EJSIT
European Journal of Science, Innovation and Technology
ISSN: 2786-4936
www.ejsit-journal.com
Volume 4 | Number 2 | 2024

Relationships between Centrifugal Force, Permissible Driving Speed, Outside Diameter, Circular Lane Width and Transverse Gradient of the Seven Selected Austrian Roundabouts

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ABSTRACT

The circular roadways at roundabouts are exposed to special traffic loads due to cornering, namely friction and shear stresses, and in smaller roundabouts (mini roundabouts) also torsional stresses (turning of tyres 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. Therefore, it is extremely important to counteract the development of asphalt road damage by selecting the right asphalt construction for the roundabout pavements. It can be stated that there is a correlation between the centrifugal force acting on the vehicle when driving through a roundabout, the permissible driving speed, the outer diameter, the circular lane width and the transversal gradient of the circular lane at roundabout.

Keywords: asphalt, bitumen, centrifugal force, circular lane width, outside diameter, permissible driving speed, roundabout

INTRODUCTION

Basis for this Work

My first dissertation and my two specialised books, completed in Montenegrin in 2016, served as the basis for this work:

1) *Osnove izgradnje kružnih raskrsnica, prva knjiga - opšti dio* (translation in English: *Basics of Roundabout Construction - General Part*) (Hrapović, 2016a).

2) *Osnove izgradnje kružnih raskrsnica, druga knjiga - Izvedeni projekti kružnih raskrsnica u Austriji* (Translation in English: *Basics of Roundabout Construction - Projects of Roundabouts Implemented in Austria*) (Hrapović, 2016b).

In this paper, seven roundabouts were selected from my second book (Hrapović, 2016b) so that all roundabouts have different asphalt pavement designs to make the comparison as representative as possible. All these asphalt constructions are compared directly with each other in a table at the end.

For the selected roundabouts, the calculated dimensions of the respective centrifugal forces acting on the circular carriageway at the points with maximum transverse gradient of the circular carriageway q_{max} are calculated in the following using the formula (Hoffmann, 2010).

The maximum transversal gradient q_{max} of each roundabout was determined on the basis of sources (Land Niederoesterreich, 2016; Land Oberoesterreich, 2016; Land Tirol, 2016). In addition, v_{zul} - the permissible speed of the vehicle during curves [m/s] was determined for all seven roundabouts according to formula [3].

For the vehicle mass m [kg], or the vehicle weight G [KN] of the relevant vehicle, the mass of a truck fully loaded with wood and trailer is selected, since the two roundabouts KV North and KV South of the Lenzing bypass, have the entrances and exits to the giant concern

Lenzing AG. The Lenzing AG group is in fact known worldwide for fiber production from wood. The legally permissible total vehicle weight in Austria is 44 tons, so it is assumed that a semitrailer combination fully loaded with wood weighs 44 tons showing (Figure 1).

Figure 1. Transports "Streinesberger" transport the round timber also for Lenzing AG (Karl Streinesberger Transporte & Handel, 2020)

Assumptions:

m = 44.000 [kg] – the legally permissible total vehicle weight in Austria

$G = m \cdot g = 44.000 \cdot 9.81 = 431.640$ [kg m/s^2] = 431.640 [N]

G ~ 432 KN

Where g is the acceleration due to gravity: $g = 9.81$ [m/s^2]

The vehicle dynamics and driving geometry when driving in a curve are shown on Figure 2 by means of a disk model and this is applied analogously to the circular roadway of a roundabout. The rigid disk model represents a strong two-dimensional simplification of the real three-dimensional vehicle. Figure 2 shows all the forces acting on a vehicle travelling at the permitted speed in a roundabout: F - Centrifugal force [KN], G - Vehicle weight [KN], m - Vehicle mass [kg] and g - Acceleration due to gravity [m/s^2].

