# Full-Scale Experimental Study of Vehicle Lateral Control System

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An ongoing experimental research project focusing on vehicle lateral control is reported. This project is being jointly conducted by the University of California's PATH Program and IMRA America, Inc. The lateral control system to be tested uses the concept of cooperation between the vehicle-borne steering control system and a discrete magnetic reference system in the roadway. The components of this experimental setup are described. The analytical and experimental research conducted before this project on the various components are reviewed, some results of the completed tests are provided, and the planned tests are outlined.

The purpose of an automated vehicular lateral control system is to maneuver, or to assist a driver to maneuver, the vehicle. These steering functions may include lane keeping, lane changing, merging, and diverging. The automated lateral guidance and control system described in this paper includes four basic components: a roadway reference system that defines a path for the vehicle to follow, sensing devices that acquire information from the roadway reference system and collect other necessary information for steering control, a controller that generates steering actuator that executes the steering command given by the controller. The system schematic is shown in Figure 1.

Automated lateral control systems have been studied for the past 30 years. Several systems using various technologies have been developed or simulated (3). However, only a few full-scale systems have been tested in a real road-vehicle environment. After an extensive literature review, PATH developed a concept of a cooperative lateral control system that allows the vehicle to receive information from a discrete magnetic reference and sensing system. The roadway reference system consists of a series of permanent magnetic markers buried in the roadway. On-board sensors measure the proximity of the vehicle to the markers and decode upcoming road geometry information. The lateral controller makes steering angle corrections according to the vehicle's tracking error and any upcoming road curvatures so that both the tracking accuracy and ride quality can be improved. This concept has been investigated in a series of PATH studies (1-4,6-8). In parallel to the PATH work on the roadway reference and sensing system and the lateral control algorithms, IMRA has been working on a design of a steering actuator for vehicle lateral control, in particular for lane keeping. This design is intended to allow automated steering control to augment the driver's steering performance on the highway.

Because of their mutual interest in automatic vehicle lateral control, PATH and IMRA agreed to conduct a joint experimental study on vehicle lateral control, beginning in January 1991. The goal of the joint project is to demonstrate the concept of automatic lateral control with a full-scale automobile. This paper reviews the work performed individually by PATH and IMRA before this project and the joint efforts in conducting the full-scale vehicle experiment.

#### AUTOMATED VEHICLE LATERAL CONTROL SYSTEM

The system used for experiments in the PATH-IMRA project includes both roadway-installed and vehicle-borne components. The discrete magnetic markers are installed in the roadway. The vehicle-borne components include the sensors, computer and control algorithms, and a steering actuator. Figure 2 shows the test vehicle with various components used in this experimental setup. The following describes these components.

#### Roadway Reference/Sensing System and Other Sensors

Several sensors are used in the PATH-IMRA experiments to measure the vehicle lateral displacement and other dynamic vehicle state information. These sensors include magnetometers for the discrete magnetic reference and sensing system and sensors that measure vehicle lateral acceleration and yaw rate.

The roadway reference and sensing system measures the vehicle's lateral displacement and provides a preview of road curvature, which has been determined to be an important input for vehicle lateral control (2,4,5). An assessment of all identified techniques for measuring the lateral deviation of a vehicle was made (3). A variety of technologies including optical, acoustic, and radar were reviewed. A roadway reference and sensing system using discrete magnetic markers was determined to have good potential for practical application on existing roadways. The simplicity of this system

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FIGURE 1 Automatic vehicle lateral control system.

leads to the expectation that the magnetic markers will be inexpensive and easy to install and maintain. The magnetic field from a magnetic marker appears to be less affected by environmental factors. More important, the reference system using magnetic markers can store roadway geometry information in a binary format, with each marker in a sequence representing 1 bit.

