REDUCING HEALTH AND SAFETY RISKS ON POORLY MAINTAINED RURAL ROADS

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Abstract

This paper presents a handful methods to measure road alignment properties and pavement damages that bring health and safety risks. These methods can be used in new approaches to reduce risks on low-volume roads. Suitable actions include road curve reconstruction, reinforcement of road edge or entire pavement, resurfacing or retexturing the wearing course, as well as mounting intelligent warning signs using radar for detection of excessive vehicle speed. The potential for crash reduction is very high in cold climate regions, where not only rain water but also snow and ice contamination may reduce road/tire friction to a minimum.

Keywords: Curvature, cross slope, gradient, roll vibration, lateral force, drainage, road grip.

1. Introduction

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

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

While most previous research have focused on vertical and pitch vibration, recent truck ride measurements on roads in the Northern Periphery (NP) of the European Union have showed surprisingly high levels of both quasi-static and transient lateral vibration. Unexpected high lateral forces in “egg-shaped” sharp curves and roll-related lateral buffeting is of outermost concern for traffic safety in cold climate, as they may initiate skidding on ice-slippery surfaces. Lateral buffeting also give rise to health issues for vulnerable ambulance car patients.

The Swedish National Institute of Public Health (2008) found that the most common types of preventable mortality in Sweden are lung cancer (death rate of 17.1), suicide (15.4) and cerebro-vascular disease (11.8). Among the therapeutic treatable death causes, diabetes mellitus is the worst “big killer” with a death rate of 4.5. However, motor vehicle crashes are worse, with a death rate of 4.9. There are large regional differences in the risk of being killed in a traffic accident. While the metropolitan areas of Stockholm, Gothenburg and Malmoe have a Standardized Mortality Ratio (SMR) of 70 for vehicle crashes, the rural areas have a SMR of 177. This means that vehicle users in the rural areas have (177 – 70) / 70 = 153 % higher risk to end up in a fatal crash, as compared to urban vehicle users. In the Swedish rural areas, vehicle crashes take 39 % more lives than diabetes does.

1.1 Extreme Skid Risk in Improperly Banked Outer Curves

Crash rates in curves have been found to be typically 2 to 4.5 times higher than on straight road sections (Leonard et al., 1994). There is good agreement in the road safety research community that sharper curves cause more accidents (Charlton & de Pont, 2007). Trucks show the highest raise in crash rates between straight and curved road sections. Single sharp curves in highways with long straight sections as well as “flat curves” create some of the most hazardous situations (Haywood, 1980).

Lindholm (2002) investigated all single crashes with fatal outcome in Sweden during four years. The results show that the crash rate ratio between outer curves and inner curves is extremely high; outer curves were found to be 5 times as dangerous as inner curves. On low volume roads, the crash rate ratio exceeds 6. If the extreme over risk seen in outer curves can be eliminated, more than 10 % of all fatal road traffic crashes in Sweden would be prevented.

The Roadex III project (Granlund, 2008) identified two unique risk factors in outer curves on the NP road networks. The first is that many outer curves on old road sections have insufficient banking, with respect to reference speed and slippery surface conditions. These curves were properly designed when constructed, considering the neglect able cornering forces of ancient low speed traffic with horse-pulled wagons. However, these old curves do not meet the needs of motorized highway vehicles. The second risk factor is that many entrances and exits of improperly designed superelevated outer curves have insufficient Drainage Gradient; below 0.5 %. During and after rainfall, there may be large areas with a very thick water film in these transition sections. The thickness of the water film between tire and road is decisive for the hydroplaning risk. In wintertime, local outer curve sections with insufficient Drainage Gradient are often contaminated by extremely slippery ice while other parts of the road surface may be dry and safe. Such unexpected local ice spots may bring even higher risk, than generic and thus foreseeable slipperiness all over longer road sections.

1.2 Bumps and Ride Vibration Cause Poor Health

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

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

McFarlane & Sweatman (2003) studied lane-keeping behaviour of heavy trucks on rough road sections. Where the road width is narrow, lateral bump steer disturbances may require the driver to increase concentration into a stress level significant for driver fatigue.

