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The curve, an accident causing element of road infrastructure

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Abstract. The curve is the main element of the road that modifies the voluntary or involuntary change of the trajectory of road vehicles in space. This scientific paper has been developed by the authors in a logical and elegant manner, in which the essential elements of road curves are treated so that readers can understand their place, role and functional character in today's road infrastructure. In this way, those interested can learn about the theoretical elements concerning the definition and calculation of the characteristic radii of curves, their superimposition and arrangement in space, as well as how curves influence the dynamics of vehicles driving on them. Concerning the concepts of vehicle dynamics in curves, readers can learn about the rolling characteristic of the vehicle tire, the adhesion of the tire to the road (friction between the rubber and the road), the longitudinal adherence of the vehicle tire to the road, the phenomenon of vehicle tire aquaplaning, transverse adhesion of the vehicle tire to the road surface, transverse stability of the vehicle when cornering, the influence of the transverse elasticity of car tires on the trajectory of the car tire when turning, and the manageability of road vehicles when turning. All these aspects present mathematical concepts and computational relations necessary for the design and realization of road curves, as well as mathematical concepts and computational relations governing the dynamics of road vehicles in curves. The paper also deals with a case study in which statistics of motor vehicle accidents occurring in the year 2023 taken in comparison with the year 2022 are presented, in which the curve, the roadway condition and other elements related to the road infrastructure generated them. The conclusions and recommendations of the authors in the field are presented at the end of the scientific article.

Keywords: *curve, overlift, overloading, conversion, road vehicle dynamics, centrifugal force.*

Introduction

The curved road is the arc-shaped public roadway junction that joins two road segments in alignment. Road accidents occur due to vehicle technical problems, bad weather, difficult roads or human error. It is known that when approaching a curve the force that governs vehicle dynamics is the centrifugal force, which becomes proportional to the square of the speed. In practice, approaching curves at a high speed that is inappropriate to the radius of curvature, which doubles, creates skidding or even overturning of vehicles. Specialists estimate that the proportion of motor vehicle accidents is 1.5 to 4 times higher in curves than in straight on curves [1]. Therefore, curves reduce the convenience and

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comfort of vehicle users, but especially traffic safety, also due to poor visibility conditions. The severity of road accidents in curves is high [2], 25-30% of fatal accidents happen in bends, as indeed almost 60% of accidents in bends involve a single vehicle leaving the road [3]. Accidents occur mainly at the ends of bends. Statistics show that 62% of fatal road crashes and 49% of other types of curbing accidents, with the underlying maneuvering at the entrance or exit of the curve [4, pp. 10-17]. The more you slow down when approaching a curve, the more likely you are to make a mistake and cause an accident (lane violation, skidding, running off the road, etc). The phenomenon becomes even more pronounced if the reduction in speed is unforeseen and sudden (isolated sharp curve), i.e., these inconveniences become more pronounced the higher the speed of vehicles on a public road where a curve is built and the smaller the radius of the curve. Curves in the horizontal plane are known as horizontal curves and are generally circular or parabolic. Curves in the vertical plane are known as vertical curves [5, pp. 109-131]. In order to increase the safety and comfort of the vehicles, the horizontal merging curves shall be designed in such a way as to ensure the correct registration of the vehicles and to maintain the safety clearances between them by overwidening the road surface and the road surface, to avoid skidding by arranging the curve in space (conversion and overlifting) and, last but not least, to ensure a safety visibility adequate to avoid any danger. The arrangement of the curve in space is realized by replacing the two-slope cross-slope profile in the alignment with a single cross-slope profile. When the single transverse slope is equal to the slope of the alignment we say that a *conversion* has been made, and when it is greater than the alignment we say that we have *overlift* the public road. Also, in order to increase the comfort and safety of vehicles in curves, designers take into account the provisions of the regulations in force and design curves with radii as large as possible and a minimum length between the points of tangency, so that the minimum length is equal to the space covered by a vehicle for 5 seconds. Other aspects are also taken into account in the design of curves on public roads, such as the sequence of curves in the same direction, which must be replaced by a single curve, or a sequence of curves with radii arranged in a normal, increasing or decreasing order. It is also necessary to interpose between the curves in the opposite direction straightening lanes with a minimum length of 1.4V and, in difficult terrain conditions, to adopt speed restrictions on the movement of vehicles through these and straightening lanes respectively, the latter having a length equal to at least the length of the load or of a convoy element, but not less than 8 m. Here, we have presented just some of the standard requirements for the design of curved roads in our country, requirements that if not taken into account in their design would frequently lead to undesirable road events characterized by skidding, off-road or overturning of road vehicles, resulting in property damage or loss of life.

1. Road infrastructure concepts

1.1 Theoretical elements on the definition and calculation of characteristic radii of curves

In order to prevent vehicles skidding off the road, minimum radii and curve-banking conditions can be determined mathematically. Compliance with the calculated parameters and conditions increases road safety and passenger comfort in the vehicle for a given design speed. In alignment, the carriageway part of the road has the shape of a house roof with two slopes. In this case, the size of the transverse slope is dependent on the type of surfacing, so that rainwater can be drained off the carriageway, thus avoiding the phenomenon of aquaplaning. In curves with large radii the transverse profile of the alignment can be maintained, skidding of vehicles entering the curve in this case can be

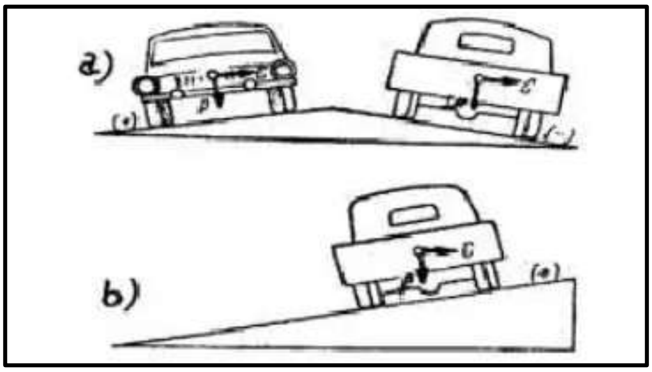

Figure 1. Positive and negative dever [6, p. 1].

favored on the outside half of the curved path and eliminated on the other half of the path. This is shown in Figure 1a. The inclination of the carriageway that fa vors vehicle skidding is called *negative dever* (Figure 1a), and that which counteracts vehicle skidding is called *positive dever* (Figure 1b), depending on the direction in which the vehicle is traveling in its dynamics. It should be noted that dever refers to the transverse inclination (slope) of the road in curves. In curves with smaller radii, to eliminate the drift of the vehicle under momentum, the profile is converted (changed). In this way, a change is made from a two-slope roof form to a single-slope roof form, with the slope of the roof towards the inside of the curve, i.e. a positive dever, as shown in Figure 1b, is achieved over the whole width of the roadway. For curves with extremely small radii, it is recommended to overlift, i.e. to create a transverse slope greater than the conversion slope.

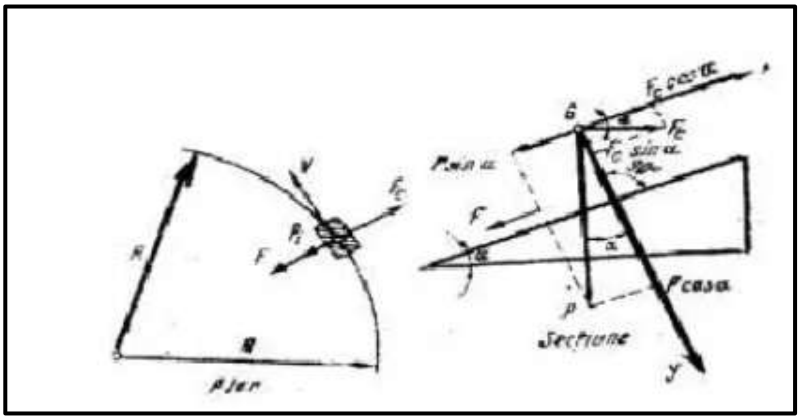

Figure 2. Combating skidding through friction and over alignment [6, p. 2]

In order to eliminate vehicle slippage in curves, certain assumptions defining the radii of curvature are made in the design of vehicles, as follows:

- eliminating slippage exclusively by friction between the track and the vehicle tire, taking into account that the track surface is horizontal;
- eliminating skidding only by overlift the carriageway;
- eliminating slippage through the simultaneous effect of friction and overlift.

Due to centrifugal force, when calculating the radii, the action of friction between the vehicle wheels and the road, as well as the overlift of the road (roadway), must be taken into account simultaneously. In this case, the forces occurring in the vehicle's center of gravity are decomposed along a system of axes originating in the center of gravity; the *Ox* axis parallel to the roadway and the *Oy* axis normal to the roadway (road surface shown in Figure 2). Analysis of the data presented in Figure 1 shows that the skidding is caused by the centrifugal force component parallel to the road *($F_c cos\ \alpha$)*. But the skid is opposed by the road-parallel component of the vehicle weight *($P\ sin\ \alpha$)* and the friction forces from the forces acting normal to the road surface ($P\ cos\ \alpha$ and $F_c\ sin\ \alpha$).

The stability condition is defined by the mathematical relation:

$$F_c\cos\alpha \leq P\sin\alpha + f\,(P\cos\alpha + F_c\sin\alpha) \qquad (1)$$

Since α is small it can be approximated: $cos\ \alpha = 1;\ sin\ \alpha = tg\ \alpha = i_t$ and so:

$$F_c \leq P * i_t + f\,(P + F_c * i_t) \qquad (2)$$

If we ignore the term containing the product $f * F_c * i_t$, being small, the relationship becomes:

$$Fc \leq P\,(i_t + f) \qquad (3)$$

on the limit

$$Fc = P\,(i_t + f) \qquad (4)$$

where,

P is the weight of the vehicle;

F_c – centrifugal force;

i_t – cross slope (the dever);

f – the coefficient of transverse friction between the vehicle tires and the asphalt.

The size of the coefficient of friction, f, depends on the nature of the road surface, the wheel tread and atmospheric factors. On dry roads the coefficient of friction varies in the range 0.4 – 0.7; in wet, muddy, snowy conditions, the coefficient of friction decreases a lot (in the case of ice $f = 0.06$). The coefficient of friction is usually considered $f = 0.1 – 0.3$. he values of f have been experimentally established, which are correlated with the way the cornering is felt by the passengers of the vehicle, namely:

- $f = 0.10$ – the curve is not felt;
- $f = 0.15$ – the curve is weakly felt;
- $f = 0.20$ – the curve is felt as an unpleasant sensation;
- $f = 0.30$ – the curve becomes dangerous by having a flipping effect.