Figure 3 illustrates the configuration of the discrete magnetic marker reference and sensing system. The roadway reference consists of a series of permanent magnets installed at 1-m intervals along the center of the lane. The magnetic fields of the markers are measured to determine the lateral location of the vehicle relative to the center of the traffic lane. By using the polarities of the magnets, road geometry information such as radius and length of curvature can be encoded. The magnetic field sensing system consists of four magnetometers mounted under the front bumper of the vehicle 15 cm above the road surface. Two sensors, one measuring the ver-



FIGURE 2 PATH-IMRA experimental vehicle.



FIGURE 3 Discrete magnetic reference sensing system.

tical and the other measuring the horizontal component of the magnetic field, are located on the longitudinal axis of the vehicle. The other two sensors, which measure the vertical component of the magnetic field, are mounted on both sides of the vehicle longitudinal axis, about 30 cm from the two central sensors. The two central sensors are used to obtain accurate measurements of the vehicle lateral position; the outer two sensors were added to extend the measurement range. Figure 4 shows the sensors mounted on the test vehicle. The acquired signal is preprocessed by a low-pass filter and then digitized using an analog-to-digital (A/D) converter before being input to the controller.

Studies were conducted to investigate different approaches for extracting the vehicle lateral deviation information from the measured magnetic field. Both analysis and experiments indicate that the magnetic field of a permanent magnetic marker is sensitive to the distance between the magnetic marker and the sensor. To eliminate the effect of the vertical movement of the vehicle, both the vertical and horizontal components of the magnetic field are measured. The relationship between the lateral displacement of the sensor and the sensor measurements was determined by experiment. An algorithm based on this relationship has been developed that contains logic for recognizing the magnetic field of the marker and a lookup table for translating the magnetic field into a measurement of the vehicle lateral displacement. The theory and the experimental results were reported elsewhere (4).

The magnetic field sensing system, along with the roadway reference markers, can measure lateral displacement over a 100-cm range. The simulation analysis and bench experiments indicate that the resolution of this sensing system is reasonably good (about 1 cm) when the vehicle is near the center of the lane, but it degrades as the vehicle's lateral displacement increases. This degradation in accuracy at larger vehicle deviations should not affect the performance of the lateral control system because when the vehicle is far from the lane center, the controller does not need highly detailed information. In this experimental study, an independent measurement system consisting of two line-scan video systems, one mounted at the front and one at the rear of the vehicle, and a reflective tape strip placed on the roadway parallel to the roadway reference system is used for calibration of the discrete magnetic marker reference and sensing system and evaluation of lateral control system performance. Figure 5 shows the experimental vehicle with the independent measurement system.

A coding and decoding strategy has been developed to encode the road geometry information into the roadway ref-



FIGURE 4 Magnetic sensors mounted on test vehicle.



FIGURE 5 Experimental vehicle with independent measurement system.

erence system using the polarities of the magnetic markers. Using this method, after the vehicle passes over a series of markers, the road geometry information is decoded and passed to the controller for preview control. The number of markers necessary to code the information depends on the amount of information desired and the coding strategy.

In addition to the magnetic field sensing system, an accelerometer, a yaw rate sensor, and a steering angle sensor are also installed on the vehicle. The measurements of the vehicle's lateral acceleration, yaw rate, and steering angle are used to derive an estimation of the tire-road cornering force. The tire-road cornering force is represented by the tire cornering stiffness, which is defined as the ratio between the side force and tire slip angle. Simulation studies have shown that the steering control decisions should be made in accordance with several factors, including changes in the cornering stiffness. These results show that without considering the cornering stiffness in the control algorithm, the vehicle tracking performance deteriorates significantly when the cornering stiffness drops to 30 percent of its nominal value. Under the same situation, the vehicle's maximum displacement can be greatly reduced (about 50 percent) by incorporating the cornering stiffness estimation in the control algorithm.

