Journal of Physics: Conference Series

PAPER • OPEN ACCESS

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To cite this article: Yu N Stroganov *et al* 2021 *J. Phys.: Conf. Ser.* **1889** 042051

Analysis of model for assessing the road train movement stability

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Abstract. In this paper, we conduct a mathematical analysis of the model of ensuring the road trains movement stability by changing the design of coupling devices to determine the critical characteristic parameters of the road trains, which result in the loss of en-route directional stability under external action. The concept of the model was to separate the process of yawing of the road trains and its elements (due to external perturbing action) on the highway into several typical stages. The main parameters of the stages (the displacement amplitude and rotation angle of the road trains elements in relation to the driving direction) were determined based on the initial conditions of the road trains movement, the force and duration of the external action. The most dangerous areas of external action application to the road trains were determined in this paper. The maximum permissible exposure limit should not exceed 0.5–1.0% of the road trains trailer momentum, with duration having the greater effect than the amount of impact. The results obtained can be used in mechanical engineering to improve the road trains performance.

1. Introduction

Since the use of motor vehicles (MV) and especially road trains (RT) continue to be the main mode to transport all kinds of freight, improving the efficiency of this type of activity (improving performance and reducing accidents on the road) remains a highly topical issue, the solution to which is also of great practical importance. It should also be taken into account that every tenth road traffic accident (RTA) in Russia involves trucks and RT [1]; in 2019 alone, the number of accidents in Russia was 147738, the number of victims was 189671, including 15158 fatalities [2], etc.

Studies by Russian and foreign scholars related to motor vehicle behaviour on the road examine in most cases the issues of improving the design parameters of suspension, control and braking mechanisms, etc. [3–5], or optimization of operating conditions [6–15]. The issues of ensuring stability of motor vehicle movement, and especially RT, on the road are scarcely examined. RT movement stability, in this case, is understood as zero deviations from the defined (optimal) trajectory of RT (and its individual elements) within the roadway.

With all the variety of proposed design and technology solutions, the main way to ensure RT movement stability on the road remains the speed limitation, which significantly narrows the field of

 1889 (2021) 042051 doi:10.1088/1742-6596/1889/4/042051

possible solutions to the problem.

A method of ensuring the stability of RT movement by upgrading the design of towing couplers has been previously proposed [16, 17], and the relevance and practical significance of this method has been confirmed by a number of patents. However, the critical values of the relevant parameters of RTs, resulting in the loss of its directional stability, have not been established, which does not allow for optimization of the technical and operational characteristics of the motor vehicles to the most effective degree.

The purpose of this work is to establish the critical characteristic parameters of RT resulting in the loss of its directional stability on the road if there are external actions.

2. Materials and methods

In paper [17], a mathematical apparatus was presented that allows for both analyzing the process of ensuring the RT movement stability and performing a correct comparison of estimated and experimental data. The concept of this model was to separate the yawing process of RT and its individual elements (due to external perturbing action) on the road into several typical stages (figure 1, figure 2). The main parameters of the stages (the displacement amplitude and rotation angle of the tractor-trailer elements in relation to the driving direction) were determined based on the initial conditions of RT movement process and the characteristics of external action (force and duration). The corresponding mathematical dependences are also given in the paper [17].

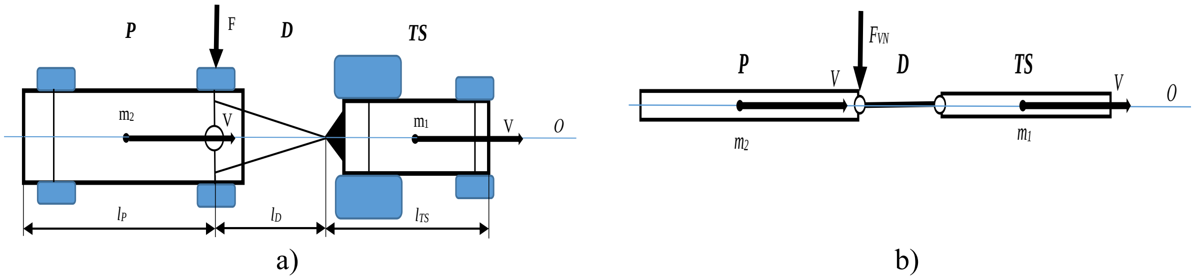


Figure 1. RT configuration (a) and simplified schematic of RT three-link mechanism (b). TS – traction truck, P – turntable trailer (PP), D – drawbar, FVN – external action, lTS, lD, lP – length of the traction truck, drawbar and trailer, O – driving direction of RT, m – weight, V – speed of respective elements of RT.

