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Authors

Tan, Han-Shue
Bouglher, Bndicte

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CALIFORNIA PATH PROGRAM
INSTITUTE OF TRANSPORTATION STUDIES
UNIVERSITY OF CALIFORNIA, BERKELEY

**Vehicle Lateral Warning, Guidance and
Control Based on Magnetic Markers:
PATH Report of AHSRA Smart Cruise 21
Proving Tests**

**Han-Shue Tan
Bénédicte Bougler**

**California PATH Working Paper
UCB-ITS-PWP-2001-6**

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ABSTRACT

This report details the PATH proving test results during the period of October 6 to December 1, 2000 on the test track of the Public Works Research Institute (PWRI) of the Ministry of Construction in Tsukuba City, Japan. This work is related to the “Attachment 5: System Evaluation by Proving Test, Section 2.2 Evaluation by Proving Test” to the “Implementation Plan for Advanced Cruise-Assist Highway System Technical Research Development for FY2000” with respect to the “Entrusted Study” entrusted in FY2000 by the “Public Works Research Institute of the Ministry of Construction” to the “Advanced Cruise-Assist Highway System Research Association (AHSRA).” Due to the late signing of the contract between The University of California and AHSRA, the scope of the report was modified according to “Response to the Minimum Specification of PATH Proving Test Specification for Lane Departure from AHSRA” on November 6, 2000.

This report focuses on the discussions of the following five proving test items that are related to the magnetic markers sensing system. The depth of the discussions reflects the amount of data available from the proving tests.

- (1) Capabilities of the PATH steering warning/guidance/control system based on the benchmark test results to support the prevention of overshooting on curve, prevention of lane departure under expressway speed condition, and prevention of lane departure under fog condition.
- (2) Results from the PATH Demo2000 scenarios to further substantiate the steering effectiveness of the magnetic marker based lateral warning/guidance/control system.
- (3) Presentation of the proving test results of the PATH steering warning/guidance/control system without the knowledge of the road curvature information.
- (4) Comparisons of the performance of the PATH steering warning/guidance/control system with respect to 2m, 4m, and 6m magnetic marker spacing.

(5) Discussions on the effects of the different magnetic markers (nail and plate types) on the PATH and AHSRA magnetic sensing system, as well as on the noise characteristics observed at different locations on the North Loop.

The discussions in this report are based on the preliminary observations from test results during the short proving test period. Those results were not obtained through an optimized process, nor do they present strong statistical significance. Any extension of the summaries should be taken with caution.

1 Executive Summary

PATH tested a vehicle that provides automatic steering control, driver lane guidance control, and lane departure warning at the test track of PWRI in Tsukuba City, Japan for the Smart Cruise 21 proving tests. The steering warning/guidance/control system developed by PATH includes magnetic sensors to detect the vehicle lateral deviation relative to the magnetic markers installed on the roadway; an antenna to receive the radio-wave control point marker information; an automatic steering actuator; a display screen showing the anticipated position of the vehicle to support the driver in steering the vehicle; and a speaker to provide an audio warning signal to the driver. This system addresses the themes of support for prevention of overshooting on curve, support for prevention of lane departure under expressway speed condition, and support for prevention of lane departure under fog and rain condition. Only the issues related to steering control are addressed; throttle and brake are controlled by the driver.

The proving tests at PWRI were performed using one of the Buick LeSabre vehicles that were previously shown at Demo '97, '98 and '99. The only hardware additions to the vehicle are a human machine interface (HMI) display for lane guidance, and AHSRA's lane marker detector for sensing system evaluation. The on-board computer receives lateral measurements from both PATH and AHSRA magnetic sensors. The PATH magnetic sensors were used for most tests performed at PWRI. The AHSRA sensor data were simultaneously recorded for evaluation purpose. The future road geometry is stored in the on-board computer and anticipated by the communication from the AHSRA radio-wave control point markers. The road geometry information is used, in conjunction with the lateral deviation measurements and the vehicle dynamic model, to generate either an automatic steering command to the steering actuator, or a display providing a preview of the future vehicle position (predictor) if the driver does not correct his steering action. The design of this guidance display, which was originally developed for snowplow drivers, was optimized to make it very easy for the driver to steer the vehicle accurately, even in zero-visibility conditions. Furthermore, PATH also demonstrated a smooth

switching method that was previously developed, allowing the driver to change between automatic and manual steering control at any location or time that he commands.