It is known that:

$$F_c = m * a;\ m = P/g;\ a = v^2/R = v^2/(3.6^2 * R) = v^2/13R \quad (5)$$

If we substitute in relation (4) we get:

$$\frac{P}{g} * \frac{V^2}{13R} = P(it + f) \quad (6)$$

From relation (6) it follows;

$$R = \frac{V^2}{13 * g\ (f + it)} = \frac{V^2}{127\ (f + it)} \quad (7)$$

The generalized mathematical relation for positive and negative duty has the following formula:

$$R = \frac{V^2}{127\ (f \pm it)} \quad (8)$$

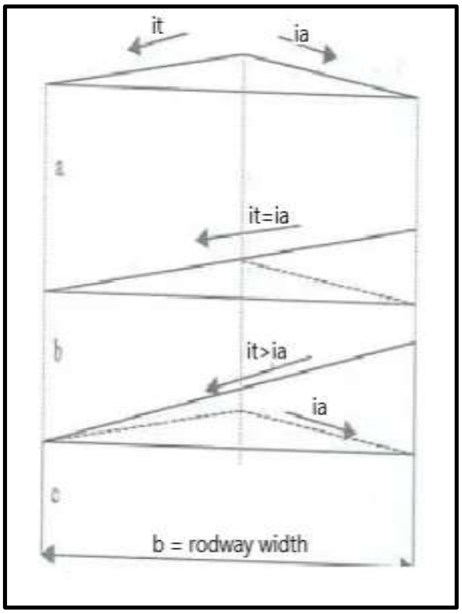

Figure 3. Transverse profile conversion and elevation. a) profile with two slopes in alignment; b) converted profile; c) elevated profile [6, p. 8]

where,

"+" is the positive dever;

"-" is negativ dever, defined in Figure 1a.

By means of the mathematical relation (8) it is possible to classify the radii of the curves in relation to the need for constructive arrangements in the cross-section. In this way, the radii of the connecting curves can be classified as follows:

- *recommended radius (R_r),* represented by the radius for which it is possible to keep the same curved cross-section as the alignment, i.e. in the form of a house roof with two cross slopes (Figure 1 and 3a). All radii larger than this type of radius fall into the category of recommendable radii. The value of the recommendable radius can be calculated with the mathematical relation:

$$Rr = \frac{V^2}{127\ (f - i)} \quad (9)$$

where $i_t = i_a$ the transverse slope of the alignment chosen according to the type of asphalt pavement that is maintained in the curve, on the negative dever considered for vehicles traveling in the lane on the outside of the curve, and f is the coefficient of friction;

- *current radius (R_c),* is the radius for which the cross-sectional profile is converted from the roof shape, as in alignment, to the eaves shape, with a single cross-slope (Figures 1b and 3b). All radii between the current radius and the recommendable radius fall into the current radius category because they retain the converted cross-section. The value of this radius is calculated with the mathematical relationship:

$$Rc = \frac{V^2}{127\,(f - i)} \tag{10}$$

where $i_t = i_a$, valoarea come together considering the positive duty. Values f și i_t same as those considered in relation (9).

- *minimum radius (R_m),*is the radius for which the cross-sectional profile is elevated, (Figure 3c) taking into account the friction and the maximum allowable cross slope. All radii between the minimum radius and the current radius form the category of minimum radii because they have an elevated cross-section, but with different amounts of elevation depending on the size of the radius. The value of this radius is calculated with the mathematical relation:

$$Rm = \frac{V^2}{127\,(f - i)} \tag{11}$$

where $i_t > i_a$, and,
i_t is the slope of the maximum overlift *(i_t* = 0.06);
f - maximum coefficient of friction *(f* = 0.2);
For private or municipal roads, Table 1 gives the radii as a function of speed.

Table 1. Speed ratios for private or communal roads [6, p. 4]

Specification radii [m]	Projection speed [km/h]					
	50	**40**	**25**	**20**	**15**	**10**
Recommended radius	340	200	80	50	30	30
Current radius	170	100	40	25	15	15
Minimum radius	85	50	20	15	10	10

For public roads, the calculation of the radii of connection is made according to STAS 86 - 85, based on the mathematical relationship (8). In this case i_t representing the cross slope takes the following values:

- *it = 0.07 or the minimum radius;*
- *it = 0.02 for the current radius;*
- i_t = 0.025 *for the recommended radius*, and *f*, which is the coefficient of transverse friction between vehicle tires and asphalt, is in the range [0.05-0.15]. The transverse slope for public roads is determined in alignment by the type of surfacing (i_t = 2...2.5%), and on the curve the size of the spokes. For public roads, in Table 2 we present the values of radii as a function of speed according to the Romanian standard STAS 863-85.

Table 2. Recommended recommended radii, by speed, for curves on public roads [6, p. 5].

Conventional radii [m]	Projection speed [km/h]						
	100	**80**	**60**	**50**	**40**	**30**	**25**
Recommended	1,600	1,000	575	400	250	150	100
Current	1,000	620	380	270	170	90	70
Minimum	450	240	125	95	60	35	25
Exceptional minimum	400	215	115	85	55	32	22

Note: For the minimum radii, according to the Romanian standard STAS 863-85, exception values that are about 10% lower than the minimum radii values may be allowed. These may be adopted only

to avoid difficult and costly works (e.g. demolition of buildings in the vicinity or on the road route) and are not accepted for roads intended for international traffic.
The dever calculation can be performed for the interval between R_m și R_c, with the mathematical relation:

$$R = \frac{V^2}{127(f + it)} = \frac{V^2}{127 * it * (k+1)} \tag{12}$$

whence,

$$it = \frac{V^2}{127 * R(k + 1)} \tag{13}$$

where: $k = f/i_t$ is the coefficient of comfort, approximated as the ratio of the contribution of friction f to the contribution of overlift i_t (the dever). To avoid skidding on curves $k = 1.5 – 3$.
In Romania, it is considered that friction contributes 2/3 of the contribution to avoiding vehicle skidding, and overlift 1/3. In this context $k \simeq 2$.

The minimum length of the curve, taken between the points of tangency, which shall be equal to the distance traveled by a vehicle in five seconds, shall be calculated by the mathematical relationship:

$$L = 5\,\frac{V}{3.6} = 1.4V \tag{14}$$

where,
V is speed and is measured in kilometers per hour;
L – the length of the road and measured in meters.

1.2 Overloading curves
This type of arrangement is made by imposing certain stability conditions for vehicles when passing through curves, so that they do not move sideways. Therefore, in order to ensure safe movement of vehicles, the carriageway on curves with radii of less than 300 m is widened by a size S equal to the sum of the overload e of each traffic lane. In order to keep the widths of the shoulders unchanged, the platform shall also be raised by the same amount S. This size S can be determined mathematically, by calculation, with relationships that are the result of studies carried out by specialists on vehicle dynamics in curves.
For trailer vehicles the relationship becomes:

$$S = \frac{D^2 + D_1^2}{2R_e} + \frac{0{,}1V}{\sqrt{R}} \tag{15}$$

or trucks the relationship becomes:

$$S = \frac{D^2}{2R_e} + \frac{0{,}1V}{\sqrt{R}} \tag{16}$$

where,
S is the overloading (m);
D – the distance between the rear axle and the front of the body tractor vehicle (m);
D_l – distance between trailer axles (m);
R_c – radius of outside curve (m);
R – radius in the axis of the curve (m);

V – speed (km/h).

On public roads with two traffic lanes, where vehicles may overtake or pass each other on bends, an extra width shall be provided for each of these lanes in the design. The value of the extra width is shown in Figure 4. Analysis of the data shown in Figure 4 result that vehicles driving around a curve are traveling on paths with different radii, and that the extra widths e_1 and e_2 are not equal. For this reason, total overwidening S is calculated with simplified mathematical relations, as follows:

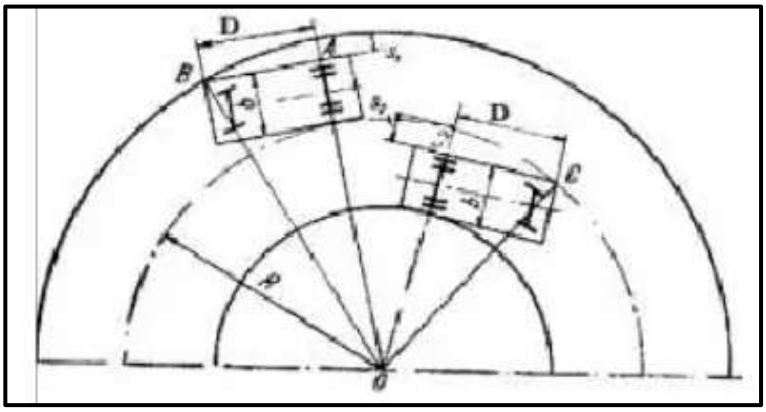

Figure 4. Curve overerloading calculation scheme for two vehicles passing each other [6, p. 7]

- for vehicles towing trailers:

$$S = \frac{D^2 + D_1^2}{R} + \frac{0{,}1V}{\sqrt{R}} \tag{17}$$

- for trucks:

$$S = \frac{D^2}{R} + \frac{0{,}1V}{\sqrt{R}} \tag{18}$$

According to the Romanian standard STAS 863/1985, for a lane of road on which vehicles of increased length (without trailer or semi-trailer) are traveling, the curve overloading are calculated on the basis of the mathematical relationship:

$$e = \frac{D^2}{2R} \tag{19}$$

where,

D is the distance between the rear axle and the front part of the bodywork of vehicles of increased length (m);

R – radius in the axis of the curve (m).

In Table 3 we present the values of the overloading for a two-lane road

Table 3. Overloading values for a two-lane road [6, p. 7].

Radius R [m]	**20**	**25**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**	**120**	**140**	**160**	**180**	**200**	**250**	**300**
Overloading [m]	3.20	2.56	2.14	1.60	1.28	1.06	0.90	0.80	0.72	0.64	0.54	0.46	0.40	0.36	0.32	0.26	0.20

Note: For single lane roads the values in the table will be reduced by 1/2.

The *S* overloading be designed and realized towards the inside of the curve. Overloadings of type *e* may be allowed for each lane of traffic in exceptional cases or in localities. Exceptions are accepted for very heavy work where supported by walls or rock excavations, or demolition. Figure 5 shows an overload positioned inside the curve. From the analysis of the data shown in figure 5, we observe that the overload remains constant along the entire length of the arc curve, merging with the alignment either along the length of the transition curve, if such curves were provided by the road designer, or along sections of the alignment within the range [10-15 m].

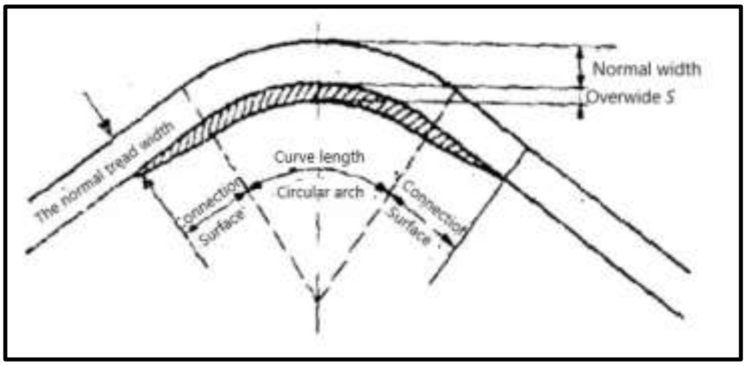

Figure 5. Overloading inside the curve [6, p. 7]

Connection length can be calculated based on the mathematical relationship:

$$L = 0.5 * V \tag{20}$$

where, *V* is the design speed in km/h. As a rule, the connecting sectors of the curve overloading coincide with the connecting sectors of the single-slope cross-sections in the curves to the two-slope profiles in the alignment, i.e. the ***spatial arrangement of the curves***

1.3 The spatial arrangement of the curves

The spatial arrangement of the curves consists of the transformation from the cross-sectional profile of the roof-shaped roof alignment with two inclined planes (Figure 3a), to the cross-sectional profile that takes the shape of a house eaves, with a single slope that slopes inwards from the curve. The transformation can be achieved by two separate actions, as follows:

- ***converting*** action achieved by transforming the two-slope profile into a one-slope profile, equal to the one in the alignment (Figure 3b);
- ***overloading*** action achieved by progressively increasing the transverse slope value from that in the alignment to the maximum slope in the turn (Figure 4c)

The length at which conversion and elevation can be achieved *(l_{cs})* coincides with the length of the progressive curve *L*. It is known as a *Connection ramp*. This connection ramp is shown in Figure 6. From the analysis of the data shown in Figure 6, if we show an extended plan of a vehicle turning in a curve, we can see that the length *L* of the connection ramp consists of the length *d* n which the conversion is performed and the length *(l - d)* on which the elevation.

