Ways to increase road train’s controllability and transverse stability

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Abstract. The problem of controllability and transverse stability is quite urgent for the road trains in operation. There are two ways to improve these operational properties: the choice of rational design parameters of the train units and the use of special devices to improve controllability and transverse stability. As a criterion for assessing the controllability and transverse stability of a multi-unit road train, it is proposed to use a dynamic magnification factor. When calculating the dynamic gain factors, a linear mathematical model of a three-link road train was used, consisting of a three-axle tractor unit, a three-axle semi-trailer and a five-axle trailer with a two-axle dolly. The simulation model allowed to optimize a number of design parameters of this road train’s units. As a result of the optimization, it was found that the values of the dynamic magnification factor decrease with movement of the fifth wheel and towing hook forward (up to 20%), as well as increasing the length of the drawbar relative to the nominal position (up to 3%). These recommendations allow choosing rational characteristics of road trains and improving their design already at the design stage.

1. Introduction

In the context of the increasingly widespread use of road trains in the agro-industrial complex, the problem of controllability and transverse stability becomes important. Due to the presence of a swivel between the road train units and the ability of pneumatic tires for lateral movement under the skid under the lateral force even with nonslipped tyres there is a risk of lateral oscillations not only during the manoeuvre but also during motion in a straight-line. During the road train’s manoeuvre lateral acceleration of a track is transmitted to the towed units with some dynamic amplification. So that even during usual manoeuvres (e.g. bypassing bumps on the road, implementation of a “lane change” maneuver) that are safe for a single car, the lateral acceleration of the last unit can reach critical value. In some cases it leads to a drift or last unit roll.

These phenomena tend to increase with an increase in the number and mass of the road train units. It is typical for modern automotive business development. In this connection it is important to ensure the high level of controllability and transverse stability at the design stage.

2. Methods

There are two possible ways to increase these operational parameters. The first is the choice of rational design parameters of road train’s units affecting controllability and stability taking into account their influence on other operational properties. The second way is the use of special devices to increase the
controllability and transverse stability. Usually the second way is used when possibilities of the first one are exhausted, paragraph after a heading is not indented (Bodytext style).

There are studies in which the consideration of stability and controllability is carried out comprehensively in connection with the essential interdependence of these properties [1, 2].

A number of criteria are used to estimate controllability and transverse stability of the road train’s units. Due to the lack of a uniform terminology for controllability and stability, in some cases there is a mixture and a different interpretation of these operational properties. In this regard, the use of the same criterion for controllability and stability assessment is encountered.

The most consistent and complete definitions are the those proposed by D. Antonov [3]: “controllability is the ability of the car to execute a control signal with the necessary accuracy and speed with minimum level of psychomotor costs on the part of the driver to ensure the giving driving mode; the stability of the car is considered as its property to keep the motion parameters (or positions) set by the driver or it is specified law of their changes after the termination of the disturbing forces”.

The critical speed is taken by many researchers as a criterion for the transverse stability of cars and road trains. Critical speed is the speed at which the lateral and angular vibrations of the train units are caused by disturbing influence from the road, the aerodynamic forces become continuous or do not decay fast enough. For trailers, for example, different authors suppose to use such critical speed in which the mean square deviation increases rapidly; the speed at which the amplitude of the lateral deviation of the trailer reaches 3% of the overall width.

It is also proposed to use the path of perturbed motion under the unit disturbance; traffic path width; extension of the path due to vibrations; exchange of rate fluctuations, etc. as a criteria for the stability of motion.

The criteria for controllability include speed limits when performing various types of maneuvers without all the wheels on one side of the road, or without sliding steering wheels; the nature of changes in the turning rate, lateral acceleration, trajectory curvature under the certain control actions; transient time, etc.

According to the researches, there are almost no complex criteria that allow making generalized assessment of controllability and transverse stability by calculation or on the basis of a limited number of experimental measurements. A number of criteria can be used only for single cars, while at the same time there are no criteria allowing taking into account characteristic features of road trains. Only some criteria can be determined by calculation. Experimental methods are mainly used for determination of others.

