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Influence of the Shear Forces on the Roundabout Carriageway

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Abstract— *The circular roadways at roundabouts are exposed to special traffic loads due to cornering, namely friction and shear forces, and in smaller roundabouts (mini roundabouts), torsional stresses (turning of tires on the spot). Especially due to the high proportion of heavy traffic, damage to the asphalt pavement is often found, such as cracks, unevenness (indentations, ruts), etc. While driving through the roundabout, the thrust and friction forces act on the asphalt pavement of the roundabout through the contact between the vehicle tires and the roundabout pavement*.

Keywords— *Shear forces, torsional stress, roundabout, asphalt, bitumen, carriageway.*

I. Introduction

The circular carriageway shall be inclined outwards with a cross gradient of 2.5 %. The longitudinal slope should not exceed 5 % according to (RVS 03.05.14, 2010) [1] or 6 % according to (RASt 06) [2] at any point. Checking the drainage with the help of elevation plans has proven to be an aid to the design.

II. Driving Dynamics and Driving Geometry When Driving in the Roundabout

Correctly, for reasons of driving dynamics, the transverse gradient in a road bend is always inclined inwards so that the vehicle does not fly out of the bend in the tangential direction (tangential path) at a certain speed due to the effect of centrifugal force (from Latin "*centrum*" = centre and "*fugere*" = to flee, hence also called "*flee force*") (Figure 1). For drainage reasons, however, the opposite is the case for the roundabout, because the transverse gradient of the circular roadway is designed to be inclined outwards, in order to avoid complicated drainage systems for the internal gradient around the circular island and to make drainage easier (Figure 2) [3].

Fig. 1. Racing cars driving through an inwardly inclined curve [3]

Fig. 2. Bending in the circular roadway [4]

The driving dynamics and driving geometry when driving in an arc are shown in Figure 3 by means of a disc model and this is applied analogously to the circular roadway of a roundabout. The rigid disc model represents a strong two-dimensional simplification of the real three-dimensional vehicle. According to this disc model for spinning in the curve (lateral drift), the following formulas apply [3]:

$$F \cdot \cos\alpha - G \cdot \sin\alpha - \mu_2 (G \cdot \cos\alpha + F \cdot \sin\alpha) = 0 \quad [1]$$

$$(m \cdot v^2/R)\cos\alpha - m \cdot g \cdot \sin\alpha - \mu_2(m \cdot g \cdot \cos\alpha + (m \cdot v^2/R) \cdot \sin\alpha) = 0 \quad [2]$$

With: $\sin\alpha \sim \tan\alpha \sim q$ and $\cos\alpha \sim 1$ for cross slope $<< q$

$$m \cdot v^2 / R - m \cdot g \cdot q - \mu_2 \cdot m \cdot g + \mu_2 \cdot q \cdot m \cdot v^2 / R = 0 \quad [3]$$

According to v, q

$$v_{zul} = \sqrt{\frac{R * g(\mu_2 + q)}{1 - \mu_2 * q}} \quad [4]$$

$$\mu_{2erf} = \frac{v^2 - g * q * R}{g * R + q * v^2} \quad [5]$$

$$R_{erf} = \frac{v^2(1 + \mu_{2*}q)}{g * (q + \mu_2)} \quad [6]$$

Mean in it:
F - Centrifugal force [KN]
G - Vehicle weight [KN]
m - Vehicle mass [kg]
μ - Skid resistance value (friction value) of the road surface [-]
α - Angle of inclination of the carriageway [°]
g - Acceleration due to gravity [m/s^2]
q - Transverse gradient of the carriageway [%]
R - Curve radius [m]
v_{zul} - Permissible speed of the vehicle when cornering [m/s]
b - Vehicle width [m]

h - Vehicle height [m]

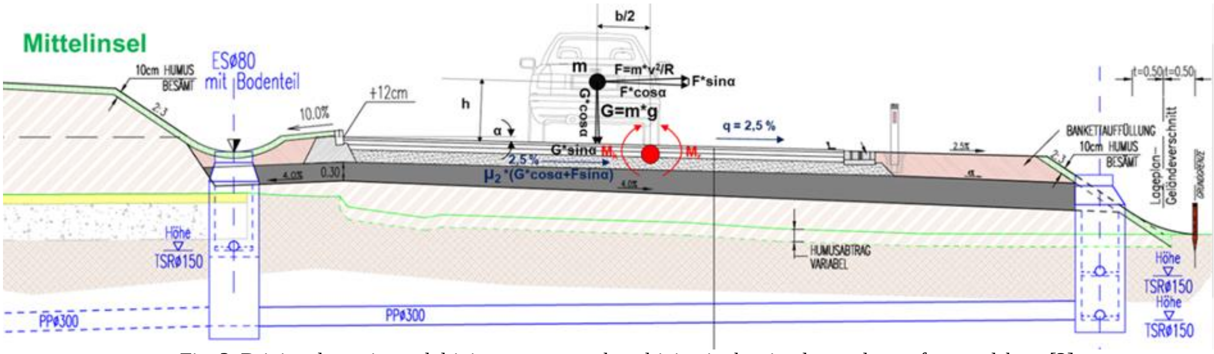

Fig. 3. Driving dynamics and driving geometry when driving in the circular roadway of a roundabout [3]