The lane departure warning system based on the magnetic markers is derived from the “steering guidance” system. A modified predictor computation triggers the departure warning signal. A lane departure warning sounds when the modified predictor estimates that the vehicle will reach the lane boundaries in one second. Lane departure prevention control is a feature that the driver can select. Once activated by the driver, the vehicle automatically switches to “automatic steering control” if the driver continuously ignores the lane departure warning and the vehicle begins to drift into the adjacent lane.

By combining the capabilities of automatic steering control, steering guidance display, manual/automatic transition, as well as lane departure warning and prevention control, the PATH lateral system based on the magnetic markers creates a high performance lateral warning/guidance/control system. With such capabilities, the vehicle provides a wide range of possibilities to the driver, from guidance to full automation and from lane departure warning to prevention control, under various curve and visibility conditions. These capabilities also enable PATH to generate substantial test results during the short proving test period. The report applies these test results to explore the five important issues related to the magnetic sensing and control systems.

(1) Benchmark proving tests:

Substantiate that each of the basic capabilities (control, guidance, and warning) based on the magnetic sensing system is capable of effectively supporting the three services discussed in this report.

(2) Demo2000 scenario:

Demonstrate that the combination of the warning/guidance/control capabilities with automatic/manual switching creates a high performance vehicle steering system based on the magnetic markers.

(3) Proving tests without curvature information:

Show that the only performance degradation resulting from the loss of road curvature information for a well-designed warning/guidance/control system is the larger transient and steady state lateral deviation on curves.

(4) Proving tests with magnetic marker spacing of 2, 4, and 6 meters:

Provide preliminary observations about the effects of larger magnetic marker spacing on the system performance degradation.

(5) PATH and AHSRA sensor comparison:

Provide observations on the characteristics of the AHSRA/PWRI magnetic marker sensing system.

The following subsections give a quick summary of these five issues. Detailed information can be found in Sections 3 to Section 7 with the same section titles. Section 8 provides brief discussions about the PATH magnetic sensors, marker installation requirements, and magnetic coding scheme.

1.1 Benchmark proving tests

This section describes the benchmark proving tests based on the 2-meter spacing magnetic markers. These tests were performed on a 1.8-km stretch of test track in the North Loop totaling 900 magnetic markers. It starts with a 400-meter straight section and continues through all the curve sections in the North Loop. The driver controls the throttle and brake following a specific speed profile between 0 and 90 km/h. The curvature information is obtained through the radio control point marker and the geometric map stored in the on-board computer. To demonstrate the effectiveness of the PATH lateral warning/guidance/control system with respect to the three services described above, three different basic benchmark scenarios are tested according to the speed profile:

(1) Automated steering control: the driver switches on the “automatic steering control” from the beginning of testing.

- (2) Driver steering control based on HMI guidance display alone: the driver uses the predictor in the “guidance steering display” mounted on the dashboard to steer the vehicle with the windshield blocked (zero visibility).
- (3) Driver steering control based on lane departure warning alone: the driver keeps his current steering angle as long as no lane departure warning is issued. He only reacts to the pending departure situation and over-steers the vehicle into in the lane during the period when the departure warning sound is on.

The main observations from the test results are summarized below:

- (1) Automatic steering control consistently maintains small lateral deviation (5 cm maximum on the straight road, and 15 cm maximum on curves regardless of vehicle speeds) as well as small curve transition error. Very small steady state lateral deviation is observed on the curves because of the curvature information.
- (2) For the steering guidance case, the driver consistently maintains small lateral deviation (15 cm maximum on the straight road, and 30 cm maximum on curves at various vehicle speeds) despite the fact that the vehicle is manually controlled with simulated zero visibility conditions. The curve transition error is relatively small for all six curve-transitions, and so is the steady state lateral deviation (within 10 cm) on the curves.
- (3) For the case when the driver steers based on the lane departure warning alone, the vehicle is consistently maintained close to the lane boundaries even under severe departure conditions. The excursions into the adjacent lane, which usually happened on sharp curves at higher speeds, are generally kept within the width of a tire. The error attributed to the curve transition and the steady state lateral deviation on curves is not significant. No false alarms or missing alarms are observed on the data sets.

