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Rotation of the Carriageway (Superelevation) in Germany and Austria – State of the Art

Kerim Hrapović*
EUR ING Civil Eng., Ph.D., Mst. AUSTRIA
General sworn and court certified expert in civil engineering, loss adjuster in civil engineering, chartered engineering consultant, Austria

ABSTRACT

The change in carriageway cross slope (rotation; torsion; superelevation) usually takes place within the transition curve, regardless of the reference line around which the carriageway surface is rotated. If there is no transition curve, half of the rotation is carried out before and half after the point where the two elements meet. In the exceptional case that the rotation takes place on a straight line, it should be positioned either at the beginning or at the end of the straight line. Rotation on structures should be avoided wherever possible (RAL, 2012). Transition curves are essential on all motorways, with one key exception: if the angle change in the curve is minimal (γ is less than 10 gon or 9°, indicating a flat curve), it may be impractical to incorporate a transition curve, followed by a circular curve, and then another transition curve. In such situations, the minimum curve length (L_{min}) should be at least 300 meters (RAA, 2008). As a rule, transition curves should be used between straight lines and circular arcs as well as between circular arcs. In justified exceptional cases, however, transition curves can be omitted if the differences in curvature between the two elements are very small. Such a waiver is possible for the transition from a straight line to a radius of $R \geq 1{,}000$ m and for a spiral line between two radii of $R \geq 2{,}000$ m (RAL, 2012).

Keywords: clothoid, curve radius, relative grade, road, road alignment, rotation of the carriageway, superelevation, transition curve

INTRODUCTION

Basics

The rotation of the carriageway (change in the carriageway cross slope; superelevation) refers to the change in the cross slope caused by the rotation of the carriageway surface around the reference line. This occurs in the transition curve due to the different cross slopes of the alignment elements connecting to the clothoid. A change in cross slope without a change in the direction of travel in the transition curve occurs, for example, when a straight section (with a cross slope of 2.5 %, for example) transitions to a circular curve (with a cross slope of 7.0 %, for example). A change in cross slope with a simultaneous change in the direction of travel occurs, for example, in a spiral line (Figure 1, Figure 2). Between circular arcs with different directions, the cross slope reaches a zero point. A measure of this rotation is the so-called "relative grade". To reduce areas with poor drainage, the relative gradient in superelevation development sections must not fall below the minimum relative grade ($_{min}\,\Delta s$) within the range from $+_{min}\,q$ (+2.5%) through 0% to $-_{min}\,q$ (–2.5%). The relative grade Δs [%] is the difference between the longitudinal gradient along the edge of the carriageway and the longitudinal gradient along axis of rotation. The crossfall of a carriageway is adjusted within a specific section of the road referred to as the superelevation development section. Throughout this

* Email: kerimhrapovic046@gmail.com

section, the edges of the carriageway are elevated, and the roadway is rotated around a designated "axis of rotation". This superelevation adjustment (or carriageway rotation) typically occurs within the transition curve, irrespective of the chosen axis of rotation. All paved strips adjacent to the carriageway are also rotated either within the transition curve or within the corresponding transition section. Transition curves are provided between circular curves and between straights and circular curves. The purpose of transition curves is (RAA, 2008):

- to allow for superelevation development between the different crossfalls;
- to allow for gradual steering in and out of the curve and in so doing
- to ensure a continual change in the centrifugal acceleration that occurs when driving in a curve; and
- to create a swift and optically satisfactory alignment by gradually changing the curvature.

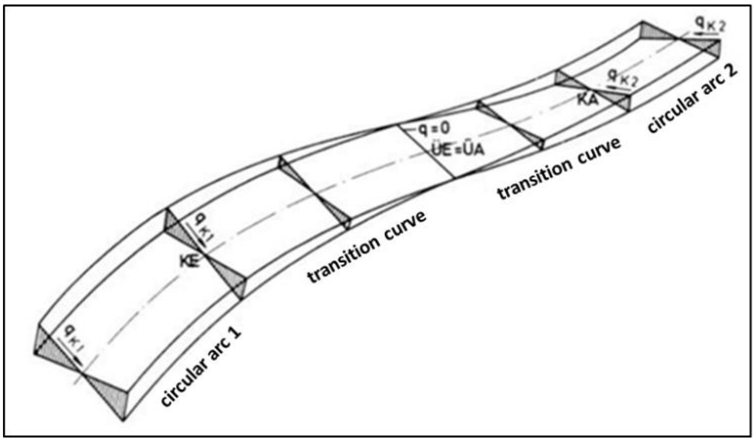


Figure 1: Perspective view of a rotation (superelevation) in a helical line with change in the direction of the transverse inclination (Berger, Meschnik, Raich, & Stark, 2011) (Edited by author)

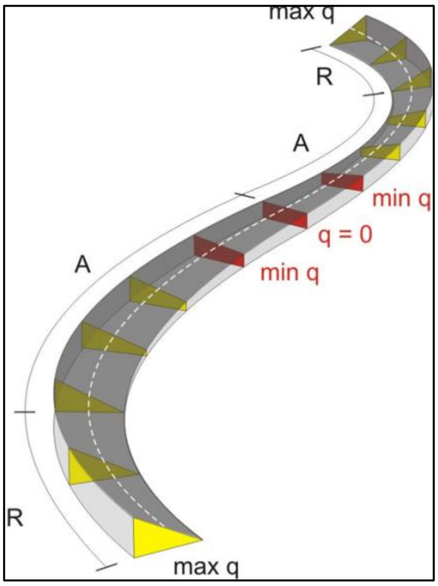


Figure 2: Perspective view of a rotation (superelevation) in a helical line with change in the direction of the transverse inclination (Ressel, n.d.)

The superelevation development areas of wide carriageways (≥ 3 FS) - areas at risk of aquaplaning are shown in Figure 3.

