The necessary conditions for the safe operation and mobility of the low-tonnage road train with the maximum load up to 3.5 tons under critical traffic indicators

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Abstract. This article focuses on the conditions for the safe operation of low-tonnage road trains (hereinafter LTRT) with trailers which are platforms with load capacities up to 3 tons that transport agricultural machines, mini-plants, and other equipment as well as tourist cabins. There are numerous risks in transporting such trailers that can occur due to a small turning radius or emergency braking. To assess the results of the research and experiments on the safe operation of LTRT with trailers, we used the works of the following scholars: Godjaev, Izmaylov, Komarov, Korolyash, Volchkov, Maloletov. As a result, we developed and tested a mechanical flexible coupling device under the leadership of the “Federal Scientific Agroengineering Center VIM” and the Volgograd State Technical University’s Department of Road Transport. Certificate No 2018137360, 22.10.2018. Further research can help define critical indicators for the safe operation of LTRT with load capacities up to 3.5 tons, so calculate the speed limit at critical turns, emergency braking, and reversing.

1. Introduction
The current requirements for road transport include safety and sustainability.

Low-tonnage road trains (hereinafter LTRT) are advantageous in their use both in cities and at industrial and agricultural enterprises. They need to be modified for certain purposes, thus there is a need for high-capacity trailers.

Such trailers (or platforms) with load capacities up to 3.5 tons can be used to transport kitchen wagons, engineering facilities, out-patient health posts, a bay for five people, mini-plants for agricultural processing. Also, such platforms can help transport machines driven by electric engines to operation sites. Moreover, platforms can serve as a vehicle servicing point and a battery charger point (for solar batteries, wind systems, gas and diesel generators). Finally, platforms can serve as a hangar for UAVs.

2. Maintenance and mobility of LTRT
Now we will examine the mobility of LTRT under critical maneuverability conditions. We shall use a mathematical model [1] which was suggested in [2].
A mathematical model which represents the car movement with a trailer is given based on the equations of motion of solid bodies. The car and the trailer are moving solid bodies. The tow bar is attached to the trailer hitch with a spherical joint. In this task, we examine two types of movement: with a coupling and with a controlled flexible coupling device. Each solid in the system corresponds with a reference system x, y, z with a reference in the center of the body.

As the independent generalized coordinates, we chose the mass center coordinates $\xi, \eta, \zeta$ in the fixed coordinate system and the Euler angles $\psi, \theta, \phi$. Thus, the movement dynamics equations are (1) and (2) first-order differential equations.

Six kinematic relations that connect first derivatives of generalized coordinates and the linear and angular velocity projection on the axis of a moving reference frame are as follows:

$$
\begin{align*}
\dot{\xi} &= V_x \cdot \alpha_{11} + V_y \cdot \alpha_{21} + V_z \cdot \alpha_{31} \\
\dot{\eta} &= V_x \cdot \alpha_{12} + V_y \cdot \alpha_{22} + V_z \cdot \alpha_{32} \\
\dot{\zeta} &= V_x \cdot \alpha_{13} + V_y \cdot \alpha_{23} + V_z \cdot \alpha_{33} \\
\psi &= (q \cdot \cos \phi - p \cdot \sin \phi) \cdot l \cdot \cos \theta \\
\dot{\theta} &= p \cdot \cos \phi - q \cdot \sin \phi \\
\dot{\phi} &= r + tg \theta \cdot (p \cdot \sin \phi + q \cdot \cos \phi)
\end{align*}
$$

where $V_x, V_y, V_z,$ $pp, qq, rr$ are the projections of the center of mass and angular velocity of the solid body on the axis of a moving reference frame, $\alpha_{11}, \alpha_{12}, \alpha_{13}, \alpha_{22}, \alpha_{23}, \alpha_{32}, \alpha_{33}$ are direction cosines between axes of moving and fixed coordinate systems.

Six dynamics equations in the moving reference frame based on the principle of momentum and the angular momentum theorem are as follows:

