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# METHODS FOR SETTING ROAD VEHICLE MOVEMENT TRAJECTORIES

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**Abstract.** The paper gives overview of the methods for setting the vehicle movement trajectory. Results have been shown, within wider research project, of the comparative analysis of methods for setting vehicle movement trajectory, bearing in mind relevant criteria and respecting the results of proving range test drives on field. Respecting the laws of geometry of movement and behaviour of the vehicle under real traffic conditions in small radii curves, optimum shaping of steering path and defining of kinematic vehicle model was tested by using computer programme of verified reliability developed in the Faculty of Civil Engineering of the University of Zagreb.

**Keywords:** geometry of movement, vehicle, small radii curves, steering path, dragging path, kinematic model, offtracking.

## 1. Introduction

Good knowledge of the geometry of movement is a prerequisite for the correct formation of the elements of road traffic zones such as turning bays, hairpin bends, intersections at grade, bus and truck stations, parking lots, etc. When driving in small radii curves, characteristic of the mentioned traffic zones, driving-dynamic requirements lose their importance due to low driving speed, while the laws of geometry of movement are fully manifested.

The only precise method of setting vehicle movement trajectory is to drive a real vehicle under real traffic conditions, i.e. on the field. Since such testing is long, organizationally demanding and expensive, simulation methods have been developed which try to represent the real vehicle movement as truly as possible: analytical methods, model testing, graphic methods and computer programmes.

Each of these has certain advantages and disadvantages, since it contains the necessary simplifications without which the simulation would be very complicated. Analytic and graphic methods as well as testing by models have lost their importance with the development of information technology, since computer programmes enable a relatively quick setting of the vehicle movement trajectory by varying influencing parameters such as design vehicle type, turning angle and curve radius.

Distributors of computer programmes for setting the vehicle movement trajectory available on the market point out that they do not take responsibility for the mistakes and damage caused by their usage (*User's guide AutoTurn 4* 2001; *User manual for AutoTrack 5, vehicle swept path analysis* 2003). Proper implementation of the mentioned computer programmes requires a good knowledge of laws of vehicle movement geometry in small radii curves.

## 2. Testing by proving range test drives on the field

Test drives on the real traffic zone or on the zone specially prepared for testing is the only precise method for setting vehicle movement trajectory. When shaping traffic elements it is essential to determine the zone covered by the vehicle at turning, which is delimited by dragging path "b" circumscribed by the right rear overhang point of the vehicle B, when the front left overhang point A circumscribes the set steering path "a" (Fig. 1). So defined vehicle movement trajectories describe real traffic conditions.

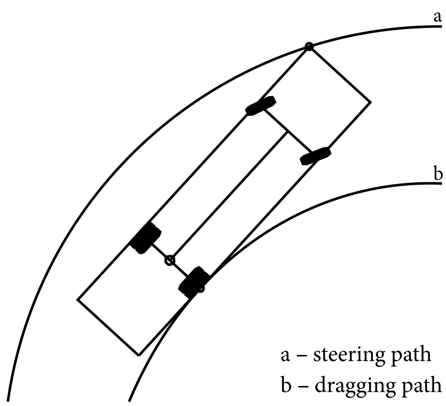


**Fig. 1.** Vehicle movement trajectories

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Proving range test drive simulations on the field are possible in three ways:

- setting the steering and dragging trajectory circumscribed by the vehicle where the vehicle starting point and the arriving point are set and the driver chooses the vehicle movement trajectory;
- steering path to be followed by the front left overhang point is set and it is necessary to set the dragging path circumscribed by the right rear overhang point and
- dragging path circumscribed by the right rear overhang point is set, and it is necessary to determine steering path circumscribed by the front left overhang point.

It has been shown that in the situation in which the dragging path is defined, it is very hard and almost impossible for the driver to follow the dragging path with the right rear overhang point, since this is reduced to driving looking into the rear-view mirror, and not forward. Bearing in mind this fact, there arises a question of the correctness of drawing the horizontal signalization at intersections at grade, where, for left turning vehicles, the path to be followed at turning is exactly the dragging path.

Testing has shown that in case of set steering path the driver can follow this line with front left overhang point with insignificant departures.

If, in geometrical terms, either steering or dragging path is defined, defining the vehicle movement trajectory is reduced to setting only one of them which simplifies and speeds up the procedure. When the driver is allowed to choose vehicle movement trajectory, it is necessary to define the shape of both the steering and dragging path. Thus, due to the simplicity in shaping traffic zone elements such as hairpin bends, intersections at grade, turning bays, etc., it is recommendable, in geometrical sense, to define the outer edge of the curve and, by the chosen method which simulates the vehicle movement, to determine the dragging trajectory which sets the inner edge shape. Since testing showed that the driver cannot, with ease, follow the set dragging path by the right rear overhang point without bigger departures, therefore the precision of so determined steering path, i.e. vehicle movement trajectory, is questionable. Respecting the comparative advantages and disadvantages of the mentioned variants, it turned out that with methods simulating the vehicle movement with the aim to optimize shaping of road traffic zones, it is optimum to geometrically define the steering path and to determine the dragging path.

