The Fifth International Conference on Railway Technology
RAILWAYS 2022
22–25 August 2022
Montpellier, France

Proceedings of the Fifth International Conference on
Railway Technology:
Research, Development and Maintenance
Edited by J. Pombo
Civil-Comp Conferences, Volume 1, Paper 31.12
Civil-Comp Press, Edinburgh, United Kingdom, 2022, doi: 10.4203/ccc.1.31.12

Multi-controller cooperative path-tracking strategy for the distributed driving virtual track train: a reconfigurable approach

Z. Wang[1] and Z. Lu[1]

[1]Insititute of Rail Transit, Tongji University

Abstract

This paper presents a new path-tracking strategy for the distributed driving all axle steering virtual track train (DDAAS-VTT). The proposed multi-controller cooperative scheme comprises the inter-unit cooperative controller and single-unit controllers. To ensure that the same motion trajectories of the adjacent unit hinge points, so as to reduce the hinge force, the centre of gravity (CG) of the first and the last unit and all of the hinge points are selected as tracking points. The target positions of every unit are computed by the cooperative controller according to the train's posture and the target path. The single unit controller adopts a hierarchical structure, where the upper layer calculates the desired CG force/moment of each unit based on model predictive control (MPC). Furthermore, the control allocation (CA) of wheel steering angle and torque is optimized by the lower layer with the tire model. The vehicle dynamic model and tire model are established. The run of the train at various velocities on the test track is carried out with a Simulink-SIMPACK co-simulation system. The result shows that the proposed control strategy can achieve high path-tracking accuracy. The advantage of minimizing hinge force and wheel sideslip angle is confirmed by comparing with Stanley and Extended_Ackermann algorithm. Moreover, the adoption of the multi-controller and hierarchical structure could reduce the control DOF, which eases the calculation enormously.

Keywords: distributed driving all axle steering virtual track train (DDAAS-VTT), path-tracking, multi-controller, vehicle dynamic.

1 Introduction

Recent traffic growth has heightened the need for a more efficient public transport system, and Virtual track train (VTT) is an effective method[1]. Distributed driving, all axle steering, and flexible marshalling have become significant features. One of the greatest challenges is to achieve considerable path-tracking accuracy and, at the same time, little hinge force and wheel sideslip angle to ensure road passability and safety.

This paper proposes a path-tracking control strategy for distributed all axle steering virtual track train (DDAAS-VTT) with three units and six axles. There has been an increasing amount of literature on kinematic controllers[2–4]. However, the methods developed assumed small steering angles and the influence of tire sideslip was ignored. More recent attention has focused on full-state control based on the dynamic model[5–8]. Nevertheless, the VTT studied has 18 actuators and 4 control DOFs whose controller is hard to realize. It is essential to employ the framework of multi-controller and hierarchical structure to achieve inter-unit cooperative control so as to ease the calculation effort.

The control strategy is composed of the inter-unit cooperative controller and single-unit controllers. Taking the CG of the first and the last unit and all of the hinge points as tracking points, the cooperative controller assigns the tracking target of every unit. The single unit controller adopts a hierarchical structure, where the upper controller obtains the needed generalized force at CG of each unit based on model predictive control (MPC). The control allocation in the lower layer is used to calculate the optimal distribution of wheel torque and steering angle to acquire small sideslip angles. This approach simplifies each controller's computational stress, and the reconfiguration can be easily realized for different actuation systems.

This paper begins with the structure of DDAAS-VTT and the control scheme. It will then go to the vehicle and tire models and algorithm implementation. The closed-loop simulation result and the comparison with other controllers verify that the proposed control strategy has high path-tracking accuracy, low hinge force and sideslip angle under curves with different speeds and radii.

2 Methods

The structure of the DDAAS-VTT is shown in Figure 1, and there are apparent difficulties in adopting the full-state control for a system with 18 actuators and 4 DOFs. Especially the calculation effort, which is unacceptable by the ECU. As shown in Figure 2, a framework of multi-controller is put forward, which would usefully improve the feasibility.

Once the posture of the tracking points is determined, the target position of each unit can be obtained by geometric calculation carried out by the cooperative controller. Therefore, only the dynamic model of the single unit needs to be established for the MPC algorithm in the upper controller. The tire model and the relation between CG force/moment and tire local forces are used to allocate wheel torque and steering angle, which happens in the lower controller. Three single unit controllers have the same structure but different inputs and outputs. These steps are repeated in real-time.

