DETERMINATION OF CORRELATION BETWEEN ROAD PAVEMENT SKID RESISTANCE AND BRAKING DECELERATION

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ABSTRACT

There are many situations when road pavement surface skid resistance drops to unacceptable levels. Skid resistance is an essential pavement property for road safety, but drivers are not able to assess its degree by visual means, although in the end they must be able to stop their vehicles safely within the stopping sight distance.

In our research normalized braking deceleration was related to SCRIMTEX SFC values and analyzed for different driving conditions (wet/dry), vehicle systems, skid resistance levels, measuring speeds and nominal initial vehicle speeds when full braking. A relation can be used to calculate the stopping sight distance and maximum safe speed in different road conditions. In the case of below-average vehicle systems, relations of this kind can be used to determine, within some degree of uncertainty, the limit SFC values at which some traffic operations and management activities should be performed (e.g. speed limits can be reviewed and new traffic signs erected to support road users in safer driving). Applying such limit values to the national regulations means that they can be directly interpreted from the traffic safety perspective.

1. INTRODUCTION

Traffic safety is frequently assessed, mainly statistically, by the number and type of road accidents on a certain road section. Although road accidents can be caused by the poor condition of the road pavement surface and/or road geometry, there are just a few direct indicators showing this, so that the reasons for accidents are rather sought among low driver attention while driving and/or high driving speed.

The appropriate geometrical road elements and an ever-changing environment including pavement condition, the momentary interaction between the vehicle's tyre and the pavement surface, obstacles on the road, and the weather, form perhaps the biggest trap in such thinking. The road accident statistics in Slovenia presently include meteorological data from the road section, but not the actual skid resistance data, which depend on the surface layer's characteristics and age, as well as on the quality of the chosen materials, if we look at it only from the pavement's perspective.

The skidding resistance of national roads in Slovenia is monitored at regular intervals, i.e. 4 years. The national roads are managed by the Slovenian Roads Agency (SRA), which also finances monitoring and assesses the results.

The results are primarily used for SRA's internal purposes, such as gathering data for assessments of the network's condition, prioritization of road sections for maintenance and planning maintenance works. These assessments themselves are based on the SRA's internal criteria or criteria defined in the so-called Technical Specifications for Roads [1]. Nevertheless, whatever the primary intention of monitoring is, the results are available to anyone who may be interested in them, and requests them. Unfortunately, in many cases the results are not used and interpreted by experts, so that wrong conclusions may be drawn.

The main misunderstanding probably originates in the structure of the criteria: the latter consist of threshold values for condition states – from very poor to very good. A set of criteria exists depending on the device speed, when measuring skid resistance on roads. Then, when the skid resistance level of a road section falls into the poor or very poor condition, some people interpret the results as meaning that driving at the same speed on that particular road section is dangerous.

Nevertheless, maintaining skid resistance at sufficiently high levels is a difficult and time-consuming task and in real life there are many road sections where drivers need to be warned about low skid resistance until appropriate maintenance measures are taken.

The condition of the Slovenian national roads network (excluding the motorways and expressways that are managed by the Motorway Company in the Republic of Slovenia – DARS) is, however, not satisfactory. About 30% of the network is in poor condition and the SRA is trying, within its budgetary limits, to improve it. One of the actions taken, that belong to research activities, has been the funding of research work with the main aim of defining appropriate skid resistance levels to satisfy drivers' needs for safe vehicle stopping in different adverse driving conditions. The results of the research work are partially presented in this paper.

2. OUTLINE OF THE RESEARCH

As already mentioned, the skidding resistance of national roads is monitored at regular intervals, by means of a SCRIM device (Sideway-force Coefficient Routine Investigation Machine). When this new device was bought and imported to Slovenia, it was introduced into the pavement management system, and the first assessment criteria were prepared. Because of a lack of experience with the device, these criteria were based on experience and criteria from other countries.

Over time the need for relating skid resistance data to safe vehicle stopping and the stopping sight distance became evident. Especially if we know that stopping distance in relation to braking deceleration forms the basic input data for road accident analyses.