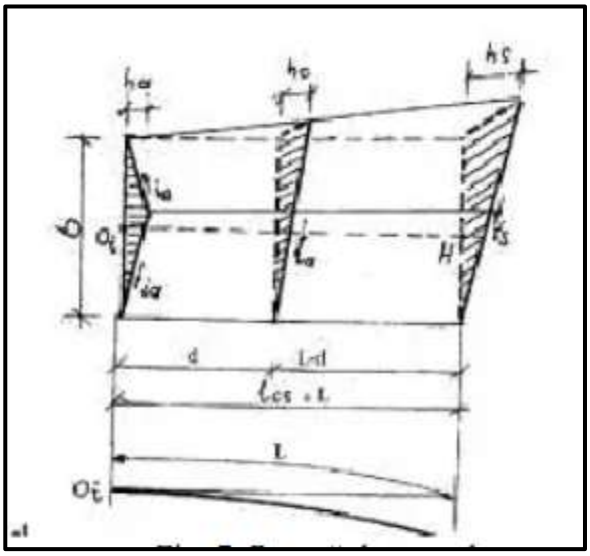

Figure 6. Connection ramp [6, p. 8]

The transverse slope (the dever) is determined from the mathematical relationship (12) and (13) from which it follows:

$$i_t = \frac{V^2}{127 \cdot R(k+1)} \tag{21}$$

where,

V is the speed (km/h);

R - radius (m);

$k = f/i$ – comfort coefficient (k = 1.5 – 3).

On logging roads, the mathematical relationship is often used to calculate the single cross slope:

$$i\% = 0{,}2\frac{V^2}{R} \tag{22}$$

The mathematical relation (22) is assumed from the basic mathematical relation, in which the frictional force *(f = 3i)*, i.e. this frictional force contributes three times as much to combating skidding as overlift.

For a curve, the connection of the two-slope alignment cross-section to the single slope alignment cross-section can be made as follows [6, p. 9]:

- by keeping the inner edge *I* of the roadway side of the road unchanged (Figure 7a);
- by keeping the road axis unchanged (Figure 7b);
- by keeping the outer edge *E* of the roadway unchanged (Figure 7c).

Typically, the in-space merging is done with the inside edge of the traffic lanes of the roads unchanged. The unchanged road centerline is used exclusively for conversions. It is not suitable for raised pavements as they are unsightly.

By knowing cross slopes in alignments (i_a) and band width (b), from the elevated curve (i_s) of the resulting road:

$$hc = b*i_a; \qquad hs = b*i_s \tag{23}$$

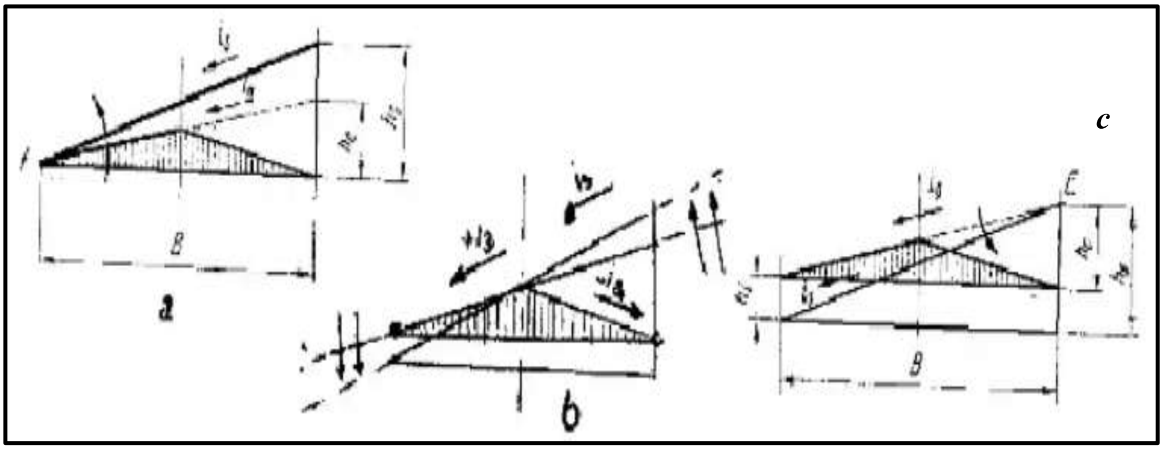

Figure 7. Space connection variants [6, p. 9]

By rounding half of the platform from the outside of the curve around the road axis, their conversion can be performed. This is shown in figure 8.

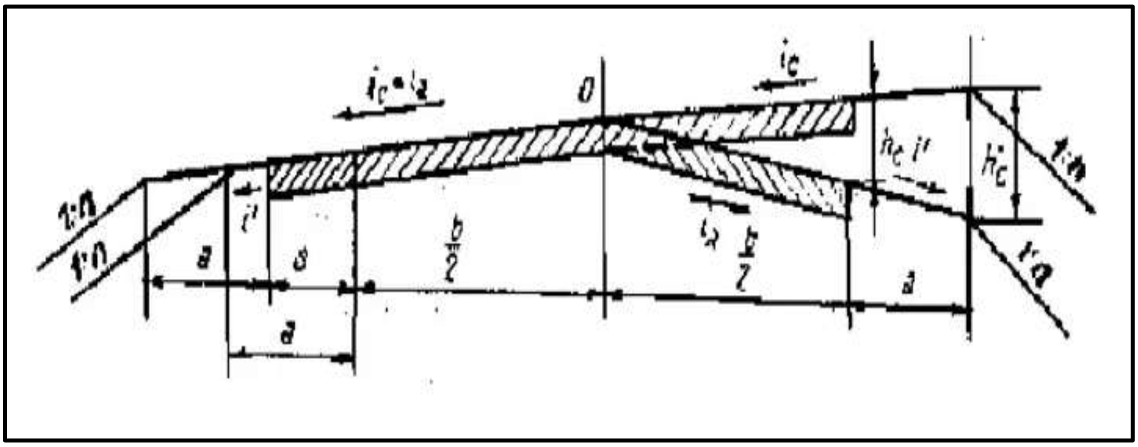

Figure 8. Converted and overwide transverse profile [6, p. 9]

Analysis of the data presented in Figure 8 shows that the *S* overloading, when essential, have a cross slope identical to that of the roadway. The pavement *(a)* nside the curve will always keep its normal cross slope. The pavement (a) on the outside of the curve will have the same inclination as the roadway. Once the conversion operation is complete, the elevation will be completed. This will be accomplished by rotating the converted profile around the edge of the roadway inside the curve that has not been raised. This is shown in Figure 9. The shoulder on the outside of the turn shall be designed in line with the roadway side and shall be rotated until it has a slope identical to that of the elevation. The inner pavement follows the shape that the inner lane will take in accordance with the slopes of the inner lane, as shown in Figure 9, and the overpasses will follow the same slope as the carriageway, i.e. the roadway side. The connection ramps will be designed and arranged at both the inlet and outlet of the curve, on the arc curve maintaining constant is elevation ramps. This is shown in Figure 10. On the constant gradient of the connecting slope, the slope of the outer edge of the road carriageway h_s/L shall not exceed the slope of the road centerline by more than the values shown in Table 4.

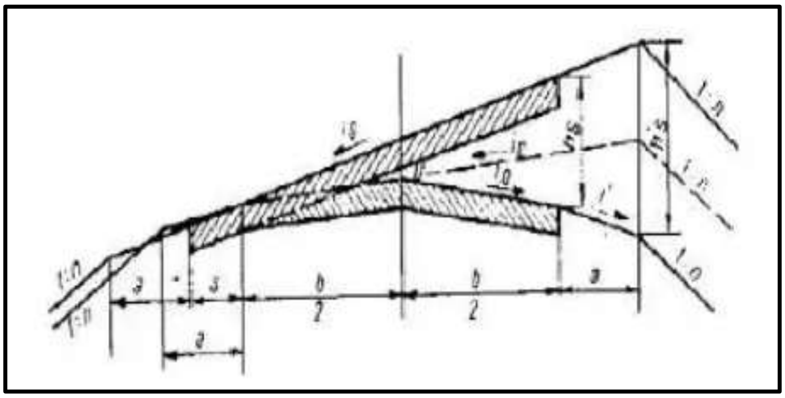

Figure 9. Overraised and overwide profile [6, p. 9]

Table 4. Exceedance of *hs/L* outer edge slopes in relation to road centerline slopes [6, p. 10]

Speed [km/h]	**40**	**60**	**80**
Exceeding declivity [%]	1.5	1	0.5

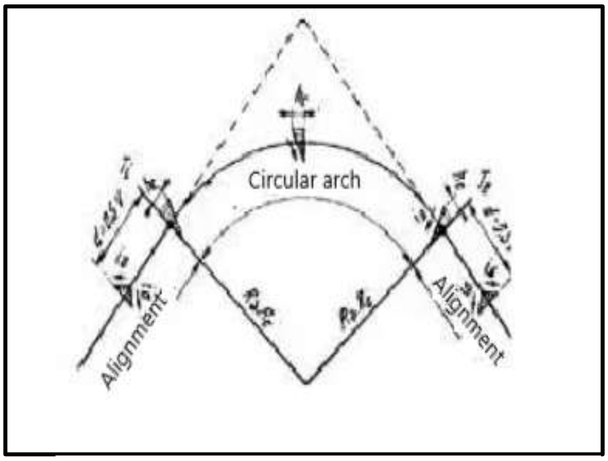

Figure 10. Construction of the connection ramp [6, p. 10]

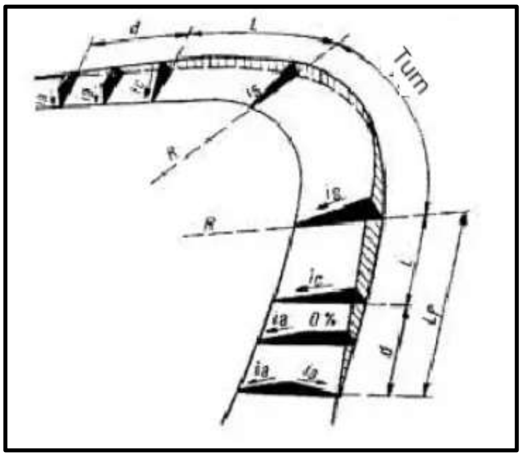

Figure 11. Connecting a curve in space [6, p. 10]

The connection in space of a curve (Figure 11), in this case an elevated profile, admits first a conversion of the profile to the only slope corresponding to the slope of the alignment, then an elevation of the profile up to the transverse slope of the curve. When entering the arc curve the cross profile must be ready raised and will remain so for its entire length. This is shown in Figure 11. In the same way curves that require conversion only will be laid out. It should be noted here that the length of the *d,* is identical in length to the progressive curve *L*. When connecting alignments exclusively by arcs, the conversion length $d = 0.5\ V$ will be applied before the input tangent T_i and after the exit tangent T_c . In this instance, the elevation ramp will be designed and constructed at both the entrance and exit of the curve, and an elevation slope will be maintained on the arc curve i_s which will be constant.