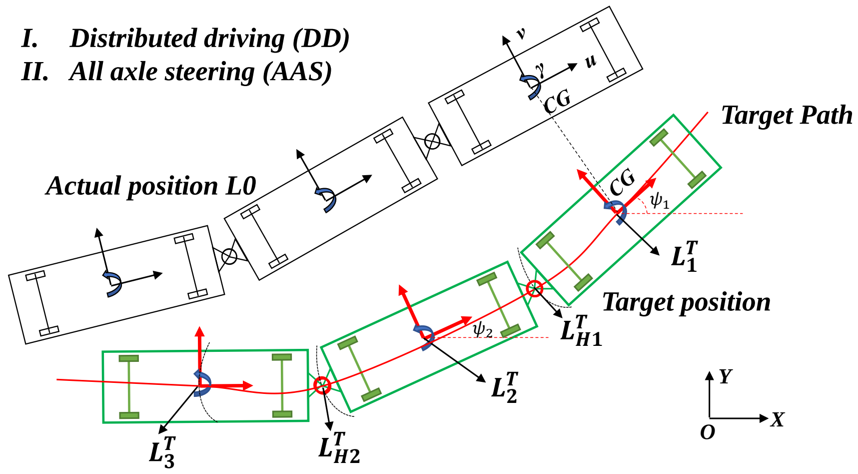

Figure 1: Architecture of DDAAS-VTT.

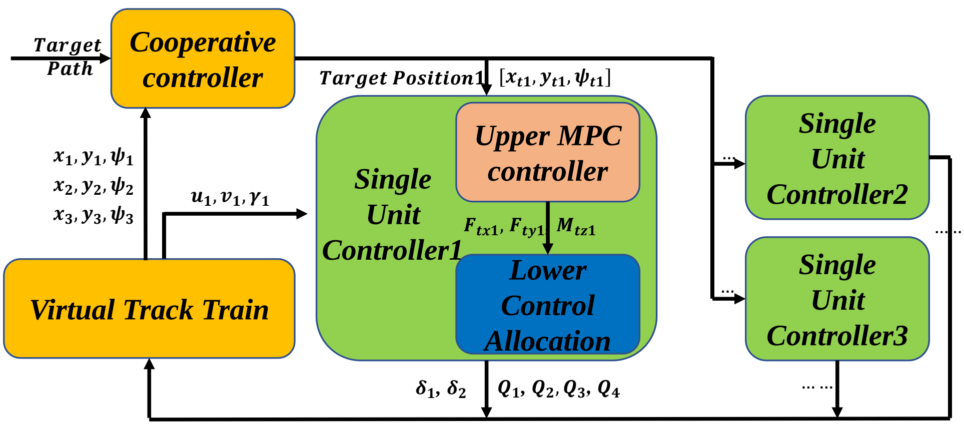

Figure 2: Control Scheme.

The equations of single unit dynamics with respect to the CG force/moment are provided. The lateral motion and the yaw motion are considered:

$$m(\dot{v}+u\cdot\gamma)=F_y \tag{1}$$

$$I_z\cdot\dot{\gamma}=M_z \tag{2}$$

$$\dot{y}=v \tag{3}$$

$$\dot{\psi}=\gamma \tag{4}$$

where m and I_z are the total mass and yaw moments of inertia. It is assumed that the longitudinal speed is constant during the prediction horizon of MPC, equations can be rearranged to the state-space:

$$\dot{X}=AX+BU \tag{5}$$

$$Y=CX \tag{6}$$

$$\dot{X}=\begin{bmatrix}\dot{v}\\ \dot{\gamma}\\ \dot{y}\\ \dot{\psi}\end{bmatrix},A=\begin{bmatrix}0 & -u & 0 & 0\\ 0 & 0 & 0 & 0\\ 1 & 0 & 0 & 0\\ 0 & 1 & 0 & 0\end{bmatrix},B=\begin{bmatrix}1/m & 0\\ 0 & 1/I_z\\ 0 & 0\\ 0 & 0\end{bmatrix},C=\begin{bmatrix}0 & 0 & 1 & 0\\ 0 & 0 & 0 & 1\end{bmatrix},U=\begin{bmatrix}F_y\\ M_z\end{bmatrix} \quad (7)$$