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

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

The Roadex III project has done an accurate assessment of truck driver’s exposure to vibration, see Granlund (2008). Measurements were made in a timber logging truck during ten roundtrips of 140 - 170 km, with most time spent on Rd 331 between the Swedish inland forest area and the coast. The results showed that for all measured working days, the daily vibration exposure A(8) was above 0.65 m/s^2, including normal pauses with zero vibration, and that A(8) = 0.76 m/s^2 is a fair estimate for an 8 hour shift on this kind of routes. This is significantly above the EU Action Value of A(8) = 0.5 m/s^2. Thereby employers of truck drivers performing long and bumpy driving in the EU are required to take necessary technical and/or organizational actions to minimize the driver’s exposure to vibration.

EU employers are also obliged to perform a special risk assessment for workers exposed to repeated mechanical shock, such as from bumpy rides. The Roadex III case study showed that even when driven at low speeds (below 40 km/h), severe bumps (> 5 cm) exposed the truck driver to an equivalent daily static compression dose S_{ed} over 0.5 MPa. This stress level corresponds to health risk, as per the ISO 2631-5 (2004) standard.

2. Identifying Hazardous or Unhealthy Road Sections where Action is needed

All the road analysis methods presented below are using data for road alignment and road condition, measured with a laser/inertial Profilometer such as the one showed in Figure 1.

[Photo: Mats Landerberg]

Figure 1 Vecturas Profilograph P45

2.1 High Curvature and Lack of Cross Slope Increase Side Friction Demand

While much energy is spent on careful alignment design of new roads to be built or rehabilitated, the constructed ratios between cross slope to curve radius are seldom inspected. Even worse is that old roads are not inspected in terms of alignment design. One reason is that many road managers consider it difficult to perform an evaluation. However, this section provides a simple but yet scientific method, which yields a single value to check.

As described by Newton’s second law of mechanics, cornering vehicles undergo centripetal acceleration acting toward the centre of the curvature. The exciting lateral force is given by velocity (squared) [m/s], divided by curve radius [m] and gravity [m/s^2]. The reaction forces needed to balance the ride is simply the sum of pavement cross slope (E [%]) and the demanded side friction factor f_{sd}, see equation 1. In order to provide acceptable stability margin for the ride, the demanded side friction must not exceed the supply side friction factor f_{ss}. The supply side friction factor f_{ss} used in Sweden is given by equation 2. For 90 km/h (25 m/s) roads, f_{ss} equals 0.118. Equation 2 does not provide conservative, “safe” values in a winter perspective, since slippery thin “black ice” may give $f_s < 0.05$ when traversed with un-studded winter tires. The lack of margin is remarkable, since more than 1 out of 2 fatal winter skid accidents in Sweden occur on ”thin ice”. See Granlund (2008) for details.

$$\frac{v^2}{R * g} \approx E + f_{sd} \tag{1}$$

$$f_{ss} = 0.28 * e^{-0.0346 * v} \tag{2}$$

For the road section of interest, the demand f_{sd} is simply calculated by inserting reference speed and data on curvature and cross slope (in 1 m steps) in equation 1. Then f_{sd} is compared to the supply f_{ss} given by inserting reference speed in equation 2. See example in Figure 2.

