RESEARCH IN KINEMATICS OF TURN FOR VEHICLES AND SEMITRAILERS

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Abstract. The parameters impacting vehicle kinematics of turn – a time period needed for turning a steering wheel, a ratio of vehicle crosbases and wheelbases were analysed. By using a model, the entering of turns by vehicles and semitrailers was researched. The momentary turning centres for vehicles and semitrailers diverged, depending on the researched turning radiuses. All vehicles with semitrailers, when turning, move along a circle after a 90° turn is performed. Articulated vehicles are an exception – their movement along a circle is possible only at large turning radiuses. It can be explained by the fact that semitrailers have large wheelbases.

Key words: vehicles, semitrailer, model, turning radius, turning angle.

Introduction

Vehicle constructions become more complex year by year. Possibilities of using vehicles are increasing. Vehicle dimensions as well as ratios of characteristic dimensions, for instance, a ratio of vehicle crosbases and wheelbases change. During the recent 30 years of vehicle development, the possibilities of using semitrailers have changed, including semitrailer dimensions. Semitrailer dimensions have substantially increased allowing road trains to carry various large-scale loads. There are some types of road trains that carry loads of railway cars, sometimes railway containers are placed right on trucks. An increase in dimensions of road trains lead to a decrease in their manoeuvrability.

Semitrailers might be coupled to trucks at various points. Semitrailers can be attached both to a truck behind its rear axles like it is in case of tractors and cars and to a truck before its rear axle like in case of classical articulated vehicles. Besides, in some trucks it is possible to change the position of truck-trailer attachment assembly relative to the towing vehicle's frame in order to provide optimal and equal load on all axles of a towing truck.

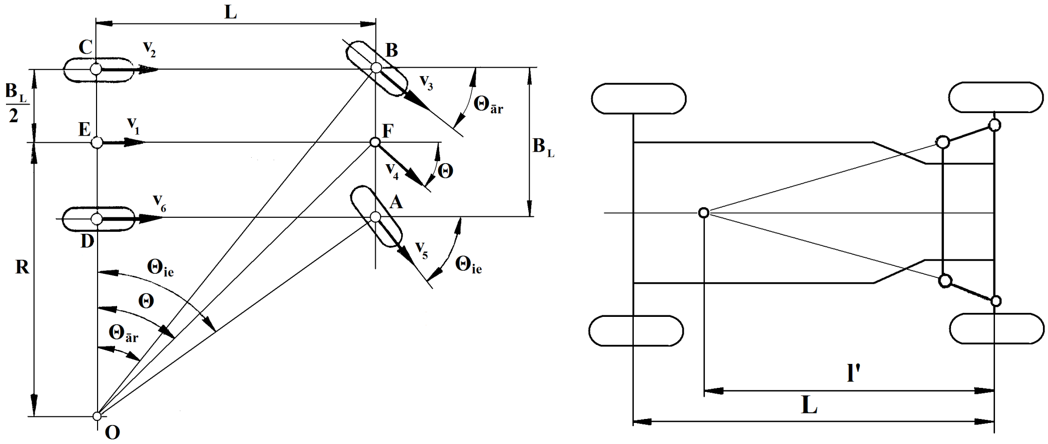
In case if a towing vehicle uses two rear axles (three axle automobiles), it is assumed in analysis that it moves, when turning, like a two-axle automobile; its rear axis is located right between automobile's rear and middle axles. If a truck pulls a semitrailer with two axles, it is assumed that the semitrailer, when turning, will move like a semitrailer with one axle that is located on a symmetry axis between both axles. If a semitrailer has three axles, it is assumed that the semitrailer will move like a semitrailer with one axle that is attached to where the middle axle is.

The aim of the research is to determine the kinematic relationships of turn for various vehicles and semitrailers which are not based on a classical vehicle theory dealing with semitrailers having small wheelbases.

Theoretical aspects for vehicle and semitrailer movement in turns

An automobile is usually steered by changing a turning angle of its steering wheels. To find the basic parameters for steering a two-axis automobile, let's assume that automobile's wheels don't deform in the cross-direction like in case of slow driving in turns and the forces of inertia impacting an automobile are ignored. In this case a two-axle automobile with guiding front wheels will be turned as it is shown in a scheme of Fig. 1. To prevent sideslipping for automobile's wheels, when moving in turns, the extensions of axes of all wheels have to cross at one point *O*, i.e., the *momentary turning centre*. The momentary turning centre changes its position depending on a turning angle of steering wheels. As one can see in Fig. 1, the turning centre lies on an extension of the rear axis. If changing the turning angle of steering wheels, the centre might move further away (turning angles of steering wheels are small) or closer to a middle point of vehicle's rear axis. In the theory of vehicles, a turning radius is a distance from momentary turning centre *O* to rear axis's middle point *E*.