The present method according to which skid resistance data are analyzed in Slovenia is unsatisfactory for this purpose. As a result research work was begun with the main focus on finding a correlation between these two important road safety parameters:
- The skid resistance based on the sideway force coefficient (SFC), measured by a SCRIMTEX device,

- Pavement/tyre friction, achievable decelerations and stopping distances by means of braking tests with passenger cars on roads in different driving conditions (i.e. the "vehicle system"): wet/dry road surface, summer/winter new/worn tyres, breaking system (ABS/no ABS), on road sections with a variety of skid resistance levels.

The chosen approach for work was based on the PIARC limit value of friction coefficient which is used for defining the limit values of geometrical elements for designing roads. According to these limits it could be said that the driving conditions on a road are safe when vehicles' driving speed remains below the design speed for that road. In reality drivers adapt their speed to their own skills and judgement, causing many changes in acceleration and deceleration.

3. THEORETICAL CONSIDERATIONS

3.1. Friction coefficient

In the Slovenian road design technical regulations [2] the design (tangential) friction coefficient between the tyre and the pavement surface is calculated by the following equation:

$$f_{T\_dop} = \mu_g = 0,2 \cdot \left(\frac{v}{100}\right)^2 - 0,629 \cdot \left(\frac{v}{100}\right) + 0,637$$

where:
f_{T_dop} and μ_g are both the design friction coefficient, and
v is the driving speed.

The above equation is used for calculating the stopping distance. Further:

$$L_z = L_1 + L_2$$

where:
L_z is the total stopping distance [m],
L_1 is the distance travelled during the total reaction time (both driver and vehicle) [m],
L_2 is the stopping distance while braking [m].

Within the research we were focused on L_2, which is calculated from the equation:

$$L_2 = \frac{1}{3,6^2 \cdot g} \cdot \int_{V_1}^{V_2} \frac{v}{f_{T\_dop}(v) + \frac{i}{100} + u(v)} dv$$

where:
g is the gravitational acceleration [m/s^2],
f_{T_dop} is the friction coefficient [-],
i is the slope of road [%],
u is the air drag [-],
V_1 is the end speed (0 at stopping) [km/h], and
V_2 is the initial speed when braking.

Design regulations define the road geometry elements which demand minimal friction coefficient for safe driving manoeuvres. On the other hand, the role of the road surface is to supply at least that minimal friction coefficient.

3.2. Braking deceleration

The actual stopping distance on road sections was measured by means of full braking measurements. For further analyses the mean fully developed deceleration (MFDD) was chosen since it was thought to be the most appropriate parameter to be correlated to the skid resistance measured by the SCRIM device. MFDD is calculated from the following equation:

$$a_{MFDD} = \left| \frac{v_{10}^2 - v_{80}^2}{2 \cdot (s_{10} - s_{80})} \right|$$

where:
a_{MFDD} is the mean fully developed deceleration [m/s^2],
v_{10} is 10% of the initial speed at the start of breaking [m/s],
v_{80} is 80% of the initial speed [m/s],
s_{10} is the distance travelled at v_{10} [m], and
s_{80} is the distance travelled at v_{80} [m].

The stopping distance L$_2$ that we are focused on is now calculated from the expression:

$$L_2 = \frac{v^2}{2 \cdot \left(a_{MFDD} + \frac{i}{100} \cdot g \right)}$$

where:
a_{MFDD} is the mean fully developed deceleration [m/s^2],
i is the slope of road [%],
g is the gravitational acceleration [m/s^2], and
L_2 is the stopping distance while braking [m].

4. MEASUREMENT METHODS

4.1. Skid resistance

In principle, on SCRIM (Side-way force Coefficient Routine Investigating Machine) a freely rotating wheel is fixed at an angle of 20° to the d irection of travel of the vehicle, and in line with the nearside wheel track. A smooth rubber tyre is fitted to the wheel and, when performing measurements, the wheel is applied to the road surface under a known vertical load.