The discrete-time state-space form of the vehicle model can be derived by discretization of Equation (5) and using the zero-order-hold (ZOH) as:

$$X^{k+1}=A_d X^k+B_d U^k \quad (8)$$

$$Y^k=C_d X^k \quad (9)$$

Then, the MPC problem can be stated as:

$$\min_U \ J(X_t,U_t)=\sum_{k=0}^{N-1}(\left\|Y_t^{k+1}-Y_D\right\|_{Q_Y}^2+\left\|\Delta U_t^k\right\|_{Q_{\Delta U}}^2) \quad (10)$$

$$\Delta U_t^k \triangleq U_t^k-U_t^{k-1},U_t^{-1}=U_{t-1} \quad (11)$$

$$s.t. U_{\min}<U_t^k<U_{\max}, k=0,\ldots,N-1 \quad (12)$$

$$\Delta U_{\min}<\Delta U_t^k<\Delta U_{\max}, k=0,\ldots,N-1 \quad (13)$$

where Y_D is the target position. The costs of the tracking error and the change rate of control effort are included in the cost function with weight matrices as Q_Y and $Q_{\Delta U}$, respectively. The desired CG force/moment is calculated in every step.

$$F_{Desired}=\begin{bmatrix}0 & F_y^* & M_z^*\end{bmatrix}^T \quad (14)$$

The tire model can be written as:

$$f_{xi}=\frac{Q_i}{R_w} \quad (15)$$

$$f_{yi}=c_\alpha(\delta_i-\frac{v+a_i\cdot\gamma}{u}) \quad (16)$$

$$F_{tire}=\begin{bmatrix}f_{x1} & f_{y1} & f_{x2} & f_{y2} & f_{x3} & f_{y3} & f_{x4} & f_{y4}\end{bmatrix}^T \quad (17)$$

The relation between local tire forces and CG generalized force can be derived:

$$F_{COG}=L_{COG}\cdot L_w\cdot F_{tire} \quad (18)$$

$$F_{COG}=\begin{bmatrix}F_X & F_Y & M_Z\end{bmatrix}^T \quad (19)$$

$$L_{COG}=\begin{bmatrix}1 & 0 & 1 & 0 & 1 & 0 & 1 & 0\\ 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1\\ -T/2 & a & -T/2 & a & -T/2 & a & -T/2 & a\end{bmatrix} \quad (20)$$

$$L_w = \begin{bmatrix} \cos(\delta_1) & -\sin(\delta_1) & & & & & & \\ \sin(\delta_1) & \cos(\delta_1) & & & & & & \\ & & \cos(\delta_1) & -\sin(\delta_1) & & & & \\ & & \sin(\delta_1) & \cos(\delta_1) & & & & \\ & & & & \cos(\delta_2) & -\sin(\delta_2) & & \\ & & & & \sin(\delta_2) & \cos(\delta_2) & & \\ & & & & & & \cos(\delta_2) & -\sin(\delta_2) \\ & & & & & & \sin(\delta_2) & \cos(\delta_2) \end{bmatrix} \quad (21)$$

After calculating $F_{Desired}$ by the upper controller, the single unit control action ([δ_1, δ_2, Q_1, Q_2, Q_3, Q_4]) are optimally allocated by the lower controller. The object function is presented as:

$$\min J = \lambda_1(\|F_{COG} - F_{Desired}\|^2) + \lambda_2(\|\delta_1 - \delta_{v1}\|^2 + \|\delta_2 - \delta_{v2}\|^2) + \lambda_3(D(Q_1, Q_2, Q_3, Q_4)) \quad (22)$$

$$s.t.\ \delta_{\min} < \delta_i < \delta_{\max},\ i = 1, 2 \quad (23)$$

$$Q_{\min} < Q_i < Q_{\max},\ i = 1, 2, 3, 4 \quad (24)$$

where F_{COG} is the CG force/moment generated by wheels, δ_{vi} is the vehicle velocity direction at the wheel fixed point, which is identical for the two wheels of the same axle, D(Q_1, Q_2, Q_3, Q_4) is the variance of wheel torques, and λ_i is weight factor of each item. The first and second items aim to eliminate the allocation error and reduce wheel sideslip angle. The third item is used to smooth the torque curve.

3 Results

The proposed control strategy was verified through simulation on the test track shown in Figure 3, which contains lane change, circular curves with different radii, and transition curves (cubic curves) with changed curvature. Therefore, this track can effectively represent the actual operation condition. The simulation was realized with a complete model, including tire, stiffness and damping suspension. It is assumed that the mass, the moment of inertia, and the road conditions are known and constant during the simulation.

