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Advances in Vehicle Control

PATH – Partners for Advanced Transit and Highways – is a collaboration between the California Department of Transportation (Caltrans), the University of California, other public and private academic institutions, and private industry. PATH's mission: applying advanced technology to increase highway capacity and safety, and to reduce traffic congestion, air pollution, and energy consumption.

CALIFORNIA PATH

Advanced Snowplow Program on the Road

Ty Lasky, AHMCT, UC Davis; Wei-Bin Zhang, PATH; Mike Jenkinson, Caltrans

Snow removal is a critical and hazardous task for winter highway maintenance operations. Adverse operating conditions such as total visual whiteout, low tire/road traction, and the difficulty of detecting roadway boundaries and obstacles buried in or obscured by snow pose significant risks. Moreover, the snow-stakes that mark the sides of the roadway are often buried by snow from earlier plowing. Snowplows that run off the roadway incur major damage to guardrails, snow-buried vehicles, and themselves. In many western states, the potential for injury to operators is great due to the mountainous terrain where much snow removal takes place. The Caltrans Advanced Snowplow Program (ASP) is now applying PATH's magnetic guidance system to help operators drive the plow even in a total whiteout by providing a visual display inside the cab of the plow's position relative to the sides of the road and to potential obstacles.

The California Department of Transportation (Caltrans) initiated the ASP in 1998 to improve the efficiency and safety of snow removal operations. The program's objective is to apply technologies previously developed under Advanced Vehicle Control and Safety Systems (AVCSS) and Automated Highway Systems (AHS) research to provide assistance to snowplow operators. Phase One of the program (ASP-I) is being conducted between April 1998 and June 1999 with three primary goals:

- to develop a testbench for experimental technologies that can potentially benefit snow removal operation,
- to develop technologies for driver guidance and collision warning functions, and
- to explore effective means for communicating guidance and collision warning information to the operator.

ASP-I includes the following partners: the Advanced Highway Maintenance and Construction Technology (AHMCT) Center at the University of California — Davis (system development), PATH (system development), Caltrans (infrastructure development and field testing), the Western Transportation Institute (WTI) of Montana State University (evaluation plan), and the Arizona Department of Transportation (ADOT — infrastructure development and field testing).

ASP-I involves five technical steps: establishing a platform for field testing and evaluation, implementing AVCSS technologies, developing a Human-

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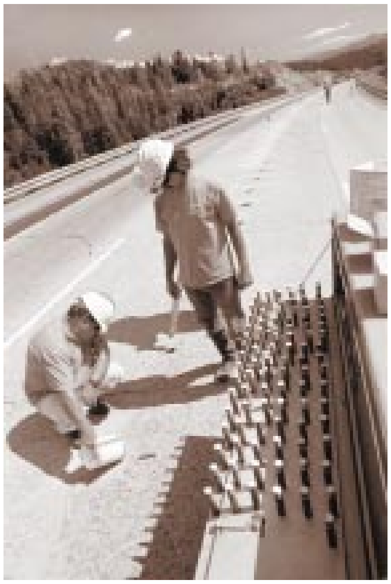
Machine Interface (HMI), performing a field evaluation, and developing methods for mitigating icepack hazards.

1. Establish a platform for field testing and evaluation

A conventional snowplow (International Paystar 5000 ten-yard sander truck with front blade and wingplow) was modified to include a computer data acquisition and information processing unit, sensors for measuring steering angle and vehicle movements, sensors for measuring the fields of magnetic markers installed in the roadway, radar sensors for obstacle detection, and a Human-Machine Interface (HMI). This test platform will facilitate the experimental evaluation of different approaches and technologies. AHMCT researchers integrated the system hardware with the platform. Caltrans installed magnetic markers in the center of the middle lane of a four-mile (6.5 km) section of Interstate 80 over Donner Pass in the Sierra Nevada, which often gets more snowfall than any other road in the lower 48 states. The Arizona DOT also installed magnets on four lane-miles (6.5 lane-km) of highway US-180 through Kendrick Park, about twenty miles (35 km) north of Flagstaff near the San Francisco Peaks, Arizona's highest mountains.



Center photo: Installing magnetic markers on I-80 over Donner Pass. Binary message is encoded by placing magnets north-up (binary 1) or south-up (binary 0).

2. Implement AVCSS technologies

Two primary technological areas are being explored: detecting the plow's position relative to the center of the lane, to assist the operator in steering; and detecting obstacles, for collision warning.

PATH's magnetic marker guidance system was selected by the ASP-I partners to provide guidance information. This system was developed for automated vehicle guidance and control applications (see "PATH Magnetic Guidance System," pages 8-9 for a detailed description). The system provides lateral position measurements relative to the center of the lane, longitudinal position relative to mileposts, and a yaw angle estimate. Binary coding of the magnetic markers when placed (north up vs. south up) also provides information about roadway characteristics, e. g. the direction and radius of curves. The system has proven to be highly reliable and robust under a variety of operating conditions, including snow and icy pavement, and has been thoroughly tested and debugged on automobiles. Two magnetometer arrays, each comprising seven magnetic sensors, have been installed on the snowplow, at front and rear. PATH's signal processing algorithm, originally designed for three-magnetometer arrays on automobiles, has been modified by PATH engineers to accommodate the larger range.

The obstacle detection system uses a commercially available Eaton-Vorad radar, incorporating a digital interface developed by AHMCT in conjunction with Eaton Vorad. A signal processing algorithm has been developed to discriminate radar return signals from vehicle obstacles (the primary detection subjects) from other return signals. The radar was tested at different positions on the plow in order to avoid interference from the plow itself.

3. Develop Human-Machine Interface (HMI)

The HMI development is a combined effort of PATH human factors and control engineers and AHMCT engineers, with significant input from snowplow operators. Various methods of dynamically representing the lateral and longitudinal positions of a vehicle relative to the road have been investigated. The focus is on developing methods of representing abstract information that are independent of display methods (e.g., liquid-crystal displays or head-up displays). Experimental studies using an automobile and a snowplow were conducted to gain an understanding of operators' behavior and information needs. These studies used abstracted information, including the characteristics and impact of look-ahead distance, as well as the rate at which a driver can adapt to the display. The preliminary design of the HMI uses a LCD panel to dynamically display current and projected vehicle positions relative to the desired path. Roadway characteristics are obtained though position updates from the magnetic marker guidance system, and the current and projected positions of the vehicle are processed using the lateral position measurements. Potential obstacles, as well as relative vehicle spacings, are obtained from the radar system.

4. Field evaluation

An integrated testing and evaluation during winter highway maintenance has been planned for ASP-I to evaluate the potential benefits of the advanced technologies being used. The ASP-I partners, led by the Western Transportation Institute (WTI) of Montana State University, have developed a comprehensive evaluation methodology that include Measures of Effectiveness (MOEs), plans for data collection, and methods for data analysis.