The road surface immediately in front of the test wheel is wetted by a controlled flow of water, to simulate wet condition of the road, which to a very large degree raises the risk for skidding accidents. The measured sideway force generated by the resistance to sliding is related to the wet road skid resistance of the surface. The ratio of this sideway-force to the vertical load on the wheel is the sideway-force coefficient (SFC), which is recorded by the measuring device.

SCRIM's test wheel assembly is free to move when test wheel is down on the road surface. The assembly includes a back plate, a swinging arm on which the test wheel is mounted, and a single damper/spring suspension unit. This shock absorber is, at one end, connected to the swinging arm fork, and at the other end to the back plate.

The Slovenian SCRIM is shown in the following figure.

Figure 1 – The Slovenian SCRIM during measurements

4.2. Braking deceleration

The assembly for measuring braking deceleration was mounted on two test cars of different categories: on a family minivan and on a compact car. Within the research boundaries, these reflect two typical personal car categories on Slovenian roads.

While measuring, two Vericom performance computers (VC 2000 PC and VC 4000 DAQ) were used to measure the vehicle's performance with the help of accelerometers (uniaxial in VC 2000 and 3-axial in VC 4000) and a brake pedal force sensor. The distance travelled was measured by a Corrsys Datron S-400 contactless distance and velocity sensor. In some tests a high-speed video was recorded as well in order to be able to analyse the behaviour of the vehicle wheels during braking.

Figure 2 – High speed cameras on a minivan

Altogether 4 types of tyres were fitted to the test cars during measurements: used and new winter tyres, and used and new summer tyres. Respectively, they can be seen in Figure 3.

Figure 3 – Test tyres

4.3. Road sections

Test fields were selected mainly on some road sections, managed by SRA. Initially a set of test fields was defined, where measurements would ideally be performed on pavement surfaces:
- on 5 most used asphalt pavement types (AC 11 surf B 50/70 A2, AC 11 surf B 50/70 A3, AC 8 surf B 50/70 A3, AC 8 surf B 70/100 A4, SD 4/8),
- in 3 condition categories regarding surface distress (good, fair and poor; defined by means of so called MSI index, which is used for assessing the surface distress condition in Slovenia), and
- in 3 condition categories regarding skid resistance (good, fair and poor).

Both skid resistance and surface distress are monitored and assessed regularly on the national roads network, so the most recent databases formed the basis for the selection of the test fields.

In the next step new skid resistance measurements were performed on selected road sections, with straight stretches of appropriate length. This step was necessary since skid resistance measurements are planned in such way that the whole network is covered within 4 years – meaning that data for some very good road section candidates were already obsolete.

Satisfying the above research boundaries turned out to be almost impossible, especially when taking into account the safety precautions which were necessary for performing braking deceleration measurements.

Nevertheless, finally 15 test fields, about 100 m long, were chosen, where both skid resistance and braking deceleration measurements were repeated within 2 to 3 consecutive days. In this way it was ensured that the skid resistance level on the test fields didn't change for practical purposes. Moreover, the selection wasn't done by chance, but rather with some normal distribution of skid resistance levels in mind.

It has to be noted that the braking deceleration measurements were performed on both dry and wet pavement surfaces. Watering was arranged using a fire-fighting tank vehicle with an appropriate hose and nozzle.

5. RESULTS

Two different measurements were performed on the same test fields, practically in parallel, at different measuring speeds. For the skid resistance measurements these were 50 km/h, 60 km/h and 80 km/h, whereas breaking deceleration was measured at initial speeds of 60 km/h and 80 km/h.

Statistically the sample, as it is at the moment, is not large enough to define correlations for specific tyre or specific pavement surfaces. Correlation can therefore be defined only for a specific vehicle system (without an anti-lock breaking system being activated) and on a wet road pavement surface.