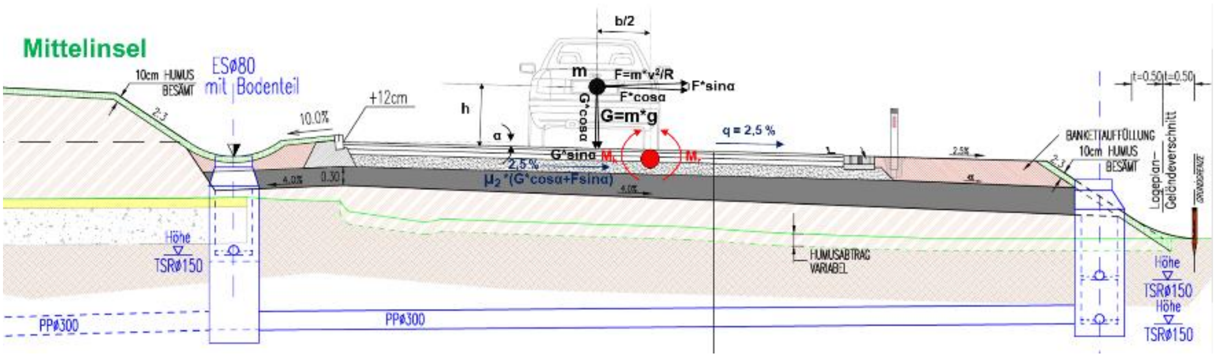

Figure 2. Vehicle dynamics and driving geometry when driving in the circular lane of a roundabout (Land Oberoesterreich, 2016) (edited by author)

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]

According to this disc model (Figure 2) for skidding in the curve (lateral drifting) the following formulas apply [6]:

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

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

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

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

For v, q

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

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

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

Out of formula [6] follows:

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

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

Centrifugal force [KN] [7]

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

In the case of roundabout pavement, the transverse gradient is usually $q = 2.5$ %.

The speed permitted for a curve at which, in simplified terms, a vehicle with the worst permissible tires and the worst permissible grip according to RoadSTAR (AIT, 2020) can still pass through on a wet road without skidding. This is calculated from formula [4]:

$$v_{zul} = \sqrt[2]{\frac{R \cdot g\ (\mu + q)}{1 - \mu \cdot q}}$$

For the calculations in Table 1 of the centrifugal forces F acting on the road surface at the selected roundabouts, the following skid resistance values μ are taken from 270,000 overruns for the sake of simplicity (Patzak et al., 2009):

1) For the mixture AC11 D S PmB 25/55-55 A: $\mu = 0.35$
2) For the mixture SMA11 S PmB 25/55-55 A: $\mu = 0.27$

For the calculations for the surface course AC16 deck PmB 45/80-65, the same skid resistance value as for the asphalt AC11 deck PmB 45/80-65 was used: $\mu = 0.35$.

Representation of the relationships between centrifugal force, permissible driving speed, outside diameter, circular lane width and transversal gradient of the seven selected Austrian roundabouts by means of the following diagrams

Figure 3 showing the roundabout at the B 145 highway exit A1 Regau (Upper Austria). It was built as a three-arm, single-lane roundabout with bypasses at the junction of the access and exit ramps to the A1 West highway with the B145 Salzkammergutstrasse.

Figure 4 showing the roundabout on the B 154 highway access and exit A1 Mondsee (Upper Austria), was built as a four-armed, 2-lane roundabout on the A1 West highway with the B154 Mondsee Strasse. The Mondsee roundabout has the largest outer diameter with D = 80.0 m.

Figure 3. Roundabout at the junction of the A1 western highway and the B 145 state road in Regau (Hrapović, 2016b: 10)

Figure 4. Two-lane roundabout B 154 / highway A1 Mondsee in October 2015 (Hrapović, 2016b: 24)

The diagram in Figure 5 shows the asphalt construction of all seven roundabouts, namely the base course, binder course and asphalt concrete. Roundabout (KV) Regau has an asphalt concrete base layer AC32trag, B50/70, T1, G4, 13 cm thick. The term "trag" means "base course" (German: "Tragschicht"). The bitumen used for this mix is a B50/70 road bitumen. The numbers 50/70 in its designation mean that the penetration of the bitumen at +25 °C is between 5.0 mm and 7.0 mm. Three asphalt types T1, T2 and T3 are distinguished for the "AC D trag" base courses, which, in contrast to the surface course types, only differ in their requirements for voids content. G4 is aggregate class of the asphalt mix according to Austrian standard (OENORM B 3580-1, 2018). A distinction is made between aggregate classes G1 to G9 and GS. G1 to G3 are intended for base and surface courses with increased requirements (e.g. skid resistance - layers over which the machine is driven directly) and G4 to G7 for binder and base courses as well as base and surface courses with low requirements or no requirements for skid resistance. An asphalt concrete AC22bind, PmB25/55-65, H1, G4, 9 cm thick serves as the binder course layer in the asphalt construction of the KV-Regau. Abbreviation "bind" comes from "binder". This binder course is coated with polymer-modified bitumen PmB25/55-65. "PmB" is name for polymer modified bitumen 25/55 - penetration of the bitumen at +25 °C is between 25 and 55 x10^{-1} mm after standard EN 1426. "65" is softening point of ring and ball is +65 °C (EN 1427, 2015). The asphalt surface layer of the KV-Regau is asphalt concrete AC11 deck PmB 45/80-65, A2, G1, 3.0 cm thick. For the surface courses "AC D deck", three asphalt types A1, A2 and A3 are distinguished according to an empirical approach, which differ in their particle size composition. In addition, these three types also differ according to their respective void content requirements. Type A1 corresponds to a particle size distribution approximating the fuller parabola, type A2 has a narrower grading curve compared to type A1. Type A2 is also subject to additional requirements regarding the deformation behaviour in the wheel tracking test.