3. Results and discussion

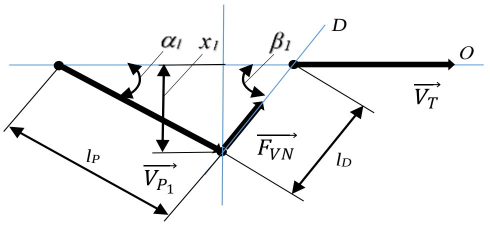
This paper presents the analysis of previously proposed mathematical dependencies [17] in order to identify the boundary conditions and actions that are most typical to ensure the RT movement stability on the road, as well as to determine the critical modes and characteristics of RT yawing process.

The research methods are mathematical analysis, mathematical simulation and prediction of RT behaviour on the road.

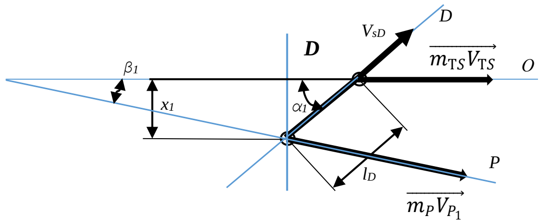
The most dangerous areas of external action application to a tractor-trailer were determined on the basis of the following considerations. It would be natural to recognize that any external action perpendicular to the line of RT movement provides greater effect on its stability in comparison with the same action directed at an angle to the direction of RT movement.

In our opinion, the most dangerous (in terms of ensuring the stability of RT movement on the road) areas of external action application are those elements of RT mechanism (figure 1) which have more degrees of freedom of their movement. Such elements are the following: for double-axle trailer – the line of trailer front axle (in its interception with the longitudinal axis of the trailer, there is a *PP* centre of the trailer located); for single-axle trailer – the point where the trailer drawbar is attached to the trailer hitch (towing device).

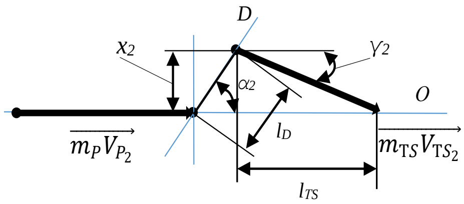
Other locations of external action application are more likely to result in deformation (destruction) of RT elements than in loss of directional stability, which, even though may be more dangerous in terms of action effect, is outside the scope of this work.



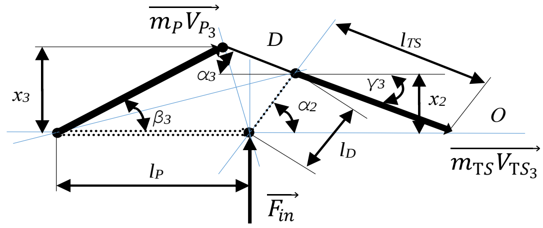
Position of RT elements at the end of Stage 1.



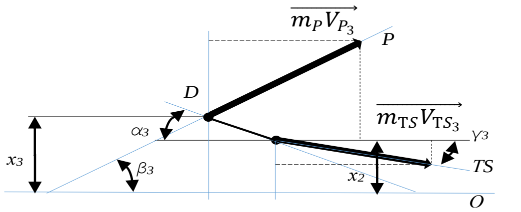
Forces acting on element D at the beginning of Stage 2.



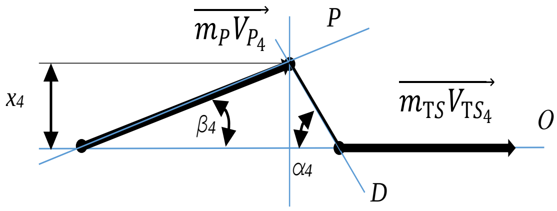
Position of RT elements at the beginning of Stage 3.



Position of RT elements at the end of Stage 3.



Forces acting on element D at the beginning of Stage 4.



Position of RT mechanism at the end of Stage 4.

Figure 2. Main stages of yawing process of *RT* and its individual elements due to external perturbing action.

