

A Gain-Scheduled PID Controller for Automatic Path Following of a Tractor Semi-Trailer

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ABSTRACT

Improving driving safety and freeway capacity is an indispensable research issue for road vehicles, especially for tractor semi-trailers, which on the one hand exhibit unstable motion modes at high speeds due to their articulated configurations and undertake the largest part of freight transportation on freeways. Automatic driving is rated as the ultimate solution of vehicle safety since it can significantly reduce accidents resulting from human driver errors.

Proposed in this paper is a gain-scheduled PID controller for automatic path-following of a tractor semi-trailer. The PID controller minimizes the vehicle's predicted lateral deviation and heading error with respect to the desired path at a preview point, and gains of the controller are scheduled with respect to vehicle speed. The gains of the controller at several given vehicle speeds are tuned using the orthogonal experimental design method (OEDM), based on comprehensive evaluation of lateral path deviation, steering angle input and vehicle stability index under a double lane change maneuver. The tuned gains are further fitted using linear and quadratic functions to form a gain-scheduled control system. The controller is evaluated by simulations using a high-fidelity nonlinear tractor semi-trailer model built in the TruckSim software. Simulation results show that the automatic path following controller can control the tractor semi-trailer to follow the desired path with quite small tracking errors and keep the vehicle stable at various vehicle speeds and road friction conditions with a reasonable steering input.

KEYWORDS: PID path-following controller, tractor semi-trailer, gain-scheduled control, orthogonal experimental design method (OEDM)

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1. INTRODUCTION

Tractor semi-trailers are now playing an important role in freight transportation on freeways. On the other hand, the number of the accidents related to tractor semi-trailers has been rising rapidly in recent years with the increase in their application. Compared to single-unit vehicles, tractor semi trailers exhibit unstable motion modes at high speeds due to their articulated configurations. Therefore, much attention has been paid on improving their driving safety and enlarging freeway capacity^[1-2]. Automatic driving is rated as the ultimate solution of vehicle safety, since it can significantly reduce the number of accidents resulting from human driver errors and shorten vehicle gaps on freeways.

A lot of studies have been carried out on path-following for single-unit vehicles^[3,4,5,6,7]. Linear and nonlinear path-following controllers are compared, and the tracking controller has to be robust with respect to uncertain, and

possibly time varying, operating conditions and external disturbances^[4-5]. Nested PID control strategy^[6] and Lyapunov theory with linear matrix inequalities (LMI) optimization^[7] are also used to design the path-following controller with the feedback of yaw rate and lateral offset.

Limited research has been done on automatic driving for tractor semi-trailers. Stefania Martini and Vincenzo Murdocco^[8] designed an H-infinity control strategy for automatic lane keeping of tractor semi-trailers by combining a feed-forward part with a feedback term and using information from a stereo vision sensor system. C. Chen and M. Tomizuka^[9] introduce a steering algorithm, mainly concerning yaw error at current time, to co-operate with an independent brake controller for tractor semi-trailers. In ^[10], A. Astolfi, et al, use Lyapunov techniques to solve the problem of asymptotic stabilization for straight and circular forward/backward motions of a tractor-trailer system and to

keep it along a desired path. C. Cheng et al^[11,12,13] propose active semi-trailer steering to improve the roll stability of a tractor semi-trailer to minimize a combination of the path-tracking deviation of the trailer rear end relative to the path of the hitch point (5th wheel) and the lateral acceleration of trailer centre of mass (CM).

Problems still remain on vehicle path-following control. For example, a systematic methodology is lacking in the process of controller design when tuning the design parameters of the controller and enhancing its adaptation to various driving conditions. Gain-scheduled controllers, suitable for parameter varying systems, have been widely applied in lots of fields^[14] for nonlinear control design. The method is suitable for a nonlinear system by using the divide-and-conquer strategy to split the non-linear control design task into a number of linear sub-problems^[15-16]. An example of the method can be found in ^[17], where the gains of controller are scheduled with the speed and the vehicle's CM height to achieve significant rollover risk reduction over the entire operating domain.

For multiple design parameters system, orthogonal experimental design is an alternative for tuning design parameters by using an orthogonal experimental design table and finding a 'best' solution for each linear sub-problem. Through OEDM, we can select parts of the representative cases to test from all the comprehensive cases, which could decrease the quantity of tests significantly while do not affect the final results. Optimization of tuning parameters using an OEDM would reduce the amount of experiments and costs^[19-20].

This paper is mainly focused on designing an automatic path-following controller for the tractor semi-trailer and tuning controller gains by using the OEDM, and the gains acquired at several vehicle speeds are further fitted to form a gain-scheduled control system.

The rest of this paper is organized as follows. An automatic path-following controller of a tractor semi-trailer combination is designed and performance index of path-following is introduced in section 2. In section 3, the gains at each of several given vehicle speeds are tuned using the OEDM based on a comprehensive performance index, and these gains are further fitted using linear or quadratic functions with respect to vehicle speeds. Simulation of the vehicle system is performed at various vehicle speeds and road friction conditions in section 4, and conclusions are drawn in section 5.

2. AN AUTOMATIC PATH-FOLLOWING CONTROLLER FOR A TRACTOR SEMI-TRAILER

2.1. Design of Automatic Path-Following Controller

The controller for automatic path-following of the tractor semi-trailer utilizes a virtual driver, which determines the front axle steering angle required for the vehicle to follow a desired path. The virtual driver is actually a PID controller with a path preview shown in [Figure 1](#). The lateral offset and yaw angle deviation between the desired path and the vehicle's current heading at a user defined preview distance from the CM (CM₁ in [Figure 1](#)) of the tractor are used as feedback for the controller. The task of the virtual driver is continuously minimizing the predicted lateral deviation, Δy , and the predicted yaw angle deviation, $\Delta\psi$, at the preview point P.

Lateral deviation and yaw angle error at the current location of CM₁ are used to evaluate path errors. We assume that the curvature of the desired path remains unchanged for the previewed path segment. Referred to [Figure 1](#), lateral deviation, e_y , is defined as the distance from CM₁ to the path along its current normal direction, and yaw angle error, e_ψ , is defined as the angle between the centerline of the tractor (heading direction) and the current tangential direction of the path. The derivative of yaw angle error can be expressed as follows

$$\dot{e}_\psi = u\rho - r_1 \quad (1)$$

where r_1 is yaw rate of the tractor, u longitudinal speed of the tractor, and ρ current curvature of the path.

Based on geometrical relationship, the predicted yaw angle deviation (heading error) and its derivative can be expressed as

$$\Delta\psi = e_\psi + L\rho - T_p r_1 \quad (2)$$

$$\Delta\dot{\psi} = u\rho - r_1 \quad (3)$$

Where T_p and L are preview time and preview distance, respectively, and $L = uT_p$.

The predicted lateral offset Δy can be calculated based on geometrical relationship as follows:

$$\Delta y = e_y + L(e_\psi - \beta) + \frac{L^2}{2}\rho - \frac{T_p r_1}{2}L \quad (4)$$