## 3. Methods of vehicle movement simulation in short radii curves

In the Dept of Transportation Engineering of the Faculty of Civil Engineering of the University of Zagreb a research has been done in which relevant criteria for choosing the method for setting vehicle movement trajectory, respecting proving range test results from the field have been considered (Korlaet 1981).

In most cases existing methods lack the verification of results according to the real vehicle behaviour, and even if it is done it is not carried out systematically taking into consideration the sufficient palette of influencing parameters but it is carried out for one or two vehicle types and, at the most, two different turning angles and radii (Fong, Chenu 1986; Garlick *et al.* 1993; Litzka 1971).

Thus in method verification it is necessary to consider the criteria which come out of the good knowledge of laws of geometry of movement and vehicle behaviour in real traffic conditions. They include the following: shaping the steering path and defining the kinematic model of vehicle.

### 3.1. Shaping the steering path

Computer programmes which simulate the vehicle movement offer the possibility of shaping the steering path by means of simple curves consisting of a straight line and circular arc.

On traffic zones where the laws of geometry of movement have a crucial influence traffic speed is low and the impact of lateral forces can be disregarded, so when passing from the straight line to the circular arc it is not necessary to perform the transition curve due to gradual and continuous overcoming lateral forces.

Testing carried out on buses, trailer trucks and tractor semitrailers on curves of 18 to 30 m radii for turning angles bigger than 210° showed that the vehicle cannot follow the steering path without departures when passing from the straight line into a circular arc there was no transition curve. This is caused by construction capabilities of the steering mechanism. Vehicle movement trajectories were determined by simulating test drives by a computer programme for which there was reliability verification with respect to movement trajectories determined by proving range testing on the field specifically for different shaping of steering path passing from the straight line to circular arc: without transition curve, with the short transition curve (the length of transition curve is from 2 m to 1,2R, when R means curve radius) and with the transition curve in the form of clothoide of the parameter $A = 1{,}2R$.

If the steering path is shaped without transition curves (Fig. 2) on the entrance of the circular arc PC (point of curve), the steering wheel should be turned suddenly which represents the difficulty for the driver and the vehicle. At the exit of the curve PT (point of tangent), with releasing the steering wheel, the problem loses importance. Thus, it is not possible to follow, with the front left overhang point, so

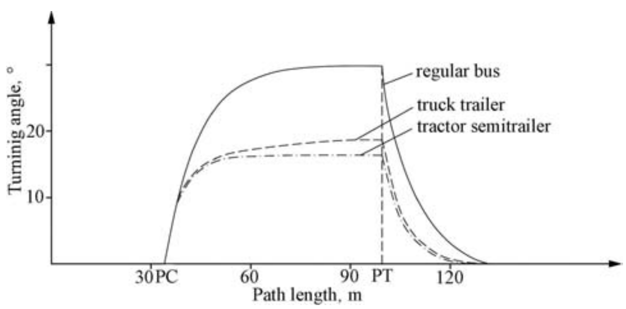


**Fig. 2.** Theoretical angles of vehicle turning for steering path shaped without transition curves ($R$ = 18 m, turning angle 210°)

shaped steering path without departures. The importance of the problem increases as so the speed does.

The procedure of determining dragging trajectory in case when the steering path is designed without the transition curves is considerably simpler and speeds up the process of getting results in computer programmes, especially if analytical or graphic methods are applied. The question was set whether a vehicle can follow the steering path designed with a short transition curve without departure. During testing the shortest transition curve was set at the length of 2 metres. If the length is increases the departure value decreases and is practically irrelevant if the transition curve is a clothoide with the parameter between R and 1,2R.

Transmission ratio of turning wheels with regard to turning steering wheel for personal vehicles amounts to 1:22, while for trucks it ranges from 1:20 to 1:25 (Lukin *et al.* 1989).

The turning speed of steering wheel for personal vehicles amounts to 1,5 to 1,7 turns per second (Lukin *et al.* 1989). Depending on the characteristics of the steering mechanism of trucks, which are less favourable regarding there turning possibilities in small radii curves, depending on the type of the truck; it is possible, in one second, to turn the steering wheel for 0,5 to 1,2 turns (Lukin *et al.* 1989), that is, for 180° to 432°. That is the reason why these vehicles cannot, without departures, follow the steering path which, passing from the straight line to circular arc, does not have the transition curve (Dragčević 1994).