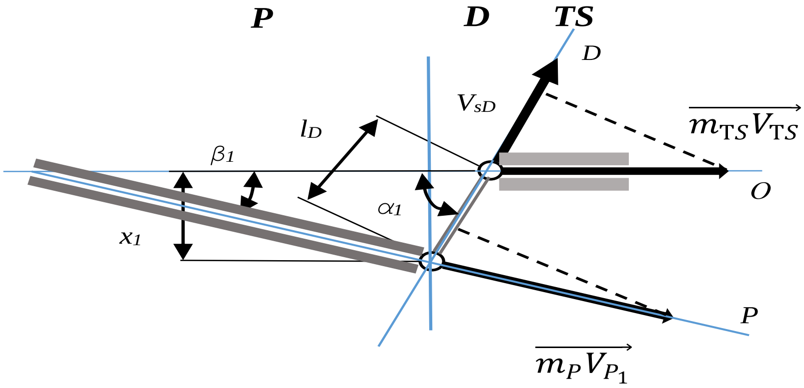


Figure 3. Condition for determining the maximum permissible external action. *TS* – traction truck, *P* – turntable trailer (*PP*), *D* – drawbar, l_D– drawbar length, x_1 – value of lateral displacement of element *P*, α_1, β_1 – angles of axis displacement of elements *D* and *P* respectively from movement direction *O*,

V_{sD} – speed of respective elements of *RT*, $\overrightarrow{m_{TS}V_{TS}}$ – momentum of element *TS*, $\overrightarrow{m_P V_{P_1}}$ – momentum of element *P*.

When determining the maximum permissible (for ensuring directional stability of RT movement) amount of external action, both the value of external force and the duration of its action should be taken into account (other factors being equal, short-term action is more likely to result in deformation of RT elements than in the loss of its directional stability). As a result, it is more appropriate to express the external (destabilizing) momentum in fractions of the initial momentum of the entire RT system (according to calculations, the limit momentum value should not exceed 0.5–1.0% of the momentum value of the RT trailer).

The destabilizing momentum limit value will be determined from the condition of ensuring the return of *RT* system element *D* to its original position, which requires an external shear force V_{sD} directed along axis *D* and rotating (by shearing element *D*) element *P* to its original position (figure 3).

The critical value of angle α_1 of rotation of axis *D* will be defined by exceedance of element *TS* momentum projection on axis *D* over element *P* momentum projection on the same axis:

$$\overrightarrow{\left(m_{TS}V_{TS}\right)}_D > \overrightarrow{\left(m_P V_{P_1}\right)}_D \quad (1)$$

Considering previously [17] proposed dependencies (figure 1):

$$x_1 = V_{Plat}t = \frac{F_{VN}t^2}{m_P} = l_D \sin\alpha_1 = l_P \sin\beta_1 \quad (2)$$

$$\alpha_1 = \arcsin\left(\frac{x_1}{l_D}\right) = \frac{l_P}{l_D}\sin\beta_1 \quad (3)$$

$$\beta_1 = \arcsin\left(\frac{x_1}{l_P}\right) = \frac{l_D}{l_P}\sin\alpha_1 \quad (4)$$

$$\vec{V}_{P1} = \frac{m_P\vec{V}_P + \vec{F}_{VN}t}{m_P} = \frac{F_{VN}t}{m_P \sin\beta_1} \quad (5)$$

it is possible to determine critical values of corresponding RT parameters resulting in the loss of its directional stability: when equality (1) is disturbed, the shear force V_{sD} will result in destabilization of the entire system.

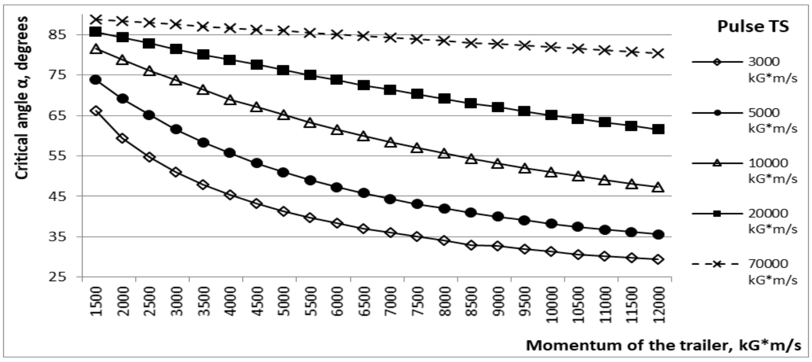


Figure 4. Critical values of rotation angle relative to the line of movement
α_1 (m_{TS}=600–3,000 kgf, m_P= 300–5,000 kgf, V=3–20 m/s, l_D= 2.0 m, l_P=6.0 m).

The RT will not return to the original movement trajectory upon completion of the external action, but will move beyond its boundaries. The critical (the road train begins to "jackknife") values α_1 are shown in figure 4 (depending on the values of *TS* and *P RT* momentum). It should be noted that this parameter has the greatest influence in case of small values of momentum of the RT elements.

It is also worth noting that the duration of the external perturbing action has a more significant effect on the value of sidewise skidding of the traction-truck trailer than its amount (figure 5). The analysis of dependencies (figure 6) also shows that the dimensions of the drawbar and trailer have a rather weak effect on the value of critical angle α_1, while significantly changing the RT manoeuvrability.

