Title:

Frequency and Safety of Small Radii on Motorway-like Roads in Greater Stuttgart Area – Recommendations for Future Guidelines of Motorways

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0. Abstract:

The German Guidelines for the Design of Motorways (RAA 2008) assume sufficient safety of a circular curvature if a vehicle does not slip of the road at a given design speed. Earlier researches indicated a higher accident-risk of small radii R<1000m frequently used on motorway-like road with a design speed of 100 kph given in German Guideline for Motorways RAA 2008. With regard to the "Vision Zero", no fatal accidents, it was examined whether minimum radii should be increased to improve safety.

For this purpose, 174 km from the entire 200 km motorway-like road network in Greater Stuttgart Area were selected. The existing circular radii were evaluated according to their frequency and accident risk using databases of the State of Baden-Württemberg about road geometry and accidents including the accident cost rate for each 100m section. Within the selected network 212 circular curves exist. All radii R≤1000m were examined for their accident cost rate. Radii with an accident cost rate above the average were classified as risky.

The investigation showed that 33% of all applied radii are below R<1000m. Circular curves with R<650m showed a significantly higher accident risk and should be excluded. Circular curves between R≥650m and R<900m showed a higher accident risk if the ratio of adjacent radii is considerably above R1/R2≥1.5. After a long straight line the minimum radius should be R≥1000m. The study results in recommendations for the geometric design introduced by the follow-up of German Guidelines for Motorways.

1. Problem Description

In the Greater Stuttgart Area there are approx. 200 kilometers of federal roads whose network function and route characteristics correspond to the design standards for motorway-like roads according to the German Guidelines for the Design of Motorways (RAA 2008, Design Class EKA 2) [1]. These motorway-like federal roads form a largely coherent network, from which the road user expects a similar technical standard. Transport policy with regard to the "Vision Zero" – no fatal injuries in traffic – also expects a maximum degree of structural road safety.

In Germany motorways and motorway-like roads are very similar. Both are dual carriageway, multi-lane, fully grade separated roads with no access to adjacent land. However, an important difference is the lower design speed of a motorway-like road, which allows smaller curve radii. Road users only can tell the difference by the entrance signs and color of the signposting.

Present guideline RAA 2008 assumes sufficient safety of a circular curve if a vehicle does not slip of the road at a given design speed. In contrast, earlier research on safety effects of low visibility in left turn curves already revealed that circular curves of R<1000 m have an increased accident risk [2]. The purpose of the investigation presented below was to find out whether, from the point of view of road safety, larger minimum radii than those listed in RAA 2008 are required for the planned expansion of the motorway-like road network and, if so, which minimum radii and constraints should be applied therefore [3]. In addition, it was to be investigated whether circular curves with R<1000m generally have a higher accident risk or whether further differentiation can be made within this group. It should also be examined whether the relation between successive circular curves with small radii and adjacent larger radii influences the safety.

2. Investigation of selected roads in the existing network

2.1 Investigation methodology

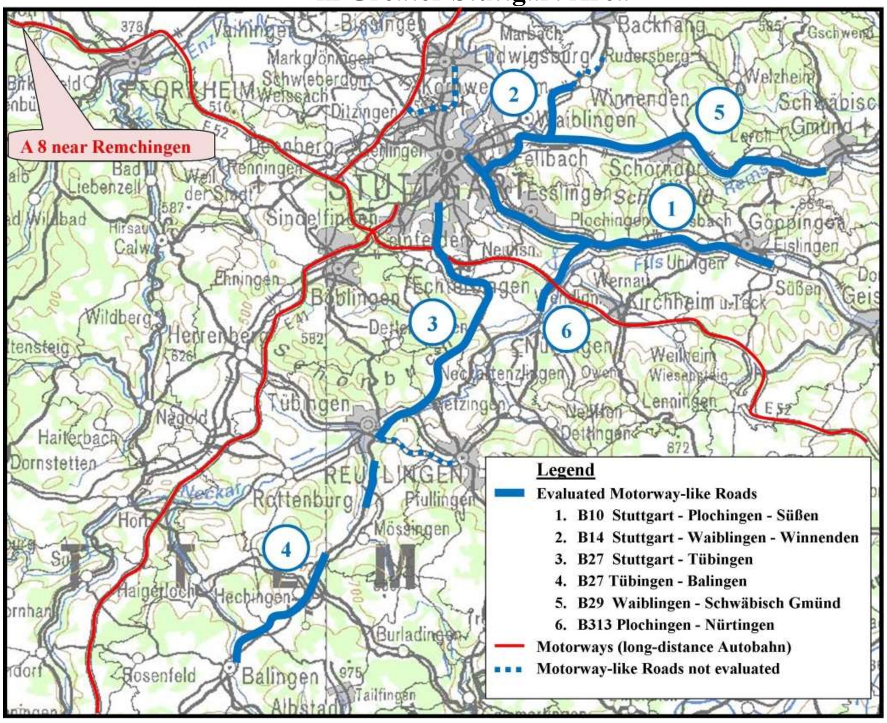
From the existing approx. 200 km long network of motorway-like roads in the Greater Stuttgart Area, only those routes were selected whose cross-sections correspond most closely to those of the Design Class EKA 2 of RAA 2008 (lane width ≥ 3.50m and largely with hard shoulders). Isolated short motorway sections with a length of less than 5 km and sections with a lane width of only 3.25 m were excluded.