In conclusion, each capability of the steering warning/guidance/control system based primarily on the magnetic markers is shown to be effective to support the three services discussed in this report.

1.2 Demo2000 scenario

The PATH test vehicle (Buick LeSabre) demonstrated three scenarios during Demo2000 at the PWRI test track in Tsukuba City, Japan. The PATH lateral sensing system reads the magnetic field of the magnetic markers (position markers) and generates accurate lateral deviation measurements every 2 meters. AHSRA's radio antenna receives information from the control point markers ("service-begin" and "service-end" markers), and transmits them to the PATH on-board computer. Using the test track map stored in the computer and counting the magnetic markers, the PATH system has the knowledge of both the curvature information and the obstacle location. PATH successfully demonstrated the functions of "automatic steering control", "driver guidance display", "lane departure warning", "lane departure prevention control", as well as "manual and automatic transition". These functions proved to be effective in supporting the three services described above. The demonstrations were very successful. Not a single failure occurred during the 4-day demonstration and 5-day rehearsal.

The capabilities demonstrated for the three demo scenarios are listed below:

- (1) North Loop: smooth switching between manual and automatic steering at any vehicle speeds and at any road curvature conditions, automatic steering control on sharp curves at high speeds, reliable lane departure warning on curves, and automatic lane departure prevention control.
- (2) Whole Loop (i.e. north loop and outer loop): same as above, and obstacle warning.
- (3) Fog Tunnel: steering guidance in zero visibility conditions (fog), automatic steering control, lane departure warning, smooth switching from manual to automatic, and obstacle warning.

1.3 Proving tests without curvature information

One important question in applying the magnetic marker sensing technology to vehicle lateral guidance and control is how crucial the curvature information is to the integrity of such a "steering control" system. To explore the answer to the above question, the same benchmark tests as those described in Section 1.2 are used in this section. The only difference is that the road curvature information is not available to the

warning/guidance/control algorithms. With no road curvature information, both the “guidance display” and “lane departure warning” assume that the road is always “straight”.

The test results conclude that:

- (1) The dynamic performance of the PATH guidance/control/warning system is very similar with or without the knowledge of road curvature.
- (2) The performance degradations due to the lack of road curvature information are (a) larger transient lateral deviation at curve transition, and (b) larger steady-state lateral deviation (bias) in the sharp curve section.

The tests demonstrate the effectiveness of the warning/guidance/control system based on the magnetic markers with and without the knowledge of the road curvature information. The curvature information, although reducing the transient and steady state error on curves, does not jeopardize the integrity of the steering system when it is not available. This ability significantly increases the robustness of such lateral warning/guidance/control system.

1.4 Proving tests with magnetic marker spacing of 2, 4, and 6 meters

The purpose of these tests is to provide preliminary observations about the effects of larger magnetic marker spacing on the system performance degradation. A simple way to simulate larger marker spacing involves systematically skipping magnetic marker measurements as the vehicle travels over them. In order to provide a fair comparison of the performance of the steering control, driver guidance, and lane departure warning systems, the only modification made is to the parameters that have a physical interpretation directly proportional to the marker spacing. No other change or re-tuning was made in any of the control, guidance, and warning algorithms. Exactly the same benchmark tests as those described in Section 1.1 and 1.3 (with and without curvature information, respectively) are used in this section for the case of various magnetic marker spacing.

The preliminary summary of the test results is:

- (1) Satisfactory performance for the proving test can be obtained using 2-meter magnetic marker spacing.
- (2) The performance degradation from 2m spacing to 4m spacing is relatively small except at very low speed or sharp curves.
- (3) Noticeable performance degradation can be observed from 4m to 6m marker spacing especially at lower vehicle speeds.
- (4) High speed on a straight curve is the least sensitive to the increase of the marker spacing, except at very large departure angles.
- (5) Low speed on sharp curves is the most sensitive to the increase of the marker spacing.
- (6) The noise level of the angle estimate increases with larger marker spacing, especially at big departure angles.
- (7) The primary performance degradation due to the lack of road curvature information is the larger transient and steady state lateral deviation on curves regardless of the marker spacing.