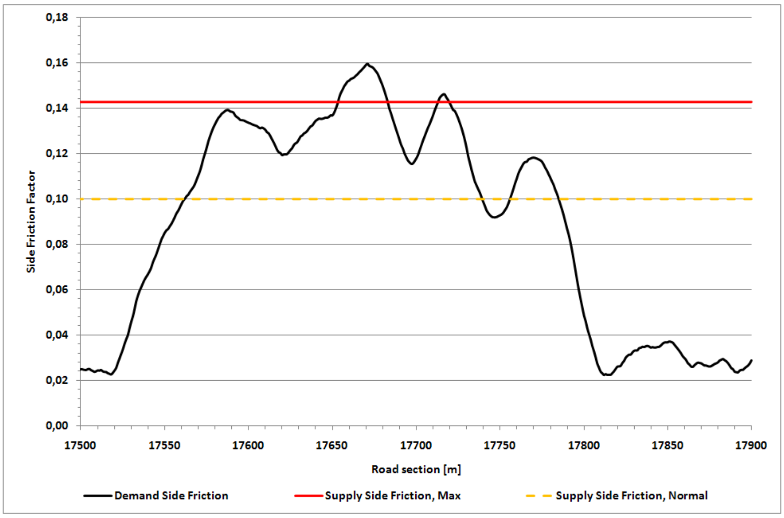

Figure 2 Excessive Friction Demand in a Sharp and Flat 70 km/h Crash Curve

Experiences in Sweden show that road sections where the demand side friction factor f_{sd} exceeds the supply side friction factor f_{ss} typically have a very high crash rate. Key factors for crash prevention at these sites are speed reduction, intensified friction maintenance, increased cross slope/banking and reduced curvature.

2.2 Raise the Drainage Gradient above 0.5 % at Outer Curve Transitions

The Drainage Gradient (DG) is the resultant of Cross Slope and Longitudinal Gradient. If the DG is too low, below 0.5 %, the road surface provides unacceptably low skid resistance. Both Cross Slope and Longitudinal Grade are measured with Profilometers as the one seen in Figure 1. Using Profilograph data from Rd 331, the Roadex III project demonstrated that most outer curves were poorly designed as they had insufficient DG. Later investigations on several other roads, including accident hot spots on brand new express roads, showed that insufficient DG at entrances and exits of banked outer curves is often built in already in the road design.

Transitions into and out of banked outer curves are less than 1 % of normal road length. Despite their small share of road length, experiences in Sweden show that a large share of all rural crashes take place in these sections. Key factor for crash prevention at these sites is to avoid poor drainage in sections where lateral forces may be significant. This can be done by redesigning the pavement geometry, so the cross slope transition is moved from the curve to a straight section where lateral forces are low. If possible, the transition should be made in an (artificially created, if needed) up- or downgrade. In some cases, permeable asphalt can be used in the curve transitions.

2.3 Ride Vibration and Shock: Keep Road Roughness IRI_{20m} below 3 mm/m

A study of 78 631 crashes showed that when road roughness level increase, also the crash rate increase (Ihs et al, 2002). A general relationship between crash rate and International Roughness Index (IRI) for roads with AADT 1000 – 4000 vehicles/day is given by equation 3. The equation shows that if the road is rough (IRI 3 mm/m), the crash rate is expected to be 20 % higher than if the road had been smooth (IRI 1 mm/m). The study also showed that high variance in roughness (local road damage) is accompanied by further increased crash rate.

$$\text{Crash rate per 100 million axle pair km} = 22.7 + 2.54 * IRI_{20m}\ [\text{mm/m}] \qquad (3)$$

Truck drivers' exposure to ride vibration was related to the International Roughness Index by Ahlin et al (2000). For a heavy truck with trailer driving at 75 km/h, equation 4 gives a relationship between seat vibration and IRI.

$$RMS(a_{x,y,z}) = 0.18 + 0.30 * IRI_{100m} \qquad (4)$$

The EU Action Value A(8) is set to 0.5 m/s^2. Assuming that 100 min/day consists of loading, unloading and pauses with zero ride vibration, the remaining 380 min of the 8 hour working day is allowed to have an intensity of 0.56 m/s^2. In order to keep the driving time exposure below this value, equation 4 shows that average road network roughness should be below IRI = (0.56 – 0.18) / 0.30 = 1.27 mm/m. This is a low road roughness level for road networks; in many rural areas not realistic to achieve without significantly raised road funding.

Experiences in Sweden show significant reduction in ride vibration and shock by eliminating bumps and other local road damage causing IRI_{20m} higher than 3 mm/m, as well as steps at road/bridge joints and potholes causing Megatexture over 0.60 mm.