Specifically, the following routes with a total length of 174 km were evaluated:

1. B 10 Stuttgart - Plochingen - Süßen/Fils (47 km)
2. B 14 Stuttgart - Waiblingen - Winnenden-Süd (21 km)
3. B 27 Stuttgart-Degerloch - Tübingen (34 km),
4. B27 TÜ-Dusslingen (6. 5 km), Bodelshausen - Balingen-Süd (19 km)
5. B 29 Waiblingen-Schwäbisch Gmünd (36 km)
6. B 313 Plochingen - Nürtingen (10 km)

The location of the motorway-like network under investigation is shown in fig. 1

Fig. 1: Investigated sections of the motorway-like road network in Greater Stuttgart Area



The investigation of the alignment was based on the geometric road data stored in the road database of the State of Baden-Wuerttemberg, Germany. Only smaller radii with $R \leq 1000m$ were examined, as only these radii showed an increased accident risk in a previous study [2]. As these small radii occur more frequently on motorway-like roads, evaluation could differentiate finer in groups of radii with a maximum of $\Delta R \leq 150m$. This allows the frequency of small and very small radii and their accident risk to be assessed much more accurately.

The examination should also determine whether small and very small radii occur regularly or only exceptionally on motorway-like roads. From this it can be estimated whether the avoidance of small radii leads to higher investment costs.

All curves with radii R≤1000m were examined for their specific accident risk with the help of the Baden-Württemberg Road Safety Screening [4]. In the Baden-Württemberg Road Safety Screening, the accident data of all recorded accidents on classified roads from 2010 are stored and can be evaluated with specially developed tools. An existing evaluation from this database showing accidents and accident cost rates of 100m intervals for the 3-year period 2014-2016 was used for the statistical analysis [5]. Using the road database Baden-Württemberg all occurring radii could be exactly located and assigned to the 100m intervals of the existing accident evaluation.

The statistical accident evaluation of the radius groups was carried out using two different methods:

Method 1: For each individual radius, the specific accident cost rate and the specific accident cost rate of a much longer homogeneous reference section are compared. If the accident cost rate of the individual radius exceeds that of the reference section, this individual radius is considered to be risky. If the majority of the individual radii within a radius group exceed that of the reference section, the entire radius group is considered to be risky. The advantage of this method is that each individual radius can be viewed, and abnormalities can be identified and examined in a subsequent evaluation with the help of the electronic accident map. The disadvantage of this method is the sometimes low number of accidents per individual radius.

Method 2: The accident cost rate of a radius group as a whole is calculated as a weighted average over all individual radii. The entire network of motorway-like roads under investigation, with the exception of the radius group examined, serves as a reference section. A radius group is considered to be risky if its accident cost rate exceeds that of the reference section assessed. It is advantageous that the statistically more reliable average from a larger accident collective is used for comparison. The disadvantage of this method is that unusual deviations on the individual radius cannot be detected.

The significance of the statistical evaluation is increased by using both methods. In addition, all radius groups classified as risky were subjected to a visual evaluation using the electronic accident map of the Traffic Safety Screening. All accidents since 2010 could be included, although the evaluation was limited to the single car accidents causally related to the curve radii.

Applied Parameters for Safety Evaluation

Parameters and cost calculation are described in the German Guidelines for Safety Analysis of Road Networks - ESN, Edition 2003 [6]. In principle, the database of Baden-Württemberg Traffic Safety Screening allows evaluation of all statistical accident parameters. In order to avoid the influences of different traffic volumes of reference road sections, the accident cost rate was selected for evaluation in the present study. The accident cost rate can take into account both the different traffic volumes and the different consequences of the accident when comparing the safety risk.

The accident costs are the sum costs of the personal injury accidents and the costs of damage-only accidents. The Traffic Safety Screening uses mean costs per accident also given in ESN [6].

The Accident cost rate (ACR) is defined as follows:

$$ACR = \frac{1000 \cdot AC}{365 \cdot ADT \cdot L \cdot t} \quad \textbf{[Equitation 1]}$$

[€ / (1000·veh·km)]

where

ADT = Average daily traffic [veh/24h] in t years
L = Length of road section [km]
T = Period under review in years [a]
AC = Accident costs [€] in t years

The evaluated accident cost rates for Motorway-like roads include all types of accidents that occur regularly on directional lanes reserved exclusively for motor traffic (single car accidents, side-impact collisions, and other accidents).

Reference road sections

For the statistical application of method 1, the entire network examined had to be divided into largely homogeneous reference sections. The reference sections should be as long as possible in order to verify the reference value (ACR_{ref}) with the greatest possible number of accidents. Criteria for the formation of homogeneous reference road sections were the traffic volume, similar speed limits and the opening of the reference route sections (in which the different design principles for the alignment over the time horizon of the years 1960-2000 are reflected). Finally, eight homogenous reference road sections are formed from the investigated motorway-like road network. These are listed in chapter 2.2.2.3.