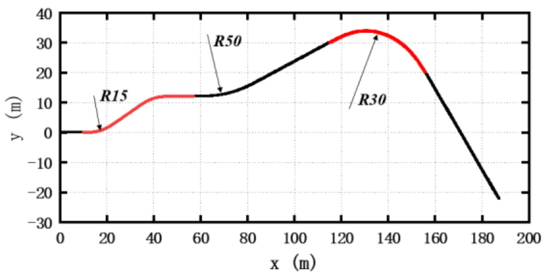

Figure 3: Test track used for simulation.

Figure 4 shows the simulation result with a speed of 10m/s. Diagrams (a) (b) show the lateral deviation and heading error, and diagrams (c) (d) display the CG force/moment of each unit, respectively. The wheel steering angle of every axle and wheel driven torque of every unit is provided in diagrams (e) (f). It is apparent from this figure that the most significant tracking error to the target position appears in the first unit. However, it remains small and decreases significantly with the augment of curve radius.

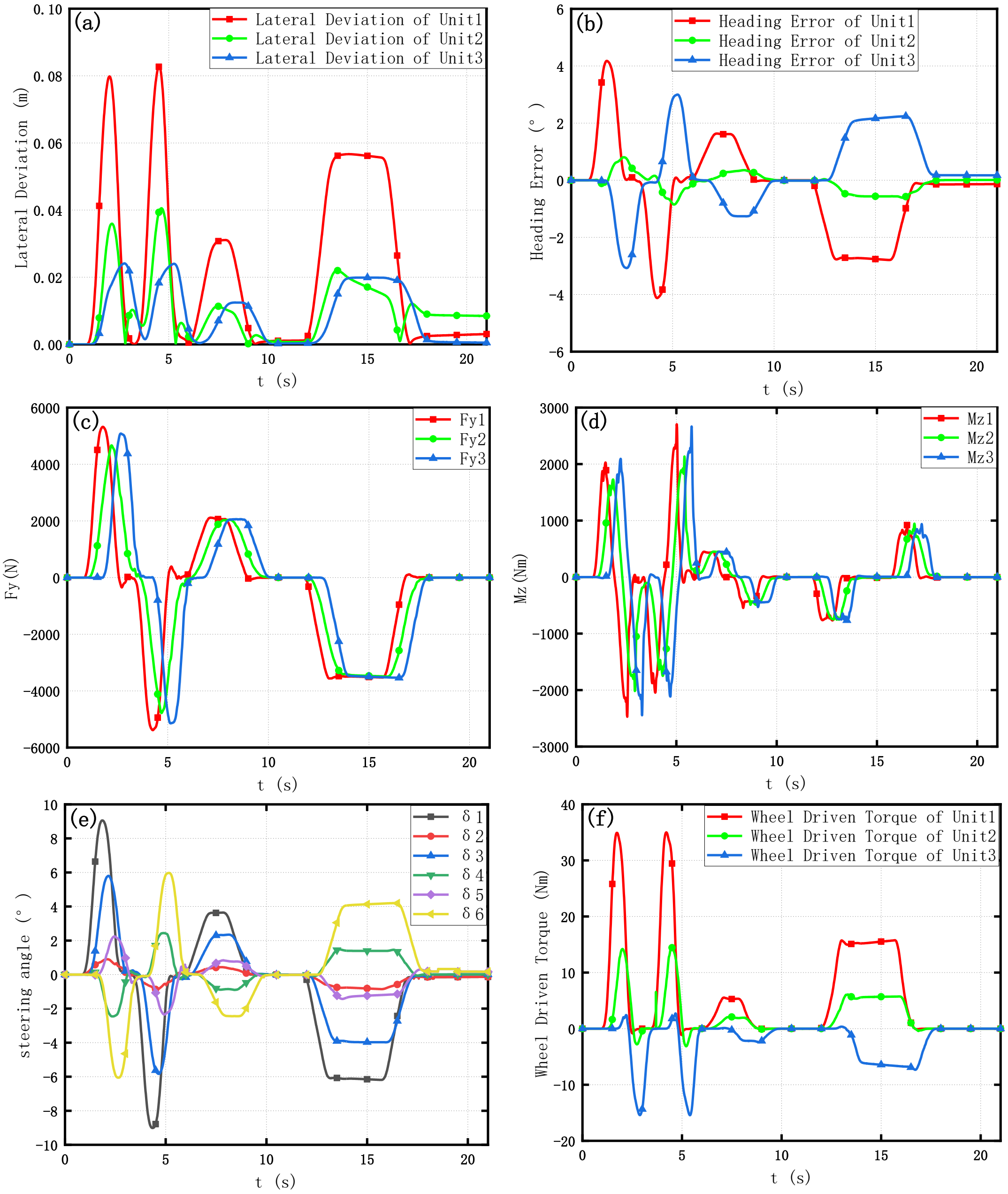

Figure 4: Simulation: Deviation, CG Force/Moment, Wheel states versus u=10m/s.