#### Controller

The lateral control algorithm processes the information gathered by the sensors—road curvature, vehicle lateral deviation, yaw rate, lateral acceleration, forward speed, and frontwheel steering angle—and generates appropriate steering commands. The control algorithm balances the opposing goals of tracking accuracy and ride quality, where the ride quality is based on the lateral acceleration in a certain frequency range (6). The control algorithms must be designed in such a way that the system performance is robust with respect to variations in vehicle speed, vehicle load, road surface condition, and external disturbances such as wind gusts. To study the vehicle response and to derive control algorithms, two vehicle dynamics models have been developed.

The two mathematical models are used to represent the lateral dynamics of a front-wheel-steered, rubber-tired vehicle (1). In order to represent the vehicle dynamics, an elaborate nonlinear model was developed. This model includes the motion of the vehicle body in all six degrees of freedom plus suspension deflections and wheel motions. As a crucial element of the nonlinear model, a tire model was developed on the basis of data obtained from the tests of the tires used on the experimental vehicle. A simplified linear model that includes only lateral and yaw motions was also derived. The linear model was used to develop the feedback and feedforward controllers, and the nonlinear model was used to evaluate the performance of the control algorithms before the field tests. The steering actuator dynamics were incorporated into the plant model and are considered in the design of the control algorithms.

Two control algorithms have been developed and simulated, including a pure feedback control algorithm and a preview control algorithm. In the feedback control algorithm, the frequency-shaped linear quadratic (FSLQ) control theory was used (6). This control algorithm allows the frequency dependence of ride quality to be included in the performance index explicitly. By properly choosing the weighting in the performance index, the high-frequency robustness (with respect to unmodeled dynamics) of the control system can be enhanced.

The preview control algorithm combines a feedforward algorithm with feedback. The feedforward algorithm was designed to take advantage of the road geometry information available through the roadway reference system and is able to negotiate a curve without steady-state error. In this case, less feedback action is required, and better tracking performance can be achieved with improved ride quality. Analysis and simulation indicate that the preview control law improves the tracking performance in the low-frequency region and the lateral acceleration in the high-frequency region simultaneously (7).

The lateral dynamics of the vehicle strongly depend on the tire cornering stiffness (6) and the longitudinal velocity of the vehicle. A control algorithm that takes this into account was developed. A parameter identification scheme is used to estimate the cornering stiffness from the measurement of lateral acceleration, yaw rate, vehicle speed, and front-wheel-steering angle based on the dynamic equations of the system. The gain-scheduling technique is used to tune the feedback and feedforward (preview) controllers using the measured velocity and estimated cornering stiffness. Figure 6 depicts the block



FIGURE 6 Preview control algorithm.

diagram of a lateral controller using the preview control algorithm.

PATH is also working on a fuzzy rule-based controller (8). This algorithm is currently being simulated on the nonlinear vehicle model. A fuzzy rule-based controller has the advantage of controlling a system based on rules formulated in a natural, linguistic setting. Also, a variety of linguistic inputs can be used efficiently in the rule base. This rule base addresses vehicle robustness to variations in vehicle parameters and to disturbances such as wind gusts. For curved sections of roadway, the rule base uses preview information provided from the discrete magnetic marker reference and sensing system.

The control algorithms and the signal preprocessing algorithm are implemented on a computer-based controller. This controller consists of a computer and a data acquisition system that includes a 32-channel A/D conversion board and a signal conditioning board. The sensor signals are first filtered through the signal conditioning board and then are acquired by the A/D conversion board at a fixed sampling rate. Upon receiving the digitized inputs, the computer converts the sensor signals into useful information and executes the control algorithm and generates steering commands accordingly.

