

# Gain Scheduling Control in Commercial Vehicles with Electrohydraulic Power Steering

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## ABSTRACT

Recent attention has been given to the energy and fuel economy benefits of replacing hydraulic power steering with electronically controlled electrohydraulic power steering (EHPS) systems for commercial vehicles. Given this emerging capability, investigation of the impact such systems would have on overall large truck stability is reported in this paper. It is found that varying the assist gain associated with the EHPS through the motor drive allows for improved stability of articulated vehicles. This paper first presents a method based on feedback of the rate of change in the articulation angle in conjunction with gain-scheduling to instantaneously vary the assist torque provided by the EHPS system. Experimental results of the design are evaluated through a hardware-in-the-loop (HIL) configuration that confirms the performance benefits of incorporating variable gain steering assist in large trucks.

## INTRODUCTION

Electric motor driven hydraulic steering systems offer improvements over conventional hydraulic assist systems by reducing overall weight and improving fuel economy.<sup>[1]</sup> Collectively referred to as electrohydraulic power steering (EHPS), or equivalently as electrically powered hydraulic steering (EPHS), these systems allow for electronic control of the steering system during vehicle operation. This includes variable effort assist which may be tuned to a desired feel and responsiveness.<sup>[2]</sup> The primary application of EHPS has been to lighter weight passenger vehicles. This has been due to restrictions on the current for electric motor drives using power semiconductor devices. As power electronic packaging and thermal management technologies continue to improve, the viability for EHPS in large truck applications is becoming a realistic alternative to conventional hydraulic assist technologies. Consequently, this opens a number of new configurations that have not been previously explored for EHPS systems. For example, there has been considerable progress in improving the stability (i.e., jackknife and roll-over protection) of class-8 tractor-trailers using electronic

braking systems (EBS). These advances have been enabled by sensor technologies that permit the measurement of yaw and roll rates. In addition, there is also the capability to transmit this data in real-time over multiplexed serial communication links such as the CAN-based SAE J-1939 protocol. In conjunction with the increased computational capacity of microcontrollers and digital signal processors, complex control algorithms can be executed in real-time to coordinate the braking action of large trucks. Correspondingly, these enabling sensor, communication and processing technologies can be applied to advanced steering systems such as EHPS. For this paper, the role of the EHPS system is to provide a variable torque assist gain that responds to the articulation angle of a large tractor-trailer.

## GAIN SCHEDULING OF ELECTROHYDRAULIC POWER STEERING

In EHPS configurations, an electric motor is used to drive the hydraulic pump of the power steering system.<sup>[3]</sup> This allows the assist torque gain to be modified by varying the speed and torque of the pump independently of engine speed. In the case of conventional hydraulic power steering, the pump is driven regardless of steering usage and presents a relatively constant load on the diesel engine. With EHPS, the electric motor drive allows for reduced draw of engine power by reducing or eliminating the torque assist when not needed. The development of small high-power motors has an area of ongoing research. Most EHPS drives are permanent magnet brushless motors with a three-phase MOSFET inverter to control pump speed and torque levels.<sup>[4]</sup> This provides for improved fuel economy by reducing engine load such that the power steering pump is only active when needed for truck maneuvering. With use of handwheel torque sensors and additional hydraulic valves, on-demand power steering systems have been developed and introduced into passenger vehicles. The configuration of an EHPS system is illustrated in Fig. 1. The relationship between the functional units of an EHPS system is shown in Fig. 2. For the EHPS system considered in this research, a provision for

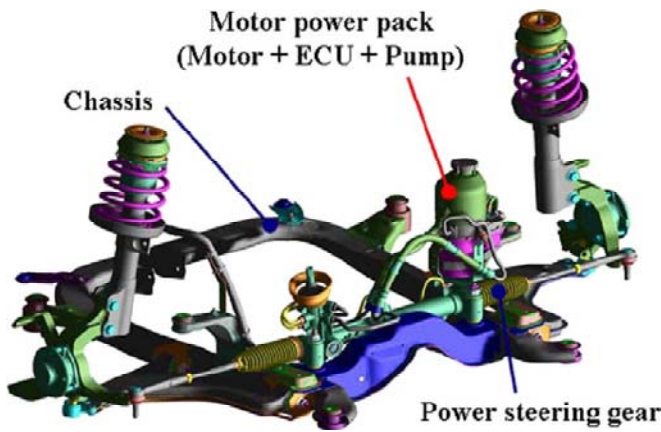


Fig. 1: Configuration of an EHPS system.