For the statistical application of method 2 the whole investigated motorway-like road network serves as a reference route, except for the sections of the examined radii. A finer division is not possible because the examined radii of a group are distributed over the whole network.

Relation of consecutive circular curve radii

In addition to the monocausal explanation of the accident risk of a circular curve due to its radius, the radius ratio between the small circular curve and the preceding circular curve including the special case of the straight line was also evaluated. This was done by using the road database of the State of Baden-Württemberg.

Evaluation with the electronic accident map

The accident cost rates used also includes accidents whose cause is not clearly due to a small radius, e.g. side impact collisions. To overcome this problem, a further detailed evaluation of those circular curves for which the statistical evaluation revealed an above-average accident rate was carried out using a tool of Baden-Wuerttemberg Traffic Safety Screening to create specific accident maps electronically [7]. To ensure a clear correlation between radius and accident occurrence only the single car accidents were considered. It was examined whether there was an apparent accumulation of single car accidents in the curve area in comparison to the preceding and subsequent route. In addition to this, the visibility conditions were examined based on the video sequences also stored in databases of road pavement surveys. With this apparent examination, the statistically determined results can be verified and additional insights into the causes of accidents can be gained, which would possibly not have been recognized solely from the consideration of the statistical accident parameters.

2.2 Results

2.2.1 Frequency of circular curves with small radii

The evaluated 174 km long motorway-like road network contains 212 circular curves. Of these, 141 circular curves with R≥1000m (66.5%) are not critical from the point of view of traffic safety. The remaining 71 curves with smaller radii R<1000m (33. 5%) are suspected for an increased accident risk after earlier researches and need to be examined more closely. The frequency of circular curves with R≤1000m divided into radii groups is shown in table 1. Very small radii with R≤750m that are excluded on long-distance motorways in Germany occur on 32 circular curves (15%), including 15 circular curves with R<650m (7%). Circular curves with radii between 750m and 900 m are particularly common, the majority with R=800m. Circular curves with R=1000m also occur frequently (8.4 %).

Table 1: Occurrence of radii on circular curves on investigated motorway-like roads

Investigated Road Section	Number of circular curves	Out of it with					
		R= 1000m	1000m < R ≥ 900m	900m > R >750m	750m ≥ R ≥ 650m	650m< R ≥600m	R<600m
B10 Stuttgart-Plochingen	39	5	1	2	3	0	3
B10 Plochingen-Süßen	42	3	3	6	5	3	0
B14 Stuttgart-Winnenden-Süd	17	4	0	4	1	1	0
B27 Stuttgart-Tübingen	24	2	1	5	1	1	0
B27 südl. Tübingen	33	2	3	3	3	2	1
B29 Waiblingen-Schw. Gmünd	41	2	2	6	3	1	0
B313 Plochingen-Nürtingen	16	0	1	2	1	0	2
Σ	212 (100%)	18 (8.5%)	11 (5.2%)	28 (13.2%)	17 (8.0%)	9 (4.2%)	6 (2.8%)

The result is not surprising because a design speed of 100 kph was usually applied to these roads in accordance with the earlier design guidelines for alignment. While in the RAL-L 1959 [8] minimum radius of R=800m was still valid, which can be found in many of the examined existing sections, this was gradually lowered to R=500m (RAS-L-1 1984 [9]) and with the RAS-L 1995 finally to R=450m [10]. The minimum radius of the RAA 2008 for the EKA 2 of R=470m is only undercut at two curves.

2.2.2 Statistical accident rates of road sections with small radii

2.2.2.1 Preface

It should be investigated whether the increasing accident risk of radii below R=1000m, which has been identified in previous investigations, can be described more precisely. In addition, it should be examined whether a minimum radius for motorway-like roads can be derived for safety reasons.

2.2.2.2 *Selected network and basis of accidents for safety evaluation*

Recently opened sections had to be sorted out from the 174 km network initially selected, as accident figures were not yet available. After that, a 167 km network remained for statistical evaluation with 906 accidents reported from 2014 to 2016. In addition, curve radii for which no traffic load and thus no accident cost rate was available and those at the beginning of the motorway-like road were excluded. Finally, 65 curves with R≤1000m and 145 accidents could be evaluated.

2.2.2.3 *Statistical accident rates of reference road sections*

For the statistical analysis according to method 1, eight homogeneous reference sections were formed. Their average accident cost rates (ACR_{ref}) are shown in table 2.

Table 2: Accident cost rate of evaluated reference road sections (ACR_{ref})

Motorway-Like Reference Road Section	Length [km]	Speed Limit [kph]	Accidents reported [n]	Accident Cost Rate Reference Road Section ACR_{ref} [€/1000veh∗km]
B 10 Stuttgart - Plochingen	20	80	160	3.16
B 10 Plochingen-Süßen	28	120	140	7.81
B 14 Stuttgart - Winnenden	18	80 – 120[1)]	192	4.52
B 27 Stuttgart - Tübingen	36	120[2)]	159	3.58
B 27 Bodelshausen - Balingen	19	120	77	4.62
B 29 Waiblingen – Schwäbisch Gmünd	36	120	114	4.78
B 313 Plochingen – Autobahn A 8	6	80	31	3.61
B 313 Autobahn A 8 - Nürtingen	4	120	33	15.20
Total evaluated Motorway-like road network	**167**		**906**	**4.72**
<u>*For comparison*</u>: • *All motorways in Baden-Württemberg*				*8.53*