With unvaried motion of the speed of 20 km/h the vehicle covers the path of 5,5 m in a second. In order to follow the set steering path without departures, a bus e.g. should in one second realize the wheel turning angle of 10,5°, and the steering wheel turning angle of 265° (transmission ratio 1:25). Even with the speed of 20 km/h not all trucks can, without departures, follow the set steering path, and, with the increase in driving speed, the departure of steering path compared to the set steering path is increased. Tests have shown that even for the biggest radii of "small radii" curves (up to 30 m) turning of the steering wheel, so that the vehicle could, without departures, follow the set steering path when moving on the curve shaped without transition curves, for most trucks is impossible.

Shaping the steering path with the short transition curve, passing from the straight line into the circular arc, of the clothoid shape of 2 m length compared to the case of shaping the steering path without transition curve, shows a negligible improvement. Namely, most of the trucks could not without significant departures follow the set steering path. Therefore, the need for the transition cannot be disregarded. Tests have shown that the observed trucks can, with the driving speed above 20 km/h, without difficulty follow the steering path shaped by small radii of circular arc if the steering path passing from the straight line into the circular arc is shaped with the transition curve of the clothoid shape of parameter $A = 1{,}2R$, when R means curve radius.

As transition curve passing from the straight line into the circular arc, the clothoide was used in testing, since the valid regulations for road construction prescribe the obligation of using clothoide of the prescribed parameter A in shaping the road axis in transition from the straight line into the circular arc, so it is optimum to use the same transition curve for shaping the steering path as well.

In accordance with the results of the described testing, recommendations of Petrović (1977) and German *Guidelines for the Design of Roads* (*RAS-L-1* (1984), *RAS-K-1* (1988)) from shaping and driving-dynamic conditions which refer to curves of big radii and the characteristics of the steering mechanism, in shaping steering path passing from the straight line to circular arc the clothoide of parameter A with regard to $R \le A \le 1{,}2\,R$. Such shaping of steering path is indispensable, so that all vehicles relevant for shaping road traffic zones in which the laws of geometry of movement are crucial could, without departures, follow the set steering path.

Since computer programmes offered on the market do not have the option of shaping the steering path with the transition curve passing from the straight line to the circular arc, the error caused by this simplification is set.

Computer programme (Dragčević 1999) developed at the Faculty of Civil Engineering of the University of Zagreb which reliability was proven with respect to proving range tests on the field, has the ability to shape the steering path passing from straight line to circular arc by transition curve of clothoid shape. The programme gives opportunities to choose different types and dimensions of design vehicle, different radii values, turning angle and the parameter of transition curve.

In the mentioned programme, the vehicle movement on plane was set as a geometrical problem and based on the independent variable when s means arc length of steps on the steering path. This approach turned out to be simpler than in relation to the movement observation as a kinematic problem, when the independent variable t means time. As the result of that, a decreased number of differential equations is in the system. If the independent variable is s, then the initial conditions are defined with linear equations. If the independent variable is $t$, it is defined with differential equations. Differential equations describing vehicle movement are the following:

$$u'(s) = \frac{x-u}{D^2} \times \left[ (x-u) \times x' + (y-v) \times y' \right],$$

$$v'(s) = \frac{y-v}{D^2} \times \left[ (x-u) \times x' + (y-v) \times y' \right],$$

where $v' = \dfrac{dv}{ds}$, $u' = \dfrac{du}{ds}$, $x$, $y$ – coordinates of the points of the steering path; $u$, $v$ – coordinates of the points of the dragging path; $D$ – dragging length (distance between two points on the disk: the first which follows the steering path and the second which circumscribes the dragging path).

Initial conditions are defined as follows:

$$u_1 = u \times (s_0 + h) = u_0 + k,$$
$$v_1 = v \times (s_0 + h) = v_0 + k,$$

where $h$ – a step of numerical integration; $s_0$ – initial parameter value s; $k$ – coefficient of numerical integration; $u_0$, $v_0$ – coordinates of the initial point of dragging trajectory.

Runge-Kutta method of the 4th order was used to solve the differential equation system. Computer programme was created in Visual Basic programming language and uses *AutoCAD* graphic user interface.

Setting vehicle movement trajectory was performed for shaping steering path: by straight line and circular arc; by straight line, circular arc and transition curve of the clothoide shape in passing from the straight line to the circular arc.

Testing was performed for regular bus (Fig. 3) by varying radii curves from 12,5 to 25 m and turning angles from 90 to 225° for the selected parameter of clothoide $A = R$. Lane width was measured at 9 cross-sections. The differences in the traffic lane width for design of the steering path with and without transition curve for the mentioned turning angles and curve radius of the curve 12,5 and 25 m are shown in Tables 1 and 2.

In shaping steering path without transition curve of the lane width at curve entrance and exit are smaller than in shaping with the transition curve in the absolute amount of 22 cm depending on the radius of the circular arc $R$ and the turning angle α. In the central part of the curve it is reversed, in case of shaping steering path without transition curve bigger lane widths are needed in the absolute amount of 15 cm depending on $R$ and α. The differences in lane width at curve entrance and exit are increased with the increased turning angle and curve radius while, in the central part of the curve they decrease.

