Small-Scale Experiments on Reversing Semitrailers

Levente MIHÁLYI[1], Dénes TAKÁCS[1]

[1] Department of Applied Mechanics, Faculty of Mechanical Engineering, Budapest University of Technology and Economics, Műegyetem rkp. 3., H-1111 Budapest, Hungary, E-mail: mihalyi@mm.bme.hu; takacs@mm.bme.hu

1. Introduction

Driver Assistance Systems have become everyday feature in modern passenger cars. However, these functions should also be implemented in freight transport, due to its benefits on safety and fuel consumption. One of the most complicated maneuvers for human driver is reversing, especially for a long, articulated vehicle, as this motion is unstable in all conditions (so as an inverted pendulum) unless it is stabilized by active control [1], [2].

In this study, the reversing of a truck–semitrailer is investigated, and the purpose is to create and validate a control scheme to ensure stability. The effect of time delay on stability is investigated, which is important not only for human drivers, but for self-driving vehicles as well.

2. Mechanical model and analysis

To model the articulated vehicle, a single track model is used with rigid wheels, i.e., neglecting the side-slip forces in the tires. Also, the longitudinal speed of the truck is considered to be constant V. These assumptions are commonly used in the literature, especially in case of reversing, when traveling speed is limited to a very low value and it varies very slowly. The mechanical model is shown in Fig. 1. The truck and the semitrailer are modeled by two rods that connect the midpoints of axles: the front and rear axles of the trailer are marked by points F and R, the semitrailer's axle by T, and point K is the hitch point. The only actuation of the system is the steering angle of the front axle of the truck denoted by δ.

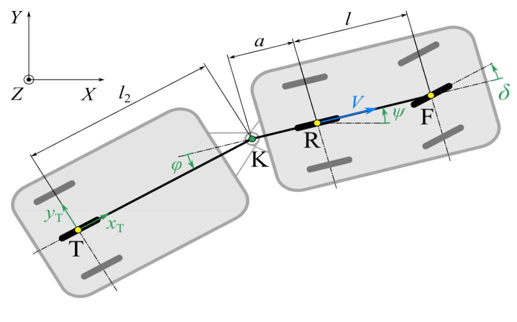

Fig. 1. Mechanical model of the truck–semitrailer.

The motion can be described by the vector of state variables:

$$\mathbf{x} = [X\ Y\ \psi\ \varphi\ \delta\ \omega]^{\mathrm{T}}.$$

Here, X and Y represent the longitudinal and lateral position of the trailer's axle in the global coordinate system, ψ is the absolute yaw angle of the truck, and φ is the yaw angle of the trailer relative to the towing vehicle. The last two states are introduced in order to consider the dynamics of the steering mechanism as a PD-controlled one degree-of-freedom system; δ is the steering angle, ω is the steering rate. The governing equations are derived from the kinematic constraints:

$$\dot{X} = V\cos\psi\,, \quad \dot{Y} = V\sin\psi\,, \quad \dot{\psi} = \frac{V}{l}\tan\delta, \tag{1}$$

$$\dot{\varphi} = -\frac{V}{l l_2}\left(l\sin\varphi + (l_2 + a\cos\varphi)\tan\delta\right), \tag{2}$$

and from the dynamics of the steering mechanism:

$$\dot{\delta} = \omega, \quad \dot{\omega} = -p(\delta - \delta_{\mathrm{des}}) - d\omega, \tag{3}$$

which includes the lower-level steering controller with gains p and d. The higher-level controller determines the desired steering angle δ_{des}. The stability is achieved by a linear feedback controller, so the control law is as follows:

$$\delta_{\mathrm{des}}(t) = -P_Y Y(t-\tau) - P_\psi \psi(t-\tau) - P_\varphi \varphi(t-\tau). \tag{4}$$

The time delay τ is considered in control loop, which has a significant effect on stability not only for human drivers (reactions time), but also for autonomous vehicles (image processing and computation time). The stability analysis of the investigated motion leads to an infinite dimensional mathematical problem due to the time delay. Stability chart can be constructed by the semi-discretization method [3] using the linearized form of Eqs. (1)–(3).

3. Results and validation

The main result of this paper is the stability chart plotted in the space of control gains P_ψ and P_φ with fixed P_Y as shown in Fig. 2. The stable area is surrounded by the black curve, meaning that if the gains are chosen from inside the curve, the motion will be stable in a linear sense. In contrary, selections outside the curve lead linearly unstable motion. The most stable gain setup is depicted by black star at $P_Y = -5$ rad/m, $P_\psi = 1.48$ and $P_\varphi = 3.40$.

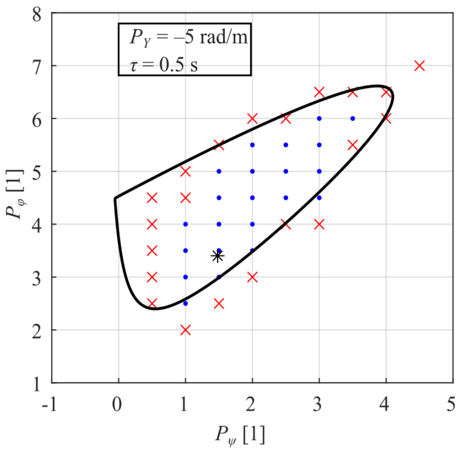

Fig. 2. Theoretical stability chart with its small-scale experimental validation.

The theoretical result is validated via experimental tests. A small-scale test rig was designed, which is presented in Fig. 3 showing the vehicle model itself and the measurement apparatus.

Validation of the stability chart is shown in Fig. 2, where gain configurations related to stable motion are depicted by blue dots, and unstable motions by red crosses. A good qualitative agreement can be observed when comparing the theoretical and experimental results. However, there is some discrepancy in the low-gain region, which can probably be explained by the fact that the steering mechanism of this small-scale truck has a threshold above which the system begins to function properly. However, having the stable area even for a relatively large time delay ($\tau = 0.5$ s) proves that this controller is suitable for reversing an autonomous truck–semitrailer combination along a straight line.

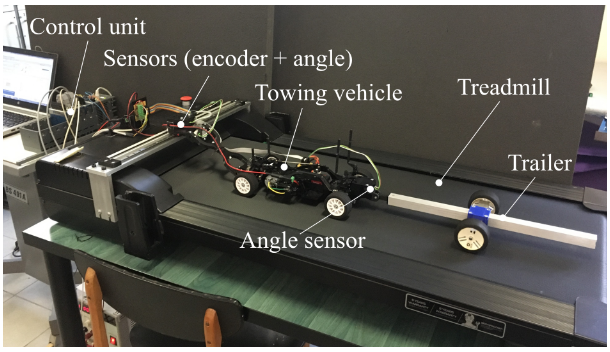

Fig. 3. Setup of the small-scale experiment.

4. Conclusions

In this paper, the rectilinear reversing of a truck–semitrailer was investigated. Based on a simple kinematic model, but taking into account the dynamics of the steering mechanism and the time delay in the feedback loop, a suitable controller is designed and validated by small-scale experiments.

Our future plan is to realize path-following tasks with articulated vehicles both theoretically and experimentally. This study has relevance in industry, especially in cases when trucks move within loading bays. In these situations, complicated maneuvers must be performed to assist the driver and speed up the loading time.

Acknowledgments

The research reported in this paper was partly supported by the János Bolyai Research Scholarship of the Hungarian Academy of Sciences and by the National Research, Development and Innovation Office under grant no. NKFI-128422 and under grant no. 2020-1.2.4- TÉT-IPARI-2021-00012.

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