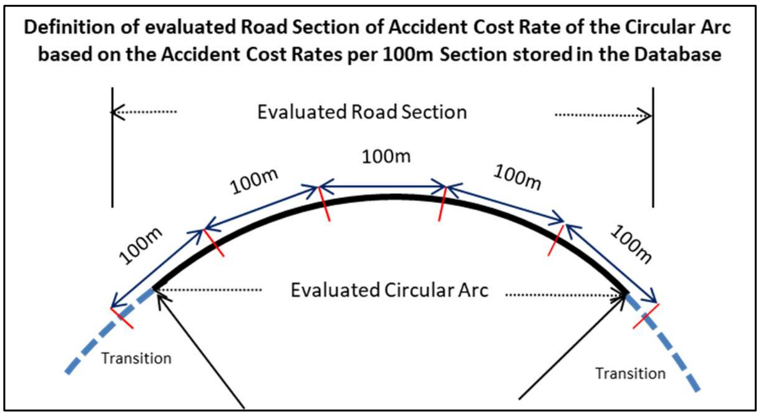
1) Some sections with traffic control system
2) Some sections with traffic control system and ramp metering

It is evident that the motorway-like roads in the Greater Stuttgart Area have very low accident cost rates compared to the motorways in Baden-Württemberg, most of them long-distance motorways. This is probably due to the traffic composition of these motorway-like roads with a significantly lower proportion of heavy vehicles, the higher proportion of local drivers and the partially very low speed limits for environmental reasons. It is noticeable that the reference section B 27 Stuttgart - Tübingen, operated at a speed limit of 120 kph, has an almost as low accident cost rate as the two other reference sections B 10 and B 313, operated at a speed limit of 80 kph. There is no simple explanation for the different accident cost rates. For the B 10 Stuttgart - Plochingen and the B 313 Autobahn - Plochingen, the speed limit of 80 kph could be a major cause. The low accident cost rate of the B 27 Stuttgart - Tübingen can be explained by the fact that this route, although completed before 2008, largely meets the requirements of the Design Class EKA 2 of the RAA 2008. Accident rates of the reference road sections B 10 Plochingen - Süßen and B 313 Autobahn - Nürtingen are significantly higher than those of the rest. An explanation may be found in their unsteady alignment with alternating stretched and curvy sections.

2.2.2.4 Safety risk of circular curves with R≤1000m

Based on the accident cost rates of 100m intervals of the classified road network for the years 2014-2016 [5], the accident cost rates of all circular curves with radii of R≤1000m on the evaluated motorway-like road network were calculated. The accident cost rate of each radius was calculated as the arithmetic mean of the accident cost rates of those 100m-intervals covering the circular curve. This process is described in fig. 2.

Fig. 2 Evaluated road section of the accident cost rate of a circular curve



The safety risk of the specific circular curve is then calculated as follows:

$$Sr = \frac{\frac{\sum_{i=1}^{n} ACR\,(100m)i}{n}}{ACR\ ref} \quad \textbf{[Equitation 2]}$$

Sr =	Relative safety risk of a curve radius compared to the reference road section
ACR (100m)$_i$ =	Accident cost rate of the i-th 100m-intervall within and adjacent of the arc of a circle
n =	Number of 100m sections inside and at the edge of the arc
ACR$_{ref}$ =	Accident cost rate of reference road section

Statistical evaluation by method 1

The safety risk of each circular curve was determined by comparing the individual accident cost rate (ACR) with the corresponding accident cost rate of the reference road section (ACR$_{ref}$). Circular curves with an accident cost rate above the accident cost rate of the reference road section were classified as above-average risky.

Sr > 1 = Circular curve with increased accident risk [Equitation 3]

Circular curves with a below-average accident cost rate on their reference section or without an accident were assessed as not risky. The more radii within a radii group have an above-average accident cost rate (ACR>ACR$_{ref}$), the higher the risk of this radii group. Radii groups in which more than half of the radii have a below-average accident cost rate of the reference section are not considered to be accident risky.

$$\text{S coll} = \frac{\sum_{i=1}^{n}(Sr>1)}{n} \qquad \textbf{[Equitation 4]}$$

S coll = Share of all circular curves with increased accident risk in a radius group
Sr > 1= Circular curve with increased accident risk (see above)
n = Number of circular curves within a radius group

In order to assess a possible cause of above-average risky circular curves, the radius ratio to the larger subsequent circular curve was also determined.

The evaluation method and its results are shown in table 3 using the radius group with R<650m as an example.