$$
\begin{align*}
m \cdot (V_x + q \cdot V_z - r \cdot V_y) &= F_x + R_{lx} + R_{rx} + T_{lx} + T_{rx} - G \cdot \alpha_{12} \\
m \cdot (V_y + r \cdot V_x - p \cdot V_z) &= F_y + R_{ly} + R_{ry} + T_{ly} + T_{ry} - G \cdot \alpha_{22} \\
m \cdot (V_z + p \cdot V_y - q \cdot V_x) &= F_z + R_{lz} + R_{rz} + T_{lz} + T_{rz} - G \cdot \alpha_{32} \\
J_x \cdot \ddot{q} - J_{xy} \cdot \dot{q} - J_{xz} \cdot \dot{r} + (J_x - J_y) \cdot q \cdot r + f_{yx} \cdot (r^2 - q^2) + p \cdot (J_{xy} \cdot r - J_{xz} \cdot q) &= F_z \cdot y_p + R_{lz} \cdot y_{rl} + R_{rz} \cdot y_{rr} + T_{lz} \cdot y_{tl} + T_{rz} \cdot y_{tr} - \ldots
\end{align*}
$$
\[-F_y \cdot z_F - R_{ly} \cdot z_{RI} - R_{ry} \cdot z_{RR} - T_{ly} \cdot z_{RI} - T_{ry} \cdot z_{RR},\]
\[-J_{xy} \cdot \dot{p} - J_y \cdot \dot{q} - J_{yz} \cdot \dot{r} + (J_x - J_z) \cdot r \cdot \dot{p} + J_{xz} \cdot (q^2 - r^2) + q \cdot (J_{yz} \cdot p - J_{xy} \cdot r) =
\]
\[= F_x \cdot z_F + R_{lx} \cdot z_{RI} + R_{rx} \cdot z_{RR} + T_{lx} \cdot z_{RI} + T_{rx} \cdot z_{RR}\]
\[-J_{xz} \cdot \dot{p} - J_{yz} \cdot \dot{q} - J_z \cdot \dot{r} + (J_x - J_z) \cdot p \cdot \dot{q} + J_{xy} \cdot (q^2 - p^2) + r \cdot (J_{yz} \cdot q - J_{xy} \cdot p) =
\]
\[= M_l + M_r + F_y \cdot x_F + R_{ly} \cdot x_{RI} + R_{ry} \cdot x_{RR} + T_{ly} \cdot x_{RI} + T_{ry} \cdot x_{RR}\]
\[-F_x \cdot y_F - R_{lx} \cdot y_{RI} - R_{rx} \cdot y_{RR} - T_{lx} \cdot y_{RI} - T_{rx} \cdot y_{RR},\]

where \(m\) is the mass of the trailer; \(J_{xz}, J_{yz}, J_x, J_y, J_z\) are components of the inertia tensor in relation to axes of the moving reference frame; \(F_x, F_y, F_z, R_{lx}, R_{ly}, R_{rx}, R_{ry}, T_{lx}, T_{ly}, T_{rx}, T_{ry}\) are the components of the \(F\) reaction of the trailer hitch which affects the trailer; \(R_{lx}, R_{ly}, R_{rx}, R_{ry}\) are force components on the left and right trailer wheels, respectively; \(M_l, M_r, M_t\) are momenta of the resistance to turn on left and right wheels; \(T_{lx}, T_{ly}, T_{rx}, T_{ry}\) are tension forces in the coupling device in the projections on the left and right cable parts affecting the trailer; \(g, \rho\) is the weight force of the trailer; \(x_F, y_F, z_F, x_{RI}, y_{RI}, z_{RI}, x_{RR}, y_{RR}, z_{RR}, x_T, y_T, z_T, x_{T1}, y_{T1}, z_{T1}, x_{T2}, y_{T2}, z_{T2}\) are coordinates of the focuses of forces in the moving reference frame connected with the trailer.

**Figure 2.** A design model for defining dimension deviation of low-tonnage road trains units under braking.

- \(B_{an}, B_{ar}\) are the overall width of the low-tonnage road train units, m;
- \(B_d\) is the width of the security corridor, m;
- \(L_o\) is the distance between the center of mass of the trailer and the towing vehicle, m;
- \(d_r\) is the distance from the centers of mass to the extreme points of the towing vehicle, m;
- \(a_r\) is the distance between the trailer hitch and the center of mass, m;
- \(a_s\) is the distance between the trailer and the center of mass, m;
- \(L_{as}\) is the length of the vehicle, m;
- \(y_{as}\) is the side deviation of the centers of mass of the road train’s units, m;
- \(y_{an}\) is the distance from the towing vehicle’s axis to the trailer’s deviation;
- \(y_{ar}\) is the shift of the center of gravity of the trailer with respect to the skid;
- \(y_{ar1}, y_{ar2}\) is deviation of the road train’s units;
- \(y_0\) is the greatest deviation of the extreme points of the vehicle under braking, m;
- \(O_n, O_s\) are the centers of mass of the trailer and the towing vehicle;
- \(\gamma_0, \gamma_s\) is the relative bearing of the trailer and the towing vehicle with a free steering wheel.
The road shall be considered flat. The way the vehicle and the trailer affect the road in the vertical direction are described through the viscoelasticity model with regard to the possibility of the loss of contact. All elements are considered to be rigid (non-deformable). For this system, we used the forth-order Runge-Kutta method. The model was devised in a computer program. [Certificate of state registration No 201.5.61.23.15 on 17 February, 2015, Maloletov A.V., Mikhola L.A., Volchkov V.M., Komarov Ju.Ja., Korolyash V.A.; VolSTU 2015]. The program includes the following functional properties:

1. Model type: without a cable, with a “controlled” cable.
2. Movement mode: speed, turning radius, emergency braking.
3. Movement direction: forward, reverse.
4. Adhesion.
5. The load of the trailer.