If the curves will contain two circular arcs (clothoid arcs), without a quotation, the raised or converted profile will also be kept constant, identical to the overshoot, for a length according to $C = 0.278\ V$, arranged proportionally to the bisector of the peak angle.

2. Specific knowledge of vehicle dynamics

2.1 Vehicle tire rolling characteristic

In order to understand the rolling characteristic of the vehicle tire on the road, the specific tangential force is defined:

$$\varepsilon = \frac{Xr}{Zr} \tag{24}$$

The rolling characteristic of the tire is defined by the dependence between the specific tangential force, ε, and the relative slip *ar* (Figure 12):

$$\varepsilon = \varepsilon(ar) \tag{25}$$

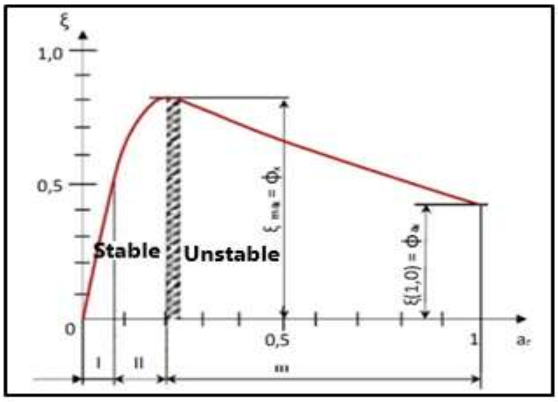

Figure 12. Tire rolling characteristics [7].

Analysis of the data presented in Figure 12 shows:

- ✓ Section I represents the pseudo-slip zone;
- ✓ Sections I and II - stability zone for tire rolling;

- ✓ Section III - unstable tire rolling.

The forces occurring during traction or braking of the vehicle can be transmitted to the roadway with ridiculed values, they are corresponding to ε_{max}, outside the area where the tire is unstable, like this:

$$X_{max} = \varepsilon_{max} * Z_r \tag{26}$$

In this case, the relative alignment through which the maximum specific tangential force is obtained takes values in the range $a_{rm} \in [0.15 \ldots 0.30]$. Relative slippage becomes unavoidable and occurs with tractive force or braking when $\varepsilon \neq 0$. This phenomenon occurs due to the elasticity of the rubber in the vehicle tires, which is manifested by deformation of the tires and, consequently, loss of rolling speed, without any actual slippage in the contact patch of the tires with the ground (so-called pseudo-slip). These aspects are shown in Figure 13.

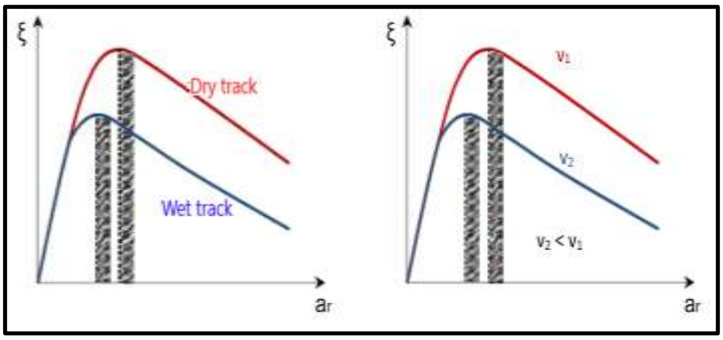

Figure 13. Influence on road vehicle tire rolling characteristics [7].

2.2 Adherence of the tire to the road. Friction between the tire and the tread

The mechanism of friction between the vehicle tire and the road is defined by:

- ➢ ***adhesion**,* a phenomenon manifested by a frictional force on the surface, which is caused by the phenomenon called stick-slip. In this case, molecular bonds occur between the contact patch of the anvil and the rolling surface, accompanied by stretching, breaking and re-bonding;
- ➢ ***histeresis***, a phenomenon manifested by energy losses in the vehicle tire material when the vehicle's tire is deformed and contoured on the road surface (concrete or asphalt aggregate). When the vehicle travels at speed v over the roadway aggregates, the pressure distribution on their surface is asymmetrical and is due to the hysteresis phenomenon specific to elastic materials (tire rubber): on the side of the asperities attacked by the rubber, the pressure is higher than on the side of the tire. In this case, the pressure force component in the direction of displacement is not zero, it opposes the displacement. This is shown in Figure 14.

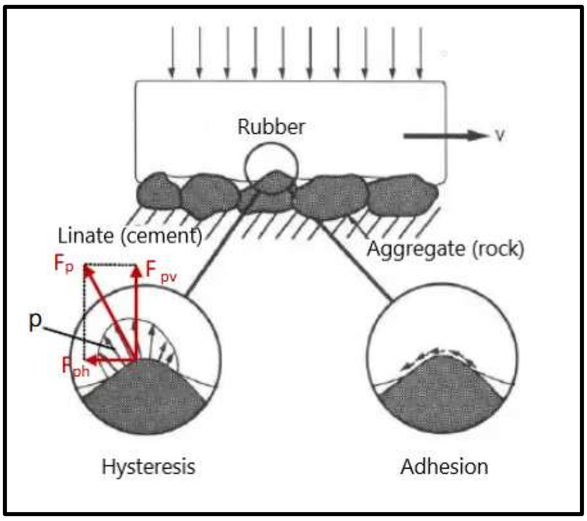

Figure 14. Hysteresis and adhesion phenomenon [7].

Under normal conditions, the hysteresis component usually symbolizes 1/3 of the friction forces. On a wet road, the adhesion component decreases significantly and the hysteresis component changes slightly. The tread of the high grip rubber tire provides the necessary friction on dry and smooth roads. For wet roads, tires with a high hysteresis rubber compound are recommended.

2.3 Longitudinal adhesion of the vehicle tire to the road surface

In this case, we're talking about the tire's grip, or grip force, which is proportional to the maximum tangential reaction:

$$\Phi_x = X_{r\,max} \quad (27)$$

The coefficient of longitudinal adherence becomes:

$$\Phi_{x\ max} = X_{r\,max}/Z_r = \Phi_x/Z_r \quad (28)$$

If we consider the rolling characteristic, it follows:

$$\Phi_x = \varepsilon_{max} \quad (29)$$

At $a_r = 1.0$ (skidding in place or braked wheel lock), the coefficient of adhesion becomes:

$$\Phi_{ax} = \varepsilon \quad (30)$$

Attention! The ***coefficient of adherence*** should not be confused with the ***coefficient of friction***. It is lower than the static braking coefficient. Factors influencing the longitudinal adhesion coefficient are:

- vehicle tire construction (tread material, contact patch and tread width);
- tire air pressure (there is an optimum value Φ_x wich is the maximum value);
- on hard or dry road surfaces, the wheel load pressure (wheel force F_z) decreases by Φ_x;
- road surface roughness (the height of irregularities in the road surface should not exceed 4-5 mm);
- constitution, height and layout of irregularities in the roadway;
- the degree of wear of the raceway (can reduce the value of Φ_x by 1/2);
- vehicle speed;
- the condition of the rolling surface (dry or wet), (Figure 15).

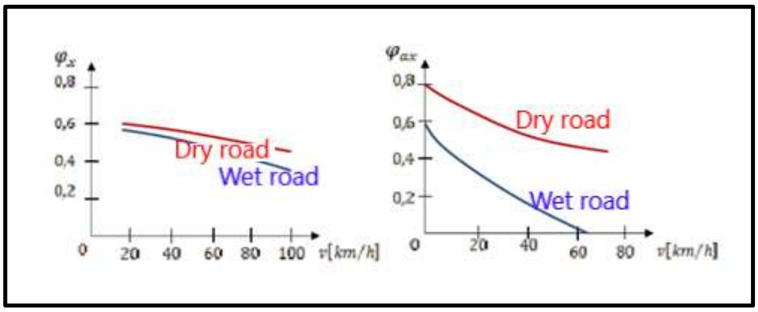

Figure 15. The value of the adhesion force *(Φx)* as a function of speed on different road surface states [7].

2.4 Aquaplaning vehicle tires

It is a phenomenon that occurs when the vehicle is running and/or braking (Figure 16). Vehicle tire aquaplaning can occur even in curves if the car is driving at excessive speed in the curve. If the road (inadequate transverse slope of up to 2% of the road surface), water from precipitation is not removed by draining into a gully or ditch on the roadway, it is involved in the phenomenon of vehicle wheel aquaplaning when the vehicle is traveling at inadequate speed. Analysis of the data presented in Figure 16 shows that the plume of water collected in front of the rolling tire creates vertical forces Z'_h and Z''_h. At a certain speed, v_1, the pressure from the liquid plume building up in front of the wheel can deform the tire so that the

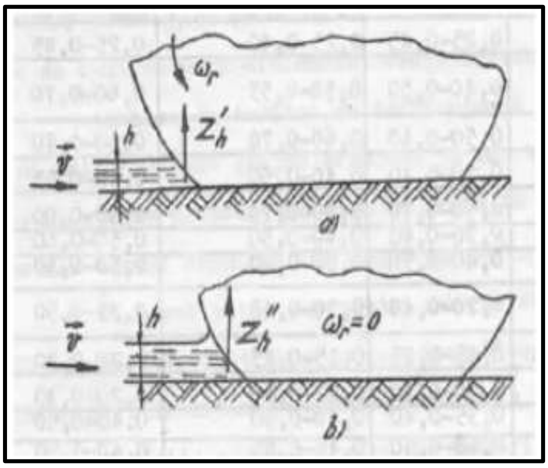

Figure 16. The aquaplaning phenomenon [7].

tire is supported in a small portion at the front on the liquid plume. If the speed increases and reaches v_2, the liquid plume extends over the entire length of the contact patch between the tire and the road. *Quantity momentum theorem for the liquid plume area* (Figure 17), is the following:

$$\rho h\ bp\ h = Q\ v_1 = \rho\ bp\ h\ v_1\ v_1 = \rho\ bp\ h \tag{31}$$

where,
ρh is the hydrodynamic pressure in the liquid plume (kg/m³);
Q – mass flow of liquid (kg/s);
ρ – density of water (under normal conditions of temperature at 0°C and pressure of 1 atmosphere, the density of water is 0.9998 g/cm³).
It follows that:

$$\rho h = \rho\ v_1^2 \tag{32}$$

But to take into account the stiffness of the tire, we set the condition:

$$\rho h = 1.2\ p_a \tag{33}$$

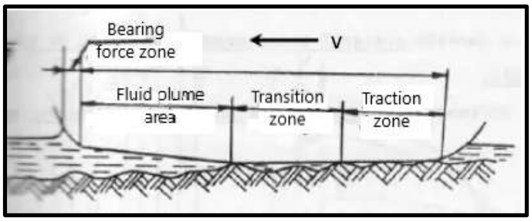

Figure 17. The tire zones of a aquaplaning wheel [7].

This gives the transition speed (the speed at which partial aquaplaning begins):

$$v_1 = \sqrt{1.2\ \frac{pa}{\rho}}\ [m/s] \text{ or; } v_1 = 39.6\sqrt{pa}\ \ [km/h],\ pa\ [bar] \tag{34}$$

The speed at which total aquaplaning occurs is calculated with the mathematical relationship:

$$v_2 = 61.5\sqrt{pa} \qquad [\text{km/h}] \tag{35}$$

Table 5 shows the adherence coefficients of car tires on different road surfaces.