Vehicle's steering wheels are turned at different angles by a steering trapeze. Any turning radius corresponds to a concrete correlation between angles $\Theta_{\bar{a}r}$ and Θ_{ie}. The maximum turning angle for steering wheels is within a range of 35°...40° to each side, but the steering trapeze cannot provide a correct correlation within the whole range. Therefore, a trapeze geometry is set in a way that a correct correlation for turning angles is provided at the turning angles of steering wheels that are commonly referred to in user manuals. At a maximum turning angle of steering wheels, the divergence of angles from the theoretically correct angle is the greatest.



a) b)

Fig. 1. **Turning scheme for an automobile with indeformable wheels (a) and determination of steering parameters (b)**

To make sure that the steering trapeze provides necessary turning angle correlations for external and internal steering wheels, the lines that are drawn from turning rods have to cross each other at a distance of l'=(0.7...0.85)L from the front guiding axis (see Fig. 1, b) [2,3].

The turning angle of automobile's steering wheels can be characterised by an average turning angle Θ. This angle forms between an extension of the rear axis and a line that goes through a midpoint of the turning centre and front axis (see Fig. 1, a). The average turning angle can be calculated:

$$\mathrm{ctg}\Theta = \frac{R}{L}, \tag{1}$$

where Θ – average turning angle, degrees;
L – vehicle's wheelbase, m;
R – vehicle's turning radius, m [1].

Vehicle's steerability is assessed by a minimum turning radius $R_{\bar{a}r}$, set in vehicle's technical characteristics, for a wheel located at the greatest distance from a turning centre. If automobile's front and rear crosbases are equal, this radius can be calculated, using the Pythagorean theorem and Equation 1, by the following equation [1]:

$$R_{\bar{a}r} = \sqrt{\left(R + \frac{B_L}{2}\right)^2 + L^2} = \sqrt{\left(L\mathrm{ctg}\Theta + \frac{B_L}{2}\right)^2 + L^2}, \tag{2}$$

where B_L – vehicle's crosbase, m.

Impact of a steering wheel's turning speed on the kinematics of turn

When a vehicle enters a turn, steering wheel's turning has two phases:

- a steering wheel is turned from a moment of vehicle's rectilinear movement till steering wheels are turned to the necessary turning angle;
- a constant steering wheel's turning angle;
- a steering wheel is turned from the maximum turning angle till a moment of vehicle's rectilinear movement.

In practise, these phases are not ideal, sometimes they overlap or it is hard to distinguish between them. According to the vehicle theory regarding movement in turns, it is assumed that any steering wheel is turned evenly and without interruption, and the above mentioned phases are strictly taken into account [4].

According to the phases of steering wheel's turning, the midpoint of the vehicle's rear axis moves along a trajectory that consists of three stages:

- a curve of entering a turn when a turning radius changes from infinity till a constant radius is reached;
- a trajectory with a constant radius;
- a curve of exiting a turn when a turning radius changes from a constant radius till infinity, which corresponds to rectilinear movement.

The curve of entering a turn has a constantly changing radius and it is characteristic of a spiral. Considering the fact that the trajectory of entering a turn depends on a speed of turning the steering wheel, vehicle's dimensions and a driving speed, this trajectory can be hardly to describe mathematically. According to the previous researches, it is believed that the midpoint of the vehicle's rear axis enters a turn and exits it by moving along a clothoid. A clothoid is a type of spirals to be described by an equation:

$$R = \frac{\sqrt{v^3}}{\sqrt{2q}\sqrt{\alpha}} = \frac{\sqrt{v^3}}{\sqrt{2q\alpha}}, \qquad (3)$$

where v – vehicle's speed, m/s;
α – turning angle, degrees;
q – conditional impulse – the third time derivative of path.

The easiest way for determining the characteristics of vehicle's entering a turn is to use a model, but in this case it is hard to compare the clothoids and it is necessary to test all the parameters impacting the change in this curve.

The easiest way for determining the length of a clothoid for vehicle's entering a turn is when the time of entering a turn is known. The time of entering a turn is equal to a time period needed for turning a steering wheel from a position of rectilinear movement to a position of stable vehicle's movement along a circle. The time needed for turning a vehicle's steering wheel can be determined experimentally.