the articulation angle of the tractor-trailer is available through a multiplexed serial communication interface. Other control inputs are also available to an electronic control unit (ECU) such as ignition status, engine-on condition, battery voltage, brake-apply status, along with vehicle security, fault modes and diagnostics.<sup>[5]</sup> The ECU, motor drive and pump are typically integrated into a single module. The resulting operation of the EHPS system is that the handwheel torque applied by the vehicle driver is amplified and through action of a piston in the steering gear mechanism that provides movement of the front wheel steering angle. Neglecting relatively high frequency effects associated with steering gear hydrodynamics and motor related electromechanical dynamics, the overall EHPS functionality can be described as a time-varying gain  $K_s(t)$  with respect to the net assist torque,  $\tau_{assist}$ , and the handwheel torque,  $\tau_{hw}$ ,

$$\tau_{assist} = K_s(t)\tau_{hw}. \quad (1)$$

Thus, the amount of power steering assist experienced by the truck operator can be varied as a function of the truck operating conditions. The motor control and hydraulic pump capability to provide the functionality of (1) is an active area of development<sup>[6]</sup>. The electrical time constants associated with electric motor drives are typically on the order of 8.0 ms, and thus are relatively fast acting compared to the mechanical dynamics of the steering system. Thus, using recently developed control methods<sup>[7]</sup> it is possible to create the functionality associated with (1) without encountering significant time-delays.

Existing EHPS systems for passenger vehicles have a variable assist gain as a function of the vehicle speed. At low speed (i.e., less than 8 kph) such as that encountered in parking situations, the assist torque gain is maximized during high operator efforts. At highway speeds the assist gain is reduced to improve handling and ride stability. In this manner, the assist level is “gain

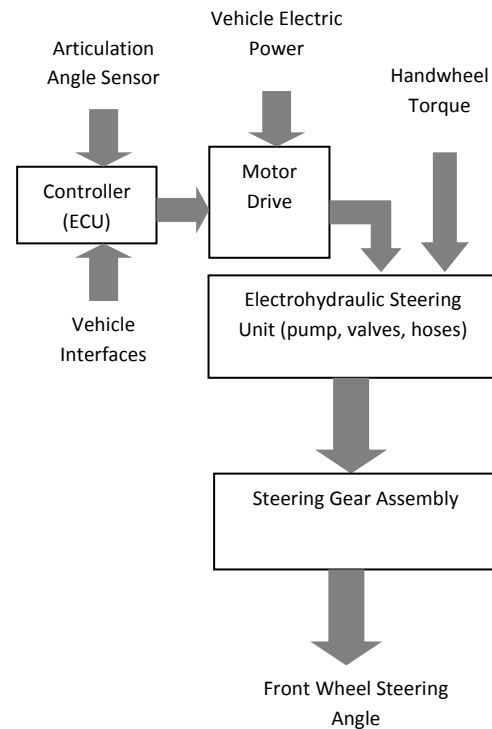


Fig. 2: EHPS Functional block diagram.

scheduled” according to vehicle speed. This research expands this concept given the capability for instantaneous torque assist variation with recent advances in EHPS motor drives. For large trucks, the assist gain scheduling is investigated as a function of the rate of change in the articulation angle. This is motivated by results from EBS research into large truck stability where rapid variations in the articulation angle,  $\psi$ , is indicative of how well the vehicle operator is performing in maintaining stable control of the vehicle during emergency maneuvering transients. The gain scheduling considered in this research allows the gain to go as low as zero (i.e., manual steering) and vary linearly up to twice the nominal assist level. The gain scheduling in the linear range is proportional to the time rate of change of the articulation angle. Thus, the assist gain  $K_s(t)$  becomes

$$K_s(t) = \bar{K}_s \left( 1 + \text{sat} \left\{ K_{gs} \frac{d}{dt} \psi \right\} \right) \quad (2)$$

where the saturation function limits are -1 to 1,  $\bar{K}_s$  is the nominal assist gain for the particular large truck chassis and steering system design, and  $K_{gs}$  is the gain scheduling constant. Various gain scheduling constants are considered in this research in terms of the effectiveness in maintaining stability of a large truck during an evasive maneuvering transient. Evaluation of the effectiveness of the gain scheduling control is performed using a detailed computer simulation of a human-in-the-loop response in order to consistently isolate the effects of control gain changes. This provides consistency in the results of various control system changes without the variability introduced by experiments with human truck drivers. Human-in-the-loop modeling is discussed in the following section.