The field evaluation for ASP-I is taking place at Donner Pass during this winter. The modified plow was deployed into the Caltrans fleet in early December 1998, and despite some initial problems with shielding the magnetometers from road slush, has by and large been operating successfully. Snowplow operators are participating in field tests, and ASP program partners are collecting data representing both objective and subjective measures. Objective measures are collected through vehicle dynamics and observation of operator behavior. Some potential measures are the operator's control of speed, deviations from the center of the lane, significant adjustments to steering angle, and off-road events. Subjective measures are ratings of performance and difficulty. Objective and subjective measures will be compared to operating parameters such as time of day, snow conditions, visibility, road geometry, and driver experience.

5. Develop methods for mitigating icepack hazards

Snowplows frequently hit icepacks on the roadway. The impact of hitting the icepack often causes the snowplow to spin, sometimes resulting in collisions with vehicles in adjacent lanes.

AHMCT and PATH researchers have conducted a preliminary analysis to investigate the possibilities of minimizing the hazardous consequences of icepack impacts. The analysis suggests that icepack effects can potentially be mitigated using both passive and active control methods. A vehicle dynamic model has been built to simulate the behavior of a snowplow under normal and abnormal operating conditions, particularly hazards such as hitting an icepack. The simulation results indicate that upon impact, the icepack gives the snowplow an impulse that initiates yawing. This yawing motion causes the snowplow to slide away from the direction of travel or, in severe cases, causes the vehicle to rotate.

Several mitigation methods have been considered, among them changing the snowplow's cornering

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Below, left to right: Magnetometers are protected from snow and slush by fiberglass housing; Standard Pentium computer reads sensors and controls display; PATH engineers and snowplow operators collaborate on field evaluation; Front-mounted Eaton-Vorad radar detects obstacles such as stalled cars; Human-Machine Interface display inside cab indicates snowplow position, upcoming road curvature and potential obstacles ahead.

Automating Comme

While Advanced Vehicle Control and Safety Systems (AVCSS) research for passenger cars has been going on for over a decade, commercial heavy vehicles (CHVs) have started receiving some attention only over the last few years. CHV operation is being considered as one of the first fields where the deployment of Automated Highway System (AHS) technologies may be practicable. The commercial benefits of automation make AHS technologies appealing to commercial fleet operators. Trucks can reap more significant benefits from automation than passenger cars, because they spend much more time on the road, they are operated for profit by professionally trained drivers, and they are generally much more expensive to purchase and maintain. The ratio of the cost of automating a commercial vehicle to the vehicle's overall cost is also much lower than the ratio for passenger cars. Moreover, reducing driver stress is of great importance in commercial operation. Because commercial drivers spend significantly more time behind the wheel than drivers of passenger cars, reducing driver stress is directly related to increasing highway safety.

Fleet operators could dramatically reduce their costs through cooperative scenarios like the so-called "electronic towbar," where two or three driverless automated vehicles follow one manually driven vehicle, while at the same time providing a safer and more comfortable working environment for their drivers. The technical requirements for the implementation of such an electronic towbar scenario include include lateral control (keeping a vehicle in its lane, following the road),

The cost of automating a commercial vehicle is much lower, relative to its overall cost, than the similar ratio for passenger cars.

Lateral Control

Pushkar Hingwe, Han-Shue Tan, Dave Nelson, Paul Kretz – PATH

Masayoshi Tomizuka, Meihua Tai, Jeng-Yu Wang – Mechanical Engineering, UC Berkeley

Our project on automated lane guidance for heavy vehicles, with the goal of achieving "hands off" guidance of 18-wheel, 65-foot (20 m) long, fully loaded tractor/trailers, has been an integral part of an ongoing PATH/Caltrans emphasis on heavy vehicles and commercial operations since Caltrans began funding PATH projects on heavy vehicles in 1994. Our project uses the PATH magnetic marker guidance system, whereby the vehicle follows a series of simple permanent magnets embedded in the pavement to define a desired path, usually the center of the highway lane. Magnetometers mounted on-board the vehicle sense the magnetic fields of the magnets, and the signal from the magnetometers is used to command a direct current motor fitted on the steering column to automatically actuate the steering wheel by means of a reduction gear and a clutch, keeping the vehicle on the magnetic path. This seemingly simple task requires a good understanding of the dynamic behavior of the vehicle. Our studies have found that at speeds exceeding 35-40 mph (55-65 kph), understanding a dynamic model of the vehicle becomes crucial.

The Freightliner experimental vehicle arrived at PATH's Richmond Field Station headquarters in October 1997. Most of the sensors were purchased by the end of 1997, and early 1998 saw installation of hardware on the truck. PATH's previous experience with passenger-car instrumentation was very useful in this regard. Some new challenges, like instrumenting the coupling between the tractor and trailer for measuring the articulation angle, were solved in a simple but effective manner.

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rcial Heavy Vehicles

and longitudinal control (keeping a vehicle traveling at a predetermined speed, without colliding with vehicles ahead of or behind it). PATH, funded by Caltrans, has been supporting two parallel projects on heavy vehicle automation for the past five years. One focuses on lateral control, under the direction of Professor Tomizuka at UC Berkeley, and one on longitudinal control, under the direction of Professor Kanellakopoulos at UCLA. After an initial period of theoretical development, the two groups have now moved into the phase of experimentally validating their results. These experiments, summarized in the following articles, use an 18-wheel Freightliner FLD120 Class-8 tractor, generously on loan from Freightliner Corporation, and a 45-foot-long (13.5 m) Great Dane trailer purchased by PATH, which have been fully equipped with electronic throttle, brake, and steering actuators, and corresponding sensors for fully automated operation.

UC Berkeley and UCLA project teams meet at PATH Program-Wide Meeting.

Longitudinal Control

Andreas Robotis, Yaolong Tan, Ioannis Kanellakopoulos
Electrical Engineering, UCLA

Keeping automated vehicles traveling at a predetermined speed, without colliding with other vehicles traveling on the same path, is an even more challenging problem for commercial heavy vehicles — big-rigs — than for passenger cars. This is primarily due to trucks' low actuation-to-weight ratio and their long actuation delays. The primary goal for all automated vehicles, of course, is to maintain an intervehicle spacing large enough to ensure that no collisions will occur, yet small enough to increase traffic throughput and fuel savings. (Another reason to maintain small intervehicle spacing between big-rigs is to discourage passenger vehicles from entering the space between the trucks, which could lead to hazardous situations.) In our theoretical research, we have developed a modular methodology for designing longitudinal control schemes for commercial heavy vehicles. Our control schemes are applicable to vehicles equipped with regular air brakes, which have large delays, as well as to vehicles with the new Electronic Brake Systems (EBS), where the delays are smaller. Our controls can operate in autonomous scenarios, where each vehicle depends only on the measurements obtained through its own sensors, as well as in cooperative scenarios, where vehicles transmit their own information to their neighbors.