#### **Steering Actuator**

The steering actuator steers the vehicle's front wheels on the basis of command signals issued by the controller. The steering actuator positioning is handled by the steering actuator controller that interfaces with the lateral control computer. IMRA's steering actuator is based on a standard rack-andpinion steering system, modified to include a hydraulic servo, shown in Figure 7. In this design, the driver's steering input is in series with the computer controlled steering actuation. The controlled steering angle is limited to about 10 percent of the full range of normal steering angle. The series control arrangement and the limited range of the controlled steering angle were selected to allow the driver to override the control system at any time. This design is intended to allow the steering actuator to augment the driver's steering performance on the highway and as such should be limited in the latitude of its control. Further tests and evaluations from the viewpoints of safety, human factors, and system dynamics are necessary to determine the steering-angle range needed for automated steering under various operating conditions.

For the purpose of testing the lateral control algorithm, it was necessary to eliminate the influence of the driver on the



FIGURE 7 Steering actuator system.

steering system while the steering was under computer control. A spring-loaded detent mechanism was designed to attach to the steering column housing. The detent fixes the position of the steering wheel during testing. The spring load was set so that the driver can overcome the detent force and take control of the steering of the vehicle. The vehicle still includes the standard hydraulic, power-assist system so that the steering performance of the vehicle without the lateral controller active and with the detent disengaged is the same as that of a standard vehicle. Braking and acceleration remain under the control of the driver.

### EXPERIMENTAL STUDIES ON VEHICLE LATERAL CONTROL SYSTEM

The specifications of the components, systems, and methods used for the experimental studies were based on simulation and on previous experiments conducted by both PATH and IMRA researchers. Before this project, many bench tests and full-scale experiments on the individual components of the proposed system, such as the discrete magnetic marker reference and sensing system, the control algorithm, and the steering actuator, were conducted separately by PATH and IMRA.

#### Test of Discrete Magnetic Marker Reference and Sensing System

Bench tests and full-scale experiments on the discrete magnetic marker reference and sensing system have been conducted by PATH in order to verify the concept under a controlled environment and in a wide speed range. A test bed consisting of a rotary arm driven by a motor in a circular path in the horizontal plane was used to test the reference and sensing system. In these tests, a magnet was fixed vertically to the end of the arm. A bench that held the magnetometers was located such that the magnetic marker passed over the sensors on each rotation. Both the vertical and horizontal distance between the sensor and the magnetic marker were adjustable. Signals were collected at different speeds (up to 130 km/hr) and various distances (10 to 20 cm). The data were used to verify the feasibility of such system under a controlled environment over a wide speed range and to develop a signal processing algorithm and filters. The bench experiments were followed by a full-scale experiment. Magnets were installed in 200-m stretch of a road at the Richmond Field Station of the University of California, Berkeley (UCB). An experimental vehicle equipped with a set of magnetic sensors and a portable computer was used to collect a data at vehicle speeds of up to 40 km/hr. Figure 8 shows the vertical and horizontal signals collected from the roadway magnetic reference system and the estimated lateral displacement of the vehicle. The experimental results indicate that the discrete magnetic marker reference and sensing system can provide adequate lateral displacement information under the conditions tested (4). In the PATH-IMRA experiments, the accuracy of the roadway reference and sensing system will be verified using a measurement system that is independent of the vehicle control system.

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FIGURE 8 Magnetic signals (top) and calculated vehicle deviation (bottom).

## Simulation of Control Laws and Tests Using Scaled Experimental Vehicle

Vehicle lateral control using feedback and preview control laws was simulated on a computer for a variety of road curvatures and under different road surface conditions. Simulations were also conducted to fine-tune the control laws using realistic vehicle parameters.

As a step before the full-scale vehicle tests, an experimental study on the proposed system was conducted using a scaled test vehicle. In this study, the accuracy of the roadway reference and sensing system and the performance of the control algorithm were evaluated over a wide range of extreme operating conditions such as variation of load, vehicle speed, and cornering stiffness. In the experiments, a PID controller with feedforward action was able to keep the tracking error within  $\pm 10$  cm at a vehicle speed of 2 m/sec. The test track that was used for the experiments included a curved section with a 4.5-m radius. The detailed experimental results are reported elsewhere (2).