2.4 Limit Truck Roll and Lateral Vibration by Keeping RBCSV below 0.30 %

The Roadex III study reported by Granlund (2008) validated a new pavement condition parameter called "Rut Bottom Cross Slope Variance" (RBCSV), by correlation with truck roll vibration as well as with truck lateral vibration. A limit value of 0.30 % was drafted for RBCSV, based on values recorded at hazardous sites / accident hot spots, on truck driver's subjective opinion as well as on statistical analysis of data from road sections in various conditions.

RBCSV is based on road profile data, laser scanned at 16 kHz in the bottom of the truck wheel paths (left and right), inertial compensated for the Profilometer vehicle roll angle versus the horizon, and eventually reported in steps no longer than 1 m.

Since Nordic HGV's typically has a track width of about 2.0 m, the height sensors recording Rut Bottom Cross Slope (RBCS) should be spaced 2.0 m. Preferably, the elevation in each wheel path is estimated by readings from several (three or more) height sensors, rather than by readings from a single sensor in the Profilograph rut bar. From the data recovered, the RBCS is calculated as described below.

The calculation is made with a crucial filtering procedure to remove very long wave slope variance, relating to superelevation change at outer curve transitions. 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 roll vibration eigenfrequencies of heavy truck suspended masses.

The long wave variance is removed from the RBCS with the following "running averaging" procedure:

1. For each road section, very long wave variance in RBCS is calculated centred over the base length relevant for the current reference speed limit, see Table 1. This is made by taking the average over as many values ”before” as ”after” the current section. Since this step is made for each section, the procedure may be called "moving averaging".
2. The derived series of "the surroundings very long wave variance" is now subtracted from the origin RBCS series.
3. The resulting series of data has an average value of 0 % (zero) and reflects only sudden variance (within 1 to 31 m) in RBCS. This series does not longer give information about the RBCS magnitude, but from this series it is now possible to calculate RBCS variance in terms of running Root-Mean-Square.

Table 1 Base length for moving averaging

Reference speed		Base length
[km/h]	[m/s]	[m]
30	8.3	9
50	13.9	13
70	19.4	19
90	25	25
110	30.5	31

The RBCS of a 400 m long road section is showed with a red dotted graph in Figure 3; data is given in step of 1 m. Since the section has 70 km/h reference speed, the base length is 19 m (see Table 1). The long wave cross slope variance, which may be a fruit of smooth curve transitions, is showed with a purple graph.

The difference between the two graphs in Figure 3 constitutes the undesired Cross Slope variance, and is showed with a blue graph in Figure 4.