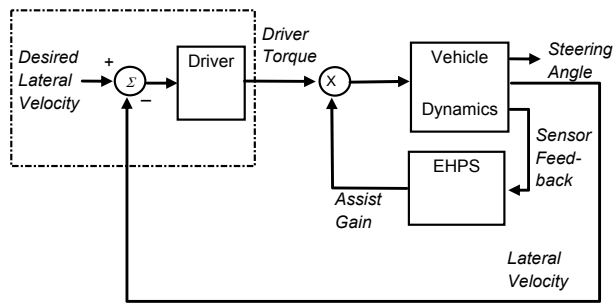


Fig. 3: Human-in-the-loop modeling with EHPS.

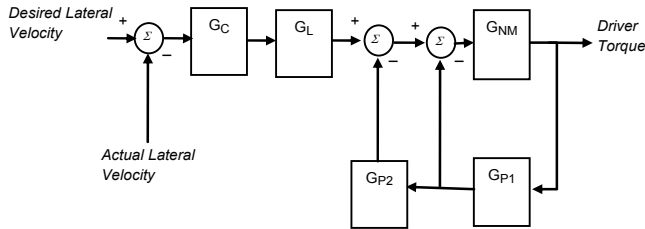


Fig. 4: Human driver behavioral model.

## MODEL FORMULATION

This section describes the mathematical models used in the computer simulations of driver and vehicle dynamics. Although this method does not exactly predict the response of a physical system, the model does correlate to trends observed from experimental results<sup>[8]</sup> of human responses to variable-effort steering.

**HUMAN-IN-THE-LOOP MODELING** – The process of maneuvering a vehicle is a complex operation to model mathematically. From a linear input-output system viewpoint, the vehicle may be considered a generalized plant with the driver acting as the feedback control element. The driver regulates the system outputs (lateral velocity and yaw rate) in order to follow a desired roadway path. This concept is shown in Fig. 3. Driver feedback based on lateral velocity is sufficient for most vehicle stability analysis. The desired lateral velocity input is derived in response to visual clues. The error between the desired and actual lateral velocity is processed by the driver and results in a torque applied to the steering handwheel. The handwheel torque is amplified by the EHPS system. The output torque of the EHPS system then couples to the vehicle system to determine the steer angle and consequently the yaw rate and lateral velocity of the tractor-trailer. The driver perception of the change in lateral velocity closes the system loop to implement path corrections. The following sections describe the driver behavior and vehicle dynamics in more detail.

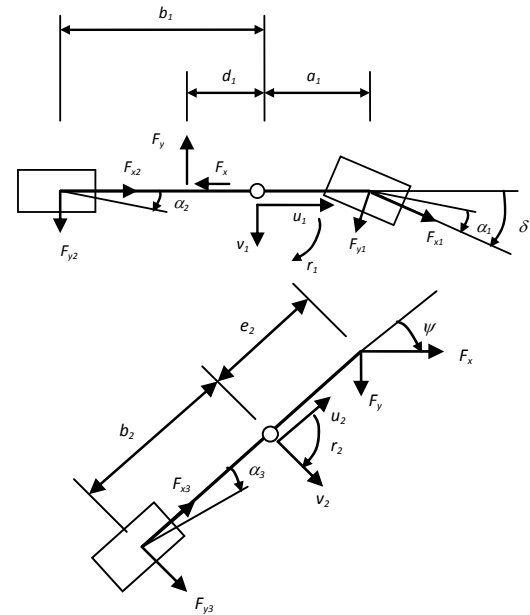


Fig. 5: Tractor-trailer dynamic forces.

**HUMAN STEERING BEHAVIOR** – The control theoretic approach developed by Hess<sup>[9]</sup> is used to model the driver steering behavior. The term “control theoretic” refers to the physiological basis of the model based on the neuromuscular responses for a given level of driver skill. A block diagram of the driver model is shown in Fig. 4. The block labeled  $G_{NM}$  represents the transfer function associated with the neuromuscular system of the driver’s hands and arms. The blocks  $G_{P1}$  and  $G_{P2}$  are feedback variables derived from the motion of human limbs and muscle tissue. These are referred to as “proprioceptive” feedback elements. The block  $G_L$  is a time delay is associated with inherent human signal processing delays. The transfer functions are

$$G_{NM} = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n + \omega_n^2} \quad (3)$$

$$G_{P1} = \frac{K_1 s}{s + \frac{1}{T_1}} \quad (4)$$

$$G_{P2} = \frac{K_2}{s + \frac{1}{T_2}} \quad (5)$$

where the parameter values used in the computer simulations are listed in the Appendix. The delay element  $G_L$  is modeled with a third order Padé approximation. The block labeled  $G_C$  is a lead compensator which accounts for low frequency driver response.