The above initial summary is made based on the specific test situations and assumptions. However, algorithms and test procedures were not optimized; many special situations were not tested; different vehicle platforms or configurations were not explored. Therefore, extreme caution should be taken before expending the interpretation of the above summaries to other situations. Detailed investigation should be performed before optimum marker spacing can be chosen for any operating scenarios and any vehicle platforms.

1.5 Observations on the characteristics of the AHSRA/PWRI magnetic marker sensing system

The PATH vehicle is equipped with two types of magnetic sensors: 3 fluxgate magnetometers 30 cm apart located 29 cm above the ground under the front bumper; and 5 AHSRA magnetometers 20 cm apart located 30 cm in front of the front bumper. The PATH on-board computer receives two different lateral measurements: one from the

processing of the raw magnetic field measurements from the 3 fluxgate sensors, and the other from the AHSRA sensors through a RS232 port. Based on the dual measurements, initial observations on the magnetic marker characteristics of the PWRI test track are as follows:

- (1) A “noisy section” exists in the range 290 to 470 markers south of the “service-begin” marker on the North Loop. The earth field “noises” in the “noisy section” are observed to be greater than those from the normal section.
- (2) Since PATH did not get any plate type magnet for examination, all the signal processing was designed based on the nail type magnet. The results do not show a clear distinction between the nail and plate types. However, this may not be true for the AHSRA sensors when the vehicle height is changing.
- (3) AHSRA sensor measurement is not smooth when the magnet is directly between two sensors. This non-smoothness was the reason PATH used only the PATH magnetic sensors for the proving tests in Sections 1.1 to 1.4 (and Sections 3 to 6).

2 Vehicle Setup for the Proving Tests

The purpose of this section is to describe the PATH vehicle setup for the proving tests. The vehicle used was a Buick LeSabre previously shown at Demo '97, '98 and '99. It was instrumented with a number of add-on devices for fully automated vehicle controls. Those devices include radar, magnetometers, communication links, computer, as well as steering, brake, and throttle actuators. For the proving tests and Demo2000 at PWRI test track, the only hardware additions to the vehicle are a human machine interface (HMI) display for lane guidance, and AHSRA's lane marker detector for sensing system evaluation. The longitudinal sensors, communication links, throttle and brake actuators were not utilized during the proving tests and Demo2000.

Fig. 2.1 illustrates the basic PATH vehicle advanced steering functionality before the vehicle arrived in Japan. The PATH lateral sensing system reads the magnetic field of the magnetic markers and generates accurate lateral deviation at every marker location. The

change in road geometry is anticipated by use of magnet coding. The vehicle warning, guidance and control functions determine the appropriate warning signals, display parameters, and steering command based on lateral displacements, curvature information, steering wheel angle, and vehicle model. Since there is no magnetic coding at the PWRI test track, curvature information is obtained by using the test track map stored in the on-board computer and counting the magnetic markers. The “absolute” location of the vehicle is identified through AHSRA’s radio antenna. The antenna receives information from the control point markers (“service-begin” and “service-end” markers), and transmits them to the PATH on-board computer.

The AHSRA’s lane marker system consists of lane markers placed along the lane on the road and a lane marker detector (a vehicle-side detector) installed on the vehicle. The AHSRA lane marker detector is installed on the PATH vehicle and thus, makes it a dual-lateral-sensor vehicle as shown in Fig. 2.2. Two kinds of markers are used in the proving tests: radio wave control point markers containing predetermined information to be transmitted to the vehicle system (“service-begin” and “service-end” markers), and magnetic position markers to detect the vehicle position based on the magnetic fields. The magnetic markers are laid down using two different methods:

- (1) 1 column of markers in the center of the lane with 2 meter marker spacing (N and S polarities are positioned alternatively);
- (2) 3 columns of markers with 1 meter column spacing and 2 meter marker spacing (N and S polarities are positioned alternatively on the center column, N polarity is placed on the right column and S polarity is placed on the left column).

Finally, two types of magnetic markers are used: nail and plate types, with the plate type being much stronger than the nail type.

