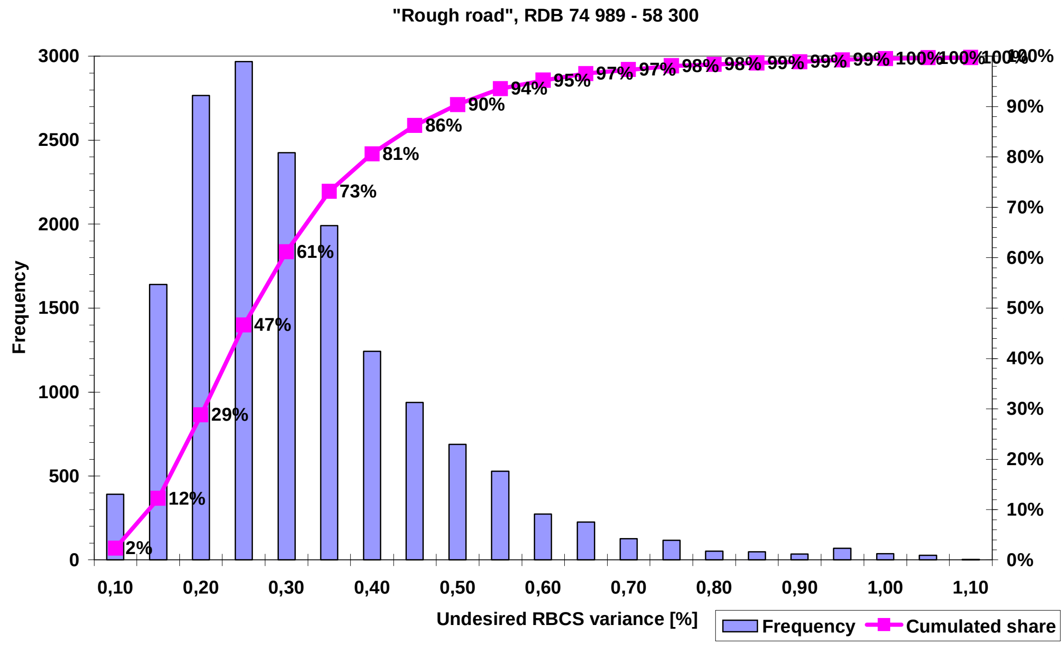

Figure 14 RBCSV distribution at the rough road Viksmon – Östergraninge

5. HIGHWAY SAFETY CAN BE IMPROVED BY EDGE REPAIR

Many of the Hazardous Sites on the Beaver Road 331 were found to have local severe pavement edge damages, characterized by high Rut Bottom Cross Slope Variance (RBCSV).

Repair of pavement edge damages with more than 0.30 % RBCSV will minimize hazardous lateral vibration in trucks. As presented by Granlund (2008), 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.

5.1 THE CHANGE IN CLIMATE CALLS FOR INCREASED RBCSV REPAIR

Change in climate is likely to make freezing and thawing more frequent in the EU northern periphery. Data from year 1961 - 1990 (left) is compared with a computer modelled scenario for 2071 – 2100 (right) in Figure 15.

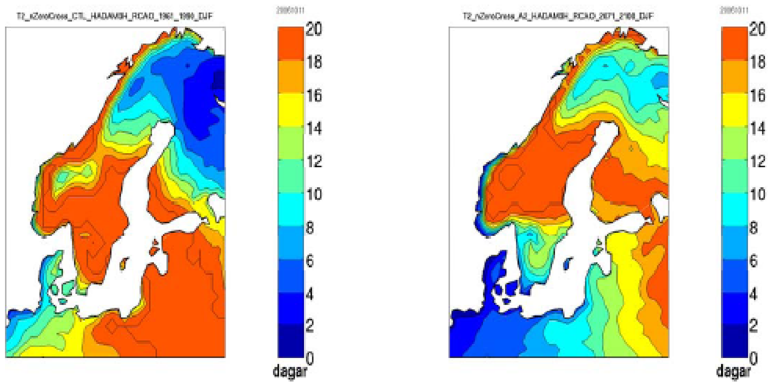

Figure 15 Freezing and thawing Dec – Jan; after Jonforsen (2007)

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 EU Northern Periphery.

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.

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