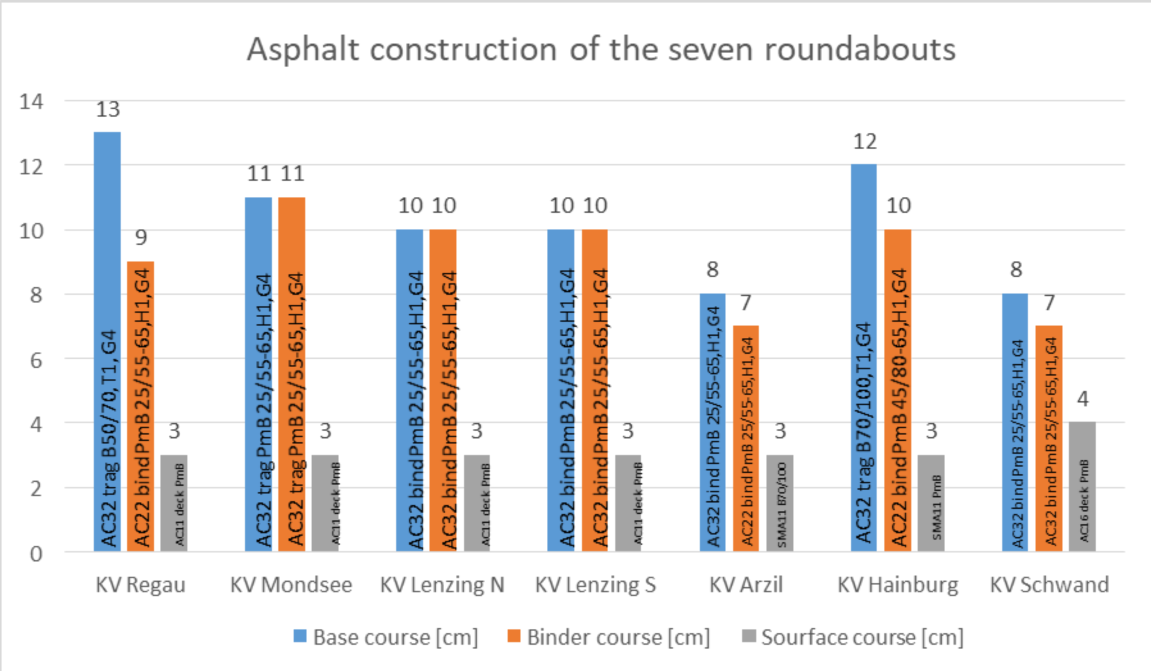

Figure 5. Asphalt construction of the seven roundabouts - layer thicknesses in cm

The small village of Lenzing is situated in Upper Austria. The former federal road B 151 (since April 01, 2002 all roads in Austria are called B the provincial roads) used to run directly through the centre of Lenzing, which caused environmental and noise pollution, especially from heavy traffic in Lenzing. It was therefore absolutely necessary to build a bypass around the village of Lenzing with the roundabouts Nord (N) and South (S). Figure 6 showing the north (N) roundabout of the B 151 Lenzing bypass and Figure 7 the South (S). Characteristically for the roundabout North is the one-sided inclination of the roundabout pavement. The special feature of the South roundabout is the cycle path underpass below the roundabout (Figure 7), through which the R 6 regional cycle path runs.

Figure 6. North (N) roundabout KV Lenzing North (N) of the B 151 Lenzing bypass (Hrapović, 2016b: 39)

Figure 7. South (S) roundabout KV Lenzing South (S) of the B 151 Lenzing bypass (Hrapović, 2016b: 46)

The diagram in Figure 8 showing the year of completion of the seven roundabouts. The oldest roundabouts, Lenzing North (N) and Lenzing South (S), were opened to traffic in 2009. The newest of these seven roundabouts are the KV Arzil, KV Hainburg and KV Schwand roundabouts, all three of which were completed in 2013.