### 3.2. Defining the kinematic model of vehicle

In the analysis of geometry of movement in small radii curves some assumptions i.e. simplifications are used which refer to the characteristics of steering mechanism and the behaviour of pneumatics under the influence of lateral forces. When defining the kinematic model of vehicle, a good knowledge of vehicle movement kinematics and dynamics is required so that the introduction of assumptions, without which such analysis is not possible, does not affect research results negatively. The movement of vehicle in models was described as the movement of the disk on the plane, and geometrical relationships are defined by trajectories circumscribed by two points on the disc.

In small radii curves which appear in shaping the mentioned traffic zones driving speed is low, centrifugal force is small, and so are sideway forces that causes skidding. Thus it can be assumed that wheels are rigid and rolling freely (there is no tyre slipping). Tandem front steered and tandem rear fixed axles are modelled by considering equivalent single front steered or rear fixed axle, whose position is in midway between the two axles. Accurately defined kinematic model of vehicle – model I (Fig. 4) simulates behaviour of the vehicle in real traffic conditions when front right overhang point follows the set steering path, while the dragging path is circumscribed by left rear overhang point.

Some methods for setting vehicle movement trajectories define kinematic model of vehicle on this way

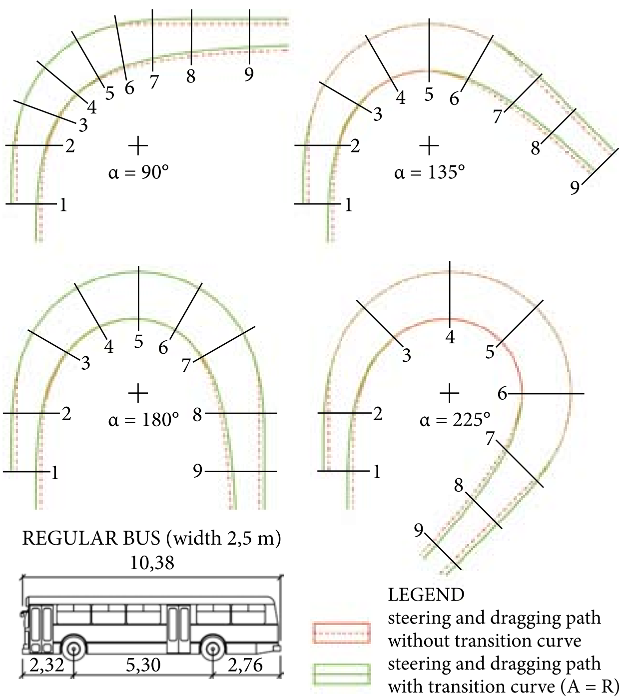


**Fig. 3.** Setting the lane width for different shaping of steering path (turning angle α = 90, 135, 180 and 225°)

**Table 1.** Difference in traffic lane width with and without transition curve for curve radii R = 12,5 m

| Cross-section | Difference in traffic lane width with and without transition curve, *A* cm | | | |
|---|---|---|---|---|
| | 90° | 135° | 180° | 225° |
| 1 | 10,54 | 10,54 | 3,59 | 3,59 |
| 2 | 7,72 | 7,72 | 19,13 | 19,13 |
| 3 | −10,4 | −8,48 | −8,48 | −6,14 |
| 4 | −7,11 | −3,98 | −3,98 | −2,56 |
| 5 | −11,41 | −2,86 | −2,56 | −0,73 |
| 6 | −14,73 | −13,15 | −0,71 | −0,95 |
| 7 | 2,90 | 8,66 | −11,31 | −4,18 |
| 8 | 7,94 | 5,64 | 6,11 | 8,05 |
| 9 | 3,52 | 2,52 | 6,10 | 3,52 |

**Table 2.** Difference in traffic lane width with and without transition curve for curve radii R = 25 m

| Cross-section | Difference in traffic lane width, with and without transition curve, *A* cm | | | |
|---|---|---|---|---|
| | 90° | 135° | 180° | 225° |
| 1 | 17,59 | 17,59 | 11,74 | 11,74 |
| 2 | 10,68 | 10,68 | 19,91 | 19,91 |
| 3 | −12,55 | −7,92 | −7,92 | −3,84 |
| 4 | −4,67 | −1,35 | −1,35 | −0,46 |
| 5 | −3,25 | −0,45 | −0,46 | 0,21 |
| 6 | −14,66 | −13,38 | −0,41 | 0,21 |
| 7 | 6,59 | 7,76 | −2,02 | −7,08 |
| 8 | 10,90 | 10,20 | 3,46 | 12,47 |
| 9 | 5,09 | 3,95 | 12,60 | 8,97 |

