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HORIZONTAL CURVE RADII VERSUS TURNING ABILITIES OF VEHICLE COMBINATIONS FOR TIMBER TRANSPORT

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Abstract

State Forests make various road investments in cooperation with local self-governments. Jointly modernized roads facilitate local transport for both parties. The prerequisite is proper selection of technologies and project parameters for the modernized roads. The paper aimed to analyze the minimum horizontal curve radii for various elements of roads (on exits, road junctions and vehicle maneuvering areas) depending on the vehicle combinations for timber transport. The scope of works comprised:

- analysis of technical conditions for public roads;
- analysis of kinematic relationships for vehicle combinations for timber transport;
- determining the types of vehicle combinations for timber transport;
- empirical determination of the turning abilities of timber haulage vehicle combinations and fire engines.

Potential vehicle combinations used for timber transport were determined on the basis of data collected from the customers. Tests of turning abilities of vehicle combinations used for long and short timber transport and for forest fire fighting used by the State Fire Service units were conducted on a maneuvering area, at the curves with radius $R = 11.0$ m; 13 and 15 m and steering angle $\alpha = 90^{o}$.

A combination of a truck with a trailer or steered cart revealed the best turning parameters. It was demonstrated that the rounding radius $R = 11.0$ m without widening of a 3.5 m wide road may be used only when entering

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very wide public roads with a not so heavy traffic. A circular curve rounding a with a minimum radius $R = 13.0$ and in specific cases with $R = 15.0$ m.

Keywords: forest roads, horizontal curve radius, timber transporting vehicles, exit parameters

INTRODUCTION

State Forests units, as the state property managers, are obliged to ensure proper parameters of forest roads and safety to internal forest road users by law regulations, such as: law on public roads, construction law and the Decree of the Minister of the Environment of 22 March 2006 stating detailed rules of ensuring fire protection. The tasks concerning communication infrastructure of forest areas in the State Forest units are also realized on the basis of internal guidelines provided by the State Forests National Forest Holding (Czerniak *et al*. 2013). Communication system of a Forest inspectorate is included in larger transport areas by joining forest roads with public ones, mainly county roads but also with other internal roads.

AIM AND SCOPE OF WORK

The aim of the paper was to analyze problems connected with determining the minimum horizontal curve radii for various elements of roads (on exits, road junctions and vehicle maneuvering area) depending on vehicle combinations used for timber transport. The scope of works covered:

- analysis of technical conditions for public roads concerning curve parameters on exits and road junctions;
- analysis of kinematic relationships for vehicle combinations for timber transport;
- determining the types of vehicle combinations for timber haulage;
- empirical stating of the turning abilities of timber transporting vehicle combinations and fire engines.

METHODS

Vehicle maneuverability is its capability of making a turn with a small radius. The smaller the turning radius, the better the vehicle maneuverability. A turning radius of a vehicle should be understood as the radius of the motion trajectory of vehicle's mass center. This value is most frequently encountered in the data concerning passenger cars. In order to assess the vehicle maneuverability, one

should measure the minimum turning radius, i.e. the one when the maneuvered wheels are turned most. Apart from the turning radius, a turning center diameter is used for the description of vehicle maneuverability. It is diameter of a circle along which the outer front wheel moves (sometimes it means the most protruding car body parts) when the driving wheel is turned to maximum. A turning circle denotes the vehicles' ability for maneuver between the obstacles. Its value is affected by the construction of steering, driving and brake systems, as well as the vehicle dimensions. Another parameter characterizing vehicle maneuverability is a contour diameter (the smallest outer D1 or inner D2), i.e. the diameter of a circle described by a projection on the road of a most outward or inward point of a vehicle. The parameter is the most important for special vehicles, usually trucks with various types of bodies. One of the parameters used for the assessment of a vehicle maneuverability is the smallest turning circle, i.e. the minimum distance between two vertical planes situated perpendicular to each other, between which a vehicle is capable of making a 90^{o} turn. The parameter is crucial for long vehicles and combinations with trailers and semitrailers.

The most frequently used timber transporting combinations and more than a dozen fire engines intended for fire-fighting in forests were tested in the investigations.