Research in trajectories of turn for road trains

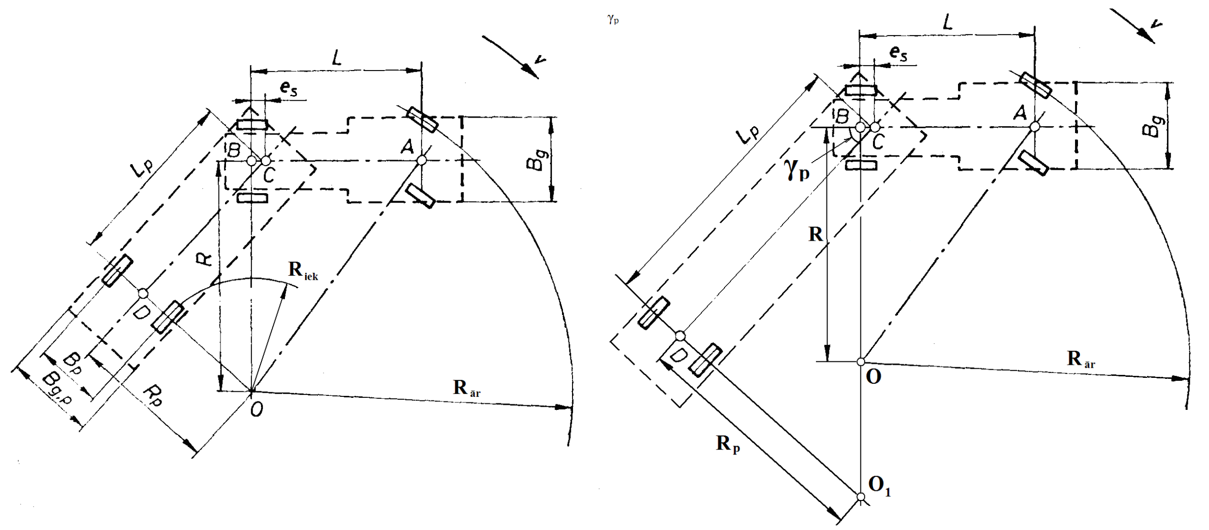
The classical vehicle theory assumes that, when making a stabilised turn, the extensions of all axes of vehicles and semitrailers cross in one point O – the turning centre. Stabilised movement along a circle is regarded as road train's movement in a turn when the steering wheel is not turned anymore, and the road train moves along a constant circle of radius (see Fig. 2).

To develop a road train model, it s necessary to ascertain the ratios between modern vehicles' wheelbases L, crosbases B_L and semitrailers' wheelbases L_P. A ratio coefficient K_b is introduced for towing vehicle's wheelbases and crosbases:

$$K_b = \frac{B_L}{L} \qquad (4)$$

After researching the ratios of bases for 10 articulated trucks, 10 cars and 10 tractors, the following average values of coefficients are gained:

- $K_{b,seg}$=0.56;
- $K_{b,vieg}$=0.55;
- $K_{b,tr}$=0.66.



a) b)

Fig. 2. **Kinematics of a road train's turn in movement along a circle**

The researched model is equipped with a changing wheelbase, but its crosbase remained unchangeable. The model's wheelbases are computed by using the coefficient K_b and model's crosbase B_m. In the same way the ratios of bases are determined for semitrailers of articulated trucks – the average $K_{b,p}$=0.25. The longest semitrailer's wheelbase was 8.115 m.

The model was constructed to verify the ratios of wheelbases and crosbases for different vehicles gained in primary research. In the model, the turning angles for the guiding (front) wheels can be changed. The correct turning angles for the internal and external wheels are provided by the steering trapeze. The turning angle for the steering wheels can be locked at any chosen position. The position for attaching a trailer can be changed in the model like it is in tractors, articulated trucks and cars. Lasers are attached on the model's rear axis, semitrailer's axis and front internal wheel's turning axis for easy finding a momentary turning centre.

The experiments were carried out in Room 238 of the Motor Vehicle Institute, LLU Faculty of Engineering. The experiments were conducted for three different model's wheelbases and appropriate positions of semitrailer attachment. All the experiments for each type of vehicle – articulated trucks, tractors and cars – were conducted with the steering wheels turned at their maximum positions which are set for the minimum turning radius, and at two randomly chosen steering wheels' turning angles which determine larger turning radiuses R. Each experiment was repeated five times. The model was moved on the floor, making a turn, until the angle between the symmetry axes in the semitrailer and towing vehicle changes little. Their movement corresponds to stable movement along a circle. The appropriate parameters for the model's wheelbase, maximum turning angles of its steering wheels or minimum turning radiuses are set. The model's movement in a turn is tested by pushing the model on the floor and measuring its turning radius with a ruler. If the position of the steering wheels doesn't correspond to the required vehicle's minimum turning radius, a correction is made.