III. Wheel Contact Point

When driving in a curve at optimum speed, the centrifugal force is parallel with the slope of the road. During cornering (Figure 2) in the roundabout pavement of a roundabout, due to the contact of the vehicle tires with the road surface, various forces and moments act between the tires and the roundabout pavement (friction and thrust forces). These forces and moments are defined by means of a coordinate system in the ISO 8855 standard in the *W* system (Figure 4). A distinction is made between vertical forces F_Z, longitudinal forces (circumferential Forces - forces in circumferential direction) F_X, lateral forces (lateral forces) F_Y, and Moments M_X, M_Y, M_Z around the respective axes [3, 5].

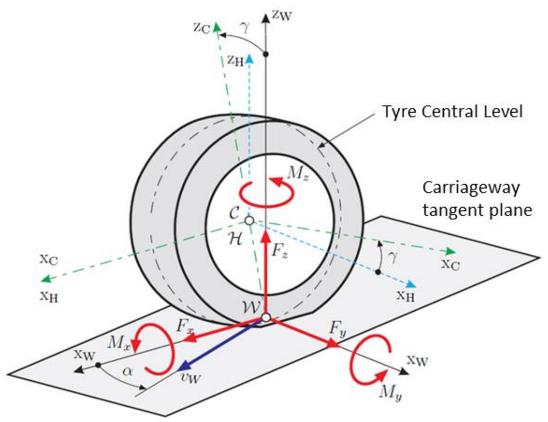

Fig. 4. Wheel axle systems, forces and moments in the wheel contact point [3, 5]

IV. The forces acting on the circular roadway: centrifugal and centripetal force

These lateral forces F_Y are particularly important for driving in a roundabout pavement, which are insignificant for driving dynamics during straight driving. These lateral forces stress the road surface by transverse thrust and are also called the shear forces. To simplify this problem, only the forces acting in the X-Y plane are considered and the moments are neglected: centrifugal force F_{Zf} (opposite direction of curve centre) and centripetal force F_{Zp} (direction of curve centre) (Figure 5).

According to the old master of road construction Dr.-Ing. E. H. Lorenz [6], during cornering, the radially directed centrifugal force *F* does not exist. The vehicle is forced to move in a curve in the road curve due to the lateral inclination and the steering wheel. As soon as these influences on the vehicle cease to have an effect, the vehicle continues to move in the direction of inertia, but not in the radial direction, as is often incorrectly claimed in the literature, but in the tangential direction (tangential path) [3, 6] (Figure 5).

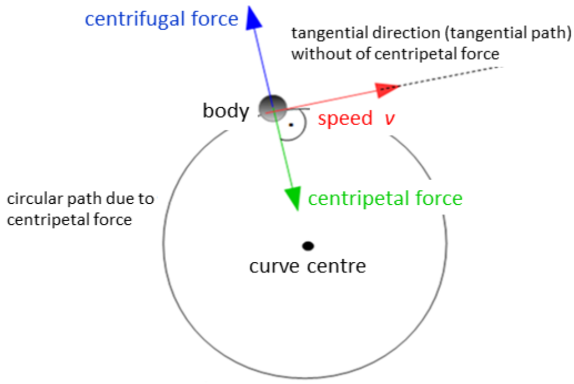

Fig. 5. The forces acting on the circular roadway: centrifugal force (blue) and centripetal force (green) [3, 7]

If, for example, a stone is thrown on a string around a circle, we need a force to hold this stone and thus force it into a circular path. When the string is released from the hand, the stone flies away, but not radially but tangentially. This is shown very vividly in the example of a hammer thrower (Figure6).