Table 3: Evaluation of radii group R<650m by method 1

Curve No.	Location	Radius [m]	Accidents [n]	ACR Specific Radius [€/1000vehkm]	ACR_{ref} [€/1000vehkm]	Safety risk Sr = ACR/ACR_{ref}	Radii-ratio (R1/R2)
	R<650m						
1	B10 Plochingen	400	1	1.19	3.16	0.38	3.7
2	B313 Köngen	450	No accident				3.9
3	B10 Esslingen-Weil	500	1	3.86	3.16	**1.22**	**6.0**
4	B10 Esslingen-Mitte	500	3	3.42	3.16	**1.08**	**2.0**
5	B27 Engstlatt	500	1	6.26	4.26	**1.47**	3.0
6	B313 NT-Zizishausen	550	5	51.21	15.20	**3.37**	**18.2**
7	B10 Faurndau	600	3	2.40	7.81	0.31	3.1
8	B14 Fellbach	600	6	6.75	4.52	**1.49**	**1.7**
9	B27 Kirchentellinsfurt	600	2	9.20	3.58	**2.57**	**2.0**
10	B27 Bisingen	600	2	3.90	4.62	0.84	8.3
11	B27 Hechingen	600	5	5.20	4.62	**1.13**	**16.7**
12	B29 Remshalden	600	1	29.98	4.78	**6.27**	**2,1**
13	B313 Wendlingen (A8)	600	8	3.41	3.61	0.94	1.3
14	B10 Ebersbach 1	600	5	17.20	7.81	**2.20**	**2.3**
15	B10 Ebersbach 2	600	2	4.63	7.81	0.59	1.3
	Total accidents R<650		**45**				

ACR = Accident Cost Rate (of specific radius)
ACR_{ref} = Accident Cost Rate of motorway-like reference section (see Table 2)
Sr>1 = accident risk above reference section printed in bold numbers

The accident risk of the radius group with R<650m is:

$$\text{S coll} = \frac{\sum_{i=1}^{n}(Sr>1)}{n} = \frac{8\,(Sr>1)}{15} = 0.60\ (above\ average\ = accident\ risky) \qquad \textbf{[Equitation 5]}$$

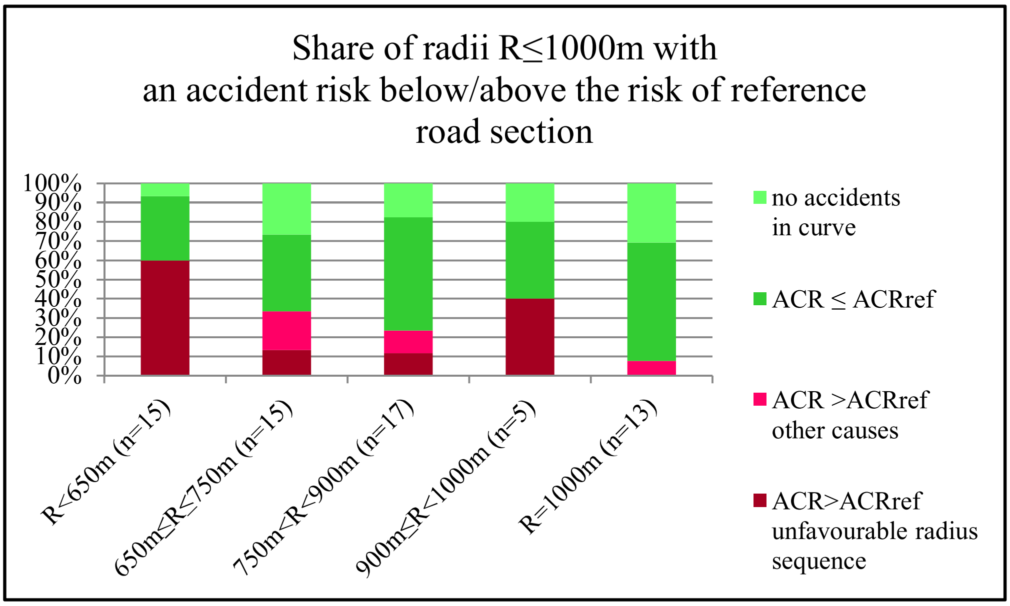
According to method 1, a total of 65 circular curves with R≤1000m were evaluated. The overall result of the risk assessment is shown in table 4 and as a diagram in fig. 3. The complete evaluation of all curve radii by method 1 can be found in [3].

Table 4: Evaluation results for the accident risk of small circular curves with radii R≤1000m

Radii groups	Number of circular curves	Accidents reported	Number of circular curves ACR [1)] < ACR_{ref} [2)]		Share	Number of circular curves Sr = ACR [1)] > ACR_{ref} [2)]		Share
			No. Accidents	ACR [1)] ≤ ACR_{ref} [2)]		Unfavorable radius sequence (R_1/R_2>1,5)	Other Reasons	
R<650m	15	45	1	5	40%	9	0	60%
650m ≤R≤750m	15	32	4	6	67%	2	3	33%
750m <R<900m	17	40	3	10	76%	2	2	24%
900m ≤R<1000m	5	8	1	2	67%	2	0	33%
R=1000m	13	32	4	8	92%	0	1	8%
Total	**65**	**157**						

[1)] ACR = Accident cost rate [Euro/1000 veh∗km];
[2)] ACR_{ref} = Accident cost rate of reference road section [Euro/1000 veh∗km];

Fig. 3: Share of curve radii R≤1000m with below-/above-average accident risk



The result can be described as follows:

- 60% of the 15 circular curves with R<650m show a higher accident risk than their reference route section. Even those radii with a very low speed limit have an increased risk of accidents.
- Circular curves with radii of 650m ≤ R <900m have a significantly lower accident risk than circular curves with very small radii R<650m. Less than one third of the examined 32 circular curves have an increased risk with an accident cost rate above the average, half of them in connection with an unfavorable radius relation.
- A differentiation of the accident risk of the two radius groups from R≥650m to R≤900m cannot be proven.