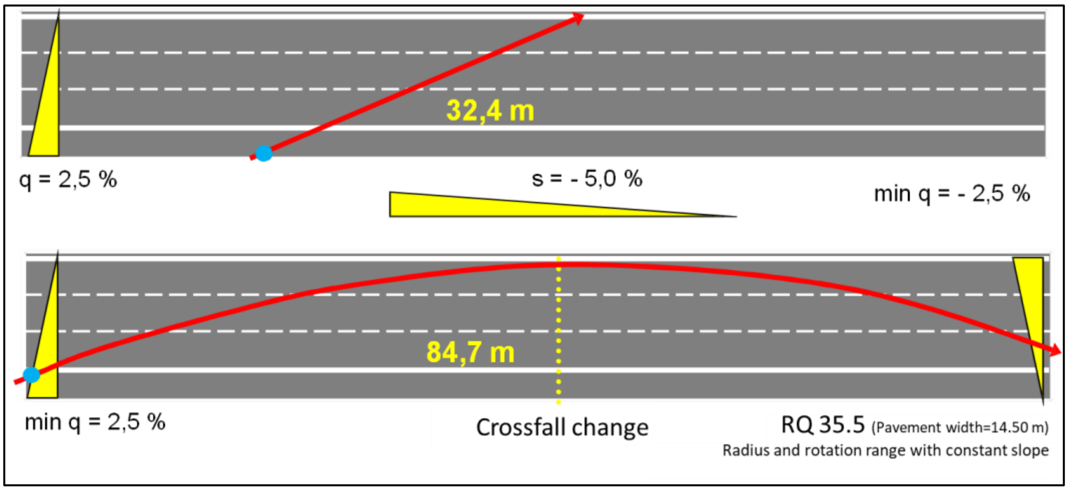


Figure 3: The superelevation development areas of wide carriageways (≥ 3 FS) - areas at risk of aquaplaning (Ressel, n.d.) (Edited by author)

ROTATION OF THE CARRIAGEWAY (SUPERELEVATION) - STATE OF THE ART IN GERMANY

Standard Rotation (Superelevation) of the Carriageway in Germany

According to the guidelines (RAS-L, 1984), (RAL, 2012) and (RAA, 2008) on all roads in Germany, the minimum cross slope is at least q = 2.5 % and the directional carriageways are equipped with a one-sided cross slope. On bends, the cross slope usually leans towards the inside of the bend. The change in cross slope on bends in opposite directions takes place in the superelevation development sections with zero crossing. This connecting area is located in the transition curve. If there is no transition curve, the rotation is divided equally between the straight section and the circular arc. The rotation of the side strips is also carried out in the transition curve.

According to (RAL, 2012), the bends are given a cross slope to the inside of the bend ("positive cross slope") for reasons of driving dynamics and for better recognisability. The maximum transverse gradient of the country roads is q = 7.0 %. The minimum crossing gradient here is also q = 2.5 %. Figure 4 shows the cross slope as a function of the radius. The values should be rounded up to 0.5 % in each case.

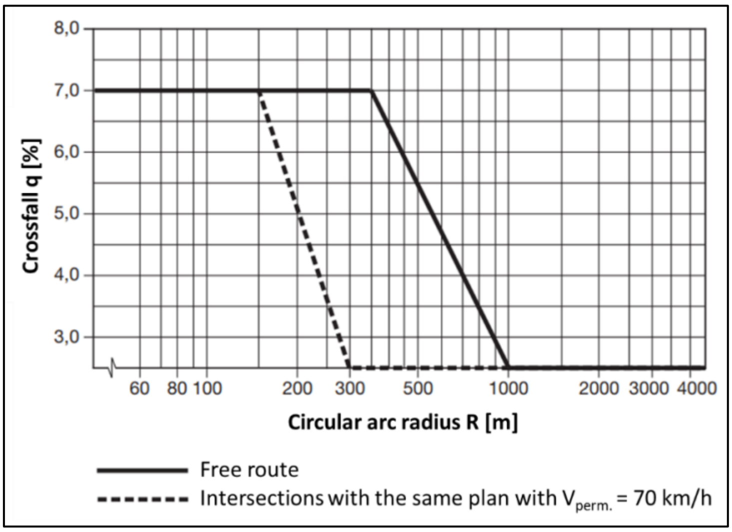


Figure 4: Cross slope of country roads as a function of the circular arc (RAL, 2012) (Edited by author)

For radii R > 3,000 m, a negative cross slope of q = –2.5 % can be arranged in accordance with (RAL, 2012) if this can avoid a poor drainage zone or, in the case of two-lane roads, drainage on the central reserve.

For motorways in Germany, the maximum cross slope is limited to max q = 6.0 % (Figure 5). In exceptional cases, e.g. if the minimum radii are not met, the cross slope can be increased to 7.0 % (RAA, 2008).

To prevent vehicles from slipping on icy roads in winter, the resultant slope *p* (slope of the fall line [see Formula 1]) on rural roads should be limited to $_{max}$ p = 10.0 % (RAL, 2012). For motorways, the inclination is limited to $_{max}$ p = 9.0 % according to (RAA, 2008). On bridges, the cross slope should be limited to $_{max}$ q = 5.0 %.

Formula 1: resultant slope

$$p = \sqrt{s^2 + q^2}$$

p [%]	resultant slope
s [%]	longitudinal gradient
q [%]	cross slope

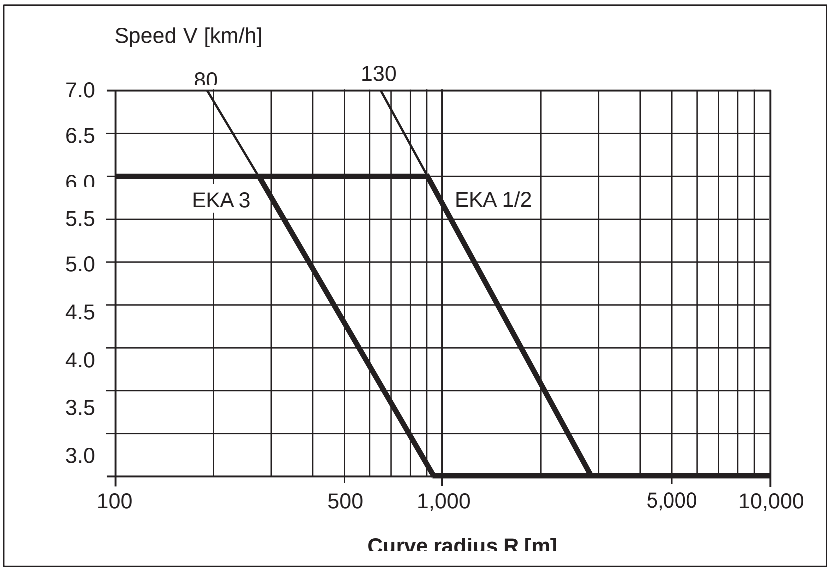


Figure 5: Cross slopes of motorways depending on the design class and the curve radii (max q = 6.0 %, exceptional case q = 7.0 %) (RAA, 2008) (Edited by author)