The analysis was based on the assumption that the reconstructed main transport roads, i.e. the roads which join public roads usually have parameters required by fire escape routes in forests, where among others the road is 3 or 3.5m wide with 0.75 m roadsides, whereas outer radii of curves are at least 11.0 m long. The passage along the road was regarded correct when there was no necessity of running onto a forest road side. Forest road sides do not have the same bearing capacity as a road construction, therefore a damage of the roadside causes destruction of the road edge. The assessment of "turning" abilities was conducted for vehicles transporting both long and short timber (a truck with trailer and truck with a semi-trailer) and for fire engines. The analysis covered vehicle of various manufacturers with different turning radii and various lengths. All analyzed vehicles had dimensions compliant with these obligatory in Poland. Non-standard vehicles were not analyzed.

Investigations on turning abilities of vehicle combinations used for long timber and short timber transport and those used for fire extinguishing in forests were conducted on a maneuvering area at the appointed curves with radii of $R = 11.0$ m; 13 and 15 m and turning angle $\alpha = 90^{o}$. It was assumed that the width of one public road lane was 2.75 m, total 5.5 m, width of a public road side – 0.75 m and the width of the negotiated curve was 3.5 m with a 0.5 m widening on the inner side of the curve. The total width of the road and the curve was 4.0 m and the 0.75 m wide roadside on both sides, whereas the total width of the road crown on the curve was 5.5 m.

The following kinds of vehicles were tested:

- a vehicle for long timber transport equipped with a bogie steered from a driver's cab;
- vehicles for transporting short wood and logs with trailers and semi-trailers;
- various types of fire engines for forest fire fighting.

The tests were conducted in:

- Forest Experimental Unit of the University of Life Sciences in Poznań located in Siemiatycze;
- a maneuvering area of Kronpol Ltd. in Żary;
- the military training ground Biedrusko near Poznań – Center for Land Forces Training.

The fire engines maneuverability analysis was conducted in cooperation with the Regional Headquarters of the State Fire Service in Poznań. The investigations were conducted as LAS 2016 project for the manpower and equipment composing a Module for Forest Fire Extinguishing. The best units of the State Fire Services, using the vehicles and the equipment intended specifically for forest conditions participated in the training. Twenty vehicles with diversified traction parameters, including the vehicles with the largest mass and sizes participated in the testing.

RESULTS AND DISCUSSION

Technical conditions for public roads concerning radii of curves on exits and road junctions

A possibility of exiting and determining technical parameters of exits are very important, because they concern both the collaboration of various property owners and interference of the State Forests units in foreign grounds (e.g. roadway). Parameters of exits from public road to internal forest roads depend on the exit classification (Act 1985) and are determined by law (Regulation 1999) ensuring the organization and safety of traffic (Act 1997, Regulation 2003). These regulations usually determine the minimum exit parameters, whereas the main principle of designing an exit, particularly from a public road to a forest road, resulting from § 77 (Regulation 1999), is matching the exit parameters to the requirements of the traffic safety and the size of vehicles for which it is intended. Parameters of the curve radii on the road junctions are stated in § 77 (Regulation 1999):

- the radius of a circular curve should not be smaller than 15 m in case of entrance from the S class road and 10 m in case of entrance from the other classes of roads;

- a compound curve with radii ratios R_1: R_2 : R_3 = n:1:m, where n and m are 2 or 3, may be used if it facilitates the movement of the vehicles turning right, but at the same time it neither worsens the traffic conditions on pedestrian crossings nor makes difficult observation of the vehicles of colliding relationships. The central radius of the compound curve should not be smaller than 9 m, while the central angles of the initial and final curve should each have 15^o .

The internal edge of the lane or a group of lanes for the vehicles turning left on a channeled road junction should be formed using a circular curve or a combination of a straight section and circular curves with radii ranging from 10 m to 40 m, depending on the road class, its cross section and the road junction geometry (§ 73 of the above mentioned regulation). Clause 75 determines the parameters of the internal and external curve on the roundabouts for the lower class roads (G, Z, L) within the range from 10-28 m and 26-40 m and their application.

Vehicle combinations for timber transport

The types of vehicle combinations for timber haulage were determined on the basis of the analyses conducted among the customers receiving large-size raw material (long timber) and short timber (4.5 or 5.0 m long).