As shown in Figure 5, one of the advantages of the proposed strategy is that the control allocation can obtain a slight and uniform sideslip angle, with a maximum value of 1.27 °, thus leading to minor tire lateral force, tire wear and improving the safety. The transformation of hinge forces is displayed in Figure 6. The advantage of a cooperative controller is that it allows the motion of hinge points of adjacent units to be consistent so as to reduce the hinge force. The maximum hinge force is 253N, and it declines with the increase of the curve radius.

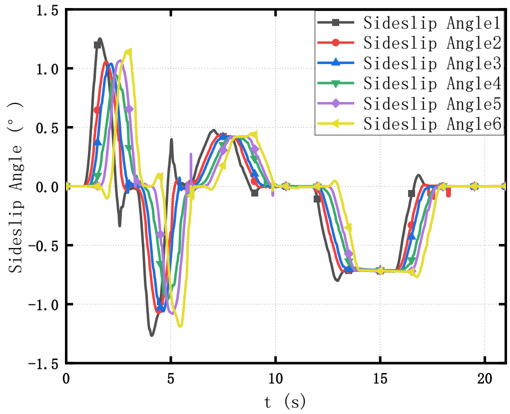

Figure 5: Sideslip angle of wheels versus u=10m/s.

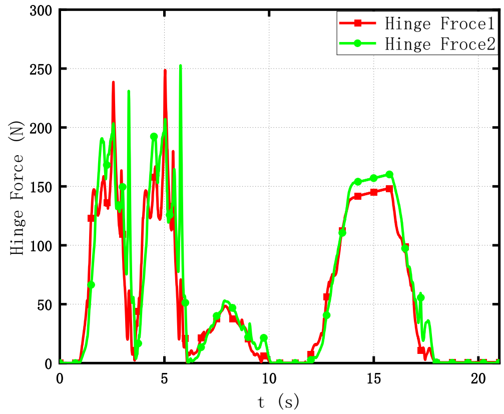

Figure 6: Hinge forces versus u=10m/s.

The advantage of the proposed control method in minimizing maximum sideslip angle and hinge force was further verified by a comparison with Stanley and Extended-Ackermann algorithm on the test track, as shown in Figure 7 and 8.

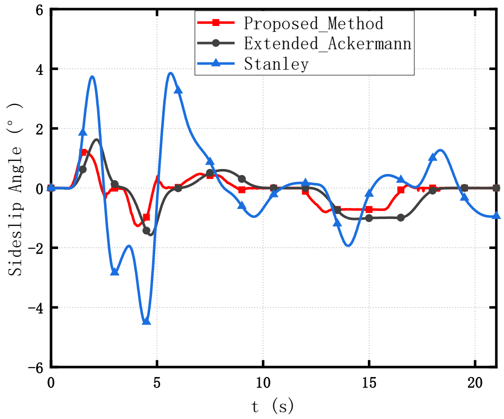

Figure 7: Max sideslip angle for different controllers versus u=10m/s.

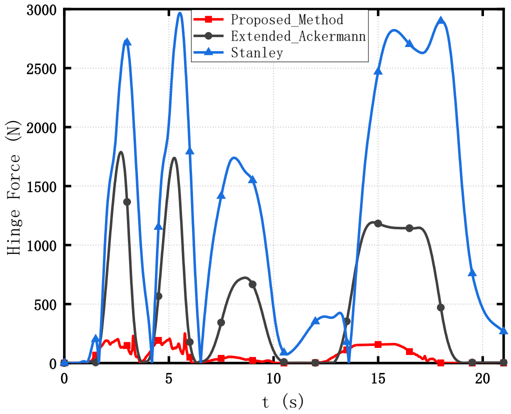

Figure 8: Max hinge force for different controllers versus u=10m/s.

As shown in Figure 9, the lateral deviation of the train drops significantly with speed. And it is less than 0.1m for u=10m/s. The path-tracking error varies in a small range, which shows the robustness of the control strategy.