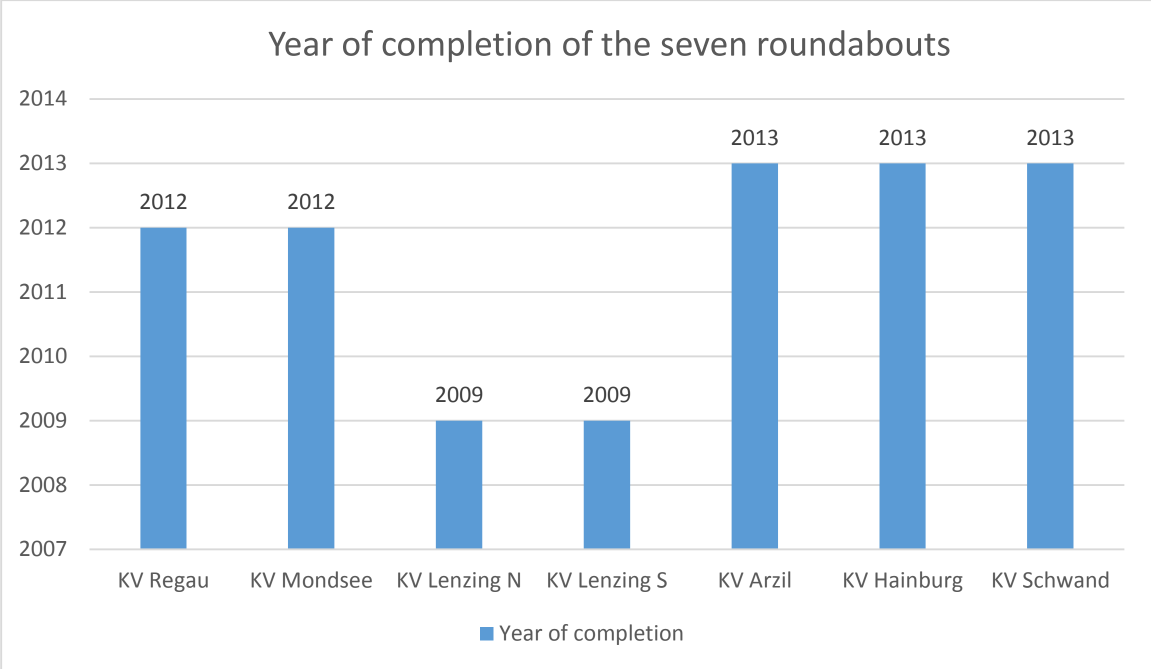

Figure 8. Year of completion of the seven roundabouts

The diagram in Figure 9 showing the pavement grip (skid resistance value) μ of the seven roundabouts. At the roundabouts KV Arzil and KV Hainburg the skid resistance value is μ = 0.27 and at the remaining five roundabouts is μ = 0.35.