According to (RAL, 2012), the carriageway of one-lane roads is generally rotated around the axis of the carriageway (in the case of two-lane roads around the axis of the directional carriageway) (Figure 6). For better adaptation to the local conditions, the turning can also take place around the inner or outer edge of the carriageway in justified exceptional cases.

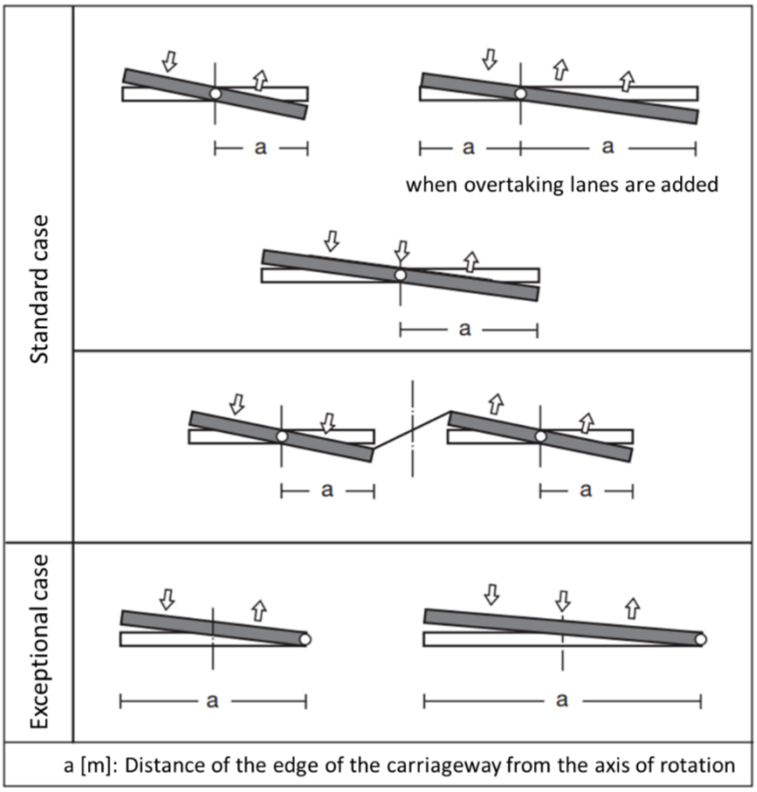


Figure 6: Axes of rotation of the carriageway on superelevation development sections (country roads) (RAL, 2012) (Edited by author)

The relative grade Δs [%] is the difference between the longitudinal gradient along the edge of the carriageway and the longitudinal gradient along axis of rotation. It is calculated as follows [Formula 2]:

Formula 2: The relative grade

$$\Delta s = \frac{q_e - q_q}{L_v} \cdot a$$

q_e [%] crossfall of the carriageway at the end of the superelevation development section

q_a [%] crossfall of the carriageway at the start of the superelevation development section (q_a should be negative if in opposite direction to q_e)

L_V [m] superelevation development length

a [m] distance between the edge of the carriageway and the axis of rotation

On motorways, the crossfall is generally changed by rotating the pavement around the axes of the carriageways (Figure 7, case 1). In special cases – e.g. around central reserve crossing points, tunnels, and in cases where visibility is reduced at central reserves – carriageways can be rotated around the edges of the carriageway at the central reserve or around the road centre line (Figure 7, cases 2 and 3) (RAA, 2008).

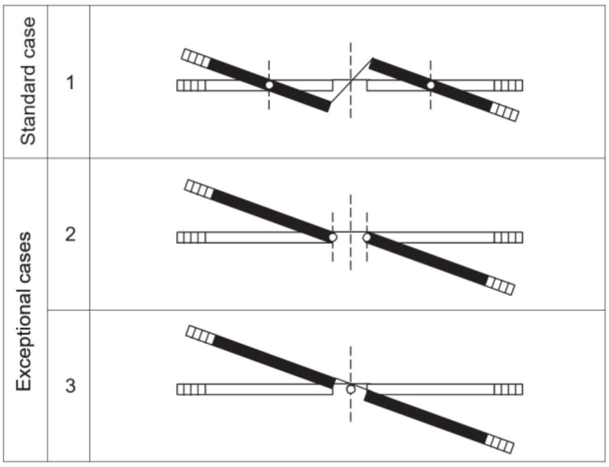


Figure 7: Axes of rotation of the carriageway on superelevation development sections (motorways) (RAA, 2008) (Edited by author)

The relative grade Δs [%] is the difference between the longitudinal gradient along the edge of the carriageway and the longitudinal gradient along axis of rotation. The maximum relative grade ${}_{max}\Delta s$ should not exceed the values in Table 1 in order to avoid a too rapid increase in the cross slope. These values are automatically adhered to when using the recommended radius ranges and the corresponding clothoid parameters. Exceeding ${}_{max}\,\Delta s$ can be counteracted by selecting larger clothoid parameters. If ${}_{min}\,\Delta s$ according to Table 1 is greater than ${}_{max}\,\Delta s$ when the axis of rotation is off-centre, then ${}_{min}\,\Delta s$ is decisive.

Table 1: Limiting values for the relative grade (country roads) (RAL, 2012)

Design class	**${}_{max}\,\Delta s$ [%]**	**${}_{min}\,\Delta s$ [%] at $q \leq 2{,}5$ %**
EKL 1/EKL 2	0,8	0,10 · a
EKL 3	1,0	
EKL 4	1,5	
a [m]: Distance between the edge of the carriageway and the axis of rotation		

Table 2 applies analogously to motorways.