Therefore, it would be reasonable to apply such complex criterion that could be determined both by calculation and experiment, and esteem controllability and stability of a train with any number of units.

As the first step it is proposed to use dynamic magnification factor \( K_d \) equal to the ratio of the maximum values of lateral accelerations and centers of masses of the considered road train’s unit when changing the line.

As the towing unit’s movements, despite the available feedback, determine control actions to the towing unit, the dynamic magnification factor will comprehensively characterize the dynamic properties of the unit at hand. The change of line includes elements of linear and curvilinear motion. The control actions are similar in nature to the effect of unit disturbance. It becomes possible to evaluate the nature of the road train’s lateral vibration in motion in a straight-line. At the same time curvilinear motion characterizes the property to execute control signal – rotation of the locotractor’s front wheels.

According to the dynamic magnification factors for each road train’s unit, it is possible to assess the controllability ad stability of the entire road train, choose rational design values of the road train.

Experimental determination of dynamic magnification factors can be carried out on the basis of lateral accelerations measurements of centers of masses of road train’s unit when changing the line. For measuring lateral acceleration, acceleration sensors of an aeronautical type with recording to
recording device can be used. Depending on the time, rotation of locotractor’s steering wheels should be done according to the law close to sinusoidal.

It is advisable to carry out the calculated determination of dynamic magnification factors on the basis of mathematical modeling of the train’s movement. The linear mathematical modeling of a three-unit road train was used (Figure 1).

The presented mathematical model of the road train provides an opportunity to analyze the influence of the variable position of trailer’s connection point with the towing link on the stability and controllability parameters.

The model consists of eight first order differential equations.

Equilibrium equation of transverse forces

\[
m_1(\dot{V}_1 + u_1w_1) + m_2(\dot{V}_2 + u_2w_2) + m_3(\dot{V}_3 + u_3w_3) + m_4(\dot{V}_4 + u_4w_4) = \sum_{i=1}^{3} F_{1i} + \sum_{i=1}^{3} F_{2i} + \sum_{i=1}^{3} F_{3i} \]

(1)

Equilibrium equation of moments acting on a tractor, semi-trailer, trailer and trailer trolley

\[
J_1 \dot{w}_1 = X_{1A} \left[ m_2(\dot{V}_2 + u_2w_2) + m_3(\dot{V}_3 + u_3w_3) + m_4(\dot{V}_4 + u_4w_4) - \sum_{i=1}^{3} F_{2i} - \sum_{i=1}^{3} F_{3i} - \sum_{i=1}^{3} F_{4i} \right] + F_{11} X_{11} - F_{12} X_{12} - F_{13} X_{13} + \sum_{i=1}^{3} M_{1i} \]

(2)

\[
J_2 \dot{w}_2 = X_{2A} \left[ m_2(\dot{V}_2 + u_2w_2) + m_3(\dot{V}_3 + u_3w_3) + m_4(\dot{V}_4 + u_4w_4) - \sum_{i=1}^{3} F_{2i} - \sum_{i=1}^{3} F_{3i} - \sum_{i=1}^{3} F_{4i} \right] - \sum_{i=1}^{2} F_{3i} - \sum_{i=1}^{2} F_{4i} \]

(3)

**Figure 1.** Diagram of forces and moments acting on road train units.
\[ J_3 W_3 = X_{3B} m_3 (V_3 + u_3 w_3) + m_4 (V_4 - u_4 w_4) - \sum_{i=1}^{2} F_{3i} - \sum_{i=1}^{3} F_{4i} \]
\[ + X_{C3} m_4 (V_4 + u_4 w_4) - \sum_{i=1}^{3} F_{3i} - \sum_{i=1}^{2} F_{4i} X_{3i} - M_{3i} \] (4)
\[ J_4 W_4 = X_{4B} m_4 (V_4 + u_4 w_4) - \sum_{i=1}^{3} F_{3i} - \sum_{i=1}^{2} F_{4i} X_{4i} - M_{4i} \] (5)