The relation between braking deceleration and skid resistance is shown in the following figures. They present the results for 3 different skid resistance measuring speeds, each one related to 2 initial breaking deceleration speeds.
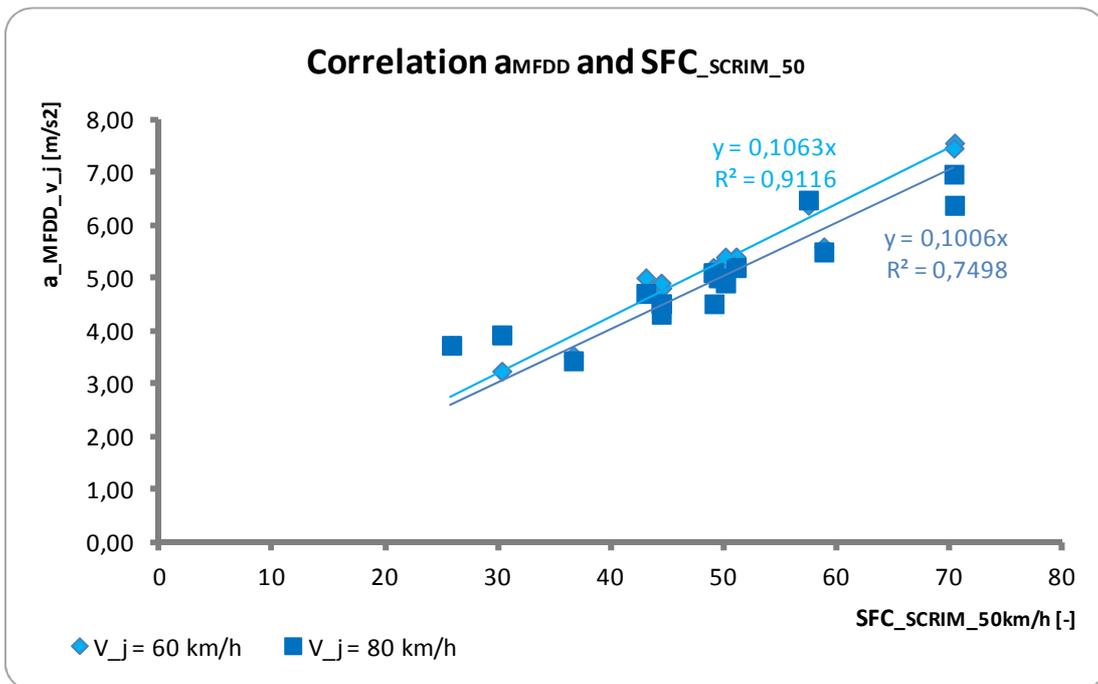

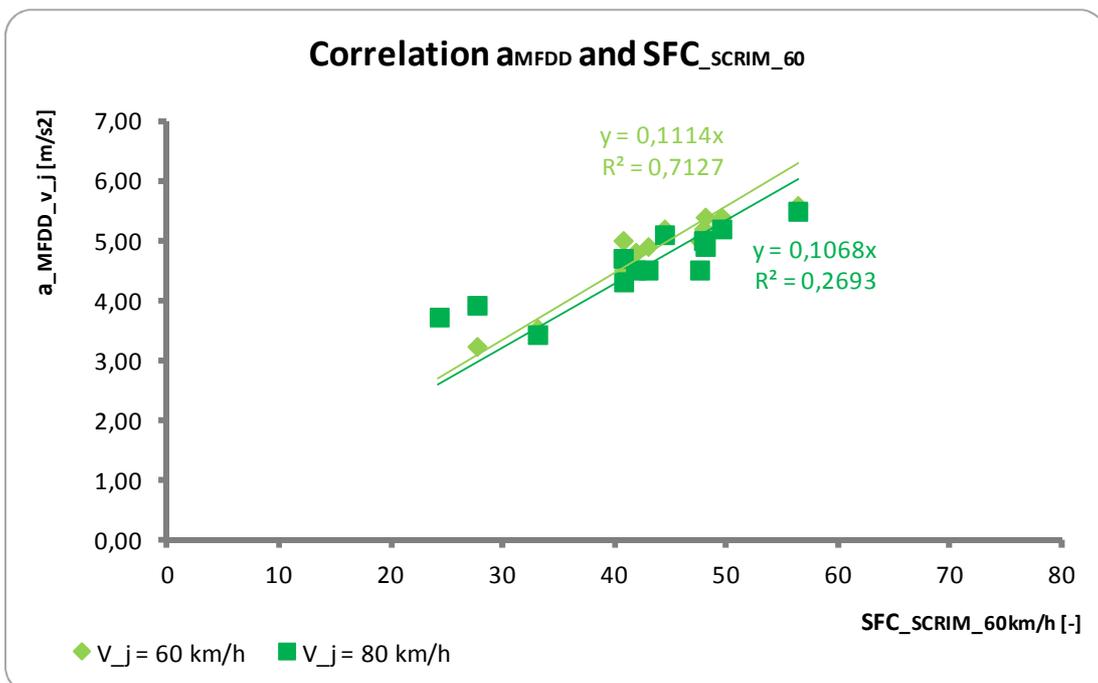Figure 5 – Correlation for skid resistance at a measuring speed of 50 km/h