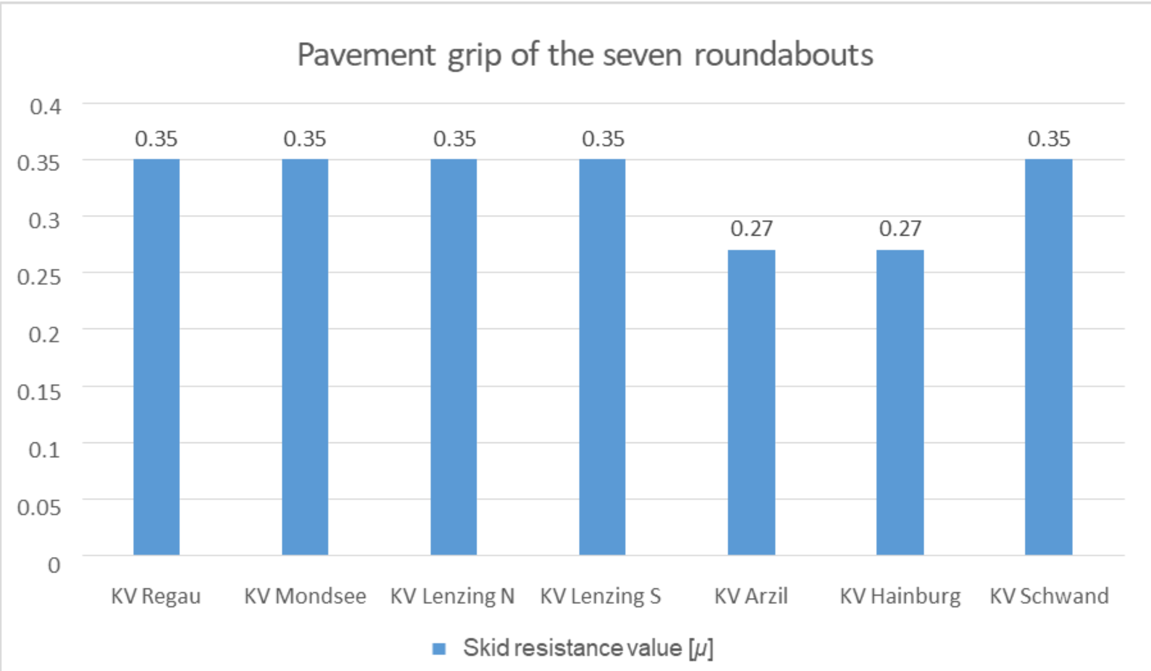

Figure 9. Pavement grip of the seven roundabouts

The Imst roundabout on Arzil was built as a six-arm, 2-lane roundabout at the intersection of two provincial roads B 171/B 189 in Tyrol. With an outer diameter of around 80 m, it is the largest roundabout in the whole of Tyrol (Figure 10).

Figure 10. The roundabout Imst on Arzil (Hrapović, 2016b: 370)

The diagram in Figure 11 showing the relationships between ADT- average daily traffic volume, circular lane width and outer diameter of the seven roundabouts. The roundabout KV Schwand has ADT- the average daily traffic volume 6,671 car/day. This is the lowest value of the seven selected roundabouts and the KV Regau roundabout has the highest value with 18,800 cars/day. The Lenzing South roundabout (S) has the narrowest circular lane width of 5.5 m (single lane) and the Hainburg roundabout has the widest at 8.4 m (dual lane).

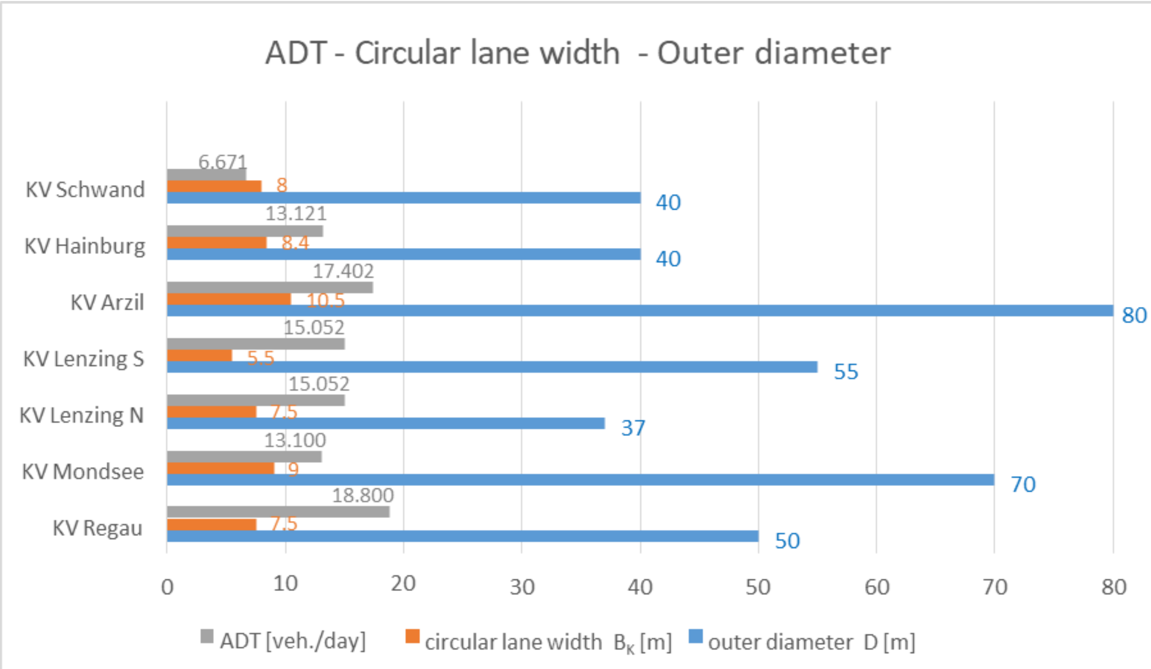

Figure 11. Relationship between ADT- average daily traffic volume (Germ. DTV – Durchschnittlicher taeglichen Verkehrsstaerke), circular lane width and outer diameter of the seven roundabouts

The roundabout Hainburg was built as a five-arm, 1-lane roundabout on the intersection of the B 9 / Kruecklstrasse at km 40.083 in Hainburg/Lower Austria. The outer diameter is 40 m is showing in Figure 12.