- An unexpected result is shown in radius group 900m ≤ R < 1000m, in which 2 out of 5 circular curves with R=900m show far above-average accident cost rates. Both curves connect, after transition, to a straight line. In contrast all other circular curves of this radii group they show a far above-average accident risk. To evaluate this result, an analysis of the single car accidents of the two circular curves with far above-average accident cost rates was carried out, which is presented in Chapter 2.2.3.5.
- The 13 evaluable circular curves with R=1000m prove to be very safe. Only one has an accident cost rate slightly above that of the reference road section.

Statistical evaluation by method 2

Method 2 uses the weighted average of the entire radius group for better statistical validation. The weighting is performed on the respective length of the estimated curve. The entire network of motorway-like roads under investigation, except for the radius group examined, serves as a reference section. The evaluated radii and radius groups are identical to those in the evaluation according to method 1.

A radius group shows an increased accident risk if its weighted average accident cost rate is higher than that of the reference section.

Method 2 relative safety risk of a radius group can be calculated from 100m-intervalls (see fig. 2 above) as follows:

$$Sr = \frac{ACRgroup}{ACRref} = \frac{\frac{\sum_{i=1}^{q} ACR\ (100m)i}{qx100m}}{ACR\ ref} \qquad \textbf{[Equitation 6]}$$

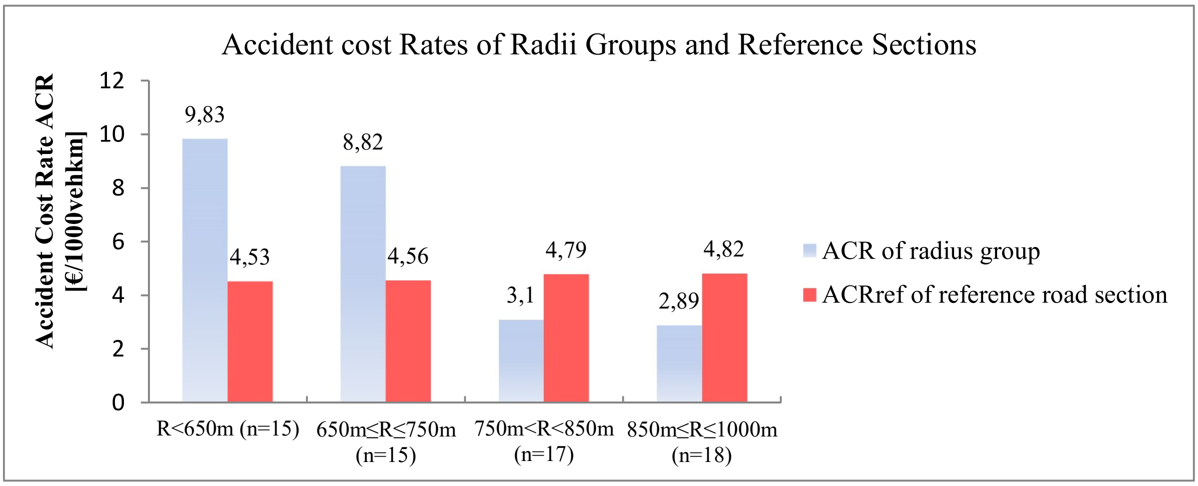
Sr =	Relative safety risk of a radius group compared to the reference road section
ACR $(100m)_i$ =	Accident cost rate of the i-th 100m-intervall within and adjacent of the arc of a circle
q =	Number of 100m sections inside and at the edge of all arcs of the radius group
ACR_{ref} =	Accident cost rate of reference road section

Table 5: Evaluation of entire radii groups

	Group of Radii				Reference Roadways			ACR/ACR_{ref}
	No. of curves [n]	No. of accidents [n]	Total length [km]	ACR [1000€/vehkm]	No. of accidents [n]	Total length [km]	ACR_{ref} [1000€/vehkm]	
R<650m	15	45	5.8	9.83	861	161.2	4.53	**2.17**
650m≤R≤750m	15	32	6.1	8.82	874	160.9	4.56	**1.93**
750m<R<850m	17	40	7.4	3.10	866	159.6	4.79	0.65
850m≤R≤1000m	18	40	6.7	2.89	866	160.3	4.76	0.61
Total	**65**	**157**	**26.0**					

ACR = Average Accident Cost Rate within the radius group
ACRref = Average Accident Cost Rate of reference roadway (= rest of evaluated motorway-like network)

Fig. 4: Accident cost rates of radii groups and their reference sections



The results of evaluation according to method 2, shown in table 5 and figure 4, can be described as follows:

- Both radius groups R<650m and 650m≤R≤750m have a significantly higher accident risk than those with larger radii.
- The accident risk of radii group R<650m is about 12% higher than that of radius group 650m≤R≤750m
- Circular curves with radii R>750m do not show an increased risk of accidents and are not critical from a safety point of view.