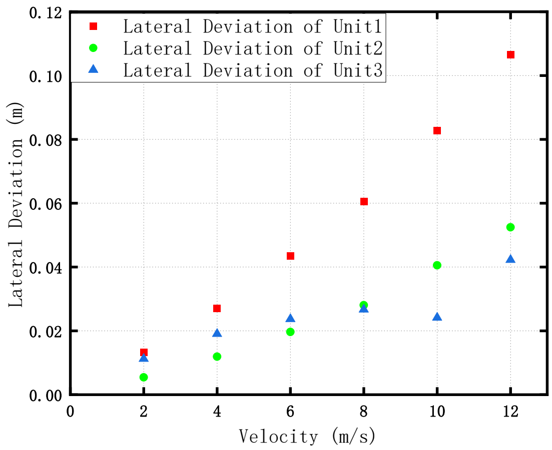

Figure 9: Maximum lateral deviation versus train velocity.

4 Conclusions and Contributions

Aiming at distributed driving all axle steering virtual track train (DDAAS-VTT), this paper has proposed a new path-tracking strategy based on a multi-controller and hierarchical structure, which can achieve considerable tracking accuracy and maintain robustness at different speeds. Meanwhile, hinge force and wheel sideslip angle are slight to keep the train's stability and safety.

Through a simulation with a speed of 10m/s on the test track, the lateral deviation, hinge force and wheel sideslip angle are less than 0.0827m, 253N, 1.27°, respectively. Compared with Stanley and Extended_Ackermann algorithm, the proposed method can reduce significantly sideslip angle and hinge force. Moreover, the lateral tracking error is smaller than 0.1065m, while the speed varies from 2m/s to 12m/s.

This work contributes to existing knowledge of VTT path-tracking control by simplifying the control system with 18 inputs and 4 DOFs into a cooperative controller and 3 single unit controllers. The single unit controller adopts a hierarchical framework, and the upper layer only has 2 DOFs and 2 inputs. This structure significantly reduces the computational complexity and cost, improving the feasibility.

The strategy proposed in this paper is not only suitable for the three-module six-axle DDAAS-VTT, but the same with the formation of two modules or more than four modules, and the expansion and reconfiguration of the controller are easy to implement. Moreover, the lower layer control allocation provides a variety of possibilities for the distribution strategy of control actions, giving freedom and reconfigurability for different actuation systems.

Further research should focus on road tests or scale model verification. It is also recommended that further study be undertaken on roll prevention and wheel slip control, which are fundamental vehicle safety problems.

Acknowledgements

The authors are grateful for helpful comments from referees to improve this manuscript.

References

[1] Xiao L, Wang K, Zhou S, et al. An intelligent multiple-articulated rubber-tired vehicle based on automatic steering and trajectory following method. Journal of Vibration and Control. 2021;107754632199918.

[2] Bolzern P, DeSantis RM, Locatelli A. An Input-Output Linearization Approach to the Control of an n-Body Articulated Vehicle. Journal of Dynamic Systems, Measurement, and Control. 2001;123:309–316.

[3] Astolfi A, Bolzern P, Locatelli A. Path-Tracking of a Tractor-Trailer Vehicle Along Rectilinear and Circular Paths: A Lyapunov-Based Approach. IEEE Trans Robot Automat. 2004;20:154–160.

[4] Wagner S, Nitzsche G, Huber R. Advanced Automatic Steering Systems for Multiple Articulated Road Vehicles. Proceedings of the Asme International Mechanical Engineering Congress and Exposition, 2013, Vol 13. New York: Amer Soc Mechanical Engineers; 2014. p. V013T14A003.

[5] De Bruin D, Damen AAH, Pogromsky A, et al. Backstepping control for lateral guidance of all-wheel steered multiple articulated vehicles. ITSC2000 2000 IEEE Intelligent Transportation Systems Proceedings (Cat No00TH8493) [Internet]. Dearborn, MI, USA: IEEE; 2000 [cited 2021 Dec 23]. p. 95–100. Available from: http://ieeexplore.ieee.org/document/881024/.

[6] Wagner S, Zipser S, Bartholomaeus R, et al. A Novel Two Dof Control for Train-Like Guidance of Multiple Articulated Vehicles. Proceedings of Asme International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Vol 4, Pts a-C. 2010. p. 1989–1997.

[7] Sorge F. A nonlinear dynamical approach to the path correction of multi-steering articulated vehicles. Vehicle System Dynamics. 2020;0:1–22.

[8] Oreh SHT, Kazemi R, Azadi S. A new method for off-tracking eliminating in a tractor semi-trailer. IJHVS. 2016;23:107.