Initially, our control schemes were tested through extensive computer simulations; in the last two years, we have moved into actual experimental implementation. We first performed a series of open-loop experiments to identify important parameters for vehicle dynamics, the two most important of which are the dynamics of the fuel actuator and brake actuators. The next step was implementation

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Automating Commercial Heavy Vehicles: Lateral Control

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Actuators and sensors

We decided to mount the steering actuator on the steering wheel end of the steering system. This was done to take advantage of the hydraulic assist already in the steering system. NSK of Japan, who make steering systems for vehicles, developed and mounted a DC motor on the steering column. Steering actuator specifications were given to NSK in November 1997, and NSK shipped the first prototype in February 1998. Steering position control was achieved by closing the loop between the steering column angle and the NSK motor drive.

Three arrays of five magnetometers each are the primary sensors for lane guidance. A five-magnetometer array gives a range of 80 cm (2.6 ft) on either side of the lane centerline. One array is mounted on the front end of the tractor, one on the rear end of the tractor, and one on the rear end of the trailer. The tractor as and the trailer both have an accelerometer and gyroscope mounted. An articulation angle indicator, to show possible trailer instabilities, was also installed.

Top: Steering actuator motor is mounted on steering column; Bottom: Five-magnetometer array, mounted below rear of tractor, is one of three arrays that sense vehicle's position.

Modeling and Analysis

A model for a tractor and semi-articulated trailer was derived by Chen (1997) from the control point of view. A complex model for simulation incorporating the suspension of the vehicle was developed. A model for an arbitrary number of trailing units was developed by Tai. This model incorporates different hitching mechanisms, quantifying the geometric constraints imposed by commonly used hitching mechanisms. Along with the development of various sophisticated models for accurate simulations, simplified control models were developed for multiple-unit heavy vehicles as well as for the special case of a tractor and semi-trailer. One of these simplified models is a linear model that assumes a constant vehicle speed. Analysis based on time domain, frequency domain, and complex domain, much along the lines of analysis done for passenger cars, was carried out for the tractor and semi-trailer model. This analysis showed the importance of the PATH magnetic marker guidance system's unique feature of enabling the vehicle controller to anticipate roadway curvatures, based on binary coding of the magnetic markers (north-up or south-up). Baseline controllers using these linear models were designed. Another important aspect of guidance of heavy vehicles occurs because the vehicle's long wheel base results in pronounced off-tracking (where the rear wheels follow a different curve, or track, than the front). Based on the dynamic models derived, the formulae for off-tracking were derived. It was shown that as much as 20 cm (7.9 in) off-tracking should be expected. Moreover, the direction and magnitude of off-tracking is dependent on the vehicle velocity.

Control Design

Several linear and nonlinear controllers were designed for lane following. The dynamics of the vehicle are nonlinear away from the nominal operating range (dry pavement, mild curves, nominal load on tires, etc.). Nonlinear control algorithms were developed based on input-output linearization. This assumed steering angle as the only control input. However, with the aim of controlling the trailer dynamics and potentially avoiding such instabilities as jack-knifing and fishtailing, a back-stepping based controller was designed.

For experimentation on heavy vehicles, 1997-1998 was a landmark period at PATH, with the emphasis on experimental verification of model and control strategies. With this in mind, linear controllers were developed. An H-infinity based controller and a loop shaping based controller were designed. The advantage in using such frequency-based approaches is that they are intuitive and straightforward. They also admit a certain amount of iterative "tuning."

Experiments

The first set of experiments on the tractor and semi-trailer, conducted in September 1998, were open-loop experiments (performed without feedback to a steering controller) with the view of verifying the dynamic model. PATH's test site at Crow's Landing, a little-used National Aeronautics and Space Administration (NASA) airfield located 100 miles (160 km) southeast of Berkeley in California's Central Valley, was used to conduct a series of open-loop tests on the vehicle for speeds ranging from 20 to 60 mph (32-96 kph). The test track is 2200 m (1.37 mi) long, defined by magnetic markers embedded at 1.2 m (4 ft) intervals. The track runs roughly from north to south in a series of straight lines, curves in either direction, and ends in a straight line. Some of the tests were conducted on a windy day. In the analysis of the data, the wind factor was assumed constant and was eliminated. The results of the open-loop data analysis are very encouraging. The close match between the model and the experiments is shown in Figure 1. The dots in the figure represent experimental data. At higher frequencies, the actual vehicle deviates from the linear model, perhaps due to unmodeled dynamics of the tire-road interaction and the suspension system.

Based on the linear model, an h-infinity based controller was implemented and closed-loop experiments (where processed output from the sensors is used as input to the controller) were performed. The test conditions were dry pavement with no wind. Another controller based on loop shaping was implemented. Speeds up to 45 mph (72 kph) for curve transitions of +800 to -800 meter (2600 ft) radius were achieved. The maximum test speed on the straight line was up to 60 mph (96 kph). The results of this controller are shown in Figure 2. The steering action was smooth and the trailer dynamics were well damped, although the transient performance needs improvement.

Conclusion and future work

With the first closed-loop experiments, the first phase of the study of control and dynamics of tractor and semi-trailer has been concluded. It paves the way for addressing issues of performance and robustness. The goal in the next phase is to achieve higher speeds, possibly up to 60 mph (96 kph) in curve transitions, and to improve transient performance in terms of the tracking error. An important achievement of the project so far is confirming the dynamic model and controllers based on the dynamic model. The dynamic model of the tractor semi-trailer is a sixth-order model, and faith in the model (at least in the range of operation) bodes well for further testing of more sophisticated schemes. Another emphasis in the future will be the use of trailer braking to control potential trailer instabilities and improve the overall tracking performance (off-tracking) for the trailer. At the same time that our project has been working on the lane guidance aspect of automating the tractor and semi-trailer, Professor Kanellakopoulos's UCLA group has achieved good results with vehicle velocity tracking. In the final phase of the project we aim at combining lane guidance and velocity tracking and to develop overall performance specifications for the combined control task.

References:

Chen, Chieh, and M. Tomizuka. Dynamic Modeling of Tractor-Semitrailer Vehicles in Automated Highway Systems. PATH Working Paper UCB-ITS-PWP-95-8. July 1995.

