Design features of the steering control systems of road trains and articulated buses

O I Chudakov* and V A Gorelov
Bauman Moscow State Technical University (BMSTU), 2nd Baumanskaya St., Bldg. 5, Block 1, Moscow, Russian Federation, 105005

*chudakov@bmstu.ru

Abstract. One of the important properties of road transport vehicles is maneuverability, which directly affects the performance and safety of transportation, as well as the total cost of freight and passenger traffic. The paper discusses the design features of various steering control systems and their effect on the maneuverability of vehicles.

1. Introduction
Improving the efficiency of freight and passenger traffic is one of the key objectives of road transport development. An important role in solving this problem is played by roadtrains and articulated vehicles [1]. The main difference between roadtrains and articulated vehicles lies in the articulator design. Roadtrains are equipped with an easily detachable nonsteerable link connection, which allows their links to be used separately. Articulated vehicles have a frame consisting of two or more parts that are interconnected by a one-piece pivot [2].

Long-range designs of multi-unit vehicles (three and more units) are developed to increase freight and passenger traffic. Their key advantages are: increased payload, lower cost of the vehicle with the same payload, reduced specific consumption of fuel, lubricants and other operating supplies, reduced number of drivers involved in transportation [3]. Figure 1 shows examples of multi-unit vehicles.

Figure 1. Multi-unit vehicles: a – four-unit roadtrain; b – bi-articulated bus
The key feature of multi-unit vehicles is a large number of axles, which can have different turning kinematics due to the considerable distance between them [4]. The large size of the vehicles in question greatly reduces their maneuverability. These features impose a number of restrictions on the applicability of mechanical linking and conventional designs of steering systems [5].

So, a conclusion can be made that improving the maneuverability of long-wheelbase vehicles is a complex engineering problem to be solved by designing special steering systems. The choice of a steering control system (SCS) for a specific vehicle depends on an intricate system of interrelating factors: purpose of the vehicle, dimensions, link connection method, etc.

2. Theory

The general flow chart of SCS of each of the articulated units can be represented by the following functionally interfacing devices (figure 2).

![General flow chart of SCS](image)

The master device generates a wheel steering pattern. It can be automatic and manual, while the latter can be stationary or portable (remote). The lead-unit master device is usually manual with a master element being the steering wheel. The slave device is designed to directly turn wheels. It can be mechanical, hydraulic, electrical and combined both for the lead and follower units. The choice of a particular type depends on the specific vehicle.

Information display system are functionally connected with both the master and slave devices and indicate SCS status.

The most difficult task for the nonlinear motion of multi-unit vehicles in a given path is the choice of the steering system master device of follower units. Performing it manually requires operators in follower units, whose work may be hampered by inadequate visibility and difficulty of synchronization with the lead-unit operator. It is preferable to equip each follower unit with an auto master device, which makes operator involvement in steering unnecessary.

Self-steering systems are the most common now, when wheels of the trailer unit turn depending on the drawbar turning (for trailers) or the articulation angle (for semi-trailers). Direct-control and power-assisted systems [6] are distinguished according to the steer wheel actuation method.

Direct-control systems include devices that turn steer wheels using force created from articulation of roadtrain units. The force is transmitted to steered wheels of the trailer unit using a mechanical or hydraulic drive. Hydraulically-driven direct-control systems has enclosed volumes of fluid (so-called hydrostatic drive). Figure 3 shows the diagram of such a drive.

![Hydrostatic drive of semi-trailer wheels](image)
Rods of master hydraulic cylinders 1 (figure 3) shift when turning with rods of slave hydraulic cylinders 2, which steer the rear axle connected to the remaining axles through trailing arms 3, moving synchronously with them.

Power-assisted SCS has a tractor unit that turns wheels and a command unit that controls their turning angle. The tractor unit can be designed as a hydraulic or electromechanical drive. In the first case, the system has a pump, a distributor and slave hydraulic motors (hydraulic cylinders), in the second case - a generator and wheel turning motors [7]. The command unit of the power-assisted SCS gives a control signal, when there is an articulation angle between the roadtrain units or when the steering wheel of the tractor deviates from the linear motion. Synchronous command is given simultaneously with the occurrence or change of the articulation angle. Figure 4 shows the diagram of a hydraulic steering control system.

