Vehicle Following Control Design for Automated Highway Systems

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In this issue, "25 Years Ago" revisits the article "Vehicle Following Control Design for Automated Highway Systems," by H. Raza and P. Ioannou in *IEEE Control Systems Magazine*, vol. 16, no. 4, pp. 43–60, 1996. Below is an excerpt from the article.

Automatic vehicle following is an important feature of a fully or partially automated highway system (AHS). The on-board vehicle control system should be able to accept and process inputs from the driver, the infrastructure, and other vehicles, perform diagnostics, and provide the appropriate commands to actuators so that the resulting motion of the vehicle is safe and compatible with the AHS objectives. The purpose of this article is to design and test a vehicle control system in order to achieve full vehicle automation in the longitudinal direction for several modes of operation, where the infrastructure manages the vehicle following. These modes include autonomous vehicles, cooperative vehicle following, and platooning. The vehicle control system consists of a supervisory controller that processes the inputs from the driver, the infrastructure, other vehicles, and the onboard sensors and sends the appropriate commands to the brake and throttle controllers. In addition, the controller makes decisions about normal, emergency, and transition operations. Simulation results of some of the basic vehicle following maneuvers are used to verify the claimed performance of the designed controllers. Experiments on Interstate-15 that demonstrate the performance of the throttle controller with and without vehicle-to-vehicle communications in an actual highway environment are also included.

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INTRODUCTION

One of the objectives of Automated Highway Systems (AHS) is to meet the increasing demand for capacity by the efficient utilization of the existing infrastructure. Capacity is calculated by the simple formula:

$$C = \frac{V}{(X_r + L)}$$

where C is the capacity, measured in number of vehicles crossing a fixed

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point/unit time, V is the vehicular speed of flow, X_r, is the inter-vehicle spacing, and L is the vehicle length. The capacity formula (1) is derived by assuming that all vehicles have the same length L, keep the same inter-vehicle spacing X_r, and follow the same speed V. The capacity C can be viewed as the maximum possible flow rate q for a given speed V, inter-vehicle spacing X_r, and vehicle length L. While the traffic flow rate may exceed C during transients by violating the maximum allowable V or minimum allowable X_r, in an AHS environment such violations have to be reduced or eliminated for safety considerations.

Therefore in AHS q has to be kept less than or equal to C during transients and C should be the desired value q should converge to in steady state. These constraints give rise to the following requirements:

i) The system should be designed for maximum capacity under the constraints of safety.

ii) The system should be designed so that the actual traffic flow rates tend to the maximum capacity at steady state and transients are not excessive and are not due to the violation of safety constraints on the vehicle level.

The first requirement can be met by using the safety considerations to decide about the maximum allowable speed V and minimum inter-vehicle spacing X_r [1]. The second requirement can be met by designing the vehicle following control system properly, getting the infrastructure involved in managing traffic flow on the macroscopic level, minimizing disturbances due to lane changing, and choosing the appropriate configurations for the roadway system [2, 3, 5].

The purpose of this article is to concentrate on the design of the vehicle longitudinal control system (VLCS) that will guarantee smooth and safe vehicle following. In an AHS environment the VLCS should be able to accept and process inputs from the driver, infrastructure, other vehicles in the vicinity as well as from its own sensors. The VLCS is designed for intelligent cruise control (ICC) applications, cooperative driving, and platooning.

Using ICC, the vehicle is autonomous in the sense that it does not communicate with the infrastructure and/or other vehicles. In cooperative driving the VLCS may accept inputs from the vehicles in front and the infrastructure, whereas in platooning the VLCS has to process inputs from the leader of the platoon as well as from the infrastructure and other vehicles. These three different modes of operation may be necessary in AHS, and the design of a VLCS to operate in each chosen mode is therefore essential.

The VLCS consists of a supervisory controller, which is the "brain" of the system, and a throttle/brake controller. Since several throttle/brake controllers have already been proposed and tested [6-11], the emphasis of this article is on the supervisory controller and its interaction with the various inputs and the throttle/brake controller. The design of the supervisory controller is similar to the design concept of event-driven state machine control. The design objective is to replace the human driver functions in the longitudinal direction. The throttle and brake controllers are used both in normal as well as in emergency situation to give complete automation in the longitudinal direction.