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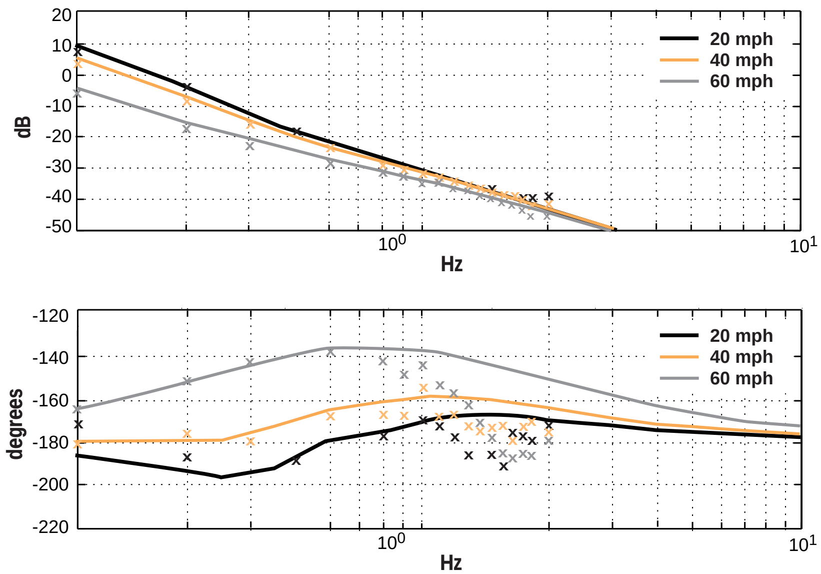


Figure 1: Open-loop test results. Frequency response: wheel to lateral position at front end.

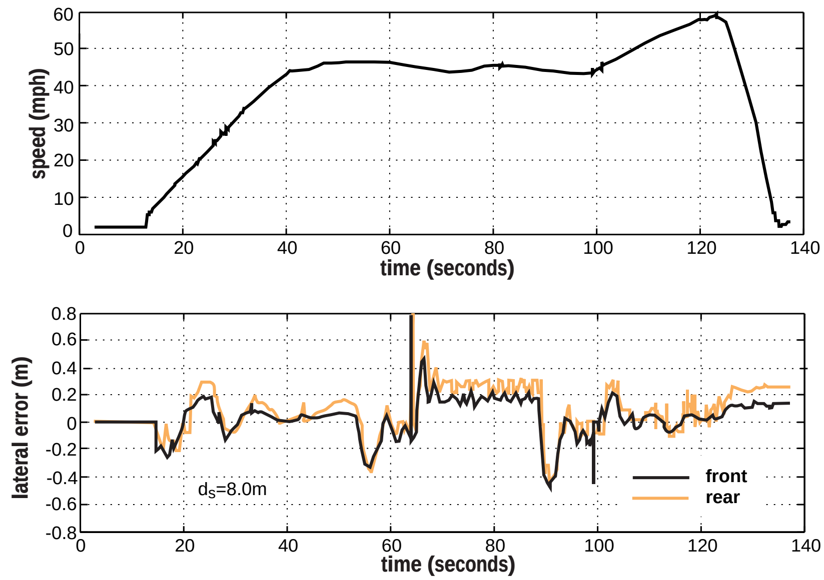


Figure 2: H-infinity based controller experimental results.

The PATH Magneti

Wei-Bin Zhang, Steve Shla

Applications, from top to bottom: Automated highway system; Advanced guidance and control for snowplows; Automated control for heavy duty vehicles; Precision docking and guidance.

PATH's Magnetic Marker Reference Sensing and Guidance System, now being implemented on highways for field operational tests, was designed by PATH researchers specifically for vehicle guidance and control. The system can provide very accurate measurements of vehicle position within a lane, absolute longitudinal location of a vehicle, and advance information about roadway characteristics.

The PATH magnetic guidance system comprises vehicle-borne sensing and processing units that obtain information from a series of magnetic markers that serve as a roadway reference. The markers are simple permanent magnets embedded in the center of a lane, about 1.2 meters apart, to indicate the lane center. Changing the magnetic polarities of the markers creates a binary code: "north pole up" equals a binary 1, "south pole up" a binary 0. The binary coding can be used to indicate roadway characteristics such as upcoming road geometry, speed limits, stop signs, and milepost locations, and to identify highway onramps and offramps. On average, it takes 25 markers taking up 30 meters' length of roadway to encode one binary-coded message. The elapsed time to read that message for a vehicle traveling at 100 km/h (60 mph) would be about a second.

Arrays of fluxgate magnetic sensors, mounted under a vehicle at front and rear, measure the magnetic fields on three axes. A Pentium computer mounted on-board processes the magnetic field data to derive lateral and longitudinal position measurements and to decode the binary information. (The same computer may also perform all other vehicle control functions.) A signal processing algorithm, by comparing the measured magnetic field strength to the "magnetic field map" of a magnet and eliminating the background noise, determines the position of the vehicle relative to the road center.

Over ten years of testing and evaluation, the PATH magnetic guidance system has demonstrated excellent performance: lateral position accuracy of 5 mm (root mean square), longitudinal position accuracy of 5 cm (root mean square), highly robust and reliable under realistic environmental conditions, and fail-safe.

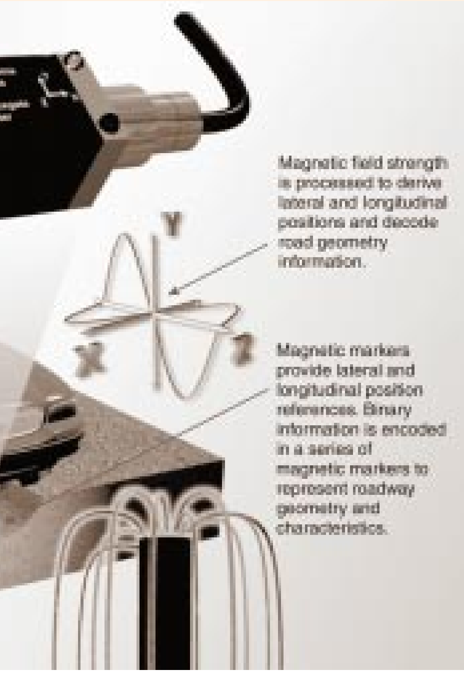
The PATH magnetic system has been tested and proven to be robust under a wide variety of operating conditions. It is not affected by falling or accumulated rain or snow. It provides extremely accurate and repeatable measurements. The infrastructure cost is low, with magnets' usable life exceeding pavement life, and no maintenance required. The combination of absolute position information with the system's coded preview of roadway characteristics offers added functionalities and performance for vehicle guidance and control.

The PATH magnetic guidance system can be used for a variety of vehicle guidance and control applications, including:

- Automatic steering control reference for all vehicle classes
- Lane departure warning reference for all vehicle classes
- Precision docking reference for transit buses
- Guidance reference for snowplows
- Special applications in difficult environments (maintenance yards and shops, tunnels, mines, terminals, or ports)
- Automated Vehicle Location (AVL) for fixed route operations.

c Guidance System

dover, Han-Shue Tan, PATH



The PATH magnetic guidance system has demonstrated considerable potential application value, and is attracting worldwide interest from industry and government agencies. Several European, American, and Japanese automobile companies have contacted PATH about the possibilities of transferring magnetic marker reference sensing and guidance technology. PATH and IMRA America (a research subsidary of Aisin Seiki) originally demonstrated a lateral guidance system using magnetic sensing between 1990 and 1993. Under the coordination of the Japanese Ministry of Construction, Toyota, Honda, Nissan, and Mitsubishi demonstrated fully automatic controlled vehicles using the PATH magnetic marker sensing approach in 1995 and 1996, both on a test track and on a segment of highway in Japan.