2.2.2.5 Influence of the sequence of radii

In the existing network of motorway-like roads, all circular curves with very small radii of R<650m and many circular curves with small radii of 650m≤R<1000m connect after transition at least in one direction to a circular curve whose radius is more than 1.5 times the small radius. This can be explained by the fact that in the earlier guidelines for the alignment prior to the RAA 2008 there was no special rule on the radius ratio on motorway-like roads.

It should therefore be examined whether a higher accident risk of circular curves with small radii can be attributed solely to the small radius of the curve or additionally to the unfavorable radius relation. For this purpose, a section with a sequence of small circular curves had to be searched for in the existing network, where the radius ratio of R1/R2≤1.5 is at least approximately fulfilled and which is free from other influences and causes of accidents such as interchanges. If the accident risk of this section of the route has a similarly high accident risk as the individual radii, this can be interpreted as an indicator that the accident risk is largely determined by the small radius.

Only two sequences of circular curves with small radii meeting the above conditions could be found throughout the network examined (see table 6):

- The B 10 near Ebersbach has three opposite circular curves with a sequence of R=600m/600m/750m, of course with a transition in between. The accident cost rate over the entire distance is 50% higher than the accident cost rate for the reference road, although there is a favorable radii ratio.

- On the 4 km long section of the B 29 near Lorch, which is perceived as “curvy”, 6 out of total 7 circular curves have radii between R=700m and R=800m. The accident cost rate of the total distance is ACR=4.76 which is almost identical with the accident cost rate of the reference section (ACR_{ref}=4.78).

Table 6: Accident cost rate of sequences of radii on motorway-like roads

Example No.		Sequence of Radii [m]	Number of Accidents	Accident Cost Rate Selected Section [€/1000vehkm]	Accident Cost Rate Reference Section ACR_{ref} [€/1000kfzkm]	Deviation [%]
1	B10 Ebersbach (0,8 km)	600/600/750	14	12,24	7,81	+56
2	B29 Lorch (4,4 km)	800/700/750/ 2500/700/800	6	4,76	4,78	None
3	B27 Schlaitdorf to junction Aichtal (4,5 km)	3000/2500/ 1500/1800	27	2,28	3,58	-34%

The results of examples 1 and 2 tend to show that circular curves with R<650m have a significantly higher accident risk than larger radii even if the radius ratio R1/R2≤1.5 is fulfilled. Example 2 shows that radii from R≥700m to R=900m do not show an above-average accident risk if the radius ratio R1/R2≤1.5 is fulfilled.

The influence of the radius ratio of radii R≥1000m can be estimated in a sequence of radii using the example 3. The 4.5 km long section of B 27 from Schlaitdorf to Aichtal has no intersection where the risk of accidents is generally higher. For this route section the accident cost rate is ACR=2.26, just two thirds of the accident cost rate for the entire reference road section (ACR_{ref}=3.58). This confirms that larger radii with R≥1000m do not have an increased accident risk, even if the radii ratio is R1/R2>1.5.

2.2.2.6 Conclusions

Both the individual assessment of the safety risk of small circular curves and the consideration of sequences of radii of small circular curves indicate that radii below R=650m should not be used for safety reasons. It is therefore recommended to use a minimum radius of R_{min}=650m on motorway-like roads in the future.

Radius sequences with R≥1000m can generally be regarded as safe, regardless of the ratio to the subsequent radius. This also results in the requirement for a minimum radius of R=1000m following a longer intermediate straight line.

Circular curves between R=650m and R=900m can be accepted as safe if the radius ratio R1/R2≤1.5 is fulfilled. However, their accident risk tends to be higher than that of circular curves with R≥1000m.

2.2.3 Evaluation of electronic accident map

As already explained in Chapter 2.1, in addition to the statistical evaluations, visual assessments of the safety risk of small circular curves with radii from R≤1000m were carried out based on the electronically produced accident maps of the Road Safety Screening and the video images from the pavement management recording. Only single car accidents were considered, but over the entire available period from 2012.

A total 15 circular curves and sequences of circular curves with small and very small radii were investigated using this method, of which the investigation of 2 curve sections are described here as an example. The complete investigation can be found in [3].

Evaluation of Radii R=900 with unexpected high accident cost rates

As described above, two radii R=900m with an unusually high accident cost rate were found in the statistical evaluation according to method 1. The electronic accident map was used to check whether the increased accident risk is related to the curve radii.

The two particularly accident-prone circular curves are part of a sequence of circular curves and two straight lines with intermediate transitions:

R=1513m/<u>R=887m</u>/**R=∞(L=220m)/**<u>R=913m</u>/**R=∞(L~1000m)**

All single car accidents in this section are shown in the fig. 5 (next page). The individual evaluation of the total of 11 accidents revealed that the cause of the accident was noted only in 5 accidents. Three of these 5 accidents occurred immediately after the long straight line with a length of L~1000m followed the transition by a radius R=900m. Only one, however, per direction in the section with R=900m following the shorter straight line (L=220m) after transition. Consequences were severe, three with severe injury and one with fatal injury. It can therefore be concluded that even on motorway-like roads a circular curve with a radius greater than R=900m should follow a long straight line. Shorter straight lines should be avoided as well. The remaining 6 accidents had other causes (influence of alcohol, fatigue, wrong merging) that cannot be attributed to the alignment.