The rotational speeds of the train units turn relative to each other can be expressed as:
\[ \gamma_1 = w_1 - w_2 \] (6)
\[ \gamma_2 = w_2 - w_3 \] (7)
\[ \gamma_3 = w_4 - w_3 \] (8)

The road train included a three-axle road tractor, a three-axle semitrailer and a five-axle trailer with a two-axle movable dolly. In order to ensure line changing, rotation angle of the trailer’s steering wheels was varied according to close to sinusoidal dependence.

3. Results and discussion
Simulated movement of the road train with nominal load at a speed of 60 km / h was done.

The control action had a period of two seconds, the amplitude of steered wheels turning angle was two degrees.

Dynamic magnification factor had the following values, taking into account nominal values of the road train’s unit design parameters:
1) for semi-trailer \( K_{d1,2} = 0.694 \);
2) for dolly \( K_{d2,3} = 1.062 \);
3) for trailer \( K_{d3,4} = 0.953 \).

To sum it up, the dolly (dynamic magnification factor constitutes 1.062) which gain lateral acceleration is the unit limiting controllability and stability.

To ensure close dynamic properties to all units of the road train, the first way should be used – finding rational values of units’ structural parameters. For example optimization can be used within the given limits of design parameters of the road train’s units in accordance with minimum value of dynamic magnification factor.

Such optimization is carried out sequentially in several stages for each unit. Initially, parameters of the first towed unit after road tractor are varied to achieve the minimum \( Kd \), then the second unit, the third and so on. After that, optimization is repeated several times with already obtained design parameters values of the unit until the change in optimized parameter is equal to a small amount compared with the previous stage.

As a result of optimization, it is found out that the values of dynamic magnification factors for considered road train decrease with forwarding of bolster and drawnhook. Lengthening of tow beam towards the nominal position is also found out. After changing the hook position and beam length dynamic magnification factors \( K_{d2,3} = 0.815 \), \( K_{d3,4} = 0.934 \) were obtained.

However, the possibilities of changing the design parameters of the units are rather limited and not always possible, since this affects other characteristics and operational properties of the train units. For example, moving a bolster changes the weight distribution along the axes, increasing the length of the towing beam and base increases the overall length of the train.

In this case, it is necessary to use the second path – the use of special devices to improve controllability and stability.

Various types of limiters of lateral pitch angles and folding units angles, bolsters and tow bars of unconventional types can be used as such devices. For example, the trailer hitch with variable effective towbar length provides high driving stability at high speed due to the long length of the towbar and the displacement of the equivalent point of attachment of the trailer forward.
The scheme of this device is shown in Figure 2.

1- tractor truck; 2- horizontal plate; 3- swivel; 4- vertical slot; 5- step plate; 6- towbar; 7 – feathering hinge; 8 – slider; 9- pin; 10– rear surface of a horizontal plate 2; 11 – extreme groove positions; 12 – side surfaces of a horizontal plate; \( \beta \) - central angle; \( \gamma \) - angle of folding the tractor truck and the towbar; \( R \) - distance between the centre of arcs of the through groove and the transverse axis of slot symmetry

**Figure 2.** Diagram of the experimental trailer hitch device.

The short length of the towing beam during maneuvering ensures high agility of train handiness, reduces the width of the movement corridor. At the same time, the design length of the towing beam and, consequently, the total length of the road train may be even shorter than when using a standard tow bar. The absence of gaps in the joints and the use of rolling bearings further increase the stability of the road train movement. In addition, they increase the durability of the tow bar.

### 4. Conclusions

The use of the proposed recommendations allows choosing rational parameters and improving the configuration of road trains at the design stage, correctly completes the road trains in operation.

### References

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