In 1997, the National Automated Highway Systems Consortium (NAHSC) conducted "Demo '97," a high-profile demonstration of automated highway systems. The PATH magnetic guidance system was one of the key technologies used by three demonstration systems at Demo '97 (PATH/GM, Honda/PATH, and Caltrans/Lockheed Martin). The eight-Buick platoon demonstration showed the technical feasibility of operating standard automotive vehicles under precise automatic control at close spacings at highway speeds. For Demo '97, magnetic markers were installed on two High Occupancy Vehicle (HOV) lanes of an eight-mile stretch of Interstate 15. Most markers used were ceramic magnets (2.4 cm diameter x 10 cm long, $0.90 each), with stronger neodymium magnets (2.5 cm diameter x 2.5 cm long, less than $10 each) used for special locations. The cost per lane mile of installation was less than $10,000. When the installation process is automated, this cost can be substantially reduced.

In 1998, the Netherlands Rijkswaterstaat (Ministry of Transport, Public Works, and Water Management) organized a large-scale European demonstration of Automated Guided Vehicle Technologies — "Demo '98." PATH, the only US organization to participate, demonstrated a fully automated platoon of passenger cars using the PATH magnetic guidance system that turned out to be the star attraction of the Demo. The PATH cars were the smoothest and most reliable of all sixteen vehicle demonstrations. Also at Demo '98, the Dutch consortium Combi-Road, formed to develop approaches for automated container transportation, demonstrated a heavy-duty automated, driverless, electric-powered truck for hauling shipping containers that steered itself within an accuracy of 5 cm using the PATH system.

At present, the California Department of Transportation (Caltrans), in conjunction with the Advanced Highway Maintenance and Construction Technology Research Center at UC Davis (AHMCT) and PATH, is demonstrating a snowplow guidance system using the PATH magnetic guidance system on a four-mile segment of Interstate 80. The Arizona Department of Transportation will also demonstrate the system on US-180 later this winter.

PATH is interested in developing additional applications for this technology, and in customizing it for such applications. We are also seeking partners for commercialization of the technology in transportation and other related fields of activity.

Instrumentation, from top to bottom: Flux-gate magnetometer and ferrite magnet; Installation of magnets in roadway; Magnetometers mounted under bumper; Central processing computer and sensor interface boxes.

Automating Commercial Heavy Vehicles: Longitudinal Control

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of speed control algorithms. With the updated vehicle dynamic model and parameters, we adjusted the control parameters for fixed-gain Proportional Integral Derivative (PID) controllers and for PIQ controllers (where the PID controller's derivative term is replaced with a signed quadratic [Q] term on the velocity error). The control algorithms were then coded as longitudinal control modules and implemented on an on-board computer to automatically manipulate the fuel and brake actuators in order to make the vehicle speed track a predetermined speed profile. Several speed tracking closed-loop experiments, some of which were very demanding, were performed. The experimental results are very encouraging and show that even fixed-gain PIQ and PID controllers are able to achieve fairly good speed tracking performance for individual vehicle control. In the next phase of our research, we plan to implement a more challenging control task: automatic vehicle following.

Hardware and software configuration

The three major parts of the hardware configuration are the fuel and brake actuators and the on-board computer, which controls all the signals to and from the actuators.

The on-board computer uses an Intel 100MHz Pentium processor running the QNX real-time operating system, which connects with the sensors to read measurements of the speed of each individual wheel and engine speed, as well as measurements of the acceleration and yaw rate.

The Freightliner is powered by a Detroit Diesel DDEC III engine, which has an electronic fuel actuator as original equipment; the gas pedal is connected to a potentiometer, which sends a voltage signal directly to the injection system.

The air brake system, modified for electronic actuation by ISE Research Corporation, uses four proportional actuators (one for the front tractor brakes, one for the rear tractor brakes, one for the left trailer brakes, and one for the right trailer brakes) and an on/off actuator (between the front tractor brakes and the trailer brakes, which are activated by the same signal), as well as ten (10) pressure transducers, one for each of the ten brakes. The brake signal is transmitted by wires from the on-board computer's I/O ports to each proportional actuator. When the brake actuators are activated, they open relay valves to suck air from the air tank to the spring brake until the air pressure in the spring brakes balances the commanded air pressure from the brake actuator.

Real-time C software developed by PATH software engineers runs the whole system. The longitudinal control algorithms became subroutines of the larger program, which also includes lateral control.

Open-loop experiments

In September 1998, open-loop longitudinal experiments (performed without feedback to a steering controller) were carried out to investigate the characteristics of the experimental vehicle. With these experiments we were able to approximate

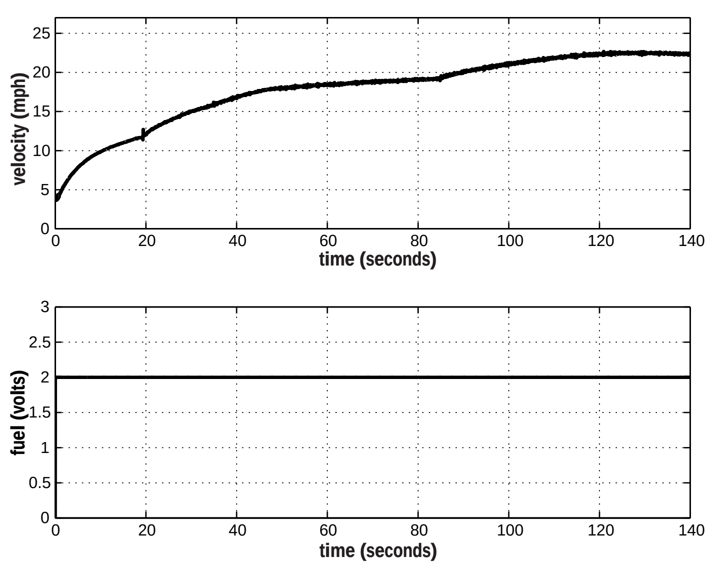

Figure 1: Vehicle velocity response to a step fuel command of 2.0V.