It is supposed that the LTRT moving will be studied with a flexible coupling device which will increase the stability and maneuverability of an LTRT and improve the safety in critical situations.

In modeling, we defined the critical turning radius dependent on the LTRT’s speed, road conditions, and the load of the trailer in forward and reverse movement for single-axis trailers with load capacities of 1.5 tons, 2 tons, 2.5 tons, 3 tons.

This study suggests a construction with a flexible coupling device that increases the maneuverability of the road train (in reverse moving as well), thus improving the safety conditions.

2.1. Forward moving

The information for a trailer with a load capacity of 1 ton as in Figure 1 are almost similar to the information in the monograph (the monograph provides information for a 750 kg trailer) [2].

If we take the values for a trailer with a load capacity of 1 ton as a basis, we can formulate the following recommendations:

For the same critical turning radius, the speed of a 2-ton trailer should be decreased by 1.25; of a 3-ton trailer – by 1.5.

These recommendations are indicative only and should be devised more precisely for a particular LTRT.

Figure 3. The critical turning radius dependent on the LTRT’s forward speed for trailer load capacities of 1 ton, 2 tons, 3 tons.

2.2. Reverse moving

In reverse moving with a heavy trailer (3 tons), the LTRT may skid off the road (without folding) especially if the speed exceeds 5 km/h (Figure 4). It is only plausible to use a flexible coupling device in such cases.
Thus, we will examine reverse moving from 3 km/h to 5 km/h. Figures 5 and 6 depict the design positions of the LTRT in different moments of maneuvering.

**Figure 4.** Skidding off the road in reverse moving with a 3-ton trailer at a speed exceeding 5 km/h.

![Figure 4](image)

**Figure 5.** Reverse moving with a 3-ton trailer at a speed of 3 km/h and a turning radius of 50 m. (a) – at 15 sec (b) at 50 sec.

![Figure 5](image)

**Figure 6.** Reverse moving with a 3-ton trailer at a speed of 5 km/h and a turning radius of 50 m: (a) at 10 sec; (b) at 30 sec.

![Figure 6](image)
Figure 7. Reverse moving with an empty trailer (at 15 km/h, turning radius of 20 m, coefficient of adhesion 0.6): the maximum critical speed. (a) with a cable; (b) without a cable.

In reverse moving, we carried out experiments only for a road train with a controlled cable in a coupling device since it is not possible to maneuver safely without a cable (only at low speeds and with a highly qualified driver).

Figure 8. The comparison between the design and experimental data for the critical turning radius in reverse moving for an empty trailer (full lines represent the design values for different coefficients of adhesion; dots represent experimental values).

The additional tension force in the cable ensures maneuverability, thus it is advisable to use a cable with a diameter of at least 9 mm. In all the aforementioned cases the tension force was less than 3–4 tons. In the majority of cases, a 10.55 mm cable with a metal core can ensure the safe maneuverability.

Figure 9 depicts the braking maneuver from the initial speed of 60 km/h (the load in the trailer is 1.5 tons; 2.5 tons; 3 tons; the lateral displacement is 0.2 m). With a flexible coupling device, the angle of heel and trim was always less than 1 grade and the tension force in the cable was approximately 0.1 ton. In braking without a cable, the LTRT folds before completing the braking maneuver (Fig. 9a). Figure 9b shows the position of the LTRT under the same conditions at the moment when the vehicle comes to a complete stop.

Figure 9. The LTRT in braking with a flexible coupling device and without it in reverse moving at the initial speed of 60 km/h (the load is 1.5 tons moved laterally to 0.2 m).

The design results are supported by experiments. All the tests were conducted according to GOST 31507-2012 with an empty trailer and the load of 1.5 tons; 2.5 tons; 3 tons at the complex “Road Laboratory KP-514MP” with a “Gazel 2705” and a trailer IAPZ-739.
As a result, we formulated the following recommendations for the safe operation of LTRT with a flexible coupling device that can improve maneuverability and road safety:

1. In forward moving, the speed at turns should not exceed the values given in Table 4.1 (depending on the turning radius). The values in the table are calculated for a trailer with a load of 850 kg. According to test results, the critical turning radius is given as 10% bigger which will ensure safe maneuvers.

2. In reverse moving and with a minimum turning radius (10-20 m), the speed should not exceed 5-10 km/h. However, in extreme conditions this device alleviates reverse maneuvering at 20 km/h. The speed depends on the cable strength.

3. According to GOST2688-80, for a flexible coupling device, it is recommended to use two types of cables with a diameter of 9 mm with 133 wires with a metal core or with 46 wires with an organic core (other cables can also be used if they can sustain a tension force of 4.5-5 tons).

### Table 1. The recommended speed for forward moving depending on the turning radius (the coefficient of adhesion is 0.6).

| Speed, km/h | Critical turning radius, m |
|------------|----------------------------|
| 10         | 15                         |
| 20         | 20                         |
| 30         | 25                         |
| 40         | 40                         |
| 50         | 60                         |
| 60         | 90                         |

### References

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