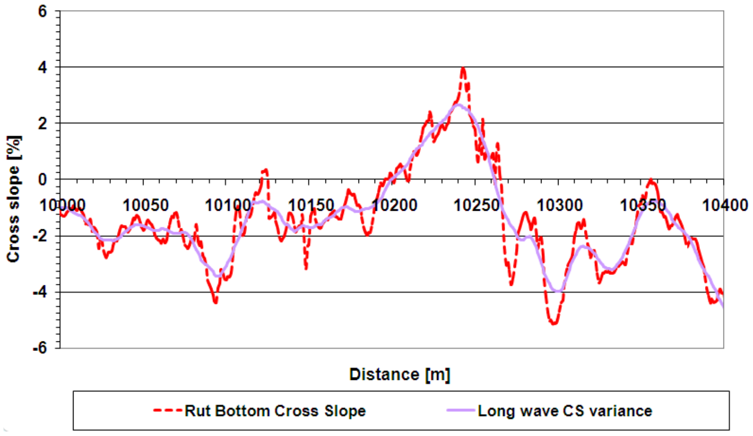

Figure 3 RBCS and its “very long wave” variance

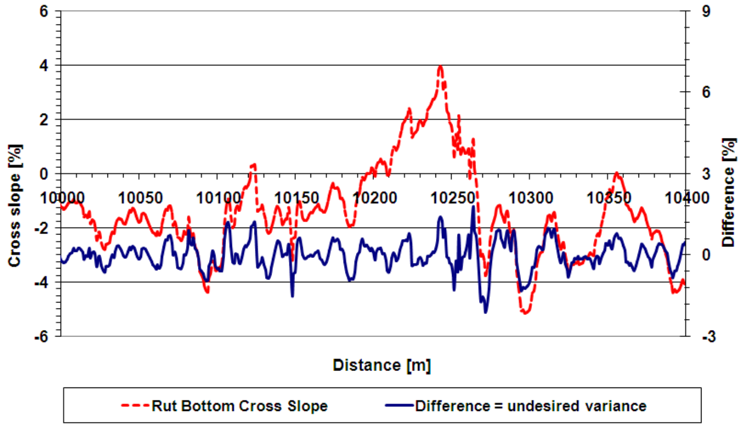

Figure 4 RBCS and its undesired variance

In the next step, running Root-Mean-Squares of undesired variances are calculated in two parallel runs. One run calculates the RMS variance over 5 m “short sections”, addressing truck wheel axle roll vibration. The other run calculates the RMS variance over 20 m “long sections”, addressing chassis/cab roll excitation. See Figure 5.

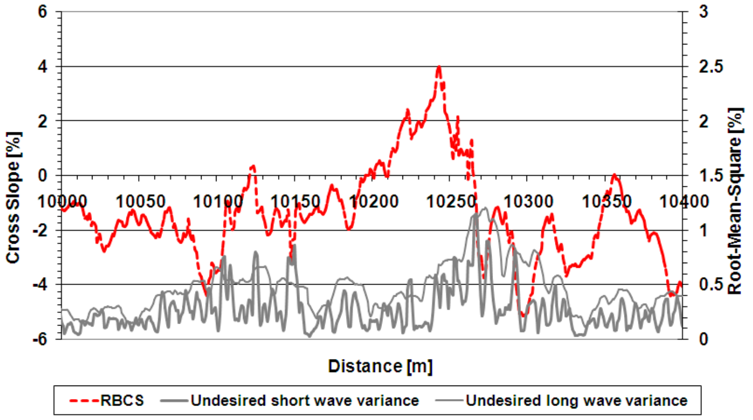

Figure 5 RMS of short wave and long wave RBCS variance

In the final step, the maximum of the two variances in Figure 5 is reported as the undesired Variance of Rut Bottom Cross Slope (RBCSV). While the long wave RMS is generally decisive, the short wave RMS is highest in some sections with local extreme pavement edge damage.

In the Roadex III project, the roll angle of a Scania R144G truck cab was measured with an Oxford Technical Solutions RT 3050 GPS/inertial unit. The variance of truck cab roll angle is compared with the variance of the RBCS (RBCSV) in Figure 6. The graphs show a good overall fit. However, there is a large local shift in magnitude between the graphs at section 125/275 km. This discrepancy was caused as the truck driver decided to leave the wheel track at the edge damage in section 125/275 km seen in Figure 7 (photo and Profilograph scan). The laser scan showed that the edge deformation was 69 mm deep. Despite the fact that the truck was driven around the worst part of the 69 mm deep edge deformation, truck cab lateral acceleration peaked at 2 m/s^2. A seat pad under the truck drivers' bottom peaked at 3.5 m/s^2 lateral acceleration on the straight road section. Obviously the experienced truck driver's decision to avoid the edge deformation by leaving the wheel paths was correct; otherwise a crash may have occurred during the test.