Fig. 6. Hammer thrower throws the ball in the tangential direction [3, 8]

Out of formula [2]:

$F \cdot \cos\alpha - G \cdot \sin\alpha - \mu_2 (G \cdot \cos\alpha + F \cdot \sin\alpha) = 0$

follows:

$F \cdot \cos\alpha - \mu_2 \cdot F \cdot \sin\alpha = G \cdot \sin\alpha + \mu_2 \cdot G \cdot \cos\alpha$

$F (\cos\alpha - \mu_2 \cdot \sin\alpha) = G (\sin\alpha + \mu_2 \cdot \cos\alpha)$

$$F = G \cdot \frac{(\sin\alpha - \mu \cdot \cos\alpha)}{(\cos\alpha - \mu \cdot \sin\alpha)}$$

F Centrifugal force [KN] [7]

In the case of roundabout pavement, the transverse gradient is usually $q = 2.5$ %. To [9] can be assumed:

$\sin\alpha \sim \tan\alpha \sim q = 2.5/100 = 0.025$

This results in the inclination angle of the carriageway with $q = 2.5$ %: $\alpha = 1.43$ °. Figure 7 shows the comparison of the limiting speeds for skidding in the curve v [km/h] for different skid grades and curve radii R [m] and a usual lateral inclination inwards of 2.5 %. The simplified model on which the calculations are based clearly shows that for typical cars as well as for trucks, skidding is decisive and tipping in the curve is the extreme exception (only in the case of extreme sudden steering angle = "tearing" as in the "elk test") [3, 9].

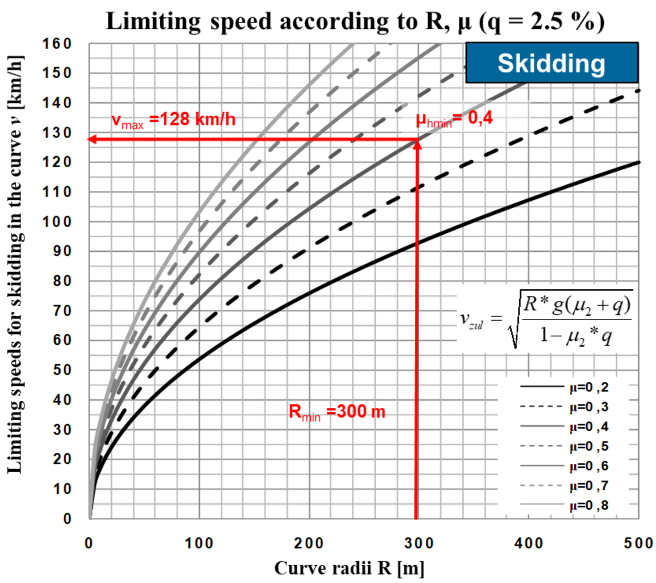

Fig. 7. Comparison of the limiting speeds for skidding in the curve for different grip levels and curve radii [3, 9]

V. The Skid Resistance Value

The skid resistance value (friction value) μ of the road μ represents a ratio between the activated horizontal force F_X and the acting vertical force F_Z according to formula [8] (Figure 8):

$$\mu = \frac{F_X}{F_Z}$$

[8]

The road grip depends largely on the polishing resistance of the aggregates used. Up to now, relevant standards and regulations have only specified the requirements for polishing behaviour for coarse aggregates (usually > 2 mm). The number of axle rollovers, the composition of the aggregate and the choice of minerals for aggregates of the asphalt mix have a significant influence on the skid resistance of the road surface. Accord to [11] the skid resistance development for two asphalt wearing courses was investigated: AC 11 D S and SMA 11 S, both with polymer modified bitumen PmB 25/55-55 A. On Figure 9 and Figure 10 the influence of the aggregate (composition, mineral type) on the skid resistance value is more than clear.

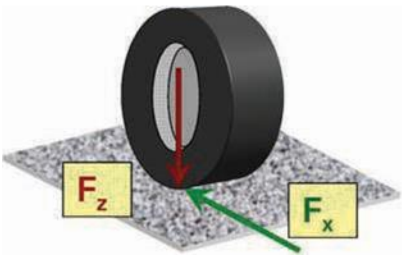

Fig. 8. Tire forces acting according to the Coloumb friction model [3, 10]

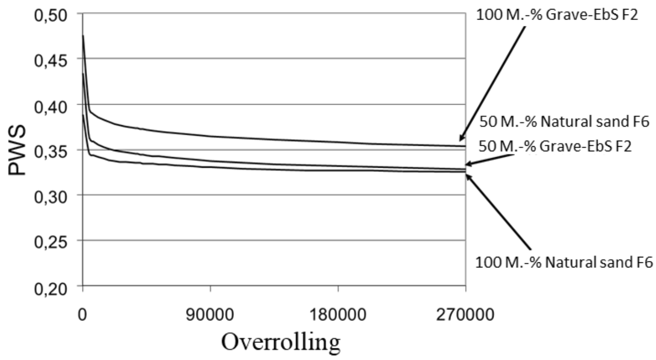

Fig. 9. Skid resistance development of the asphalt surface course AC11 D S [3, 11]