Table 5. Adherence coefficients of car tires on different road surfaces [7].

Rolling track		**Coefficient of adherence Φ_x for tires**		
Name	**Stay**	**High pressure**	**Low pressure**	**High pass capacity**
Concrete/asphalt	Dry	0.5 – 0.7	0.70 - 0.80 (1.00)	0.70 – 0.80 (1.00)
Concrete/asphalt	Wet	0.35 – 0.45	0.45 – 0.55	0.50 – 0.60
Concrete/asphalt	Water with mud	0.25 – 0.45	0.25 – 0.40	0.25 – 0.45
Broken stone	Dry	0.50 – 0.60	0.60 – 0.70	0.60 – 0.70
Broken stone	Wet	0.30 – 0.40	0.40 – 0.50	0.40 – 0.55
Earth road	Dry	0.40 – 0.50	0.50 – 0.60	0.50 – 0.60
Earth road	Wet	0.20 – 0.40	0.30 – 0.45	0.35 – 0.50
Earth road	Impracticable	0.15 – 0.25	0.15 – 0.25	0.20 – 0.30
Snow	Fluffy	0.20 – 0.30	0.20 – 0.40	0.20 – 0.40
Snow	Beaten	0.15 – 0.20	0.20 – 0.25	0.30 – 0.50
Ice	T < 0º C	0.08 – 0.15	0.10 – 0.20	0.05 – 0.10

2.5 Transverse adherence of the vehicle tire to the road surface
The maximum value of transverse tangential reaction is identical to the transverse adherence or transverse adherence force:

$$Y_{r\,max} = \Phi_y \tag{36}$$

Transverse coefficient of adherence is:

$$\Phi_y = \frac{Yr\ max}{Zr} = \frac{\Phi y}{Zr} \tag{37}$$

We know that the automobile tire has an anisotropic structure (it does not have the same physical properties throughout its structure). The tire also presents an asymmetry in the evolution of processes with respect to the center of the contact patch ($\Phi_x \neq \Phi_y$).

Factors influencing transverse adherence are:

- on a wet road Φ_y decreases linearly with the vehicle rolling speed;
- the longitudinal tangential force acting at the same time as the transverse force creates a reduction in the Φ_y by consistently reducing the driving or braking force of the vehicle wheel to high values.

We know that, for a given longitudinal force, we have a force acting on the side of the vehicle, which has a maximum value and which can be transmitted by the wheels and reciprocally. The size of one of these forces creates transverse slip, that is, it creates skidding or sliding, if the wheels are in traction or are in braking.

The result of the two forces (longitudinal and transverse) at the adherence limit describes an ellipse when their magnitudes and directions change, taking form through the mathematical relationship:

$$R = \sqrt{X_r^2 + Y_r^2} \tag{38}$$

But in order to avoid transverse or tangential slippage in the contact patch between the tires and the road surface, it is necessary that $R \leq R_{max}$, uwhere R_{max} is the maximum adhesion force in the direction of the angle θ.

At the limit of adherence, the components $X_{r\Phi}$ și $Y_{r\Phi}$, (Figure 18), is calculated with the mathematical relationship:

$$\sqrt{X_{r\Phi}^2 + Y_{r\Phi}^2} = Rmax = \Phi * Zr \tag{39}$$

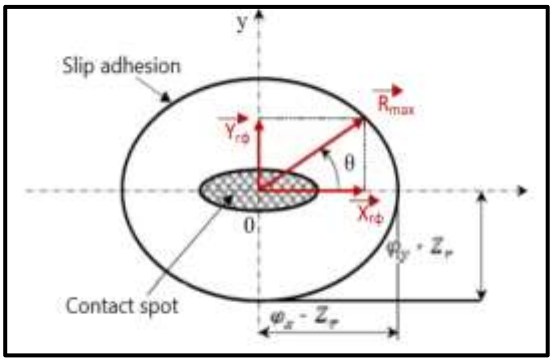

Figure 18. $X_{r\Phi}$ and $Y_{r\Phi}$ components at the adhesion limit [7].

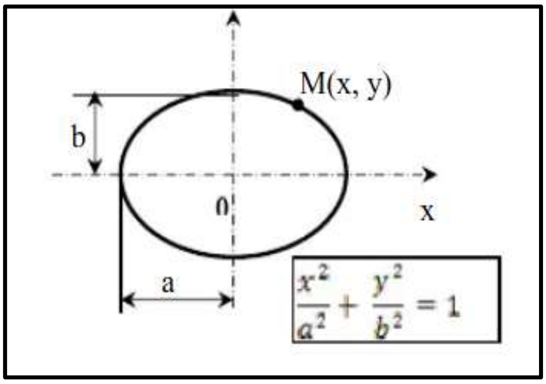

Figure 19. $X_{r\Phi}$ and $Y_{r\Phi}$ components at the adhesion limit [7].

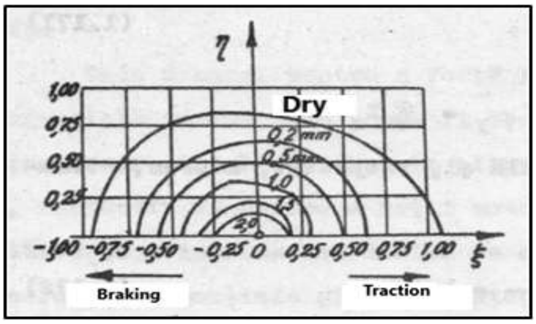

Figure 20. Normalized adhesion ellipses as a function of adhesion and water layer thickness [7].

where Φ s the coefficient of adhesion in the direction of the resultant reaction R_{max}. Because the peak of the vector R_{max} describes an ellipse, it follows:

$$\frac{X_{r\Phi}^2}{\Phi_x^2 * Z_r^2} + \frac{Y_{r\Phi}^2}{\Phi_Y^2 * Z_r^2} = 1 \tag{40}$$

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From which follows:

$$Y_{r\Phi} = \Phi_y * Z * \sqrt{1 - \frac{X_{r\Phi}^2}{\Phi_x^2 * Z_r^2}} \quad (41)$$

where, $Y_{r\Phi}$ represents the maximum value of the lateral force, without transverse slip (skidding), when the vehicle wheel transmits the tangential force (Figure 19).
If $X_{r\varphi} = 0$, then $Y_{r\Phi} = \Phi_y * Z_r$. In this case, the wheel can take a lateral force equal to the transverse adherence. If $X_r = X_{r\Phi} = \Phi_y * Zr = \Phi_x$, i.e. the wheel is below the slip or blocking limit, then $Y_{r\varphi} = 0$, i.e. the wheel loses its ability to take lateral forces and any lateral force causes the wheel to skid. We know that effective braking requires the braked wheel to roll and not lock. This is where the Anti-lock Braking System (ABS) comes in, which prevents the wheel from locking under braking to allow safe steering while braking.
The adherence elipse changes its parameters depending on speed and road condition (Figure 20). From analyzing the data presented in Figure 20, we note:

- $Y_{r\Phi}/Z_r$ as the specific lateral tangential force;
- $X_{r\Phi}/Z_r$ as the specific longitudinal tangential force.

2.6 Vehicle transverse stability in curve

The carriageway, in curve, is elevated on the outside of the curve, making the cross-sectional profile inclined at an angle β. As a result the normal reactions are different in left whell than in right whell. The loss of stability of the car occurs in this case by overturning or skidding. The forces and moments acting on the vehicle when traveling in a curve on a road with transverse inclination β, is shown in Figure 21.

A) The overturning the vehicle can occur if the moment of the forces tending to overturn the vehicle is greater than the moment of the forces tending to stabilize it. To do this we write the equation of moments of the forces resulting from the decompositions in relation to a straight line passing through the right-hand wheel fulcrums, i.e. in relation to the point *"O"*. This gives the mathematical relationship:

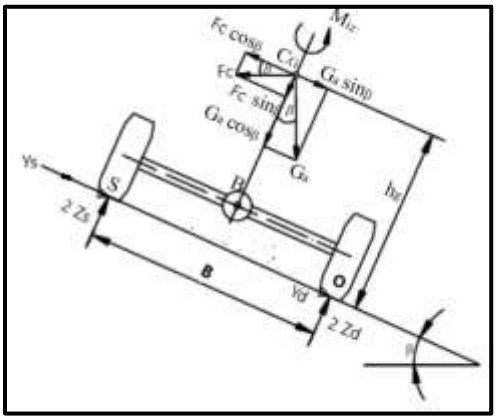

Figure 21. The forces and moments acting on the vehicle when travelling in a curve on a road with transverse inclination β.

$$\sum M0 \quad 2Zs*B+(Fc \cos\beta - Ga \sin\beta)*hg > (Fc \sin\beta + Ga* \cos\beta)\, B/2 \quad (42)$$

Bearing in mind that in the event of overturning $Zs = 0$ we will get:

$$Fc*hg*\cos\beta - Ga*hg*\sin\beta > Fc\,(B/2)*\sin\beta + Ga*(B/2)*\cos\beta \;/:\cos\beta \Rightarrow Fc*hg - Ga - hg*tg\,\beta > Fc*(B/2)*tg\,\beta + Ga*(B/2) \quad (43)$$

From the mathematical relation (43) we derive $tg\,\beta$:

$$tg\beta < \frac{Fc*hg - Ga*\frac{B}{2}}{FC*\frac{B}{2} + Ga*hg} \quad (44)$$

$$Fc = ma*(v^2/R) = (Ga/g)*(v^2/R) \quad (45)$$

From this we derive the mathematical relationship of vehicle overturning risk in the form:

$$tg\beta < \frac{\frac{v^2}{g*R}*hg - Ga*\frac{B}{2}}{\frac{v^2}{g*R}*\frac{B}{2}+hg} \tag{46}$$

From this mathematical relationship we can deduce the speed of the vehicle at which the overturning can occur. From the mathematical relation (46) we derive *v*:

$$(v^2/2)* (B/2)\ tg\,\beta+hg\ tg\,\beta < (v^2/gR)\ hg - (B/2) \tag{47}$$

By calculation we arrive at the final mathematical relationship of the speed *v*:

$$v > \sqrt{\frac{gR(tg\beta+\frac{B}{2hg})}{1-\frac{B}{2hg}tg\beta}} \tag{48}$$

Warning! At higher speeds than those given in the mathematical relationship (48) the vehicle overturns.
There are two possible situations:

1) If the transverse profile of the road in a curve is not inclined (*β = 0)*:

$$v > \sqrt{\frac{g*R*B}{2hg}} \tag{49}$$

2) If $tg\,\beta = (2hg/B) \Rightarrow v \rightarrow \infty$. (50)

B) The skidding occurs when the sum of the forces tending to push the vehicle out of the curve is greater than the sum of the opposing reactions.
This gives the mathematical relationship:

$$Fc\cos\beta - Ga\sin\beta > Ys + Yd \tag{51}$$

Maximum sum $Ys + Yd$ results from the adherence condition being:

$Ys +Yd = \rho\ (Fc\sin\beta + Ga * \cos\beta)$; $Fc\cos\beta - Ga\ sib\,\beta > \rho\ (Fc\sin\beta + Ga * \cos\beta)/: \cos\beta \Rightarrow$
$\Rightarrow Fc - Ga\ tg\,\beta > \rho\ Fc\ tg\,\beta + \rho\ Ga$ (52)