Table 2: Limiting values for the relative grade (motorways) (RAA, 2008)

Design class	**min Δs [%]** at $q \leq 2.5$ %	**max Δs [%]** at $a < 4.00$ m	**max Δs [%]** at $a \geq 4.00$ m
EKA1, EKA 2	0.10 · a	0.225 · a	0.9
EKA 3		0.25 · a	1.0
a [m]: Distance between the edge of the carriageway and the axis of rotation, ${}_{max}\,\Delta s \geq {}_{min}\,\Delta s$			

Design Classes according to RAL and RAA

General

The (RAL, 2012) (German Guidelines for the Design of Rural Roads) form the basis for the design of safe and functional rural roads. The main aim of the specifications is to largely standardise the design of rural roads. To this end, four design classes for rural roads are defined. The design classes are mainly determined by the function of a road in the road network, which is expressed by the road category according to the "Guidelines for Integrated Network Design"

(Germ. “Richtlinien für integrierte Netzgestaltung”) (RIN, 2008). This categorisation helps to determine the appropriate equipment and design of rural roads to meet specific requirements.

The design classes according to (RAL, 2012) serve the purpose of both promoting the uniformity of roads of a certain category and clearly distinguishing roads of different categories from one another. This supports an appropriate driving style according to the network function. By ensuring that roads in the same category have similar design and layout features, the driving experience becomes more consistent, which improves predictability and safety. At the same time, roads of different categories are designed to take into account the specific requirements and needs of road users for each road type. This targeted differentiation and standardised design makes it easier for drivers to recognise what type of road they are on, leading to an adapted driving style that optimises traffic flow and road safety. It is an important approach to improving the functionality of the road network and making traffic flows more efficient. The (RAL, 2012) apply to rural roads of category LS I to LS IV according to the (RIN, 2008) (Table 3). The road category according to the (RIN, 2008) is the input parameter for determining the design class for rural roads.

Table 3: Design classes for rural roads depending on the road category. Own representation according to (RAL, 2012)

Road category	Design class
LS I	EKL 1
LS II	EKL 2
LS III	EKL 3
LS IV	EKL 4

Design class EKL 1

According to (RAL, 2012), roads in design class EKL 1 are three-lane roads with a standard cross-section of RQ 15.5. These roads are routed without level crossings at the junctions. Both directions of travel are separated from each other by a central reserve. The road is characterised by a regular alternation of two-lane and single-lane sections. Approximately 40% of the total route is equipped with traffic-safe overtaking facilities for each direction of travel. This means that vehicles can overtake safely and legally on these sections in order to improve traffic flow and reduce potential traffic jams (Figure 8, Figure 9 Figure 10).

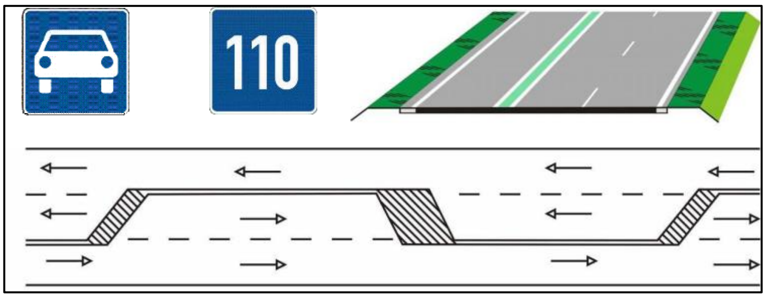


Figure 8: Design class EKL 1 (Hartkopf, 2013) (Vetters, 2012) (Edited by author)

Figure 9: Example of a road in design class EKL 1 (Vetters, 2012)

Figure 10: Example of a road in design class EKL 1 (Hartkopf, 2013)

Design class EKL 2

Roads in design class EKL 2 are two-lane roads with a standard cross-section of RQ 11.5. Overtaking lanes are created in sections on these roads, either for one or, as a rule, for the other direction of travel. This concept allows overtaking manoeuvres to be largely concentrated in overtaking sections that are safe from a traffic point of view, while overtaking manoeuvres that require the use of oncoming traffic lanes are to be largely avoided. The targeted arrangement of overtaking lanes in certain sections is intended to facilitate safe overtaking and minimise the risk of dangerous situations that could arise from unsafe overtaking manoeuvres (Figure 11, Figure 12 Figure 13).

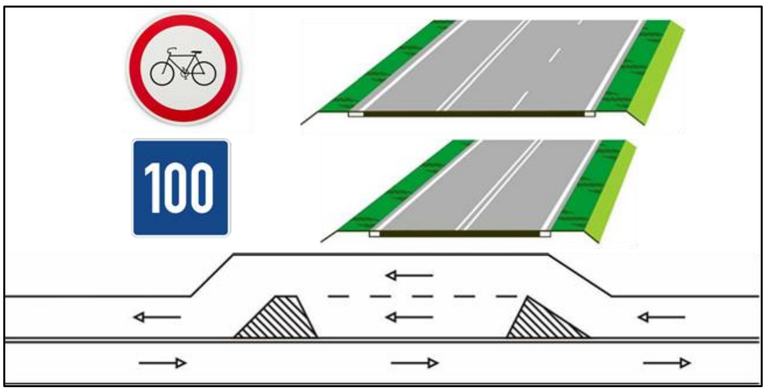


Figure 11: Design class EKL 2 (Hartkopf, 2013) (Vetters, 2012) (Edited by author)

Figure 12: Example of a road in design class EKL 2 (Vetters, 2012)

Figure 13: Example of a road in design class EKL 2 (Hartkopf, 2013)

Design class EKL 3

Roads of design class EKL 3 are two-lane roads with a standard cross-section of RQ 11. The two lanes are separated from each other by a simple guideline in the centre of the carriageway. In sections with appropriate geometric and traffic conditions, overtaking is permitted on these roads with the use of the oncoming lane. This means that in certain sections where visibility, curve radii and other safety factors are suitable, vehicles can cross the guide line if necessary and use the oncoming lane to overtake other vehicles. However, special care must be taken to ensure that oncoming traffic is not jeopardised (Figure 14, Figure 15).