(Dragčević 1999), while most of other methods, for example, method presented in Austrian *Guidelines and standards for intersection design (RVS 3.41* (1987) *and RVS 3.42* (1987)*)* and method described by Petrović (1977), also methods used within specialized software's for vehicle swept path analysis AutoTurn and Autotrack described in user's manual *User's guide AutoTurn 4* and *User manual for AutoTrack 5,* define kinematic model of vehicle in the centre line (between front and rear axle) of vehicle. In case when the kinematic model of vehicle is situated in its centre line, most often the point which follows the steering path *V* is situated in the front axle axis, while the point circumscribing the dragging path *P* is situated in the rear axle axis, model II in Fig. 5. Within the scope of testing the influence of the kinematic vehicle model on setting the lane width in case the kinematic model of vehicle is defined as: model I (Fig. 4) corresponding to the real traffic conditions, model II (Fig. 5), *V* point is situated on the front axle centre line, and P on the rear axle centre line and model III (Fig. 5), *V* point is situated on the vehicle front part centre line, while *P* point is situated in the rear axle centre line.

The steering path for the kinematic model I is shaped by straight lines and the circular arc of 12 m radius. It is removed from the roadway edge for the protective lateral width of 0,25 m (Fig. 4). The steering path for the kinematic models II and III is also shaped by the straight lines and the circular arc, but in the way that it is removed by 1,25 m from the steering path defined for the kinematic model I (Fig. 5). Since with the models II and III *V* point is situated on the front axle centre line, i.e. the centre line of the vehicle front part this departure is necessary to make the comparison of the models possible. In that case all kinematic models have the same initial and final position, with the straight line driving front right overhang point of models II and III follows the steering path of the kinematic model I, and it is possible to make the model comparison in case of circular arc drive.

Kinematic model I has shown certain advantages compared to 2 other models. The steering path has been defined which, in geometrical terms, is shaped by simple curves, straight lines and circular arc.

The dragging path is set by the selected method. These paths represent the necessary width of the lane. The outer edge is, in geometrical sense, defined by shaping the steering path, so the shaping of intersection elements is simplified, since it is necessary to shape only those intersection