#### **Open-Loop Experiments**

PATH and IMRA have conducted open-loop experiments to identify vehicle parameters and evaluate the performance of the steering actuator under normal load conditions. In the experiments, the steering actuator position was set by the control computer. Selected steering commands were sent to the steering actuator in the form of step and sinusoidal inputs. Input amplitudes and frequencies were tested at vehicle speeds ranging from 20 to 60 km/hr. The response of the vehicle—including the position of the steering actuator—the lateral acceleration, and the yaw rate were recorded at a sampling rate of 100 Hz. The tests were repeated to ensure the reliability of the data. Figure 9 gives a set of test results at a speed of 40 km/hr with a 0.5 Hz sinusoidal steering input. The test data have been used to validate the vehicle dynamics model and the control algorithms. In the analysis, the steering system



FIGURE 9 Open-loop experiment results.

and vehicle parameters were identified. The vehicle models were modified on the basis of the test data. In Figure 6, the dotted lines show the test results and the solid lines indicate the simulation results. These results show that the modified overall vehicle model predicts the vehicle response satisfactorily for the current test conditions.

#### **Planned Closed-Loop Experiments**

The closed-loop experiments will be performed at the UCB Richmond Field Station. A 480-m test track has been built. Figure 10(a) shows the geometric layout of the test track. The vehicle path will be defined by discrete magnetic markers. To use the test track effectively, two curves with radii of 60 and 75 m have been placed at the location of the 90-degree curve and several gentle reverse curves have been placed in one of the straight sections. Several hundred capsules, shown in Figure 10(b), have been installed on the test track. The capsules are designed to house the magnetic markers and to allow the



FIGURE 10 Test track layout (*a*); capsules for magnetic markers (*b*).

location of the markers to be adjustable so that the effect of placement accuracy of the magnetic marker on the performance of the lateral control system can be tested. This design also allows the road geometry information encoded in the magnetic reference system to be changeable. However, it should be noted that an operational system using the magnetic marker reference system would not need the capsules but would have the simple markers (10 cm long, 2.5 cm in diameter) installed directly in the pavement.

The closed-loop experiments are designed to examine the tracking performance of the lateral control system using the proposed sensing devices, control algorithm, and steering actuator. Several tasks will be performed in the closed-loop experiments. These tasks are

1. Testing of the feedback control algorithms: The tests will be conducted at various vehicle speeds from 20 to 60 km/hr.

2. Testing of the preview-FSLQ control law: The experiments in Task 1 will be repeated using the preview-FSLQ control law.

3. Determination of marker spacing: Experiments using both feedback and preview lateral control with different marker spacings will be conducted to determine the effect of different marker spacing.

4. Evaluation of the robustness of the integrated control system: Lateral control under some nonideal conditions will be performed. In performing this task, several nonideal conditions are created, including adjusting the locations of magnetic markers to create errors and reducing the pressure of some or all of the tires to vary the cornering stiffness. Tests will be conducted to evaluated the performance of the system with respect to various levels of resolution of the coded upcoming road geometry information.

These tasks are expected to be performed in early 1992. From these experiments, the proposed lateral control system using the previously described components and control algorithms will be evaluated. The performance specifications for the sensing systems and actuating devices will be verified. The performance of the system with different control algorithms will be compared. The dynamic models can be further validated so that they can be used to more accurately simulate the performance of the lateral control system under a wide range of conditions under which experiments cannot be easily performed.

#### CONCLUDING REMARKS

Extensive research in vehicle lateral control through computer simulation has shown that this technology has potential. To

bridge the gap between computer simulation and full-scale hardware implementation in a roadway environment, PATH and IMRA initiated the collaborative experimental research project described in this paper. To date, the various components necessary for vehicle control and performance evaluation have been developed, tested separately, and integrated into the vehicle system. The project is now in its final stage of preparation for full-scale testing. The full-scale closed-loop experiments are planned to be conducted in early 1992. The

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test results will be reported in a future paper.

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