Longer sequence of small radii on a long-distance motorway

A section of the A 8 long-distance motorway near Remchingen (Location see fig. 1) originally built in 1937 was realigned in the 1970s with a sequence of opposite circular curves with the following radii (each with transition in between):

R=1175m/580m/580m/609m/580m/1200m/700m/800m/1500m

The gradient is around 5%. This is the only reference route with such small radii on a long-distance motorway in Baden-Württemberg that was built after 1970. The motorway had 3 lanes uphill and 2 lanes downhill before the 6-lane extension was completed in 2016. Due to the 6-lane extension, no accident cost rates for a 3-year period are currently available for the route. For this reason, only the accident data on single car accidents were evaluated before the expansion. The speed was limited to 100 kph.

The result is shown in fig. 6 (next page). At the beginning of the sequence of R=600m radii, accidents occur frequently, although the alignment was completely uniform. The larger radius ratio of R1/R2>1.85 leads to accident accumulations even with a radius of R=800m. It turns out that the results of investigation into the accident risk of small radii on motorway-like roads also apply to motorways.

Fig. 5: Single car accidents of an R=900m after a straight line/transition – electronic accident map

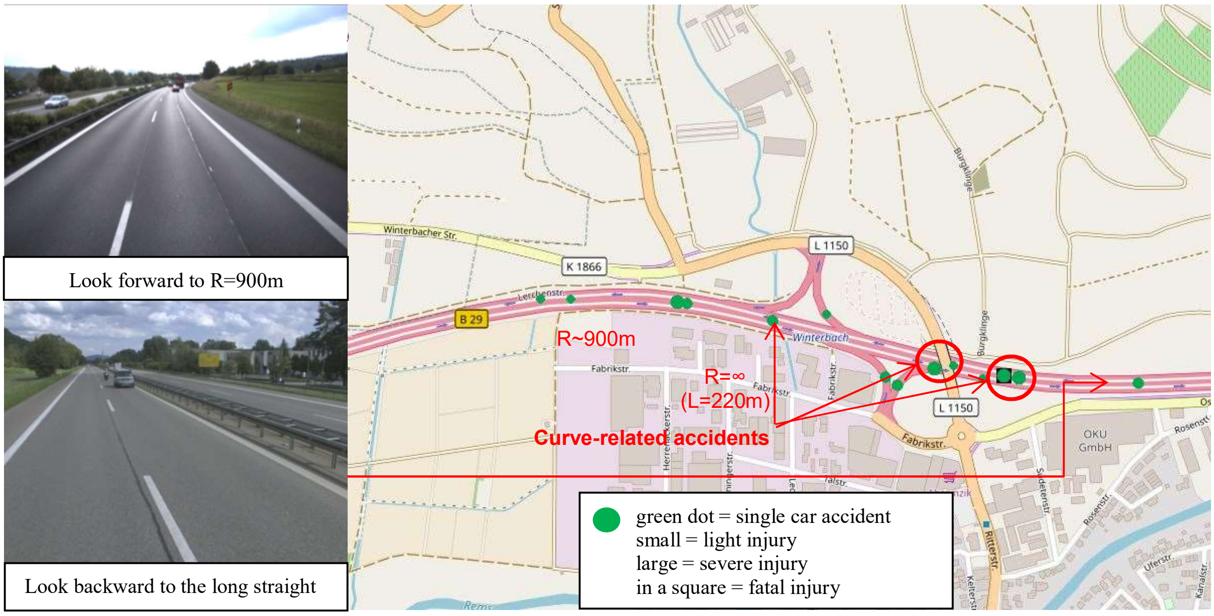


Fig 6: Single car accidents of a sequence of radii R=600m, R=700m und R=800m on the long-distance Motorway Autobahn A 8 near Remchingen, Germany

3. Recommendations for the geometric design of motorways

The results of the investigation show that circular curves with very small radii of $R<650m$ have an above-average accident risk despite speed restrictions. Radii in the range between $R\geq650m$ and $R=900m$, on the other hand, have a significantly lower accident risk if the radius ratio is $R1/R2\leq1.5$. Circular curves with $R\geq1000m$ can generally be classified as safe.

The study results in recommendations for further extension of motorway-like roads to be introduced by the follow-up of German Guidelines for Motorways:

- The minimum radius of circular curves for motorway-like roads of Design Class EKA 2 should be increased to $R=650m$.
- In addition to the minimum radius of $R=650m$, the new Guideline should also contain a recommendation for the EKA 2 to avoid radii $R<750m$ if possible.
- The radius relation for smaller successive radii of $R1/R2\leq1.5$ should be mandatory up to a radius of $R1\leq1000m$.
- The minimum radius following a long straight line should be $R=1000m$.
- The design speed of the EKA 2 should be adapted to the actual driving behavior and raised to V=110 kph. Thus, the other elements of the alignment, dimensioned dynamically by the given design speed also adapt better to the larger minimum horizontal radius recommended for safety reasons.

Addendum: The results have now been introduced into the draft of the new German Guidelines for Motorways. The state of Baden-Württemberg is already planning some 30 km of motorway-like roads with the new parameters. This did not result in increased construction costs.

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