The system operates as follows. When the tractor turns relative to the semi-trailer, the follower turns through the mechanical system and moves the rod of master hydraulic cylinder 1 (figure 4) through the roller using the trailing arm. The master hydraulic cylinder rod displaces a certain volume of fluid, which moves the rod of slave hydraulic cylinder 4 through the pipeline to the appropriate length. The latter displaces the rod of spool 3 directing the fluid flow from pumps to hydraulic power cylinders 2. The force is transmitted from the hydraulic power cylinders through drag and steering linkage to the semi-trailer wheels turning them. At the same time, arm 5 moves spool 3 relative to the rod into its original position stopping wheel turning. The pump can be driven from the tractor or a stand-alone unit installed on the trailer unit.

The disadvantage of the above systems is that the control signal (articulation angle) is immediately transmitted to the tractor unit. That is why the motion trajectory of the lead and follower units does not always coincide. This problem is most vivid when multi-unit vehicles move along complex trajectories with several radii (figure 5). Such problems may arise when driving through road intersections with roundabouts or traffic circle sections of roads [8].

![Figure 4. Hydraulic steering control system diagram](image-url)

![Figure 5. Complex motion trajectory of a multi-unit vehicle](image-url)
Reducing the overall traffic path can be achieved by using a special servosystem in the actuator of trailer units to turn wheels depending on steering wheel turning of the tractor unit, but with a time lag for the trailer units to travel from their wheels to the tractor unit wheels.

Additional difficulties arise when trailer wheels have driven (active trailers). When the propelling force of the trailer exceeds the tractive force of the tractor, a free hinge in the link connection will cause roadtrain jackknifing [9]. This problem has been successfully solved in articulated buses with rear drive axle through the use of an active articulation pivot. In addition to the direct function of bus articulation, the active articulator creates damping and steering forces to stabilize the bus movement depending on operating conditions (speed, articulation, twisting and bending angle, direction of travel). Figure 6 shows the alternate design.

![Figure 6. HUBNER SDK 420 articulator design](image)

When turning, fluid flows from the chamber of one cylinder into the opposite chamber of the second cylinder. Fluid acting on the piston moves both rods in opposite directions, engaged rods turn the planet gear mounted on the turntable and thus rotate the turntable.

Articulator steering issues are well studied for articulated buses with one steering axle, however, they are insufficiently studied for bi-articulated ones, where the number of steering axles increases in addition to a second articulator. The key challenges here as in the case of multi-unit roadtrains are following by follower units the path of the lead unit (Figure 7).

![Figure 7. Complex motion trajectory of a bi-articulated bus](image)
The mathematical model of roadtrain planar motion described in detail in [10] may be used to study the nonlinear motion of multi-unit vehicles with active trailer units. The dynamics of an individual unit of a roadtrain is described by the following system of equations:

\[
\begin{align*}
\dot{a}_{ij} &= \frac{dV_{ij}}{dt} - \omega_{ij} \cdot V_{ij} = \frac{1}{m_j} \left( \sum_{i=1}^{6} R_{ij} - m_j \cdot g \cdot \sin(\alpha) - P_{ws} + \vec{F}_{ij} \right); \\
\dot{a}_{ij} &= \frac{dV_{ij}}{dt} + \omega_{ij} \cdot V_{ij} = \frac{1}{m_j} \left( \sum_{i=1}^{6} R_{ij} - P_{wy} + \vec{F}_{ij} \right); \\
J_{ij} \cdot \dot{\omega}_{ij} &= \sum_{i=1}^{6} M_{pki} + \sum_{i=1}^{6} M(\vec{R}_i) + M_j; \\
V_{ij} &= \frac{dx_j}{dt} = V_{ij} \cdot \cos \theta_j - V_{ij} \cdot \sin \theta_j; \\
V_{ij} &= \frac{dy_j}{dt} = V_{ij} \cdot \sin \theta_j + V_{ij} \cdot \cos \theta_j; \\
\dot{\theta}_{ij} &= \frac{d\theta_j}{dt},
\end{align*}
\]