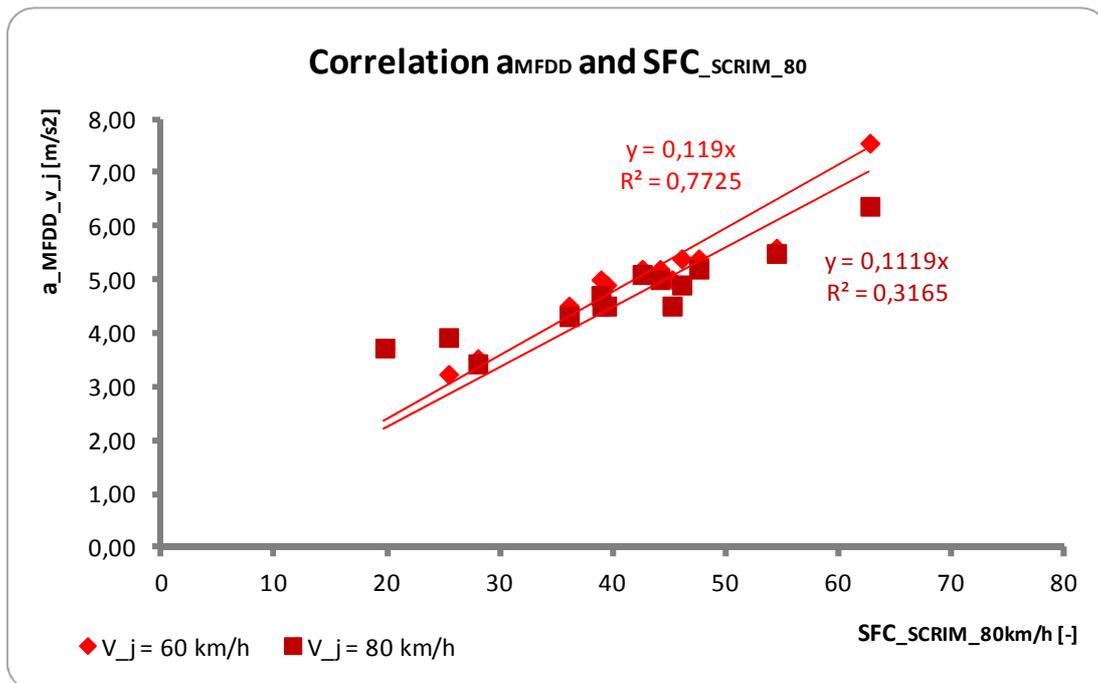Figure 6 – Correlation for skid resistance at a measuring speed of 60 km/h

Figure 7 – Correlation for skid resistance at a measuring speed of 80 km/h

A comparison of the results indicates a linear dependence with braking deceleration shown as a fraction of negative gravitational acceleration.

But is this a real correlation? Normally, a regression model would be needed and in this specific case it seems logical to use a linear regression model with the MFDD being the dependent variable and the SFC being the independent one. This is because the aim of the work has been to define the braking deceleration on pavement surfaces with known skid resistance levels.

An indicator of (good) correlation between the variables is shown with the coefficient of determination (the statistical R-squared value). Figure 5 shows high R-squared values at a skid resistance measuring speed of 50 km/h, explaining most of the variance of the MFDD, measured at both 60 km/h and 80 km/h. A similar conclusion can be drawn for the other 2 skid resistance measurement speeds, but only for the initial braking deceleration speed of 60 km/h.