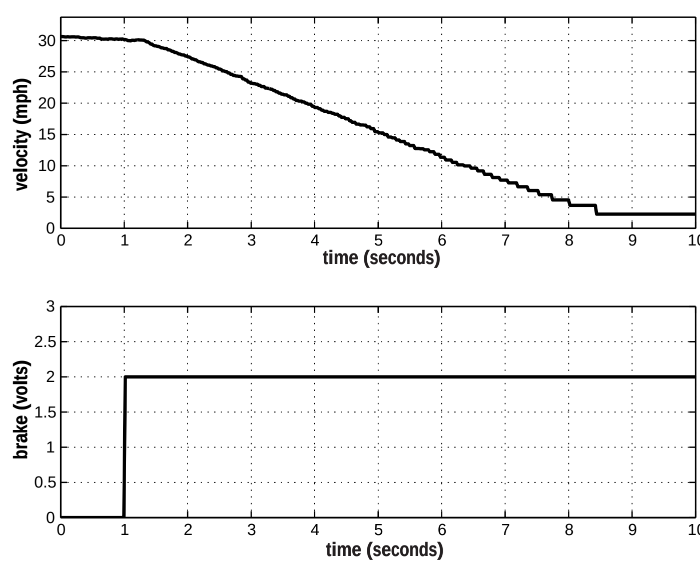

Figure 2: Vehicle velocity response to a step brake command of 2.0V.

the dynamics (transfer function) from a fuel or brake command to the vehicle speed. Giving a voltage signal ranging from 1.3V to 5.0V as input and measuring the vehicle velocity as output, we repeatedly measured the step response of the system. Figure 1 shows a typical response curve.

At the beginning of this run, we release the brake pedal, wait for the tractor to reach its steady-state speed with the engine idling, then issue a fuel command of 2.0V. The dynamics from the fuel command to the vehicle speed can be locally approximated as a first-order system with appropriate choices of parameters. We used the step-input brake command in a similar way to test our brake dynamics. Figure 2 shows a typical step input brake response.

At time t=0, we release both brake and accelerator pedals and put the truck in automatic mode. At time t=1, a brake command of 2.0V is issued to all four brake actuators and, the vehicle starts to decelerate until it stops. Because the sensors cannot measure speeds below 1.1888 mph (0.5283m/s), the speed appears not to reach zero, although in reality it does. Despite the fact that in our modified system the brake signals are transmitted electronically rather than by air traveling through brake lines, there is still a delay of 0.3s in the brake response, because we are still using an air brake system with slow dynamics, where air pressure needs to build up before the brakes are activated.

PID and PIQ controllers

For our longitudinal control design we model the dynamics from the fuel/brake command to the vehicle speed as a simple linear first-order system. This simple model is used only for design; the model we use in our simulations is far more complex, since it models the details of the diesel engine with the turbocharger and the intercooler, the automatic transmission with the torque converter, and the air brake dynamics including the delays.

In the first stage of our experiments, we focused on speed control with the two simplest control schemes we have designed: fixed-gain PID and PIQ controllers. We used a fixed-gain PID controller as the starting point for our closed-loop experiments, because it is the simplest candidate scheme that we would expect to work in an experimental setting. The PID can achieve regulation of the velocity error to zero, while providing some robustness with respect to unmeasured disturbances.

The PIQ controller replaces the derivative term of the PID controller with a signed quadratic (Q) term on the velocity error. This nonlinear term becomes very small when the speed error is small, but grows fast as the error grows. Therefore, it has the effect of generating aggressive control action to reduce large errors quickly, yet it turns itself off for small errors, thus avoiding the occurrence of undesirable overshoot. This feature helps achieve tight control.

Closed-loop experiments

Determining effective working ranges for the fuel and brake actuators should be based on ride quality, response speed, and safety. For example, a higher upper limit on the fuel would give us faster response during acceleration, but it can also cause undesirable jerk and possibly overshoot; a higher upper limit on the brake would give us quicker

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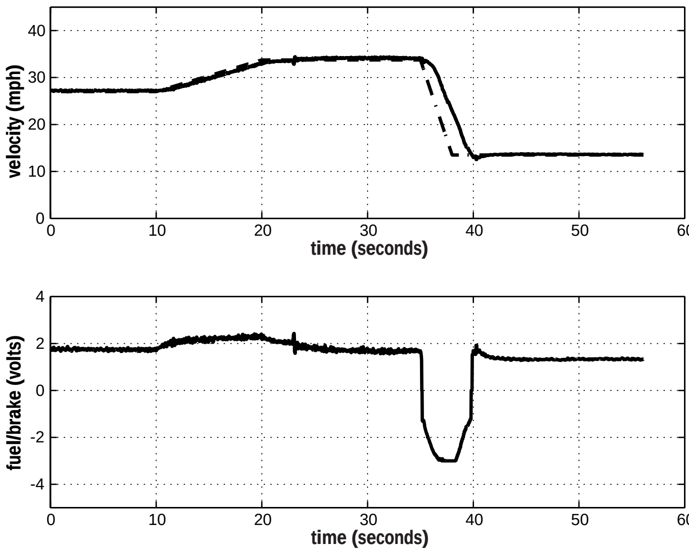

Figure 3: Closed-loop experiment with PID controller.

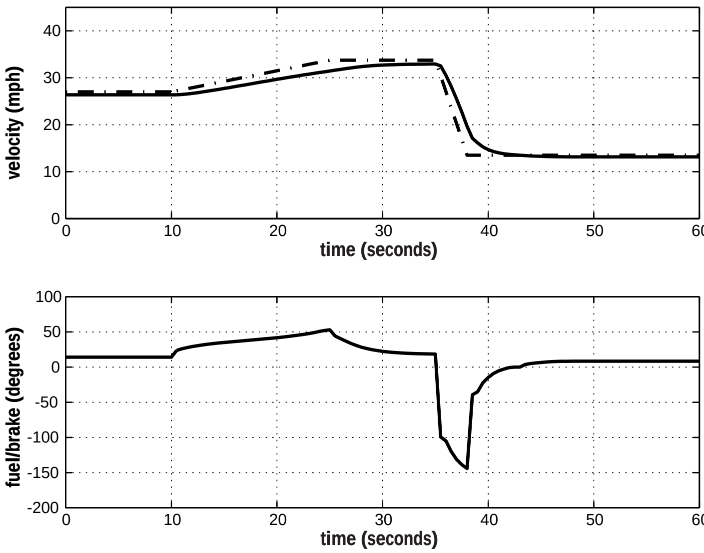

Figure 4: Closed-loop simulation with PID controller.

Dashed lines are speed profile in simulation; solid lines are actual speed in experiment.