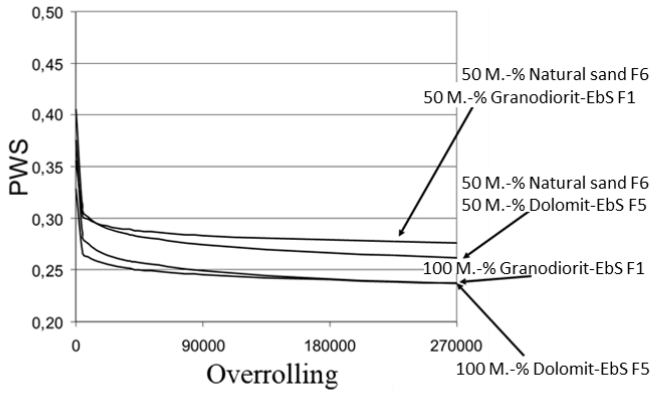

Fig. 10. Skid resistance development of the SMA11 S asphalt-wearing course [3, 11]

The skid resistance value of the road surface μ varies between 0.2 and 1.0. The term skid resistance in road construction engineering refers to the effect of the roughness of the road surface (surface texture) on the frictional resistance in interaction with the tires of the vehicle. The skid resistance value depends on a number of factors such as driving speed, road condition (dry, wet, covered with leaves, icy, etc.) (Tab. I), rubber compound used, curve radius and duration of road use or "wear"/polishing of the road surface.

TABLE I. Skid resistance values (friction values) as a function of road condition [3, 12]

Road condition	Skid resistance value µ
dry	0.7 - 1.0 In motorsport, values above 1.5 are possible; in addition, a higher downforce is achieved through various measures
dry (passenger car)	0.8
dry /truck)	0.7 Somewhat lower values than for passenger car in favour of higher running performance
wet, but no aquaplaning	0.4 – 0.6
wet leaves, snow	0.2 – 0.3
at ice	~ 0.1
aquaplaning	≪ 0.1 Driving and braking are only possible to a very limited extent

In Table I it can be seen that the coefficient of static friction (skid resistance value μ) is 40 % lower on a wet road compared to a dry road and in case of an ice road this value is only μ ~ 0,1! Aquaplaning depends on the driving speed (from 70 km/h), the tread depth and width of the tire and the thickness of the water film (Figure 11).

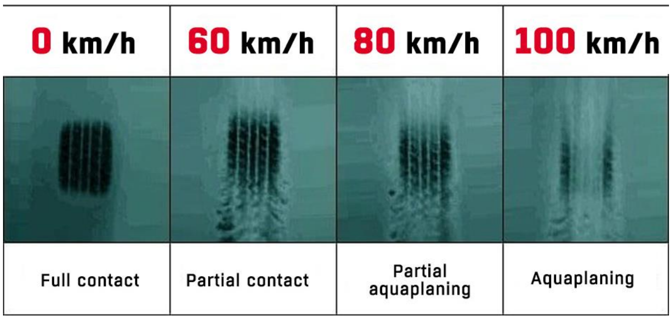

Fig. 11. Picture of the contact patch of a new tire at various speeds; depth of the water pool – 0.5 cm [13]

It can be clearly stated that the greater the transverse slope of the circular roadway and the smaller the radius of the traffic circle, the greater the centrifugal force F or the thrust force acting between the vehicles tires on the road surface. In the same way, the permissible speed v_{zul} at which a vehicle can drive through the traffic circle without skidding is also lower.

VI. The Skid Resistance of the Road Surface Measured with the "RoadSTAR"

The skid resistance of the road surface can be measured e.g. with the "RoadSTAR" system (Figure 12).

The grip of the road surface is determined with the modified Stuttgart friction meter, System RoadSTAR [15]. For this purpose, a rotatably mounted measuring tire is moved in longitudinal direction on wet road surface under constant wheel load and constant slip of 18%. To measure the skid resistance of the road surface, the frictional force, i.e. the activatable force between the measuring tire and the road surface, is set in relation to the wheel load and the calculated value is called friction coefficient μ [14].

Fig. 12. The "RoadSTAR" system for measuring road skid resistance, road surface etc. [3, 14]

Macro texture measurement [16] is carried out by means of a special laser sensor mounted on the measuring vehicle in front of the watering unit of the skid resistance measuring tire in the area of the right wheel track. During driving, texture profiles of the road surface with a length of at least 100 mm are scanned at high frequency (1 mm measuring point distance) in 1 m longitudinal intervals. The texture characteristic MPD (EN ISO 13473-1 [17] or EN ISO 13473-2 [18]) is calculated on the basis of the height profiles [14].

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