Figure 12. KV Hainburg on the B 9 federal state road/Kruecklstrasse in Hainburg (Province of Lower Austria) (Hrapović 2016b: 280)

Figure 13 showing the correlation between permissible speed, circular lane width and outer diameter of the seven roundabouts. Although the roundabout Lenzing Nord (N) with smallest outer diameter is D = 37.0 m and v_{zul} = 24.66 km/h, the lowest permissible speed is however the roundabout KV Hainburg v_{zul} = 21.18 km/h and outer diameter of D = 40.0 m. The highest permissible speed is however the roundabout KV Mondsee v_{zul} = 34.62 km/h and outer diameter of D = 70.0 m.

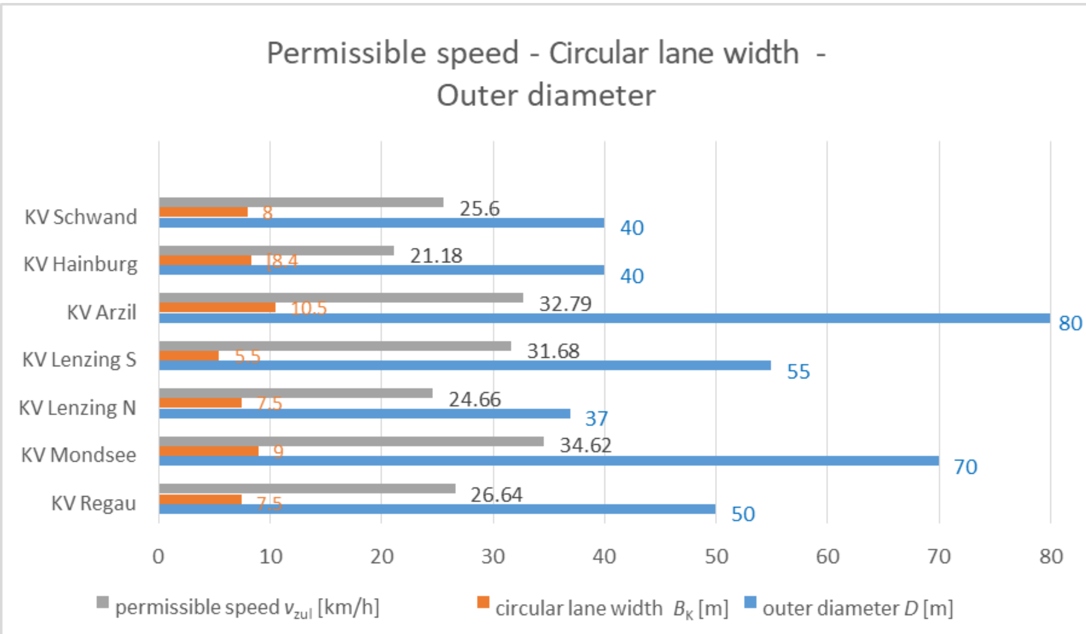

Figure 13. Correlation between permissible speed, circular lane width and outer diameter of the seven roundabouts

Figure 14 showing the relationships between centrifugal force, maximum transverse gradient of the circular lane and outer diameter of the seven roundabouts. The centrifugal force F = 128 KN at the point of maximum transverse gradient q_{max}= 2.5 % of the roundabout pavement of the roundabout on Arzil, which acts on a semi-trailer combination fully loaded with wood during cornering, has the lowest value of all seven roundabouts. The highest value of the centrifugal force (F = 172 KN), has the roundabout KV Regau.