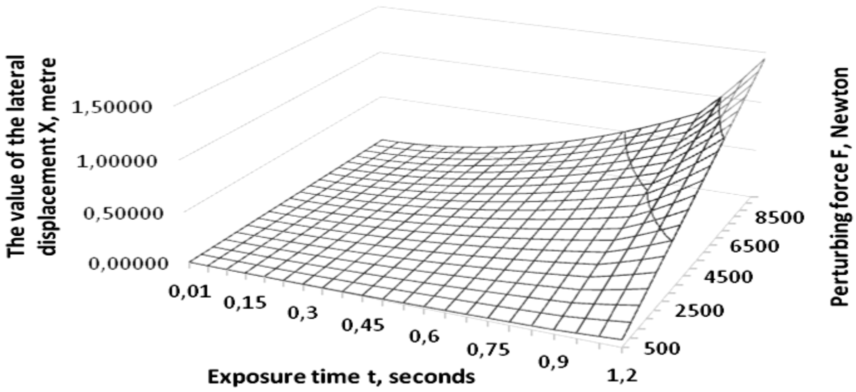


Figure 5. Trailer lateral displacement as function of value *F* and exposure time *t* (m_{TS}=1,000 kgf, m_P= 1,500 kgf, *V*=10 m/s, l_D= 1.5 m, l_P=2.0 m).

The maximum permissible amount of external action (for ensuring the RT stability in a safe travel corridor) can be estimated either through the trailer lateral displacement x_1 exceeding the safe travel corridor limits (width of roadway or road lane) or the exceedance by this value of the trailer drawbar length (RT starts to "jackknife"). The situation for the second case was presented above. In the first case, however, the limit value of the lateral displacement of RT elements on the road will be defined as follows:

$$x_1 = \frac{h_{RL} - h_{TS}}{2} \qquad (6)$$

where h_{RL} – road lane width, m; h_{TS} – vehicle width, m.

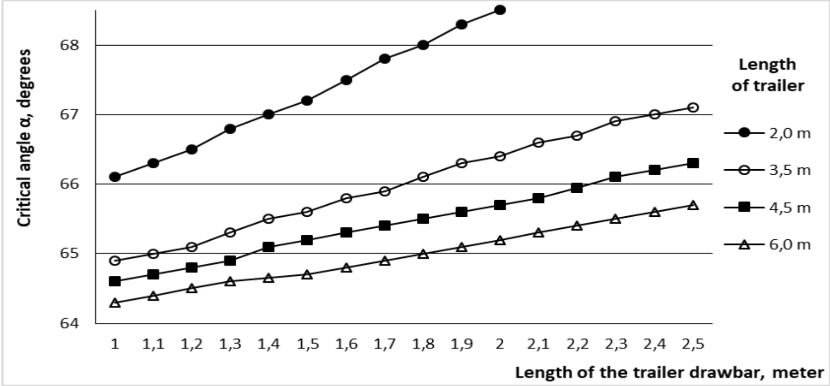


Figure 6. Critical values of rotation angle α_1 relative to the line of movement as functions of trailer and drawbar lengths (m_{TS}=600 kgf, m_P= 300 kgf, *V*=3 m/s).

By applying values: h_{RL}=2.75–3.75 m and h_{TS}=1.5–2.6 m to formula (6), we shall obtain: 0.08 m$\leq x_1 \leq$1.13 m. The most "widespread" value is $x_1 \approx$0.5–0.95 m, which allows for using it as a "boundary" permissible value when optimizing characteristics of road trains.

4. Conclusion

The most dangerous (for ensuring RT movement stability on the road) areas of external action application are the following: for double-axle trailer – the line of trailer front axle; for single-axle trailer – the point where the trailer drawbar is attached to the trailer hitch (towing device).

The limit value of external (destabilizing) momentum shall not exceed 0.5–1.0% of the RT trailer momentum value, otherwise it is impossible to ensure the trailer stability. The duration of the external perturbing action has a more significant effect on the value of sidewise skidding of the RT trailer than the magnitude of the external perturbing force. Increasing the RT momentum results in the increase in the permissible critical angles of displacement of its elements (increase in the RT stability).

The dimensions of the drawbar and trailer have a rather weak effect on the value of the critical angle of trailer axle displacement relative to the original line of movement, while significantly changing the RT manoeuvrability.

The established dependences of the drawbar rotation angle and the trailer lateral displacement on the values of momentum of the trailer and vehicle, lengths of the drawbar and trailer, magnitude and duration of impact can be used to improve both technical (dimensions of RT elements, such as drawbar length) and operating (rotation radius, critical speed, etc.) characteristics of road trains.

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