Among 202 tested combinations, the transport combination composed of a vehicle and a trailer constituted 99 units transporting short timber, whereas in 91 cases it was a semitrailer tractor transporting mainly short timber (10 transports of long timber). A haulage combination composed of a vehicle with a bogie was observed 5 times – it carried only long timber, whereas in seven cases it was a tractor with a flatbed semi-trailer. Haulage combinations constituting of a drive unit – tractor and a trailer become more common among the carriers because they are more universal and allow for transporting both long and short timber, whereas combinations with a flatbed semi-trailer allow for diminishing the combination's unladen mass (without the loading unit) – it enables to carry a bigger timber weight. As shown by Trzciński (2011), transport combinations with a bogie are less frequent, since only 85 were encountered among the analyzed 473 hauling combinations. Increasingly less common use of a vehicle with a bogie may be due to a change of the Regulations of the Minister of Infrastructure (2002) and difficulties with technical overhauls of such combination necessary for its entry into service (Interpellation 2013, the National Police Headquarters 2017).

Kinematic dependencies for vehicle combinations for timber transport

Vehicle's steering behavior, i.e. its easy driving and keeping it on an intended trajectory, as well as maneuverability, i.e. its ability to turn within

a circle with a small radius, are crucial during a vehicles' movement along a curvilinear trajectory.

Initial analyses assumed a two-axle vehicle making a turn on a horizontal surface at small speed (Flekiewicz 2007). If we assume that all wheels run without obstacles, their movement should proceed along the concentric circles, i.e. all wheel axles extensions should intersect at one point called the midpoint of a turn.

Therefore, if the curvilinear movement of a two-axle vehicle is realized by turning the front wheels, the turn midpoint 0 will be situated on a straight line constituting an extension of a common axle of the rear wheels (Fig. 1a).

When the average steering angle α changes, OB straight will constitute a movable centroide. The unmovable centroide will be a curve marked with a dotted line. If, in simple terms, we assume that the vehicle's wheels are placed in the corners of a rectangle with a length *l* equal to a wheelbase and width *d* equal to the average track of wheels, the dependence between the steering angle of an outer wheel α_z and inner wheel α_w, necessary to ensure the proper turn may be determined, by subtracting by the sides of expression on the cotangents of these angles:

$$ctg\alpha_z = \frac{R + \frac{d}{2}}{l} \; ; \qquad ctg\alpha_w = \frac{R - \frac{d}{2}}{l} \tag{1}$$

The radius (2) will be called the turning radius.

$$R = \frac{L}{tg\alpha} \tag{2}$$

The dependence (1) is actually realized by the steering linkage which is a connection of both front wheels by means of a trapezoidal lever system.

Considering kinematics, a vehicle's movement on the bend is flat movement, which may be regarded as a sum of progressive movement along the vehicle's longitudinal AB axis (Fig. 1b) and a circular motion at the speed (3) around point B, situated on a perpendicular to AB axis drawn from the momentary center of rotation 0.

$$\omega = \frac{V}{R} \tag{3}$$

Point B is a special point, for which the instantaneous speed vector is pointing along AB axis. For any other point the instantaneous speed is a vector sum of speed V pointing along AB axis and the instantaneous speed $r\omega$ perpendicular to radius vector *r*, e.g.

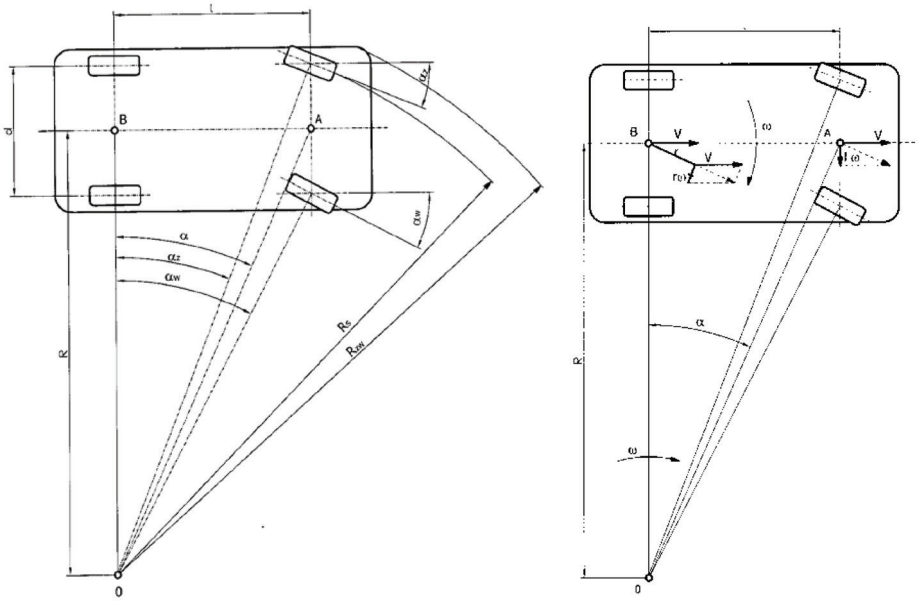
$$V_A = \sqrt{V^2 + L^2\omega^2} \tag{4}$$