Take out *tg β:*

$$tg\beta < \frac{\frac{v^2}{g*R}-\rho}{\rho\frac{v^2}{g*R}+1} \quad \Rightarrow \quad < arc\ tg...... \tag{53}$$

In this way, we can derive the vehicle speed at which skidding starts from the mathematical relation (53), as follows:

$$v > \sqrt{\frac{gR(tg\beta + \rho)}{1 - \rho \, tg\beta}} \quad (54)$$

There are two possible situations:

1) $\beta = 0 \Rightarrow \quad v > \sqrt{g * R * \rho}$ (55)

2) $tg\,\beta = (1/\rho) \Rightarrow v \to \infty$. (56)

Of course, it is desirable for the vehicle to skid before it overturns, which means that the speed at which it skids is less than the speed at which it overturns. For the case of $B = 0$, this means that:

$$\sqrt{g * R * \rho} < \sqrt{g * R * (\frac{B}{2hg})} \quad (57)$$

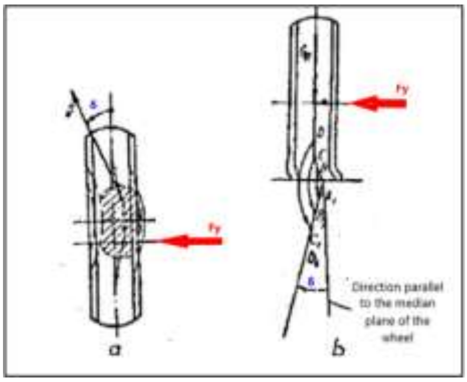

Figure 22. Road vehicle wheel running diagram a) without lateral deviation; b) with lateral deviation [9, p. 9].

The condition is met for most vehicles, except for high buses where *hg* is high.

2.7 The influence of the transverse elasticity of car tires on the car's curve trajectory

The road vehicle tire (Figure 22 a) is not a rigid object, it has a certain elasticity which allows it to deform. This can cause the vehicle to deviate dynamically from the curve path imposed by the driver. The cause of transverse deformation of a road vehicle tire is the higher centrifugal force (high curve speed) or a strong side wind. In this case, the path of the steering wheels is deflected by an angle δ called the ***drift angle*** (Figure 22b).

The instantaneous center of turn correctly is found at the point of origin *"O"* where the extension of the vehicle rear axle axis Fy due to a strong side wind, the velocity vectors change direction with angle $\delta 1$ at the front axle and $\delta 2$ at the rear axle (Figure 23).

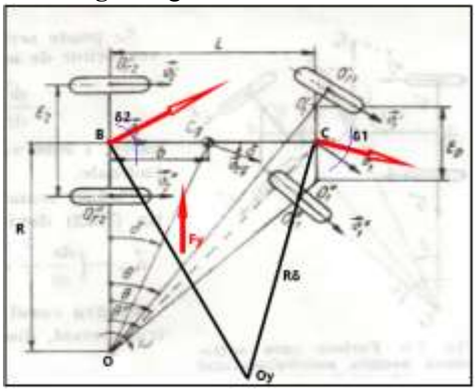

Figure 23. Schetch of a road vehicle turning a right.

There are the following possible situations:

A) ***δ1 > δ2.*** In this situation *Rδ > R,* and the vehicle is ***understeering***, (Figure 24 a). This situation is more common in cars with the drive axle at the front, or if they skid by losing adherence on the front drive axle;

B***) δ1 = δ2.*** In this situation *Rδ = R,* and the vehicle is turning ***normal*** or ***neutral*** (Figure 24 b);

C) ***δ1 < δ2.*** In this situation *Rδ < R,* and the vehicle is ***oversteering***. In this situation, the steering wheel needs to be turned less in order to be able to negotiate the curve. The vehicle with a rear drive axle is predisposed to oversteer in curve. The same phenomenon also occurs if the rear axle loses grip (Figure 24 c).

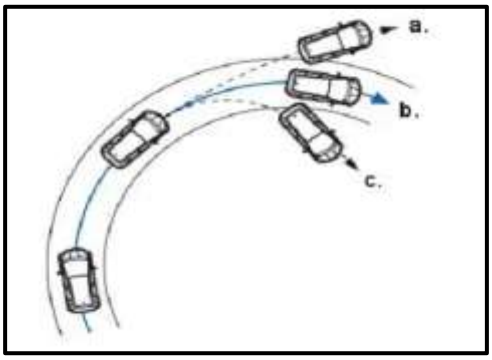

Figure 24. a) Understeer; b) Normal or neutral turn; c) Oversteer [10, p. 2].

The tire's transverse elasticity depends on:

- the lateral force acting on the tire;
- tire construction characteristics;

- tire air pressure.

2.8 Maneuverability road vehicle in curve

Maneuverability is the ability of a car to maintain a straight line and to follow the desired trajectory in curves. Vehicle handling and stability are very important factors contributing to road safety.

These factors largely depend on:

- the driving speed imposed by the driver;
- vehicle construction parameters;
- parameters of the construction of the carriageway.

All these factors form the man-vehicle-road triad.

The following situations are also identified for maneuverability:

A) ***The case of the rear drive axle car*** (Figure 25), where the planes of the steered wheels are parallel forming the same steering angle *"θ"*.

Ft is the traction force;

Fî – the pushing force;

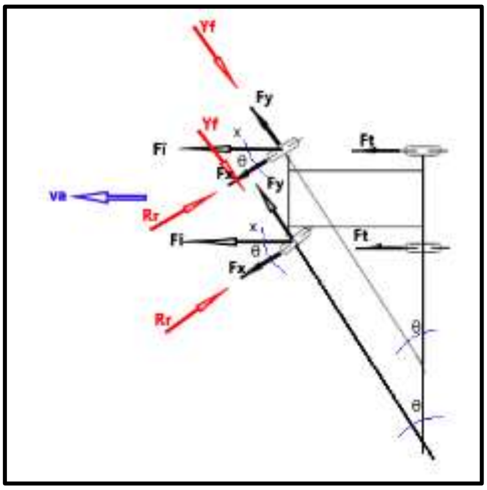

Figure 25. Maneuverability of the rear-wheel drive car.

$$Fî = Ft \tag{58}$$

The traction force *Ft* from the rear drive axle is transmitted to the steered axle in the form of a pushing force. It is decomposed into components *Fx* and *Fy*. The *Fx* components are opposed by *Rr* reactions. The *Fy* component is opposed by the lateral reactions of the road *Yf*.

The forward condition of the vehicle is that $Fx \geq Rr$.

$$Fî * \sin\theta \geq Rr \tag{59}$$

$$Fî * \sin\theta \geq f Z_f \tag{60}$$

$$Fî \geq \frac{fZf}{\sin\theta} \tag{61}$$

The condition for ensuring the direction of travel is that $Fy \leq Y_f$.

$$Fy \cos\ \theta \leq \varphi * Z_f \tag{62}$$

$$Fî \leq \frac{\varphi * Zf}{cos\theta} \tag{63}$$

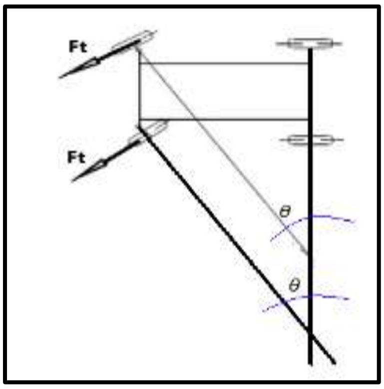

Figure 26. The case of the car with the front drive axle and wheels braced parallel.

$$F*\cos\theta < \varphi \sin\theta/{:}\cos\ \Rightarrow \boldsymbol{f < \varphi\ tg\ \theta} \tag{64}$$

For most cases the inferred condition is fulfilled because:

$$\theta\ < 45^o \Rightarrow tg\theta < 1;\ \varphi \gg f;\ (f \ll \varphi) \tag{65}$$

However, in certain situations when cornering at very steep angles and when the grip of the car's tires on the road is reduced, the inequality can no longer be satisfied and the car will travel in a straight line even if its wheels are angled *θ*.

B) ***The case of the car with the front drive axle and wheels steered parallel*** (Figure 26). In this case the tractive force *Ft* occurs at the front axle wheels in the forward direction of the vehicle. As can be seen, the outboard side components are missing. Hence the superiority of front-wheel drive vehicles. The tractive force *Ft* pulls the vehicle in the cornering direction.

Correct turning of the vehicle (Figure 27) occurs when all the wheels are moving in concentric circles centering on a fixed point (point "*O"*), called the *instantaneous turning center*. This center is located at the intersection of the rear axle and the axles of the two steered wheels in front of the vehicle. In order to keep it as the "O" center, it is necessary that the wheel inside the turn be steered at a larger angle. From the righting triangles *OAB* and *ODC* can be deduced:

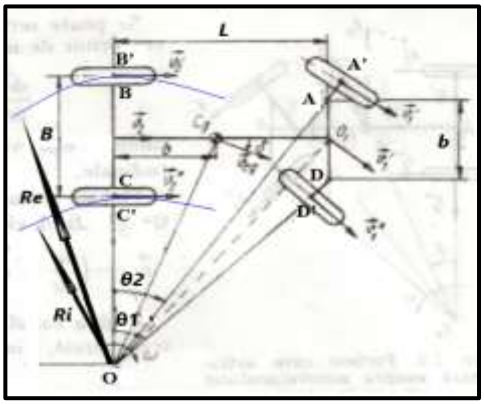

Figure 27. Turning the vehicle

$$ctg\ \theta 1 = \frac{OB}{AB}\ ;\ ctg\ \theta 2 = \frac{OC}{CD} \quad (66)$$

$$ctg\ \theta 1 - ctg\ \theta 2 = \frac{OB}{AB} - \frac{OC}{CD} = \frac{OC+b}{L} - \frac{OC}{L} = \frac{b}{L} = constant \quad (67)$$

The mathematical relation (67) shows the correct cornering condition of the vehicle, but today's deformable square steering mechanisms cannot always meet this condition. This causes wheel slippage in tight turns. The outer radius *Re* and the inner radius *Ri* of the turn can also be determined with the following mathematical relations:

$$Re - OA' + \frac{B-b}{2} = \frac{L}{\sin\theta 1} + \frac{B-b}{2} \quad (68)$$

$$Ri - OC' = OC - \frac{B-b}{2} = \frac{L}{\mathrm{tg}\,\theta 2} - \frac{B-b}{2} \quad (69)$$

If we analyze the mathematical relations (68) and (69), we see that as the turning angles *θ1* and *θ2* increase, the radii *Re* and *Ri* decrease. This is why cars are sometimes made and used with steering mechanisms that have all steered wheels. This reduces turning radii by half.

3. Curve component of road infrastructure, together with other accident generating elements in Romania. Case study

Since the latest data on this research are provided in the Road Safety Bulletin, Year Report 2023, realized and edited by the General Inspectorate of the Romanian Police, the Road Directorate and the Institute for Research and Crime Prevention of the Ministry of Internal Affairs, we will report with this case study on road accidents that occurred in curves in 2023, as a result of the failure of drivers of road vehicles to comply with the specific traffic conditions. The data in this report was collected online. Data comparing 2023 with 2022 are presented.