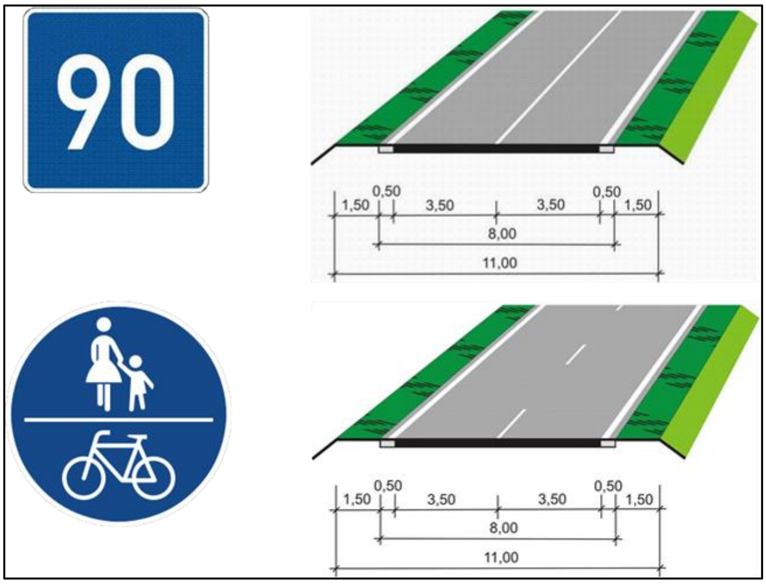


Figure 14: Design class EKL 3 (Hartkopf, 2013) (Edited by author)

Figure 15: Example of a road in design class EKL 3 (Lippold, 2013)

Design class EKL 4

Roads in design class EKL 4 are one-lane roads with a standard cross-section of RQ 9 that are used for local traffic. This means that these roads can only be travelled in one direction and are mainly intended for regional or local traffic (RAL, 2012) (Figure 16, Figure 17 and Figure 18).

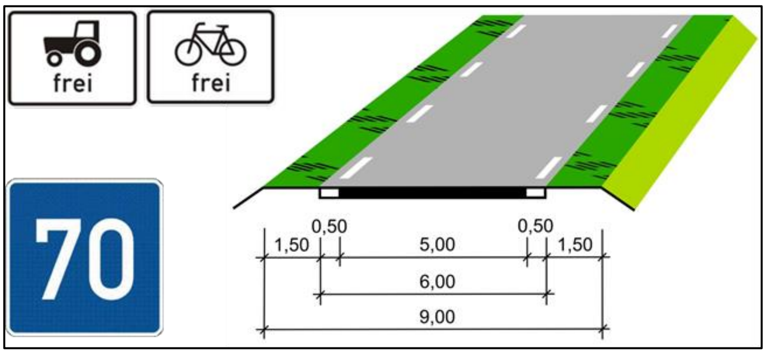


Figure 16: Design class EKL 4 (Hartkopf, 2013) (Lippold, 2013) (Edited by author)

Figure 17: Example of a road in design class EKL 4 (Hartkopf, 2013)

Figure 18: Example of a road in design class EKL 4 (Lippold, 2013)

Forms of Superelevation Development Sections in Germany

The superelevation development length

The minimum superelevation development length is calculated as follows (RAL, 2012) [Formula 3]:

Formula 3: The minimum superelevation development length

$$_{min} L_V = \frac{q_e - q_a}{\max \Delta s} \cdot a$$

$_{min}$ L_V [m]	minimum superelevation development length
q_e [%]	crossfall of the carriageway at the end of the superelevation development section
q_a [%]	crossfall of the carriageway at the start of the superelevation development section (q_a should be negative if in opposite direction to q_e)
$_{max}$ Δs [%]	maximum relative grade
a [m]	distance between the edge of the carriageway and the axis of rotation

The basic forms of superelevation development sections are illustrated in Figure 19 und Figure 20.