where \(j\) is the number of the roadtrain unit; \(m_j\) is the mass of the \(j\)-th unit; \(J_{ij}\) is the inertia moment of the \(j\)-th unit relative to \(z\) axis; \(\vec{V}\) is the center-of-mass velocity vector of the unit; \(\vec{a}\) is the center-of-mass acceleration vector of the unit (absolute derivative of the center-of-mass velocity vector of the unit); \(d\vec{V}/dt\) is the relative derivative of the center-of-mass velocity vector of the unit; \(\dot{\omega}_j\) is the turning angular rate vector of the unit; \(\theta_j\) is the turning angle of the \(j\)-th unit relative to \(x'\); \(x, y\) are center-of-mass coordinates of the unit in fixed reference; \(x', y'\) are moving coordinates referred to the unit; \(\vec{R}_i\) is the vector of interaction force with the ground acting on the \(i\)-th wheel; \(\vec{P}_w\) is the vector of air resistance force; \(M_{pki}\) is the moment of resistance to turning of the \(i\)-th wheel; \(F_{ij}\) is the force acting from the side of the drawbar along \(x\) axis; \(F_{ij}\) is the force acting from the side of the drawbar along \(y\) axis; \(M_j\) is the moment transmitted to the body of the \(j\)-th unit by drawbar forces.

Articulator forces and moments are determined according to the diagram shown in figure 8.

\[\text{Figure 8. Diagram to determine the direction of articulator forces and moments}\]
Let us assume that at the i-th modeling step, the distance between the pivots of roadtrain sections in fixed coordinates is equal to \( \Delta \), and its variability over time is \( \dot{\Delta} \), then the articulator force is calculated using the following formula:

\[
F_s = C_F \cdot \Delta + \mu_F \dot{\Delta};
\]

\[
\Delta = \sqrt{(X'_j - X'_{j+1})^2 + (Y'_j - Y'_{j+1})^2} ;
\]

\[
\dot{\Delta} = \frac{(X'_j - X'_{j+1}) \cdot (\dot{X}'_j - \dot{X}'_{j+1}) + (Y'_j - Y'_{j+1}) \cdot (\dot{Y}'_j - \dot{Y}'_{j+1})}{\Delta},
\]

where \( C_F \) is the longitudinal stiffness coefficient of the drawbar, \( \mu_F \) is the longitudinal resistance coefficient of the drawbar shock absorber, \( X'_j, X'_{j+1}, Y'_j, Y'_{j+1} \) is the projection of drawbar pivot points on the fixed reference axis.

Articulator force projections on the fixed reference axis can be calculated from the following formulas:

\[
F_{xs} = F_s \cdot \cos \beta;
\]

\[
F_{ys} = F_s \cdot \sin \beta;
\]

\[
\frac{X'_j - X'_{j+1}}{\Delta} = \cos \beta; \tag{2}
\]

\[
\frac{Y'_j - Y'_{j+1}}{\Delta} = \sin \beta,
\]

where \( \beta \) is the angle of articulator force direction relative to the fixed reference.

Articulator force projections on coordinate axes referred to unit bodies as well as the moments from this force are determined using the following relationships:

\[
F_{ij} = \cos \theta_j \cdot (F_{xs}) + \sin \theta_j \cdot (-F_{ys});
\]

\[
F_{ij} = \sin \theta_j \cdot F_{xs} + \cos \theta_j \cdot (-F_{ys}); \tag{4}
\]

\[
M_j = F_{ij} \cdot d_j.
\]

Articulator forces are factored in when determining normal responses of wheels with the abutment face for each unit.

A diagram of a computer model of a triple combination (fifth wheel-trailed) roadtrain implemented in the MATLAB Simulink package is shown in figure 9.