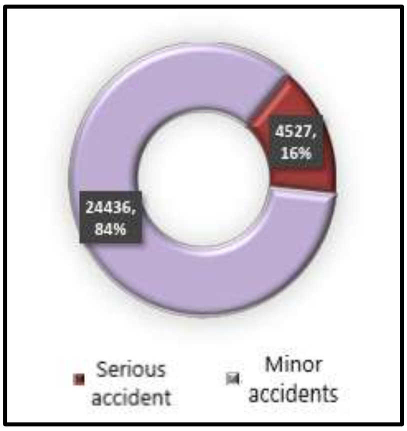

Figure 28. Total road accidents in Romania in 2023 [8, p. 39].

In 2023, there were 4,527 (16%) serious road accidents on public roads in Romania, road events that caused the death of 1,545 people, serious injuries to 3,537 people and slight injuries to another 2,172 people. On average, every day in 2023, there were 12 serious road crashes, in which 4 people lost their lives and 10 people were seriously injured, and 24,436 minor road crashes (84%). In 2023, Romania recorded a rate of 81 deaths per million inhabitants. Compared to 2022, there were 188 fewer serious road accidents in 2023 (-3.82%). Figure 28 shows the total number of serious and minor road accidents in 2022 in Romania compared to 2023, and Figure 29 shows the number of accidents and their consequences in 2022 and 2023. Also, the number of injured persons (fatalities and seriously injured) in such events is lower by 246 persons (-4.61%). The fatality rate (number of fatalities in relation to the number of serious accidents x 100) was 34.1% in 2023, slightly lower than in 2022 (34.6%). In relation to the environment of their occurrence, in 2023, the highest number of serious road accidents was recorded in rural areas, 1,857 events, 41% of the annual total. Rural areas had a fatality rate of 36.6%, while urban areas had a fatality rate of 19.4% in 2023 [8, pp. 8-12].

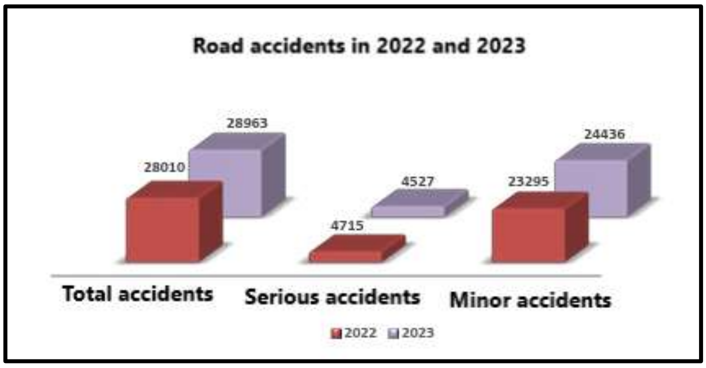

Figure 29. Road accidents in Romania in 2022 and 2023 [8, p. 40].

On the other hand, although fewer in number, serious road events on roads outside settlements have the highest fatality rate (54.7%). Outside settlements, there were 9.8% fewer serious road events in 2023 compared to the previous year (-107 serious road accidents), 85 more fatalities and 51 fewer seriously injured people. Similar to 2022, streets were the road sector on which most serious road crashes occurred in 2023 (37.9% of all serious road crashes). National roads represented the second category in terms of the number of serious road accidents occurring on this road sector (32.7%). In terms of casualties, 45.3% of all road fatalities on national roads in 2023, more than twice as many as in road events that occurred on the street, a similar situation to the previous year [8, pp. 8-12].

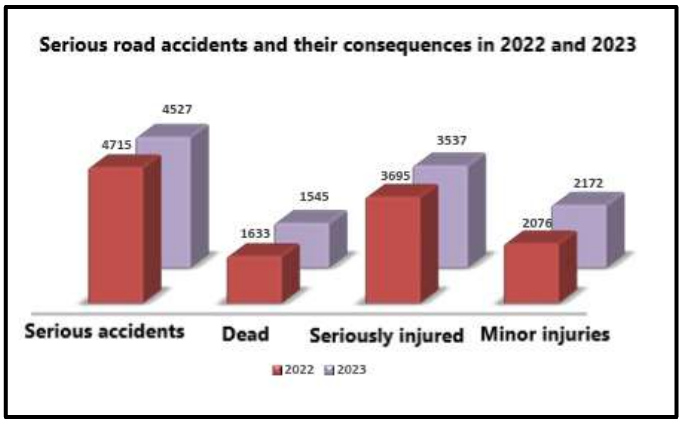

Figure 30. Road accidents in Romania in 2022 and 2023 [8, p. 40].

Although they rank first in terms of the number of serious road accidents, street events have the lowest fatality rate. As in previous years, junctions and bends are infrastructure elements with a higher potential road risk. Two thirds of all serious road crashes occurred on road segments with no special features. In 2023, speed not adapted to the road conditions is the generating cause of most serious road accidents when the road condition is wet, with a total of 176 serious road accidents recorded, as well as in bad weather conditions (snow, ice, slush, ice, slush, etc.) with 45 serious road events produced. The number of victims killed in serious road accidents in 2023 is about 5% lower than in 2022 (by 88 persons) and the number of victims seriously injured is about 4% lower (by 158 persons) [8, pp. 8-12].

After pedestrians, drivers of 4-wheeled motor vehicles are the second most common category of road fatalities (28.8% of fatalities), followed by passengers (23.2%). 1 in 5 drivers of vehicles, motorized or not, who died in road crashes in 2023 were aged between 18 and 30. 58.7% of road users aged 18 to

35 who died were drivers. Males accounted for 75% of those killed in serious road crashes and 63.4% of those seriously injured [8, pp. 8-12].

As shown in Figure 31, special road characteristics (curve, tunnel, intersection, bridge, railroad crossing) are not a major factor influencing the occurrence of serious road accidents. Therefore, in the total number of serious road accidents in 2023, about two thirds of the events occurred on road sections without special characteristics. As in previous years, intersections and bends are infrastructure elements with a higher potential for road risk (Figure 31). In 2023, there is a slight decrease in the number of serious road events occurring on these infrastructure elements with a higher potential for serious road accidents: compared to 2022, serious accidents on bends decreased by 24 events and those on intersections by 52 events. Although serious road crashes occur more frequently at intersections than in curves, the number of fatalities is comparatively lower. Accidents occurring on curves in 2023 indicate that 296 people died and 615 people were seriously injured, while 161 people died and 644 people were seriously injured in serious intersection crashes [8, pp. 44-45].

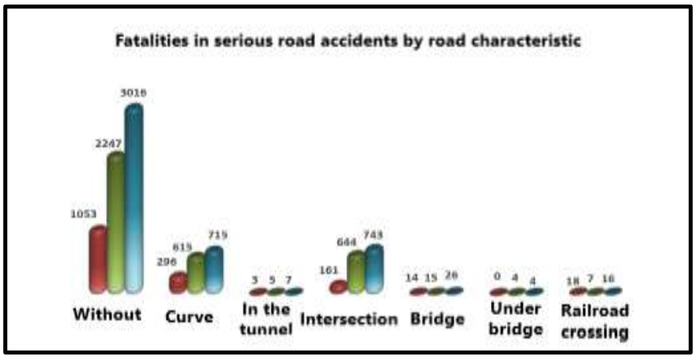

Figure 31. Serious road accidents by road characteristics [8, p. 45].

Figure 33 shows a comparison of the number of c asualties in serious road accidents by road characteristic. From the analysis of the data presented in Figure 31, it can be seen that a significant number of road crashes occurred on curves, with this being the second highest number of casualties compared to other road characteristics. We note that accidents occurring on curves occupy second place in the accident rankings according to the data presented in this figure. Only at intersections a slightly higher number of such accidents occurred. In Table 6 we present a comparative table with the values of the fatality index recorded in Romania as a result of serious road accidents that occurred in 2023 on road sectors with different characteristics.

Table 6. Comparison between the values of the fatality rate recorded in Romania as a result of serious road accidents, occurring in the year 2023, on road sectors with different characteristics [8, p. 46].

Road characteristic	**Number of serious road accidents**	**Number of persons deceased**	**Mortality rate [%] (no. of fatalities x 100/no. of serious accidents)**
Without	3,016	1,053	24.9
Curve	**715**	**296**	**41.4**
In the tunnel	7	3	42.9
Intersection	743	161	21.7
On the bridge	26	14	53.8
Under bridge	4	0	-
Railroad crossing	16	18	112.5
TOTAL	**4,527**	**1,545**	**34.41**

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Analyzing the data presented in Table 6, we can see that there have been quite a number of road events with serious consequences in the curve, and this element of road infrastructure remains a dangerous one that generates a high number of human casualties and significant material damage. There have been 715 serious motor vehicle accidents, in which 296 people lost their lives, with a fatality rate of 41.4%.

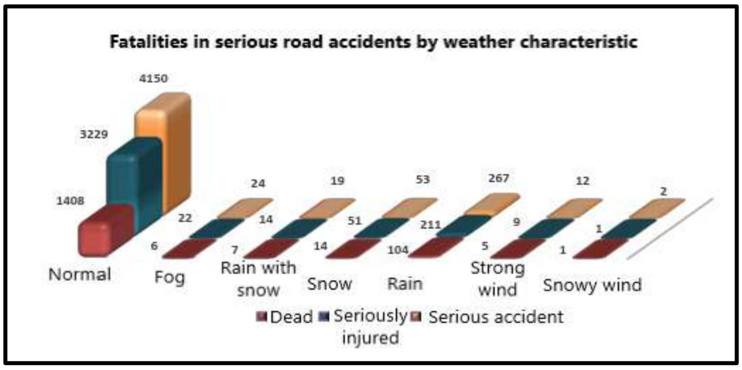

Figure 32. Fatalities in serious road accidents by weather characteristics [8, p. 47].

Weather conditions are conducive to serious road accidents, especially in curves, when vehicle speeds are not adapted to the weather. On a wet, icy or snowy road, tyre grip becomes poor, which is conducive to serious road accidents. However, 91.7% of serious road accidents in 2023 occurred in normal weather conditions. Similar to previous years, the weather factor is not explicitly reflected in the number of serious road accidents produced. As a rule, special weather conditions are accompanied by repeated warnings from the authorities, which leads to more cautious behavior of road users. At the same time, in the absence of extreme weather conditions, high traffic levels may be accompanied by a lower level of caution and attention [8, p. 45].

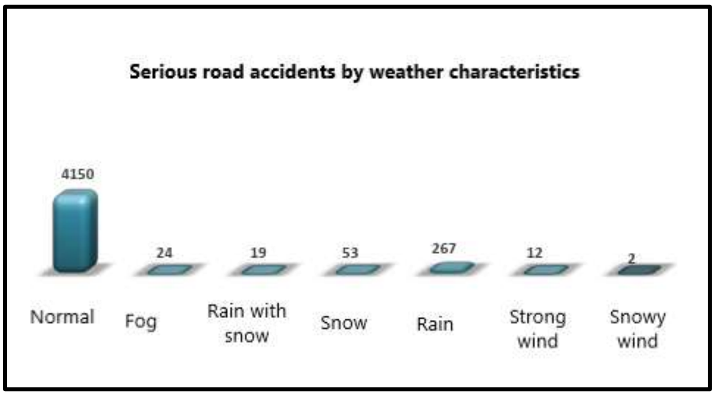

Figure 33. Serious road accidents by weather characteristics [8, p. 47].