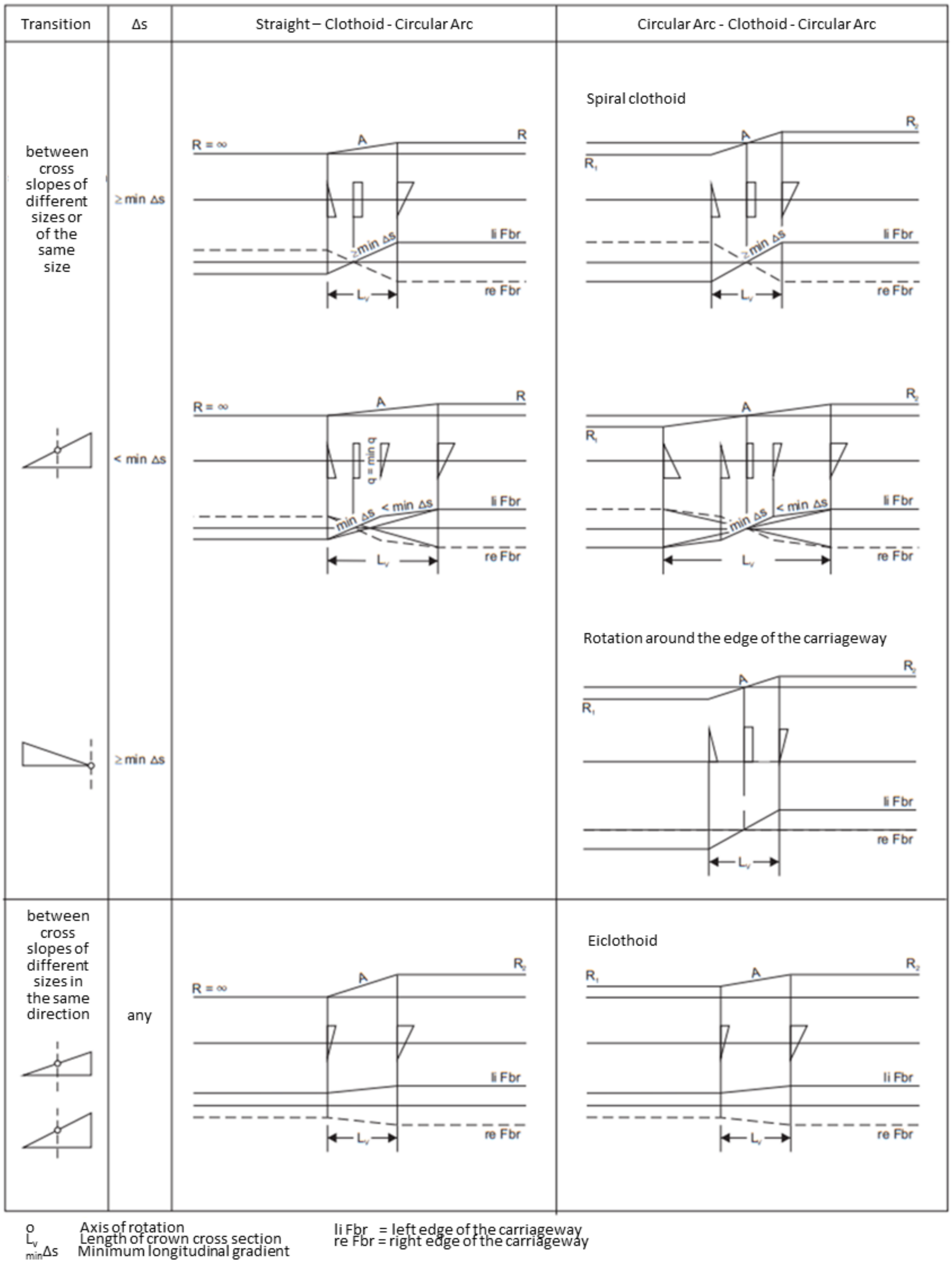


Figure 19: Forms of superelevation development sections (RAL, 2012) (Edited by author)

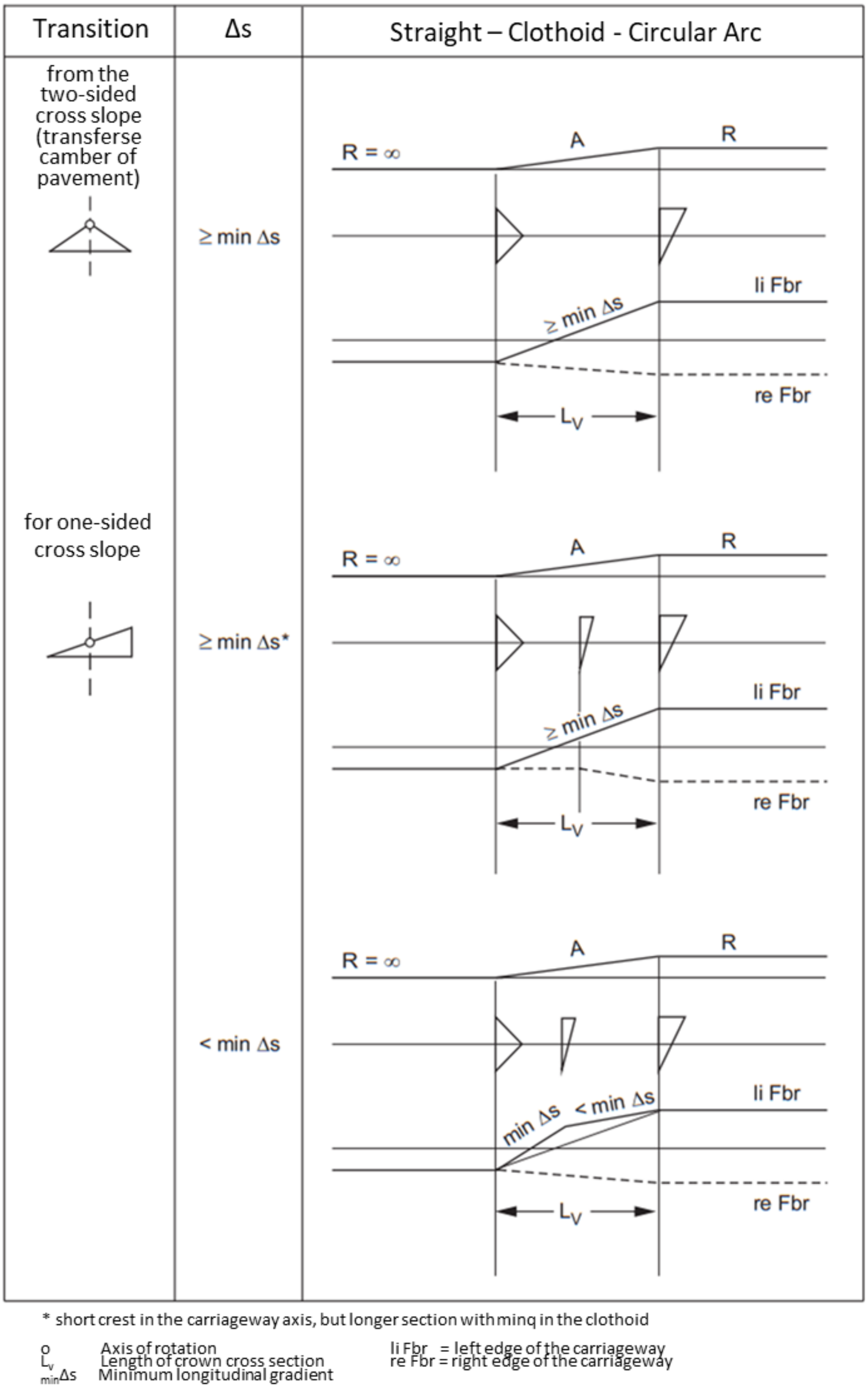


Figure 20: Forms of superelevation development sections (Transferse camber of pavement) (RAL, 2012)

The crest rotation of the carriageway (the crest superelevation) in Germany

The (RAS-L, 1984) and the (RAA, 2008) provide for the use of diagonal rotation of the carriageway (the crest superelevation) as a solution for eliminating sections with poor drainage capacity, especially in areas with rotations that have a zero point (Figure 21, Figure 22). However, diagonal rotation of the carriageway (the crest superelevation) is described as technically complex, as it has to be partially installed by hand (Lippold, Vetters, Ressel, & Alber, 2019).