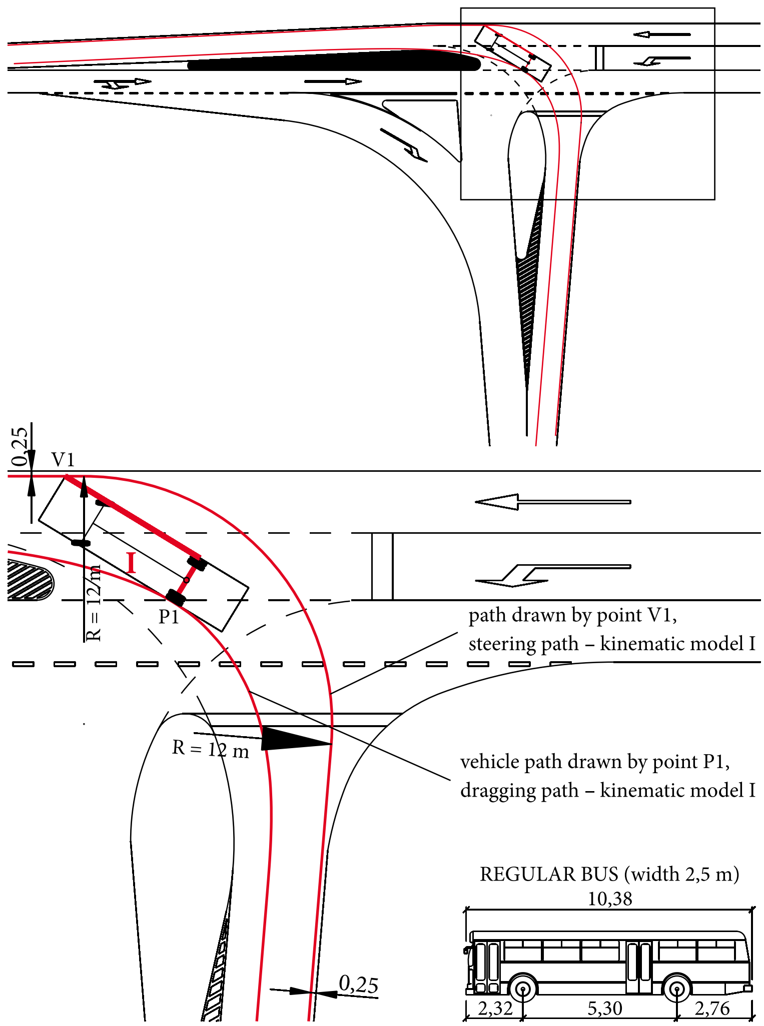


**Fig. 4.** Setting vehicle movement trajectory – kinematic model I

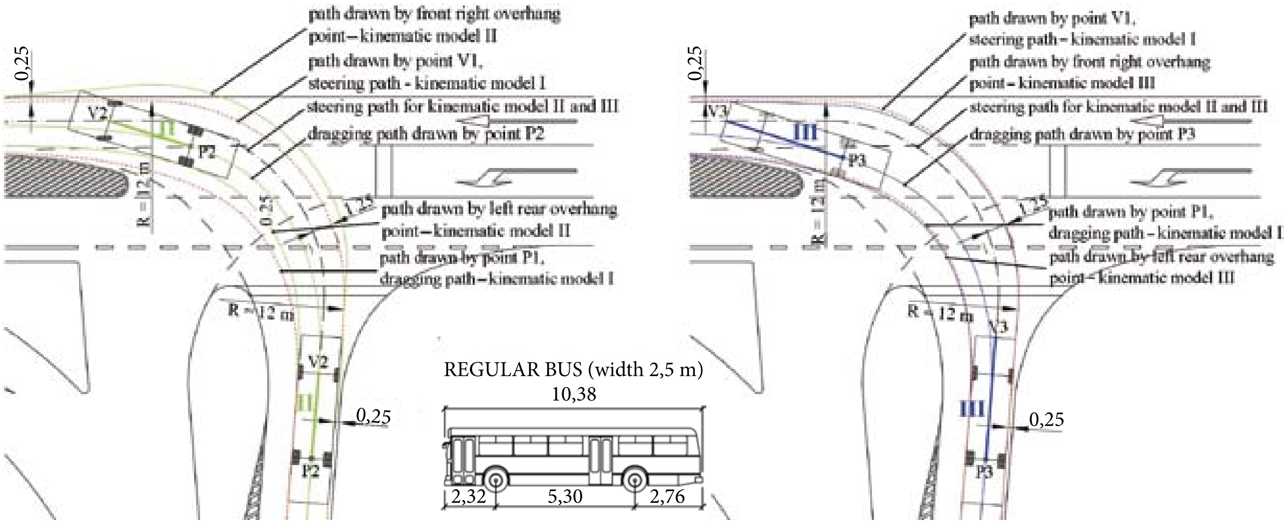


**Fig. 5.** Setting vehicle movement trajectory – kinematic model II and III

elements which shaping is influenced by dragging paths. This model is suitable to test off tracking control of the designed intersection on the basis of previously defined movement trajectories.

It was shown that the results of the analysis of vehicle geometry of movement are significantly influenced by both, the correct defining of the vehicle kinematic model and its position on the vehicle. Therefore, when selecting the method for setting the vehicle movement trajectory, the described criteria should be respected.

### 3.3. Definining the vehicle kinematic model by means of the „reduced wheel base"

In defining the kinematic model of complex vehicles such as tractor semi-trailer and truck trailer, methods for setting the vehicle movement trajectory described in Austrian *Guidelines and standards for intersection design (RVS 3.41(1987) and RVS 3.42 (1987)),* Swiss norm for determining offtracking in horizontal curve *Swiss norm (SN 640 105b (2003))* and those presented by Petrović (1977) use the method of "reduced wheel base". This is done in order to simplify and speed up the process of setting the complex vehicle movement trajectory by its reduction to a one disk vehicle which movement trajectories determined by the model describe the movement of the complex vehicle. The vehicle tractor semi-trailer consists of two disks of the trailer which makes the first disk and semi-trailer which is the second disk of the vehicle, and a three-disk truck trailer, where the first one is the truck, the second one the axle and the third the trailer (Fig. 6). In Fig. 6 the length $D$ represents the reduced wheel base, whose length changes depending on the vehicle type and the outer curve radius $R_a$. By comparing the dragging curve set for the truck trailer and tractor semi-trailer and for similar replacing vehicles (according to the method of reduced wheel base) in 12 m radius curve at 180° turning angle it was noticed that for

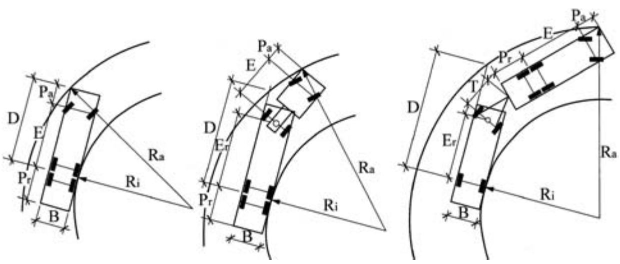


**Fig. 6.** Reduced wheel base $D$ for different vehicle type

the same steering curve dragging curves for the same vehicle type differ (Figs. 7 and 8, Tables 3 and 4).

The differences are specially pronounced at the curve entrance and exit. At the entering part in the absolute amount the differences amount from 5,55 to 21,27 cm, and at the exit from 6,55 to 39,49 cm (Figs. 7 and 8, Tables 3 and 4). Although the method of reduced wheel base simplifies and shortens the procedure of setting vehicle movement trajectories, the application of methods based on such kinematic vehicle model and their precision are highly questionable, especially for curve with small radii.