Regarding the different unfavorable weather circumstances, rain is the situation in which most serious road accidents occurred (5.89% of serious road accidents occurred in rain), (Figure 32). Although less numerous, serious road events occurring in bad weather conditions generate a higher level of victimization (expressed as the number of persons killed and seriously injured in road accidents relative to the number of such accidents). Although fewer in number, serious road accidents in extreme weather conditions lead to a higher level of victimization (expressed as the number of persons killed and seriously injured in road accidents relative to the number of such accidents) [8, pp. 46-47].

Most serious road crashes 3,777 (83.4%) of the total number of events recorded in 2023 occurred in dry road conditions, demonstrating once again that weather conditions are not the main factor in the etiology of the occurrence of such incidents. However, it should be pointed out that 13.7% of accidents occurred in wet road conditions and only 2.8% in situations where the road was covered with snow, ice, slush, ice, slush, etc. However, the large number of accidents caused by inappropriate road speed, particularly in curves, in wet road conditions or road covered with snow, ice, slush, etc., is noteworthy, compared to accidents caused by other causes in these conditions. In fact, speed inappropriate to road conditions is the second most common cause of serious road accidents in dry road conditions, closely followed by pedestrian crossing (Figure 33).

In Table 7 we present the analysis of the fatality index values recorded in the year 2023, where we notice a higher fatality rate in the case of accidents produced in blizzard, strong wind and rain conditions, accidents generated and in curves.

Table 7. Analysis of fatality index values recorded in the year 2023 for accidents occurring in blizzard, high wind and rain conditions [8, p. 48].

Road characteristic	Number of serious road accidents	Number of persons deceased	Mortality rate [%] (no. of fatalities x 100/no. of serious accidents)
Normal conditions	4,150	1,408	33.9
Fog	24	6	25.0
Rain with snow	19	7	26.8
Snow	53	14	26.4
Rain	267	104	39.0
Strong wind	12	5	51.7
Snowy wind	2	1	50.0
TOTAL	**4,527**	**1,545**	**34.1**

As the data presented in Table 7 demonstrate, there are some differences in the specifics of serious road crashes in different weather conditions. The large number of accidents caused by inappropriate road speed in wet or snow-covered roads, ice, etc, especially on curves, or on the entrance to curves, is noticeable compared to those caused by other causes in these conditions. Speed not adapted to road conditions is the second most common cause of serious road accidents in dry road conditions.

4. Authors' conclusions and recommendations

Increasing the radius of curvature is often the proposed solution to reduce the number of horizontal curve accidents. However, this intervention can be very costly and its economic effectiveness must be verified before action is taken. Other possible solutions include: improvements in warning measures to warn drivers more effectively about the presence of the curve: better sight distance, better readability of the curve, signage, markings, delineation; minor geometric improvements, including changes to the characteristics of the road shoulders and edges, aiming at better "forgiveness" of possible driver errors.

The different characteristics of the road infrastructure that have an impact on the speed practiced - route in plan, cross-sectional profile, condition of the road edges, sight distance - need to be very well coordinated. Improving an isolated element (e.g. increasing the radius of curvature) without modifying other elements (narrow cross-sectional profile, steep slope of the embankment, rigid obstacles on the roadside) may have a negative impact on safety. In addition, measures must be taken to ensure that improving one curve and subsequently increasing speeds does not cause the problem to migrate to the next tight curve.

The minimum values of the radius of curvature used in the road design stage range from about 100 m at a design speed of 50 km/h to about 500 m for 100 km/h. Such radii are calculated, using reduced transverse friction coefficients, which allow the following: taking into account difficult but not exceptional driving conditions (wet road, worn tires); limiting large increases in braking distances in curves; ensuring relative comfort for occupants.

In extra-urban environments the frequency of accidents increases as the radius of curvature decreases. The frequency of accidents in curves is influenced not only by the characteristics of the curve (radius, deflection angle, friction, deflection, etc.) but also by the characteristics of the route in plan (length of the alignment ahead of the curve, general sinuosity of the road). It is therefore not unusual that two similar curves may have different accident outcomes, depending on the road context.

The overall sinuosity of a road has a direct influence on a driver's level of attention and their expectations of the route ahead. A tight curve is therefore more problematic on a relatively straight road than on a very winding road. Sudden changes in the radius of a curve can surprise drivers and

therefore increase the likelihood of error and should be avoided. The risk is greater if a curve with a small radius follows a curve with a larger radius. A 50% reduction in radius of curvature over a distance of more than 30 m increases the frequency of accidents. A curve with an irregular radius can normally be modified to obtain a uniform circular radius, a clothoid or a combination of the two, without having to overload the road plan too much.
The coefficient of transverse friction has a predominant influence on the maximum cornering speed. For example, for a curve with a radius of 300 m, a duty of 0.06 and a coefficient of transverse friction of 0.30, the (theoretical) maximum speed is 108 km/h; it reaches 148 km/h if the coefficient of transverse friction is increased to 0.80. The values of the coefficient of transverse friction used in road design are normally much lower than the friction values available on the road (it typically varies between 0.08 and 0.016, depending on the design speed).
In favorable conditions, curves can be handled at speeds higher than the road design speed. Realizing this, some drivers get into the habit of driving at relatively high speeds, thus reducing their margin of safety. It is a driving habit that can prove problematic if grip on the road surface is poor in a particular curve or if the driver does not reduce speed sufficiently (it is often difficult for a driver to detect grip gaps). When the available cornering friction becomes less than the friction required for the driver's speed, loss of control of the vehicle occurs.
The presence of water between the tire and the road surface reduces surface adherence, which explains why locations with low friction coefficients can have high crash concentrations on wet roads. Because the grip required is higher in curves than on the alignment, the problem is more acute at these locations. Some experts estimate that the proportion of wet accidents is higher in curves than on alignments, especially when the coefficient of friction is low (road surface condition).
Skidding occurs when the centrifugal force becomes greater than the resistance offered by transverse friction and the dever. The driver then loses control of the vehicle, which slides to the outside of the curve (although it sometimes stops on the inside of the curve in the case of oversteer). The skidding speed depends on a number of factors, including: vehicle characteristics (engine power, maneuverability or axle providing traction), driver maneuvers and road surface conditions. However, for various reasons, the slip limit is not necessarily reached at the same time on all wheels of a vehicle. These may be differences between: the loads on each wheel, the braking forces applied to the wheels, the characteristics of a vehicle's tires, the characteristics of the running surface, etc. If the vehicle has a rigid configuration (e.g. a larger vehicle such as a truck), friction may then develop at wheels that have not yet reached the slip limit. In the case of an articulated vehicle (semi-trailer, trailer, tractor-trailer), wheel slippage may cause the rigid parts to rotate and completely change the configuration of the vehicle (this may also be due to the phenomenon of folding, which practically "kinks" the tractor-trailer at the articulation of the tractor head with the semi-trailer or trailer. In the paper we have presented the speed calculation relationships for both overturning and skidding, but in order to calculate this speed accurately, instrumented friction tests must be carried out immediately and the results adjusted to account for differences between the test conditions and those prevailing during the event under study. This type of analysis is mainly carried out in accident reconstruction (Clothing Condition - Adjustment Factors). The speed at which a skid may occur should always be well above the posted speed limit. If this is not the case, warning measures adapted to the situation should be provided and should be placed far enough ahead of the curve to give drivers time to prepare themselves properly.
If dever is excessive slip and very little grip (e.g. a icy road surface), some slow moving or stationary vehicles may slide into the curve. Recommended values for duty are 2%. A transition zone between the alignment and the curve should be provided for the gradual build-up of the camber. In part of this area, the road cross-section flattens out on the outside, which can lead to water accumulation and cause skidding and hydroplaning problems. It is therefore necessary to ensure that this area is filled in before the curve is initiated, while taking care of the quality of drainage at the location.

It is necessary to increase the road width (overloading) in some horizontal curves. The necessary width (overloading) depends on the radius of the curve, the speed practiced and the characteristics of the heavy vehicles on the road.

In the extra-urban environment, shoulders should be stabilized and free of obstacles to allow overtaking vehicles to recover their lane. In this respect, particular attention should be paid to the quality of the shoulders in curves, as the risks of lane departure are higher than in the alignment. Erosion can cause rapid degradation of unconsolidated pavements, especially in areas where rainfall is heavy and rainwater washes away heavily (e.g. concav e vertical curves). Unevenness of the pavement slope relative to the travelway increases the risks of loss of control and should therefore be avoided.

When drivers are required to reduce speed when approaching a curve, they should be warned in advance with appropriate signage so that they can adapt their driving to the road conditions. In addition to signs marking the presence of a bend (and in some cases indicating the recommended speed), other warning measures may also be used: road markings, delineation (on clothing or on signposts), cross markings, audible slow-down devices. The nature and intensity of the message should be adapted to the road context and road category: the importance of slowing down, the importance of traffic flows, drivers' expectations regarding the presence of the curve, visibility of the curve, the possibility of traffic conflicts in the curve, etc. The same warning messages should be used for the same types of situations to reduce the possibility of driving errors (drivers' expectations and driving load).

Figure 34. The *"pearl"* of highways in Germany [11] .

From a psychological point of view, the difficulties associ ated with driving on bends are such as to make it difficult for a driver to deal simultaneously with additional stimuli that may be found in the road environment. Therefore, it is necessary to ensure that the presence of potential sources of conflict (intersections, crossings, private driveways), distractions (advertising, commercial activities, etc.) or other elements which may add to the complexity of the task (slope, narrow bridge, lane loss, etc.) is controlled in and around the bend.

As everywhere on the road, the sight distance at all points of a curve must be sufficient to allow safe stopping maneuvers. The various obstacles on the inside of a bend can impair visibility: embankment, vegetation, buildings, etc. Sufficient lateral clearance must therefore be provided, the width of which depends on the braking distance in the curve. These issues are resolved by overloading the inside of bends, thus eliminating obstacles which reduce visibility in curves.

In order to prevent skidding and overturning of vehicles in curves, it is recommended to design and construct curved roads with the outside of the curve excessively overlift to prevent the centrifugal force from pushing the vehicles in the dynamic outwards out of the curve. This curve design is practiced in Germany, particularly on the highways known as *"Autobahnen"* which have a unique design detail on their curves called the *"pearl"* (Figure 34). This system consists of tilting the asphalt on the inside of the curve to form an elevation at the edges. The main purpose of this slope is to compensate for the centrifugal force acting on the vehicles inside the curve during cornering dynamics. This improves vehicle stability and reduces the risk of overturning at high speeds. In addition, the “bead” facilitates the flow of water from precipitation or melting snow, thus avoiding puddles and contributing to better grip of the tires on the asphalt. This reduces the risk of water soaking into/on to the asphalt, a risky situation in which tires lose contact with the road (aquaplaning) due to water accumulation.

In conclusion, the engineering feature presented not only improves road safety, but also extends the durability of roads by reducing wear or deterioration caused by water retention. Although the ingenious solution cannot be applied in our country on the highway infrastructure, because they do not have such small radii of curvature that the centrifugal force would throw the vehicles outside them, nevertheless, this variant could be applied in the tight curves of the European (E) express and national roads, where the speed is 100 km/h outside the localities, or on the other categories of roads, where the speed is 90 km/h outside the localities, by the effect of oversteer or understeer would cause skidding or overturning. The method of this type of infrastructure is more than welcome when drivers do not respect the speed limit and do not drive preventively in bends on these categories of roads.

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