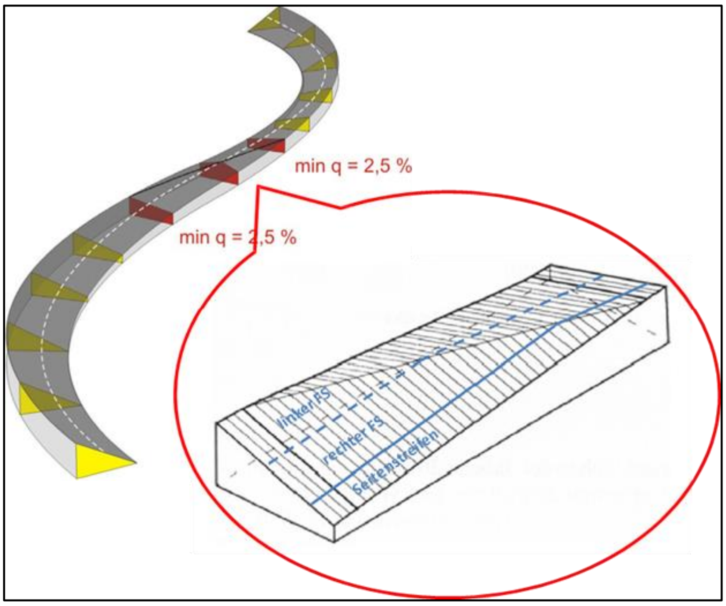
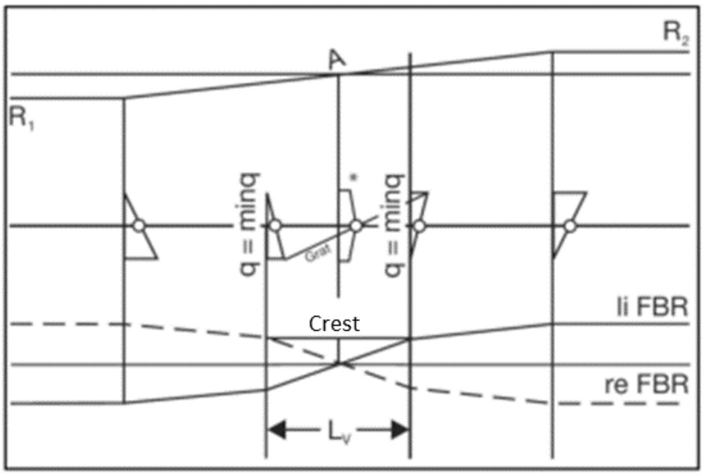


Figure 21: Reverse curves: Transition from the one-sided cross slope for one-sided cross slope (the crest superelevation, Germ. "Schrägverwindung" (Ressel, n.d.) (Edited by author)



li Fbr = left edge of the carriageway; re Fbr = right edge of the carriageway

Figure 22: The crest superelevation (Germ. "Schrägverbindung") (Lippold, Vetters, Ressel, & Alber, 2019) (RAA, 2008) (Edited by author)

For reasons of driving dynamics, the crest superelevation length is determined as a function of the carriageway width and the design speed [Formula 4]:

Formula 4: The crest superelevation length

$$L_V = 0{,}1 \cdot B \cdot V_e$$

L_V [m]	the crest superelevation length
B [m]	carriageway width
V_e [km/h]	design speed

In the guidelines for the design of motorways (RAA, 2008), the use of the crest superelevation is currently restricted to expansion. There is currently no information on the crest superelevation length and the design of the crest. This information is to be added in a future revision of the regulations (Lippold, Vetters, Ressel, & Alber, 2019).

ROTATION OF THE CARRIAGEWAY (SUPERELEVATION) - STATE OF THE ART IN AUSTRIA

Standard Rotation (Superelevation) of the Carriageway in Austria

According to (RVS 03.03.23, 2014), the minimum cross slope for the entire carriageway is q = 2.5 %. This cross slope is implemented on directional carriageways with a one-sided cross slope. On bends, the carriageway is generally inclined towards the inside. The rotation of the carriageway takes place in the transition curve. In order to avoid poor drainage zones, the minimum ramp slope according to Formula 5 must be observed for rotations with a zero crossing in the range of $-2.5\ \% \leq q \leq 2.5\ \%$.

Formula 5: Minimum relative grade

$$_{min}\,\Delta s = 0{,}1 \cdot a$$

$_{min}\,\Delta s$ [%]	minimum relative grade
a [m]	Distance of the edge of the carriageway including the hard shoulder from the axis of rotation

If the minimum relative grade is not reached, then a split rotation must be applied. In the range of $-2.5\ \% \leq q \leq 2.5\ \%$, the minimum relative grade must then be applied. The remaining rotation is produced on the remaining length of the transition curve. These two forms of rotation of the carriageway are shown in Figure 23.