PATH Presentations

Recent and Upcoming Presentations of PATH Sponsored Research

TRB 78th Annual Meeting, Washington DC, January 10-14, 1999

Application of Infrared and Millimeter Wave Imaging for Traffic Surveillance and Detection
Arthur MacCarley with Brian Hemme, Lawrence Klein, California Polytechnic State University

Analysis of Automobile and Transit Commuters and Non-commuters Response to Traveler Information in the San Francisco Bay Area: the Results from the TravInfo Project, (publication only)
Asad Khattak, Youngbin Yim, Linda Stalker

Evaluation of Mobile Surveillance and Wireless Communications Systems Field Operational Test (991178)
Kimberley A. Mastako and Lawrence Klein, California Polytechnic State University

Evaluation of the Anaheim Adaptive Control Field Operational Test: Technical and Institutional Issues (991560)
Michael G. McNally and Steve Mattlingly, University of California, Irvine; James E Moore and Hsi-Hwa Hu, University of Southern California; C. Arthur MacCarley, California Polytechnic State University

The Effects of Incident Information on Travel Choice (990696)
Ronald Koo, Harvard University; Youngbin Yim, University of California, Berkeley

The Market for Traffic Information — A Study of Industry Structure and Prospects
Shirley Chan, Matthew B. Malchow, and Adib Kanafani, University of California, Berkeley

Lessons Learned from a Review of Evaluations of Automated Highway Systems (990776)
James Bret Michael, Naval Postgraduate School, Monterey, California; Mark A. Miller, University of California, Berkeley

Short Term Freeway Traffic Flow Prediction using Genetically-Optimized Time-Delay-Based Neural Networks (990658)
Baher Abdulhai, University of Toronto, Canada; Himanshu Porwal and Will Recker, University of California, Irvine

Benefit-Cost Evaluation of the Electronic Toll Collection System: A Comprehensive Framework and Application (991092)
Jianling Li, University of Texas, Arlington; David Gillen and Joy W. Dahlgren, University of California, Berkeley

Using Dual Loop Speed Traps to Identify Detector Errors (990550)
Benjamin A. Coifman, University of California, Berkeley

TRAVINFO 817-1717 Caller Study (990695) (Poster Session)
Youngbin Yim, Mark A. Miller, University of California, Berkeley; Ronald Koo, Harvard University

Intellectual Challenges to the Deployability of AVCSS (990343)
Steven E. Shladover, University of California, Berkeley

Breaking the Highway Capacity Barrier: An Adaptive Cruise Control Based Concept (990749)
Datta N. Godbole, Natalia Kourjanskaia, Raja Sengupta, Marco Zandonadi, University of California, Berkeley

Use of Vehicle Signature Analysis and Lexicographic Optimization for Vehicle Reidentification on Freeways (991379)
Carlos C. Sun, University of California, Berkeley; Stephen G. Ritchie, Kevin Tsai, and R. Jayakrishnan, University of California, Irvine

Determining the Capacity Benefits of Real-Time Signal Control at an Intersection (990850)
Alexander Skabardonis, University of California, Berkeley; Brian R. Gallagher, Los Angeles Department of Transportation

Multimodal Daily Activity Travel Planner: An Interactive Programming Approach (990912)
Cynthia Chen, University of California, Davis; Ryuichi Kitamura, Kyoto University, Japan; Jiayu Chen, University of California, Davis

Integrated Multiple Objective-Attribute Methodology to Determine the Overall Value of Implemented New Technology in Transportation (991453)
Steve Mattlingly, R. Jayakrishnan, and Michael G. McNally, University of California, Irvine

Consumer Response to ATIS Products and Services: Introduction to Speakers
Youngbin Yim, University of California, Berkeley

Session on Station Cars and Shared Cars
Susan Shaheen, University of California, Davis, Presiding

A Multi-Faceted Investigation of Vehicle-Highway Automation on the Houston Katy Freeway: Concepts, Analytical Methods, and Results (990848)
Mark A. Miller, James A. Misener, Datta N. Godbole, and Akash R. Deshpande, University of California, Berkeley

Derivation and Use of Section Measures in Dynamic Origin / Destination Demand Modeling
Carlos C. Sun, University of California, Berkeley

Car Sharing and Partnership Management: Past, Present, and Future (990826)
Susan Shaheen, Daniel Sperling, and Conrad Wagner, University of California, Davis

Toward a Consumer Demand Driven ITS Policy: Findings from Southern California (991474)
Kimberly J. Wells and Thomas A. Horan, Claremont Graduate University Research Institute

A New Methodology for Evaluating Incident Detection Algorithms (990875)
Karl F. Petty, Peter J. Bickel, Jaimyoung Kwon, and John Rice, University of California, Berkeley

Some Observations of Highway Traffic in Long Queues (990094)
Karen R. Smilowitz, Carlos F. Daganzo, Michael J. Cassidy, and Robert L. Bertini, University of California, Berkeley

Advanced Snowplow Program

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stiffness immediately after an impact is detected. Simulation results indicate that a notable reduction of the yaw motion and the lateral motion of the snowplow can be achieved by increasing the cornering stiffness of the rear tires while decreasing the stiffness of the front tires. This also reduces the settling time (the time it takes the snowplow to stop sliding or rotating after impact) remarkably. Reducing the settling time permits corrective steering of the snowplow by the driver if the impact cannot be minimized. Methods of changing tire cornering stiffness include spreading sand or other materials around the tire, or changing the tire pressure.

Future Work

AHMCT and PATH have proposed a second phase of the Advanced Snowplow Program to evaluate the results obtained by Phase One, and to further investigate methods for lateral guidance and collision avoidance. These include: further development of methods of representing abstract information that are independent of display methods; the application of magnetic markers to identify permanent signs and structures so that they can be tracked by an in-vehicle database, for collision avoidance; improved collision warning sensors and algorithms; sensor fusion of magnetic reference and GPS/INS, for continuous and robust vehicle position measurements; and further work on mitigating icepack impact. Caltrans also plans to work with the Minnesota Department of Transportation to develop Measures of Effectiveness (MOEs) for evaluation of the technologies under development, and to collaboratively conduct evaluations through field testing.

Partners

Partners on this project include the following organizations and individuals: Caltrans (Kirk Hemstalk, Mike Jenkinson, Monica Kress, Jerry Lander, Jerry Oliver, Stan Richins, Terry Rogers, Rick Sheasby, Kris Teague, Dale TenBroeck, Bonnie Wells, Tom West, Randy Woolley); AHMCT (Hassan Abou Ghaida, Ron Kappesser, Ty Lasky, Aaron Raley, Bahram Ravani, Colin Thorne, Kin Yen); California PATH (Bénédicte Bougler, Dan Empey, Paul Kretz, Dave Nelson, Aaron Steinfeld, Han-Shue Tan, Wei-Bin Zhang); ADOT (Steve Owen); WTI (Steve Albert, Eli Cuelho, Russ Gomke). This work was supported by Caltrans through the AHMCT Program at UC Davis, under IA65X875-T.O.96-9.