$r = L$

Because $R = \dfrac{L}{tg\alpha}$

While $\omega = \dfrac{V}{R} = \dfrac{V}{L} tg\alpha$

$$V_A = V\sqrt{1 + tg^2\alpha} \tag{5}$$



a) b)

Source: Own study

Figure 1. a) A two axle vehicle's turn at a small speed; b) vectors of speed in curvilinear vehicle motion

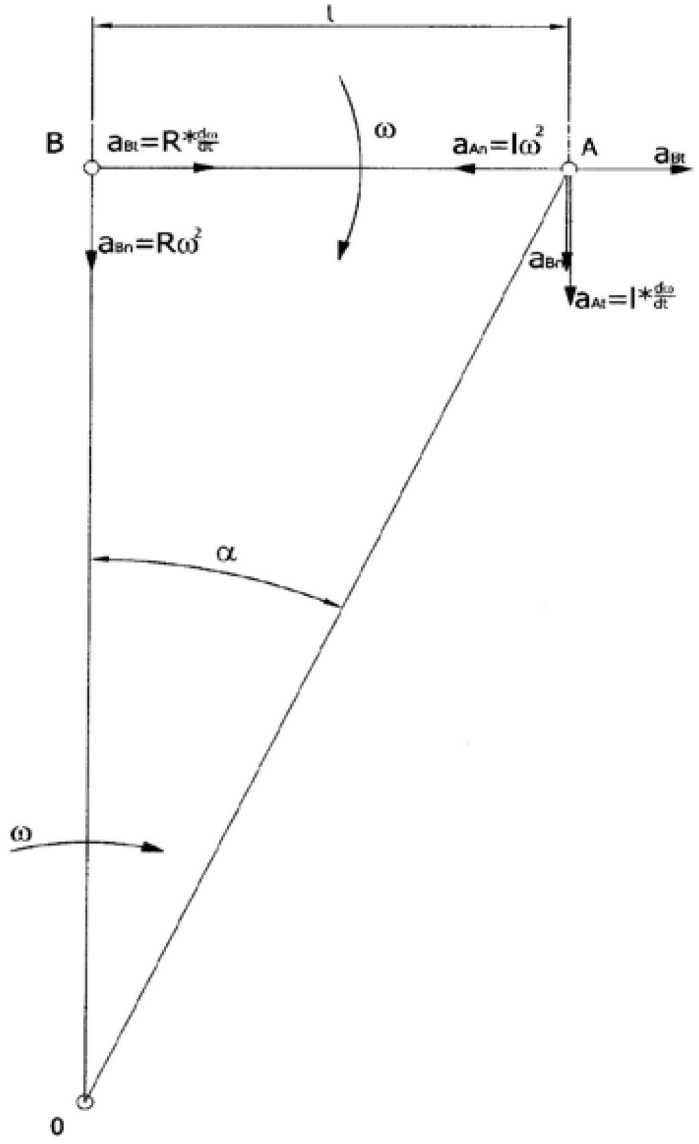
Acceleration at individual points may be determined, considering that at point B normal acceleration will occur:

$$a_{Bn} = Rw^2 = \frac{1}{tg\alpha}\frac{V^2}{l^2} tg^2\alpha = \frac{V^2}{l} tg\alpha \tag{6}$$

Tangential acceleration is given by the formula:

$$a_{Bt} = R\frac{dw}{dt} = \frac{l}{tg\alpha}\left(\frac{tg\alpha}{l}\frac{dV}{dt} + \frac{V}{l\cos^2\alpha}\frac{d\omega}{dt}\right) \tag{7}$$

$$a_{Bt} = \frac{dV}{dt} + \frac{2V}{\sin 2\alpha}\frac{d\omega}{dt} \tag{8}$$



Source: Own study

Figure 2. Acceleration vectors in a curvilinear vehicle movement

The same accelerations as at point B will occur at all other points, as well as normal and tangential accelerations resulting from the rotation of the AB segment around point B at the speed ω. For instance, at point A additionally normal acceleration:

$$a_{An} = l\omega^2 = \frac{V^2}{l} tg^2\alpha \tag{9}$$

as well as tangential acceleration (10) will occur.