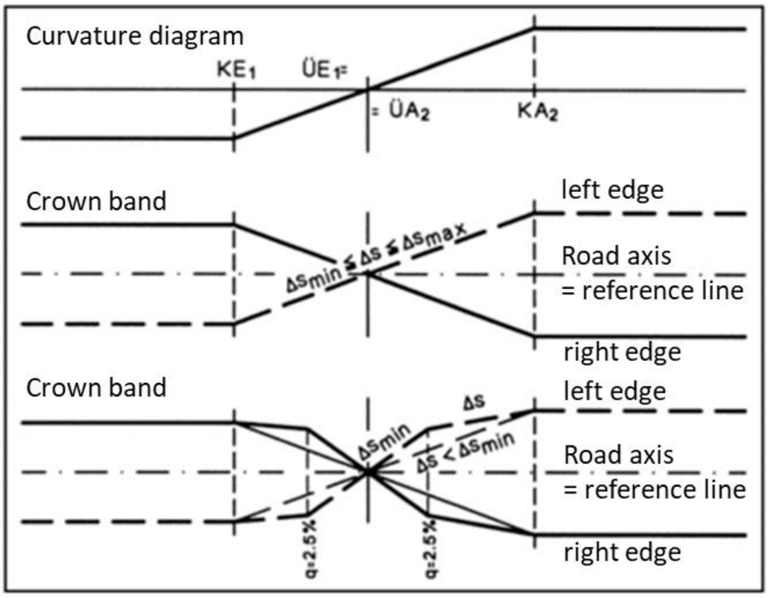


Figure 23: Rotation of the carriageway (superelevation) and split rotation in Austria (Lippold, Vetters, Ressel, & Alber, 2019) (RVS 03.03.23, 2014)

Crest Rotation (Crest Superelevation) of the Carriageway in Austria

According to the Austrian Guidelines for Planning, Construction and Maintenance of Roads (RVS 03.03.23, 2014), if an equal longitudinal slope of the edges of the carriageway s $\geq 0.3\ \%$ cannot be maintained in the range of $-2.5\ \% \leq q \leq +\ 2.5\ \%$, then a crest superelevation (diagonal rotation of the carriageway) can be ordered. The cross slope for the entire carriageway surface is always 2.5 % for crest superelevation (Figure 24, Figure 25).

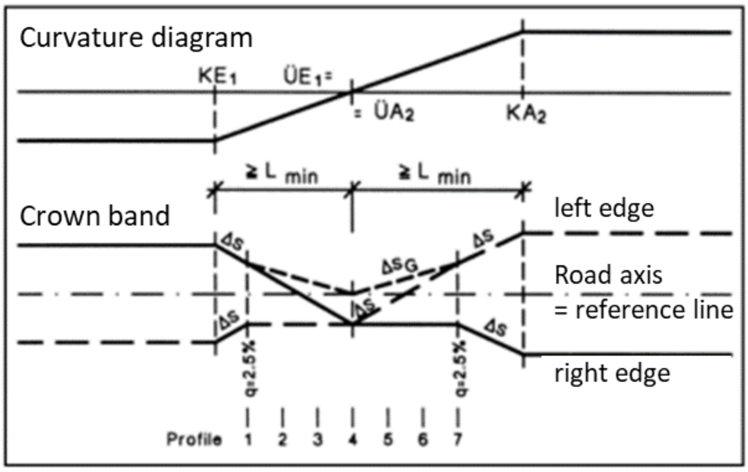


Figure 24: Crest superelevation in Austria (Lippold, Vetters, Ressel, & Alber, 2019) (RVS 03.03.23, 2014)

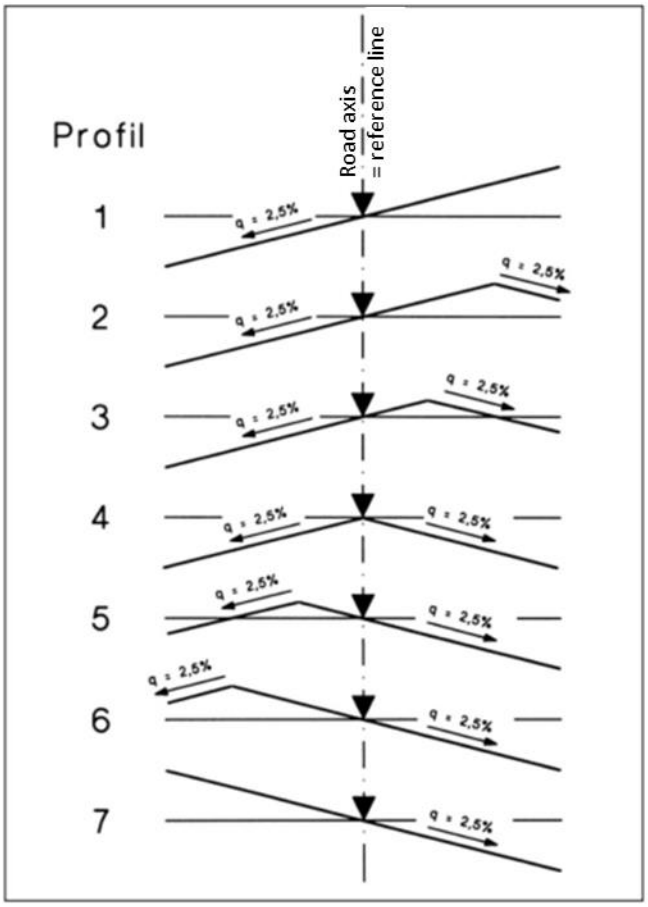


Figure 25: Crest superelevation in Austria (Profile) (Lippold, Vetters, Ressel, & Alber, 2019) (RVS 03.03.23, 2014)

CONCLUSION

The superelevation adjustment (or carriageway rotation) typically occurs within the transition curve, irrespective of the chosen axis of rotation. All paved strips adjacent to the carriageway are also rotated either within the transition curve or within the corresponding transition section. Transition curves are provided between circular curves and between straights and circular curves. To minimize areas with poor drainage, the relative grade in superelevation development sections must not drop below the minimum relative grade ($_{min}$ Δs) within the range of +$_{min}$ q (+2.5%) through 0% to – $_{min}$ q (–2.5%). If, in a continuous superelevation development section, the available relative grade is less than the minimum relative grade ($_{avail}$ Δs < $_{min}$ Δs), the superelevation development must be divided. In such cases, the area where the crossfall passes through zero (between +2.5% and –2.5%) must maintain a relative grade of at least $_{min}$ Δs. The remaining superelevation is then applied over the remaining portion of the transition curve until the crossfall necessary for the circular curve is achieved, while considering the minimum relative grade (Δs < $_{min}$ Δs). Additionally, the longitudinal gradient and the minimum relative grade should be aligned to ensure proper drainage. Designers should strive for a difference of 0.2% between the longitudinal gradient and the relative grade to guarantee this. Neither of the two edges of the carriageway should have a slope that opposes the gradient.

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