A line is drawn on the floor with a piece of chalk. The model with its semitrailer is placed on this line; its position corresponds to rectilinear movement. The model is moved till a position, corresponding to a turn of 90°, is reached. The model is stopped, and in this position it is precisely photographed from above. The photos, after their printing, are used for measuring the angle γ_p formed by the symmetry axes of the trailer and towing vehicle (see Fig. 2). The measurements are made with a protractor. All the three lasers are switched on, which are attached to the model, and momentary turning centre O is found in a point of intersection of laser beams. In the same way, point of intersection O_1, which is made by the extensions of the rear axes of the trailer and vehicle, is found. These points of intersection are marked with a pencil. The turning radius R is determined for the model. The divergence between points of intersection O and O_1 is measured as a difference in radiuses:

$$\Delta R = O_1B - OB \tag{5}$$

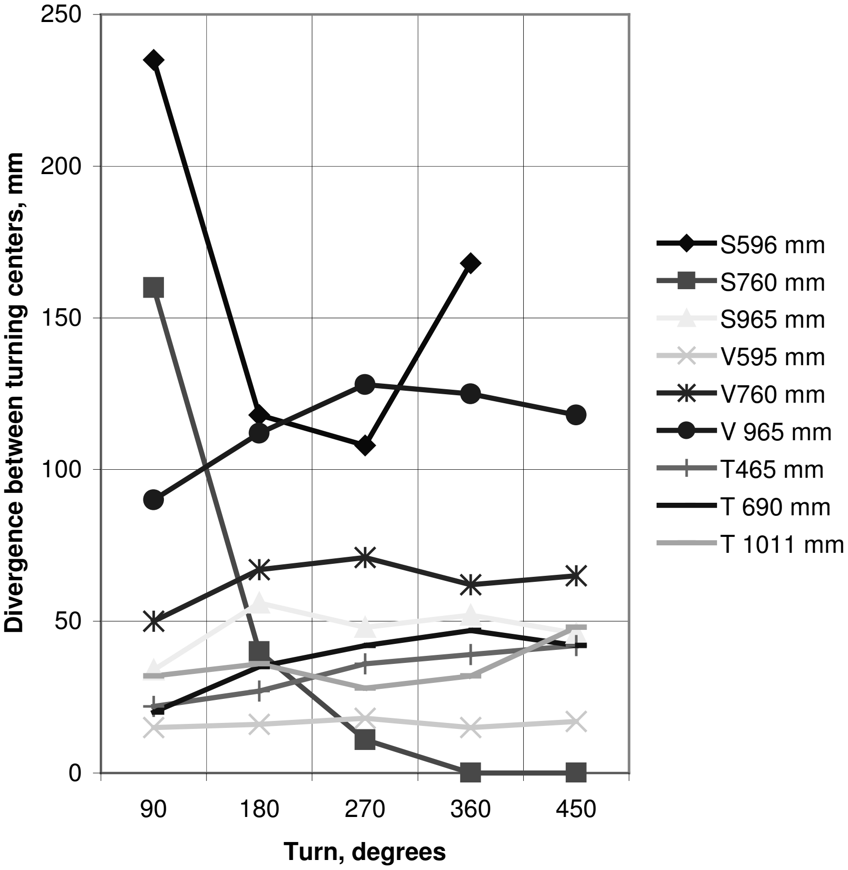


Fig. 3. **Divergence between model's turning centres**

The model is moved into a position that corresponds to its turn by 180° and all the above mentioned operations are repeated. Similar measurements are carried out for model's turns by 270°, 360° and 450°. The gained data are compiled in tables and processed into graphs that are shown in Fig. 3 and Fig. 4.

Articulated trucks have a relatively small wheelbase and, therefore, they are manoeuvrable. If the towing vehicle's front wheels are turned to the maximum position (see Fig. 2), it is possible to use trailers with large wheelbases. In this case the trailer's wheelbase L_p substantially exceeds the towing vehicle's turning radius R. If $R < L_p$, the extension line of the trailer's axis has neither theoretical nor practical possibility to go through towing vehicle's momentary turning centre O. The extension of the axis of towing vehicle's semitrailer will cross the extension of towing vehicle's rear axis in point O_1 that is located further away from the midpoint of vehicle's rear axis than point O.