### 4. Conclusions

Shaping traffic zones such as intersections at grade, turning bays, hairpin bends, etc. according to the design vehicle movement trajectories is the prerequisite of the undisturbed and safe traffic flow. In contrast with the approach of shaping the mentioned traffic zones, where for the designed traffic zone horizontal offtracking control is checked, in this way horizontal offtracking control is ensured with the minimum occupied space, since the shaping is carried out in the way that sufficient, but not excessive lane width is ensured. That is because the process of shaping the traffic zone elements is optimized. The computer simulates the real vehicle behaviour on the observed traffic zone. At 1st vehicle movement trajectories (steering paths) are drawn for all possible

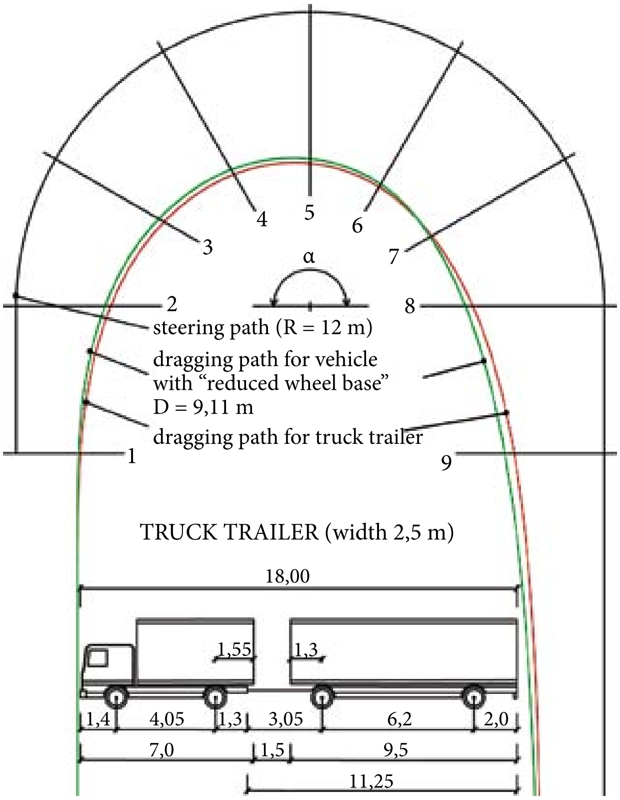


**Fig. 7.** Setting a complex vehicle movement trajectory (truck semitrailer) by the method of reduced wheel base

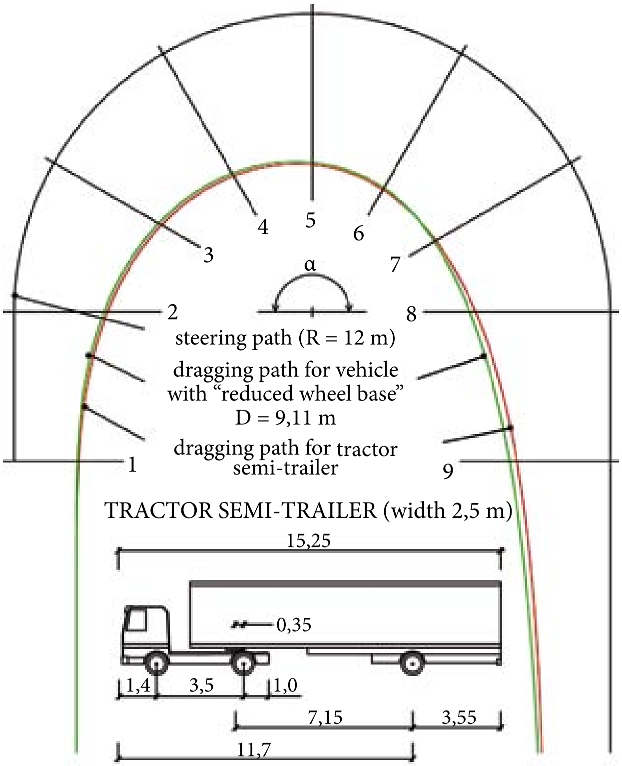


**Fig. 8.** Setting a complex vehicle movement trajectory (tractor semi-trailer) by the method of reduced wheel base

**Table 3.** Difference in traffic lane width for truck trailer and their replacing vehicle (Fig. 7)

| Cross-section | Traffic lane width, m | | Difference, cm |
|---|---|---|---|
| | Truck trailer | Replacing vehicle $D$ = 9,10 m | |
| 1 | 2,6146 | 2,5443 | –7,03 |
| 2 | 3,8360 | 3,6283 | –20,77 |
| 3 | 5,0847 | 4,8720 | –21,27 |
| 4 | 5,7563 | 5,5742 | –18,21 |
| 5 | 6,1331 | 5,9927 | –14,04 |
| 6 | 6,3493 | 6,2527 | –9,66 |
| 7 | 6,2395 | 6,3405 | 10,10 |
| 8 | 5,3417 | 5,6698 | 32,81 |
| 9 | 3,6652 | 4,0601 | 39,49 |