The developed model of the triple roadtrain is currently used to validate the operation concept of the servosystem subject to the tractive force in trailer units. One of the problems arising from this is possible jackknifing due to the propelling force caused by trailers. Effective operation of such a steering system might require an additional information parameter, one of which may be the measurement of drawbar forces, which was offered and tested in [11] to prevent jackknifing of the roadtrain when braking.

3. Conclusions

The analytical review showed that mechanical and hydraulic actuators (direct-control or power-assisted steering systems) are mainly used in the design of steering systems for multi-unit roadtrains. These steering systems are synchronous, i.e. turn steer wheels of the trailer simultaneously with the occurrence of an articulation angle between units. This creates constant wheel drive ratio, which does not allow yaw motion of tractor and trailer units to be prevented when moving along variable curvature trajectories.

The most promising from the point of view of enhancing the maneuverability and traffic safety of multi-unit vehicles is a command guidance system that turns wheels of trailer units with some delay relative to wheel turning of the tractor unit. Such systems are currently used only on heavy-duty trailers.
with a particularly heavy payload, which have relatively low speeds (up to 10 km/h). Introduction of such a system on a line-haul train will increase its composition to five or six units, which will significantly improve the efficiency of carriage.

Further research will be focused on the design of an automatic system of shared steering and active drive of trailer units. Of considerable scientific and practical interest is the optimization of power distribution parameters during curvilinear motion using various electronic control systems, the effectiveness of which is to be proved using mathematical computer simulation.

Figure 9. Computer model of a triple roadtrain

Acknowledgments
This work was carried out at the Bauman Moscow State Technical University, with financial support from the Council on grants of the President of the Russian Federation (grant registration number MD-582.2019.8).

References
[1] Diakov A S and Kotiev G O 2015 Establishment of production of special wheel and track technology for extreme natural-climate conditions of the Arctic MATEC Web of Conferences vol 224 02096
[2] Kotiev G O, Padalkin B V, Kartashov A B and Diakov A S 2017 Designs and development of Russian scientific schools in the field of cross-country ground vehicles building ARPN Journal of Engineering and Applied Sciences vol 12 pp 1064–71
[3] Farobin Y E 1993 Trekzvennye avtopoezda (Moscow: Mashinostroenie Publishing House) p 224
[4] Gladov G I and Morozova A Y 2004 Sistemy upravleniya povorotom spetsial'nykh transportnykh sredstv (Moscow: MADI) p 88
[5] Belousov B, Ksenevich T I and Naumov S 2015 Automated system to control steering and wheel springing parameters in vehicle locomotion module SAE Technical Papers 2015-26-0085
[6] Pakhter I H and Tseytlin GD 1976 Sistemy upravleniya pritsepow-tyazhelovozov (Moscow: NIINavtoprom) p 65
[7] Belousov B, Demik V, Kozlova A, Ksenevich T, Naumov S, Medvedev E, Lyushnin S and Kuzminkov K 2018 The schematic diagrams of actuators of an mechatronic wheel steering system FISITA World Automotive Congress 2018
[8] Vysotskiy M S, Kochetov S I and Kharitonchik S V 2011 Osnovy proyektirovaniya modul'nykh magistral'nykh avtopoyezdov (Minsk: Belarusian science) p 392
[9] Skotnikov G I, Jileykin M M and Komissarov A I 2018 Increasing the stability of the articulated lorry at braking by locking the fifth wheel coupling IOP Conference Series: Materials Science and Engineering vol 315 012027
[10] Gorelov V A and Tropin S L 2011 Matematicheskaya model' krivolineynogo dvizheniya avtopoyezda po nedeformiruemomu opornomu osnovaniyu AAI Journal vol 2 pp 18–22
[11] Vasilevskiy V I 2013 Algoritm bortovoy sistemy monitoringa protsessa tormozheniya sedel'nogo avtopoyezda na osnove izmereniya i analiza silovykh faktorov Ph. D. thesis (Mogilev) p 131