Good correlation at a skid resistance measuring speed of 50 km/h is actually – good, since monitoring of this pavement characteristic on national roads is performed at this speed. Nevertheless, the linear regression model doesn't show good correlation in some cases, but the correlations have been used for further assessment and calculation of stopping distances at different driving speeds.

The mean fully developed deceleration is based on the determined correlations, and finally calculated from the following equation:

$a_{MFDD} = \beta_{xy}\ SFC_{SCRIM}$

where:
a_{MFDD} is the mean fully developed deceleration [m/s^2],
SFC_{SCRIM} is the level of skid resistance based on the sideway force coefficient measured by the SCRIM device

β_{xy} is a coefficient depending on the SFC and MFDD measuring speeds and it can be read from the slopes of lines in Figures 5 to 7

The above relationship and the equation for calculating stopping distances while braking have been used to prepare several diagrams where stopping distance is related to skid resistance, and depends on the driving speed of a vehicle.

The diagrams have been supplemented with minimal stopping distance values that satisfy road design regulation requirements in terms of vehicle safe stopping. From minimal stopping distance values and with the use of the relationship determined within the research work, minimum skid resistance levels were calculated. Minimum values for different vehicle driving speeds in practice define the ultimate limit state for the safe manoeuvring of vehicles on the road.

Furthermore, partial factors were introduced and new stopping distances calculated when preparing a proposal for characteristic skid resistance threshold values. These partial factors are, in principle, applied to the mean fully developed deceleration, but using the relationship they in fact affect also the level of skid resistance. A factor of 1,0 is appropriate for the minimum MFDD which corresponds to a specific skid resistance level. To increase safety or to define a warning level or investigatory level, some partial factor needs to be defined. A factor lower than 1,0 means that we intentionally set as appropriate longer stopping distances than actually result from the design regulation requirements. Or, to the same aim and when the relationship is used, the skid resistance level is intentionally raised. For example, a partial factor of 0,85 raises the minimum skid resistance value calculated for a road section limit speed of 90 km/h (and for a skid resistance measuring speed of 50 km/h) from a value of 35 to 40.

6. CONCLUSIONS

The skid resistance of Slovenian national roads is monitored at regular intervals. The results are primarily used for assessment of the network's condition, for the prioritization of road sections for maintenance, and for the planning of maintenance works. The assessment itself is based mainly on criteria that were prepared at the time when the skid resistance measuring device was acquired.

Over time the need for relating skid resistance data to safe vehicle stopping and the stopping sight distance became evident. The current method according to which skid resistance data are analyzed in Slovenia is unsatisfactory for this purpose, which finally led to research work with the main focus on finding a correlation between two important road safety parameters. The first parameter is the skid resistance of the pavement surface based on the sideway force coefficient, measured by the SCRIM device. The other parameter is concerned with achievable decelerations and stopping distances by means of full braking tests in different driving conditions (wetness of the road surface, tyres, braking system, skid resistance levels).

Within the scope of the research work two different measurements were performed on the same test fields, practically in parallel, at different measuring speeds. The main hypothesis was that if the skid resistance of a pavement surface is below a certain limit then the achievable braking deceleration is insufficient for safe vehicle stopping within the required stopping distance.

Correlations have been defined for a specific vehicle system (without its anti-lock braking system being activated) on a wet road pavement surface. These correlations have been used to determine the relationship between braking deceleration (in terms of the mean fully developed deceleration) and the skid resistance levels of pavement surfaces. For the first time in Slovenia, and within its particularities (climate, road pavement related – asphalt mixes, materials used etc.), stopping distance has been related to skid resistance, and depends on the driving speed of the vehicle.

From the minimum stopping distance values that satisfy road design regulation requirements in terms of vehicle safe stopping, and with the use of relationship determined within the research work, minimum requested skid resistance levels have been calculated. Minimum values for different vehicle driving speeds in practice define the ultimate limit state for the safe manoeuvring of vehicles on roads.

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