The emergency situation handling logic, as a part of the supervisory controller, is designed on the principles used by the human drivers to handle emergencies. It comprises a situation assessment logic to detect the presence of emergencies and a compensation logic to handle emergencies of different severities.

The effectiveness of this scheme relies on the quality of the sensors and actuators that can provide low detection and actuation delays. In addition, the supervisory controller chooses the mode of operation and handles the transitions from manual to automatic and vice-versa.

The article is organized as follows: Some of the possible AHS configurations are discussed next. The concept of vehicle longitudinal control and a detailed description of the design of supervisory controller are presented in the third section. The stability and performance analysis of the overall closed-loop system is given next, and following this the simulation and experimental results for different vehicle following scenarios are discussed.

The article ends with the main results summarized in the conclusion section.

EXPERIMENTS ON INTERSTATE 15

These vehicle-following tests were conducted on dedicated lanes of I-15 in San Diego, CA. The tests were performed by using two vehicles. The vehicles were equipped with ranging sensors, which can measure relative distance up to about 20 meters, and v-v communication devices. Through the communication, the leading vehicle passes its speed, acceleration, and other information to the following vehicle. The vehicles were equipped with the throttle actuators only, hence the desired speed profiles were chosen so that the required deceleration can be achieved without using brakes (by using engine torque only) For each controller designed in [10], tests were conducted with two kinds of time headway, 0.25 seconds and 0.4 seconds.

There were 3 speed profiles for the leading vehicle. The first speed profile was starting at 30 mph, going to 60 mph with small acceleration, staying at 60 mph for a while, decreasing to 40 mph slowly, going back to 60 mph slowly, and then staying at 60. For simplicity, we use 30-60-40-60 to indicate this speed profile. The second speed profile is 40-50-40-50 or 40-50 with large acceleration. The third speed profile is that the leading vehicle was driven manually following some sinusoidal speed curve The results of only PID controller are included here, for a detailed description of this test conducted on I-15 the reader is referred to [17].

The test results of nonlinear PID throttle controller and no v-v communication are shown in Figs. 23-24. It can be seen from Fig. 24 that the negative position error is within 1 m, which allows the following vehicle to travel close to the leading vehicle without any collision. The speed profiles in Fig. 23 show that the following vehicle tracks the speed profile of the leading vehicle closely except near transitions, where a sudden change in speed of the leading vehicle creates a large position error, which is reduced by making the speed of the following vehicle greater than that of the leading vehicle during that interval. In this test the headway is set to be 0.25 seconds, hence as shown in Fig. 24 the actual headway is smoothly reduced from an initial value of 0.265 seconds to the desired value of 0.25 seconds. As pointed out earlier, the controller design ensures that the acceleration of the vehicle is within the specified bounds. The claim is obvious from the acceleration profiles shown in Fig. 23, where the acceleration of the following vehicle is less than the set limit of 1 m/sec^2, even though the leading vehicle accelerates beyond the set limit.

The test results of nonlinear PID controller with communication for a speed profile of 40-55-40-55 are shown in Figs. 25-26. By comparing Fig. 25 with Fig. 23 it is obvious that the addition of v-v communication has helped the following vehicle to closely track the speed profile of the leading vehicle. Hence transmission of the acceleration of leading vehicle reduces the time delay incurred by assessing the same information through the sensor measurements. Similarly, Fig. 26 shows that the maximum negative position error is close to 1 m, which is satisfactory considering the fact that no brake actuator was used in the experiment and the required deceleration was obtained by the engine torque only.

CONCLUSION

In this article we have designed and tested a vehicle control system for achieving full vehicle automation in the longitudinal direction. The vehicle control system is an interconnection of a supervisory controller and a throttle/brake controller. The supervisory controller is designed so that it can operate in different configurations of AHS, allowing the vehicle to operate with varying distribution of authority between the driver and external agents. The supervisory controller helps the driver during transitions and generates the desired trajectory of the vehicle based on available inputs. Overall system safety is improved by inclusion of emergency situation handling algorithm as a part of supervisory controller. The simulation results of some of the basic vehicle following maneuvers are used to test the performance of the designed controllers. Finally, the experimental results of a vehicle following test conducted on I-15 verifies the system performance in an actual highway environment.