$$a_{At} = l\frac{d\omega}{dt} = tg\alpha\frac{dV}{dt} + \frac{V}{\cos^2\alpha}\frac{d\alpha}{dt} \tag{10}$$

The resultant acceleration will be a vector sum of component accelerations, for instance as shown in Figure 2.

$$a_A = \sqrt{(a_{Bn} + a_{At})^2 + (a_{Bt} - a_{An})^2} \; ; \quad a_B = \sqrt{a_{Bt}^{\;2} + a_{Bt}^{\;2}} \tag{11}$$

Forest roads are used by vehicles with various turning parameters. These are usually roadworthy vehicles after various adaptations and modifications. Considering external parameters of various transporting combinations (wheel steering angle, length of the combination and wheelbase), Trzciński (2011), on the basis of theoretical analyses, computed minimum radii on circular curve for the exit and road junctions on the level of 8.4-10.7 m, but a considerable road extension is required. Therefore, the author recommends 12.0 m minimum internal radius, at the road width of 6.4-8.8 m.

Turning abilities of timber transporting vehicle combinations and fire engines

Negotiating road curves depends not only on vehicle construction, but also on its technical condition, carried load, speed and driver's skills. The same curve is usually negotiated in different ways (Fig. 3). Most vehicles (at R = 11.0 m), when turning from a forest road to the right had to use two traffic lanes of a public road (Fig. 4). Timber haulage using vehicles with semi-trailers (at R = 11.0 m) was impossible without running onto a forest road side. Fire engines, particularly their off road versions also used the roadsides while negotiating the appointed curves with R = 11.0 m long radius (Fig. 5). Passing along the track with minimum parameters requires running over a verge of the forest road and in case of vehicles with semi-trailers, even over a forest ground (Fig. 4). Coming out of the forest road to the right proved particularly difficult, because in this case the truck front had to drive onto the opposite lane of the public road. The investigations demonstrated that a 13.0 m minimum radius of a curve should be recommended on exits and road junctions for timber transporting vehicles combinations.

Similar 12.0 m or 15.0 m minimum curve radii, at necessary road widening, are recommended by the manuals on forest road designing in Ireland or in Canada (B.C. Ministry of Forests 2002).

Source: Own photo

Figure 3. Testing the trajectory for a combination composed of a truck and a semi-trailer

Source: Own photo

Figure 4. Testing the trajectory for a truck-bogie combination for long timber transporting

Source: Own photo

Figure 5. Testing the trajectory for fire engines

CONCLUSIONS

1. A truck-trailer combination as well as a truck with a bogie have the best steering parameters. Transport vehicle combinations and off road fire trucks (particularly with trailers) intended for forest fire fighting require the radius of R bigger than 11.0 m at the wheel steering angle of $\alpha = 90^{o}$.
2. The minimum dimensions assumed for public exits, i.e. the 3.5 m wide road and crossing the edge of the exit surface, roads curved by circular arc of R = 5.0 m, are sufficient only for smaller vehicles with considerable maneuverability. They are insufficient for haulage vehicles (usually with protruding load) and the largest fire trucks of the State Fire Services.
3. The investigations demonstrated that in the case of exits to public roads with minimum traffic lane width, it is recommended to design widened exits, i.e. the roadsides on both sides of the road should be reinforced along a straight segment of 23 m (from the edge of the public road) to obtain a road of uniform construction with a width of 5 m. On the passages from 5.0 m wide road to 3.5 m wide road, 1:1 diagonals should be applied.
4. Crossing of the exit surface edge and road should be rounded by a circular curve with a radius R = 13.0 m and in specific cases R = 15 m. The rounding radius R = 11.0 m without the 3.5 m wide road widening may be applied for vehicles with small maneuverability only for exits to very wide public roads with little traffic.
5. Additionally, the tests revealed that on the road with a turning angle $\alpha = 90^{o}$ the length of the radius R = 11.0 m, at the road width 3.5 m and widening a = 0.5 m, is insufficient. It applies both to forest transport roads and fire accesses.

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