When a road train enters a turn, both the midpoint of the rear axis of truck and that of semitrailer, according to the mentioned above, moves along a clothoid. At a moment when the steering wheel is not turned anymore, vehicles start stable movement along a circle, but semitrailers continue moving along a clothoid. Especially it is characteristic if the vehicle's steering wheel has been turned to the maximum turning angle. Besides, the longer is a semitrailer, the longer time it takes for movement along a clothoid, and its stable movement in a turn with a constant turning radius is achieved later.

In some instances, the semitrailer doesn't achieve stable movement along a circle with the steering wheels turned to their maximum turning angle. It occurs in cases when semitrailer's momentary turning centre O_1 lies further away from the midpoint of the truck's rear axis than truck's momentary turning centre O.

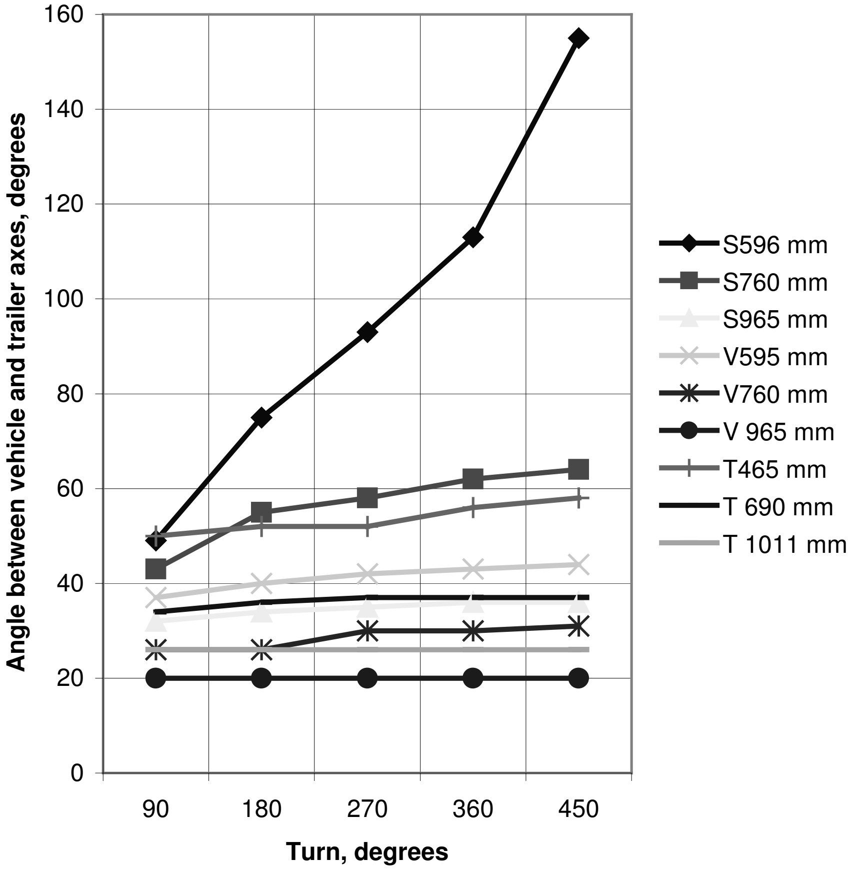


Fig. 4. **Angle formed by the axes of the model's semitrailer and towing vehicle**

Conclusions

1. Vehicles enter a turn along a curve specific of a clothoid, the characteristics of which depends on a vehicle's wheelbase, a driving speed and a time period of turning the steering wheel.
2. After the movement of a vehicle has stabilised in a turn, its semitrailer continues moving along a spiral characteristic of a clothoid, especially in instances when semitrailers have large wheelbases.
3. The largest divergence between the momentary turning centres of trucks and semitrailers can be observed for articulated trucks with long trailers.
4. The correlation between the momentary turning centres of trucks and semitrailers is possible neither theoretically nor practically if a semitrailer's wheelbase exceeds a truck's minimum turning radius for articulated trucks with a large wheelbase trailers at the maximum steering wheels' turning angles.
5. In the experiments, the gained divergence between momentary turning centres is less than 50 mm, especially at large turning radiuses, can be explained by small play in turning rod joints, discrepancies in the operation of laser and steering trapeze.

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