**Table 4.** Difference in traffic lane width for tractor semi-trailer and their replacing vehicle (Fig. 8)

| Cross-section | Traffic lane width, m | | Difference, cm |
|---|---|---|---|
| | Tractor semi-trailer | Replacing vehicle $D$ = 9,10 m | |
| 1 | 2,5996 | 2,5441 | –5,55 |
| 2 | 3,7691 | 3,6256 | –14,35 |
| 3 | 5,0095 | 4,8674 | –14,21 |
| 4 | 5,6909 | 5,5682 | –12,27 |
| 5 | 6,0869 | 5,9857 | –10,12 |
| 6 | 6,3225 | 6,2435 | –7,90 |
| 7 | 6,2679 | 6,3334 | 6,55 |
| 8 | 5,4257 | 5,6623 | 23,66 |
| 9 | 3,7614 | 4,0550 | 29,36 |

vehicle movements, in order to ensure the sufficient safety distance for passing by vehicles. This part was shown in the 1st step on Fig. 9. In the 2nd step demonstrated on Fig. 9 the continuation procedure was shown. On the basis of the drawn steering paths then dragging paths are drawn, and after that ensuring the sufficient value of protective lateral width, geometrical shaping of lane edge elements, islands for directing and separating the traffic and the right edge of the intersection at grade, etc. are carried out.

Since in designing practice a solution applied to one location can rarely be copied on the other, the optimum shaping of special traffic zone elements is dependent on the operative options of the selected computer model for setting vehicle movement trajectories and on its precision. Knowing the laws of vehicle movement geometry, which reflect shaping the steering path and the selection of vehicle kinematic model as well as an order of magnitude of error caused by the simplifications used in the model, ensures the optimum shaping of elements of the mentioned

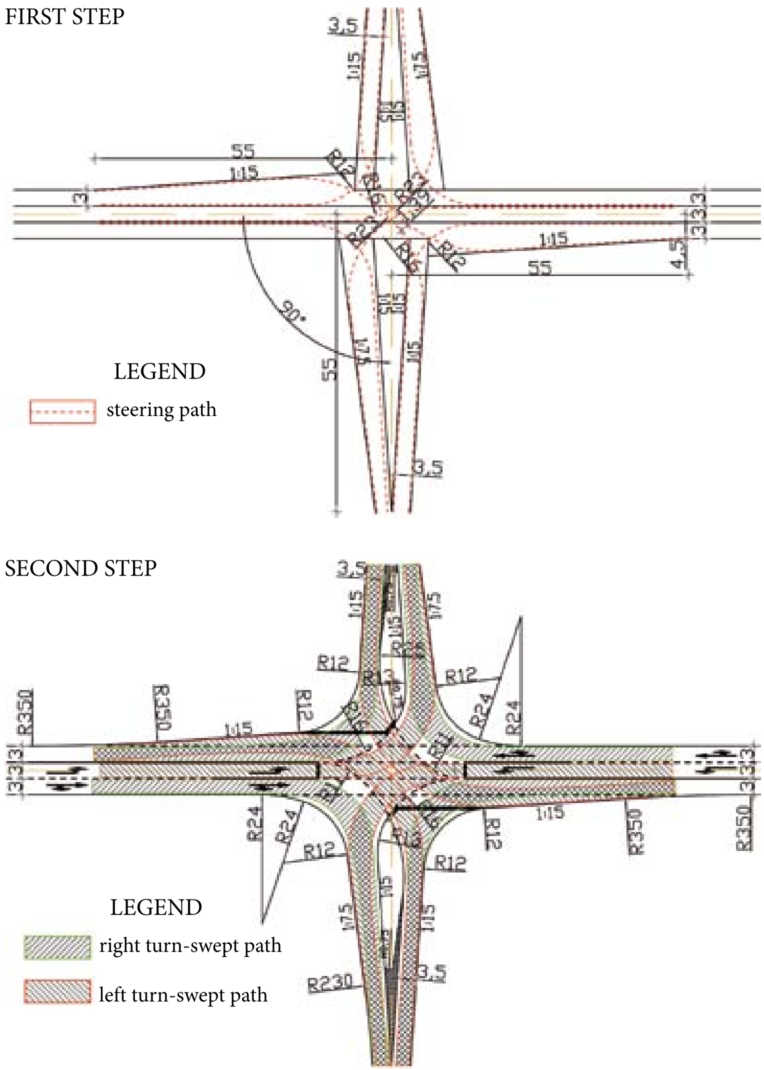


**Fig. 9.** Four-leg intersection at grade (90°-angle between main and auxiliary traffic direction)

traffic zones. In this way, the undisturbed and safe traffic flow is ensured and overcapacitation of the elements of intersections at grade, parking spaces, truck and bus stations located in high-quality city spaces is avoided.

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