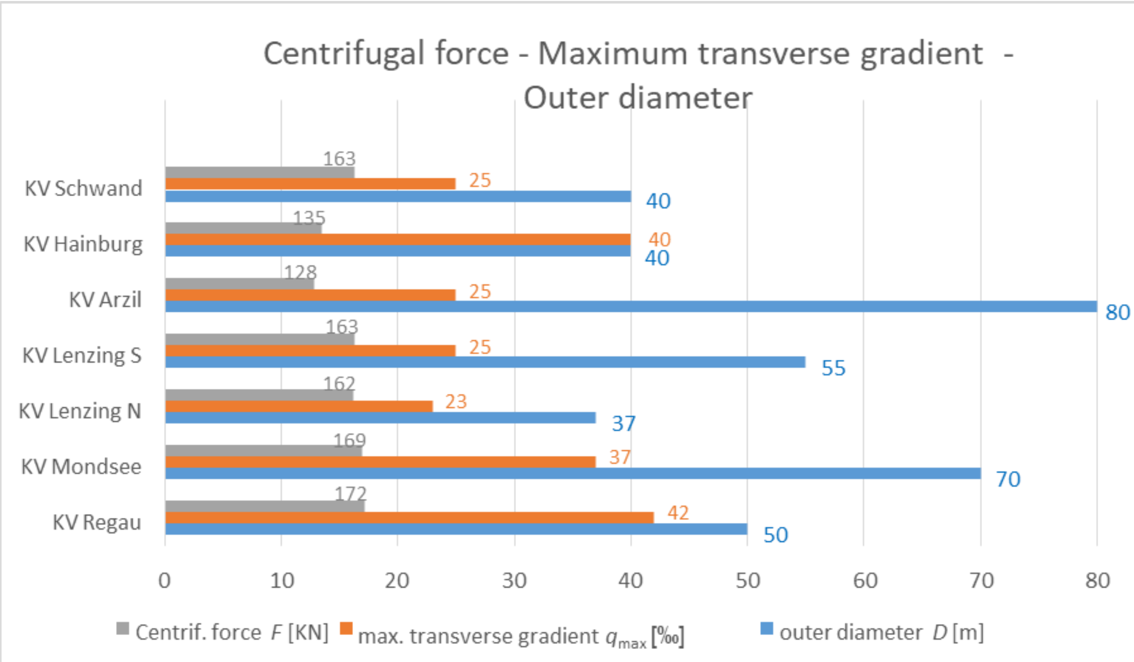

Figure 14. Relationship between centrifugal force, maximum transverse gradient of the circular lane and outer diameter of the seven roundabouts

Last but not liest, the roundabout KV Schwand was built as a four-arm, 1-lane roundabout at the junction of the L 1101 state road in Schwand/Upper Austria. The outer diameter is 40 m is showing in Figure 15.

Figure 15. The roundabout KV Schwand on the L 1101 federal road of type L in Schwand (Upper Austria) (Hrapović, 2016b: 244)

Summary of the Seven Selected Roundabouts

All-important parameters of these seven Austrian roundabouts are shown in Table 1.

Table 1. Summary of the seven selected roundabouts (Germ. Kreisverkehr = KV)

Roundabout (KV)	KV Regau	KV Mondsee	KV Len. North	KV Lenz. South	KV Arzil	KV Hainburg	KV Schwand
DTV [veh./day]	18,800	13,100	15,052	15,052	17,402	13,121	6,671
Outer diameter D	50.0 m	70.0 m	37.0 m	55.0 m	80.0 m	40.0 m	40.0 m
Curve radius R	21.25 m	30.5 m	14.75 m	24.75 m	34.75 m	15.8 m	16.0 m
Circular lane width B_K	7.5 m	9.0 m	7.5 m	5.5 m	10.5 m	8.4 m	8.0 m
Max. cross gradient q_{max}	4.2 %	3.7 %	2.3 %	2.5 %	2.5 %	4.0 %	2.5 %
Skid resistance value μ	0.35	0.35	0.35	0.35	0.27	0.27	0.35 *
Asphalt surface layer	AC11 deck PmB 45/80-65, A2, G1, 3.0 cm	AC11 deck PmB 45/80-65, A2, G1, 3.0 cm	AC11 deck PmB 45/80-65, A2, G1, 3.0 cm	AC11 deck PmB 45/80-65, A2, G1, 3.0 cm	SMA11 70/100, S2, G1, 3.0 cm	SMA11 PmB 45/80-65, S1, G1, 3.0 cm	AC16 PmB 45/80-65, A2, G1, 4.0 cm
Asphalt binder layer	AC22 binder PmB 25/55-65, H1, G4, 9.0 cm	AC32 binder PmB 25/55-65, H1, G4, 11.0 cm	AC32 binder PmB 25/55-55, H1, G4, 10.0 cm	AC32 binder PmB 25/55-55, H1, G4, 10.0 cm	AC22 binder PmB 45/80-65, H1, G4, 7.0 cm	AC22 binder PmB 45/80-65, H1, G4, 10.0 cm	AC32 binder PmB 25/55-65, H1, G4, 7.0 cm
Asphalt base layer	AC32 trag 50/70, T1, G4, 13.0 cm	AC32 binder PmB 25/55-65, H1, G4, 11.0 cm	AC32 binder PmB 25/55-55, H1, G4, 10.0 cm	AC32 binder PmB 25/55-55, H1, G4, 10.0 cm	AC32 binder PmB 45/80-65, H1, G4, 8.0 cm	AC32 carrier 70/100, T1, G4, 12.0 cm	AC32 binder PmB 25/55-65, H1, G4, 8.0 cm
Centrifugal force F	172 KN	169 KN	162 KN	163 KN	128 KN	135 KN	163 KN
Permissible speed v_{zul}	26.64 km/h	34.62 km/h	24.66 km/h	31.68 km/h	32.79 km/h	21.18 km/h	25.60 km/h
Opening	2012	2012	2009	2009	2013	2013	2013