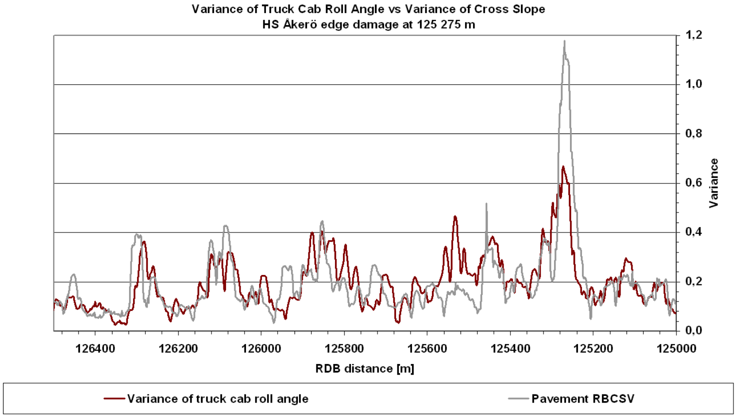

Figure 6 Pavement RBCSV versus Variance of Truck Cab Roll Angle

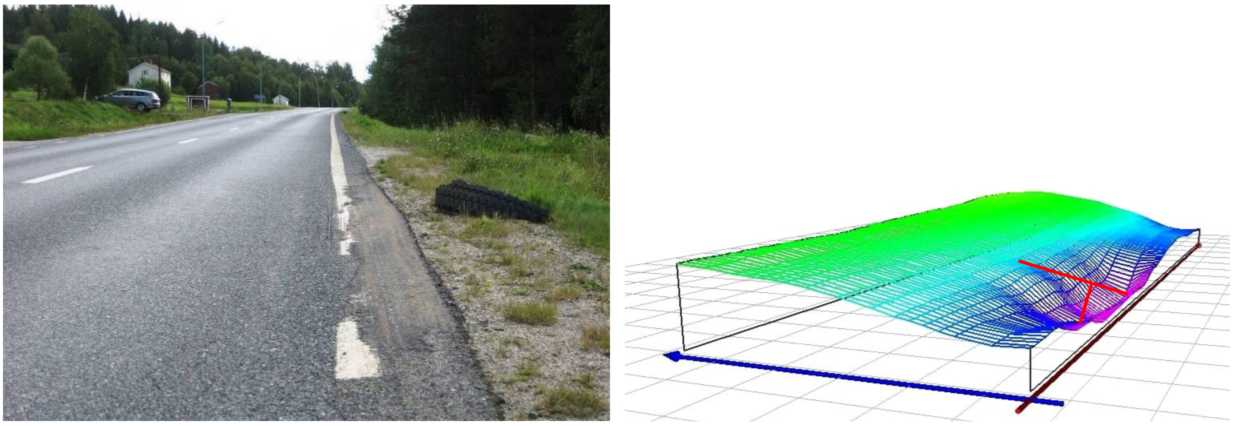

Figure 7 Pavement edge deformation at 125/275 km

As showed in the Roadex III project, RBCSV is strongly correlated to both roll and lateral vibration in heavy vehicles. Furtermore, it has been showed that road sections with RBCSV exceeding 0.30 % are overrepresented "hot spots" in the crash records.

2.5 Avoid Low or Split Friction by Keeping Macro texture above 0.6 mm in Both Ruts

When driving in rain, too low pavement texture depth can be as hazardous as having slick worn tires. The minimum level of "safe" Macro-texture (MaTx) varies somewhat with surface type and texture measurement method. For MaTx-data from the Profilograph in Figure 1, a benchmark value is MPD 0.6 mm.

Poor patch repair often create large variance between wheel paths, in terms of colour and MaTx. The outcome may include hazardous Split Friction when braking hard in wet (freeze/thaw) road condition. The result may be jack-knifing or trailer swing.

There were 5 crashes in a curve on Swedish HW 61 within 2 weeks after the edge patch repair seen in Figure 8. Profilograph data showed good MaTx, MPD 1.0 – 1.3 mm, on the intact asphalt. However, the patch had less than MPD 0.3 mm. The patch did not only give too low wet friction, but also Split Friction compared to the other wheel path.

Photo: Bengt Andersson and Mats Ekehov

Figure 8 Hw 61: After Edge Repair, the Curve had 5 Crashes in 2 Weeks

3. Conclusion

The health and safety risks are unacceptably high on poorly maintained rural roads. Key factors for risk reduction are road roughness, lateral force, drainage and road grip. Parameters that affect the key factors include pavement (edge) bearing capacity, speed, curvature, cross slope, gradient and texture. This paper presents a handful of analysis methods that can be used to identify risk sections, where actions should be taken.

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