PATH on Paper

An Updated List of Recent PATH Sponsored Research Publications

PATH publications (which include research reports, working papers, technical memoranda, and technical notes) can be obtained from:

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UCB-ITS-PRR-98-33

Data Utilization at California Transportation Management Centers, Shirley Chan, Elbert Chang, Wei-Hua Lin, Alexander Skarbardonis, November 1998, $10
UCB-ITS-PRR-98-34

Testing A Proposed Decision-Oriented Framework to Understand ITS Deployment Issues: An Examination of the TravInfo ATIS Project, Mark A. Miller, December 1998, $10
UCB-ITS-PRR-98-35*

Intelligent Cruise Control Systems and Traffic Flow Stability, Swaroop Darbha, K.R. Rajagopal, December 1998, $10
UCB-ITS-PRR-98-36*

Modeling the Santa Monica Freeway Corridor: A Feasibility Study, Alexander Skabardonis, Joy Dahlgren, Adolf D. May, December 1998, $15
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Daily Activity and Multimodal Travel Planner: Phase II Final Report, Ryuichi Kitamura, Cynthia Chen, Jiayu Chen, January 1999
UCB-ITS-PRR-99-1*

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California System Architecture for Intelligent Transportation: Models for Transportation Systems Management, Randolph W. Hall, Viral Thakker, November 1998, $15
UCB-ITS-PWP-98-29*

TravInfo Evaluation (Technology Element) Traveler Information Center (TIC) Study: Operator Interface Component-Phase IV: Institutional Analysis, Mark A. Miller, Dimitri Loukakos, December 1998, $10
UCB-ITS-PWP-98-30*

Incident Management: Process Analysis and Improvement, Phase 1: Review of Procedures, Randolph W. Hall, Yatrik Mehta, December 1998, $15
UCB-ITS-PWP-98-31*

PATH ATMIS/Systems State of the Research Annual Report: Fiscal Year 1997/1998, Robert Tam, December 1998, $10
UCB-ITS-PWP-98-32*

Beyond Tele-substitution: A Broader Empirical Look at Communication Impacts, Patricia L. Mokhtarian, Ravikumar Meenakshisundaram, December 1998, $10
UCB-ITS-PWP-98-33

*Available online at: http://www.path.berkeley.edu/Publications/PATH/index.html

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Automating Commercial Heavy Vehicles: Longitudinal Control

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deceleration and shorter brake distance, but it would also deteriorate the ride quality and increase brake wear. In our closed-loop experiments (where processed output from the sensors is used as input to the controller) we chose the working range of the fuel command to be 1.25-4.5V and that of the brake command to be 1.2-3V.

Closed-loop speed control with PID controller

Even the simple PID controller can achieve pretty good tracking performance if the parameters are chosen appropriately, since the longitudinal vehicle dynamics is essentially a slow linear process. One closed-loop experimental result with the PID controller is shown in Figure 3 (on page 11).

The speed profile we used in this set of experiments is the same used in the experiments shown in Figure 1. This makes it possible to compare our experimental results with our previous simulation results, shown in Figure 4. The vehicle starts out at an initial speed of 27 mph and stays at this speed for 10s. At time t=10s the vehicle is given a command to accelerate at 0.3 m/s^2 for 10s so that the vehicle velocity is 33.75 mph after the acceleration. Then at time t=35s, a deceleration command of 3m/s^2 is issued for 3s. In these figures, the commanded speed profile is shown using a dashed line, and actual velocity using a solid line.

Closed-loop speed control with PIQ controller

The PID and PIQ controllers have similar behavior and performance as we can see from the PIQ closed-loop results in Figure 5 and Figure 6. The PIQ controller was tested with the same speed profile as the PID controller. As we can see from these figures, our experiments confirm our theoretical results and simulations, which implies that the detailed nonlinear model we used for our simulations was quite accurate.

Our closed-loop experiments also revealed several problems that we need to overcome in the future in order to be confident that our automated vehicle can be operated safely under all possible conditions. The main issue to be addressed is robustness with respect to vehicle parameter variations, such as the vehicle load. In our theoretical work, we were able to significantly attenuate this problem by using on-line adaptation to adjust the controller parameters. These more complex controller structures will be implemented and tested in the next round of experiments.

Conclusion

Throughout these experiments not only was the tracking performance good, but the ride was very smooth and comfortable for both the driver and the passenger. In our next round of experiments, we plan to use more advanced controllers such as adaptive PID and PIQ, as well as backstepping with predictor to counteract the actuator delays. We are also planning to test our algorithms for vehicle following, first with "virtual" vehicles, where the separation error is artificially generated by a computer subroutine, and eventually with real ones. Our goal

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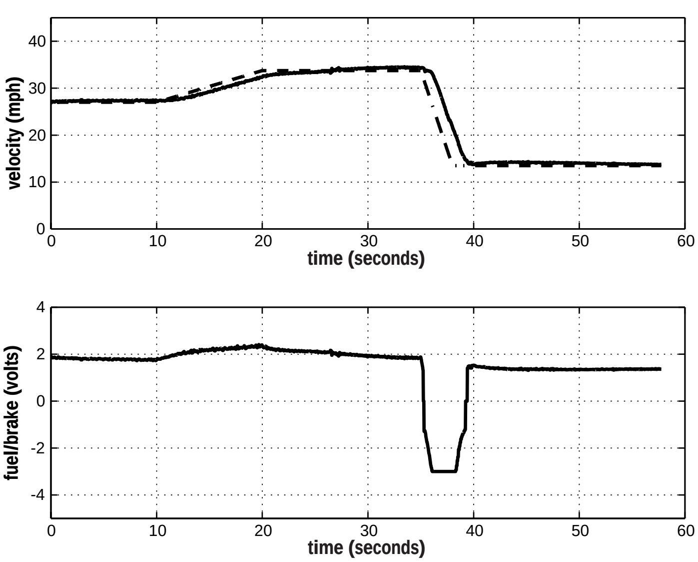

Figure 5: Closed-loop experiment with PIQ controller.

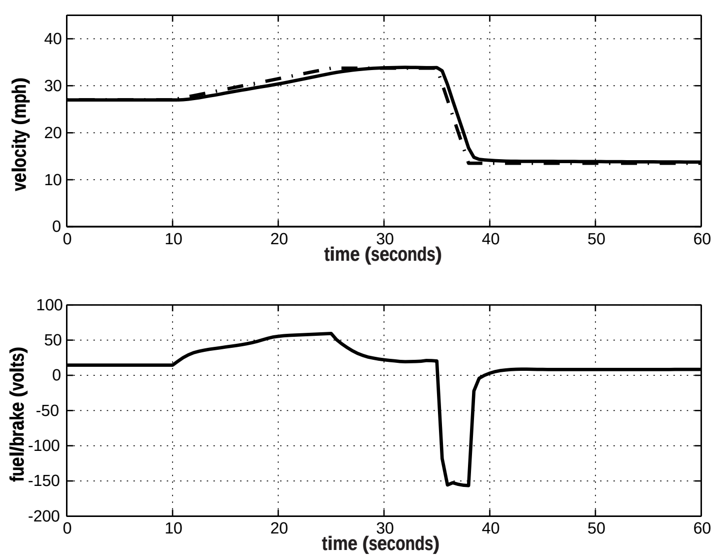

Figure 6: Closed-loop simulation with PIQ controller.

Dashed lines are speed profile in simulation; solid lines are actual speed in experiment.

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is to be able to operate this experimental vehicle in fully automated "driverless" mode in the near future, by integrating and coordinating our longitudinal controllers with the lateral controllers developed by Professor Tomizuka's group.

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