CONCLUSION

The direct comparison of the seven selected roundabouts shown in Tab.1 shows the following:

1) KV Regau has the highest annual average daily traffic volume at 18,800 vehicles/day and the Schwand roundabout the lowest traffic load with a ADT = average daily traffic (Germ. DTV= durchschnittlicher taeglicher Verkehr) value of 6,671 vehicles/day.

2) The Mondsee roundabout has the largest outer diameter with D = 80.0 m and the Lenzing Nord KV has the smallest with D = 37.0 m.

3) With q_{max} = 4.2%, the Regau KV has the largest cross slope of the roundabout pavement and the Lenzing Nord KV has the lowest cross slope with q_{max} = 2.3%.

* For the surface course AC16 deck PmB 45/80-65, the same skid resistance value was adopted as for the asphalt AC11 deck PmB 45/80-65.

4) The roundabouts of the Lenzing Nord and South bypass are the "oldest" ones with a service life of 11 years and the roundabouts at Arzil in Tyrol, Hainburg in Lower Austria and Schwand in Innkreis with a service life of seven years are the "youngest".

5) The Regau, Mondsee, Lenzing Nord and Lenzing South roundabouts were asphalted with the asphalt AC11 deck PmB 45/80-65 as surface course.

6) The KV on Arzil was the only one to be paved with the SMA11 wearing course with conventional bitumen B 70/100 and the KV Hainburg with SMA11 but with polymer-modified PmB 45/80-65. With a $\mu = 0.27$, these two roundabouts have the lowest skid resistance value of all seven because they were asphalted with SMA 11 as a 3 cm thick surface course.

7) The four roundabouts (KV Regau, KV Mondsee, KV Lenzing Nord and KV Lenzing South) were asphalted with the chippy asphalt concrete AC11 deck PmB 45/80-65 as a 3 cm thick surface course and therefore have the higher skid resistance or friction value $\mu = 0.35$.

8) With the asphalt AC16 deck PmB 45/80-65 as a surface course, KV Schwand was the only one of the seven roundabouts to be paved with a mix with a maximum grain size of 0/16 mm in a thickness of 4 cm.

9) For the KV Regau the greatest centrifugal force $F = 172$ KN (flee force) was calculated. The reason for this is the maximum transverse gradient of the roundabout pavement of this roundabout with a value $q_{max} = 4.2$ %.

10) In contrast, the lowest centrifugal force $F = 128$ KN (centrifugal force) was calculated for the KV on Arzil. The reason for this is firstly the largest outer diameter with a proud $D = 80.0$ m, which is why this roundabout is the largest in the whole of Tyrol. The second reason is a minimum value of the cross slope $q_{max} = 2.5$ %. It is precisely for these two reasons that the theoretical calculated admission speed $v_{zul} = 32.79$ km/h is the highest of all seven roundabouts.

11) Although the roundabout Lenzing Nord with smallest outer diameter is $D = 37.0$ m and $v_{zul} = 24.66$ km/h, the lowest permissible speed is however the roundabout Hainburg $v_{zul} = 21.18$ km/h and outer diameter of $D = 40.0$ m. The reason for this is that the Hainburg KV has the higher value of maximum transverse gradient ($q_{max} = 4.0$ %) and the Lenzing Nord KV has the value of $q_{max} = 2.3$ %).

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