A vehicle component that receives infrastructure support from the roadside base station through roadside antenna is the 5.8 GHz vehicle-side terminal. The 5.8 GHz terminal performs radio communication with the roadside radio equipment using a 5.8 GHz radio wave, and receives infrastructure data such as curvature information and road surface conditions. Since PATH’s main focus is on the capabilities of the magnetic marker

systems, although this component is installed in the test vehicle, it was not used during the proving tests. For the proving tests at PWRI, the PATH system simulated the 5.8 GHz communication system by counting magnetic markers from the absolute position of the “service-begin” radio wave lane marker. By using the map of the test track stored in the on-board computer, the PATH vehicle has the knowledge of the test track infrastructure information, such as incoming and current road curvature. The results presented in this report can be interpreted in the same way as using a simulated 5.8 GHz communication system. The only difference is whether the infrastructure information is coming from the 5.8 GHz antenna or from the information stored in the computer.

The following sections describes the hardware components, software structure, and advanced steering functions.

1.1 Hardware components

The vehicle used for the proving tests at PWRI is a 1996 Buick LeSabre, which was first used for Demo ‘97. It is instrumented with a number of add-on devices in order to deliver automated driving features such as tight lane tracking and close following. However, longitudinal control was not used in these proving tests thus the related hardware will not be explained. The add-on devices required for the proving tests and their features are:

- 3 fluxgate magnetometers under the front and rear bumpers to detect the lateral positions of the vehicle relative to the center of the lane.
- 4 wheel speed sensors to provide the “vehicle” speed.
- AHSRA lane marker detector, which includes 5 magnetic sensors for position measurement and a radio wave antenna for control point marker information.
- Electronically controlled steering actuator attached to the upper steering column to turn the steering wheel in automatic control mode.
- Human machine interface (HMI) screens located in front of the driver (5.7 inch) and in the dashboard (6.4 inch) to display the guidance parameters and the warning signals, so that the driver can steer even in zero visibility conditions.

- Buttons on the steering wheel to switch the automatic control on, the guidance on or the lane departure prevention control on.
- Pentium computer (industrial grade desktop with heavy-duty chassis placed in the trunk) to provide the intelligence needed for magnetic signal processing as well as automatic/guidance/warning controls.

2.2 Software structure

The real-time software for vehicle lateral control is developed using C programming language under the QNX operating system environment. The functions of the real-time software are to process the signals obtained from the sensors; give the steering control command as well as the display and warning signals based on those signals; send either the steering control command to the steering actuator, or the display and warning signals to the human machine interface. Refer to Fig. 2.3 for the basic software structure.

To achieve those functions, the real-time software was structured in the following five basic component groups: lateral control module, guidance and warning module, human machine interface, device driver and database manager.

- (1) Lateral Control Module: The steering control module retrieves sensor signals from the database, processes sensor signals, calculates the steering command, and writes the steering command to the database.
- (2) Guidance and Warning Module: The guidance and warning module retrieves sensor signals from the database, calculates the guidance parameters and the warning signal, and writes them to the database.
- (3) Human Machine Interface: The human machine interface displays the parameters used for guidance and warning.
- (4) Device Driver: The device drivers, which are running in background when the control program is invoked, handle all the communication with the data acquisition boards

and the RS232 board. The device drivers gather sensor signals from the magnetometers every 2 msec and write them to the database.

- (5) Database Manager: The database manager maintains a set of variables, which are updated or retrieved by the device drivers, the lateral control module, the guidance and warning module, and the human machine interface.

Fig. 2.4 shows the function of and interaction between those software components.

2.3 Advanced Steering Functions

Five advanced steering functions previously developed by PATH were applied to the AHSRA proving tests and Demo2000:

- (1) Automated steering control: The driver switches the vehicle into automated steering control any time he chooses. The base of the controller is a high gain feedback algorithm with virtual “look-ahead” capability.
- (2) Driver steering guidance display: The driver uses the “predictor” in the display for steering guidance to maintain the vehicle in the road center, even when he can not see anything through the windshield. The predictor is the estimated future vehicle position when the driver keeps his current steering angle. This function was first developed for the California Snowplow Project.
- (3) Lane departure warning: The HMI displays and sounds a lane departure warning signal to the driver when the vehicle is one second away from reaching the lane divider. This is accomplished by calculating the modified “predictor” at a location of one-second headway. The lane departure warning starts as the predictor reaches 0.85 meter of lateral deviation to the lane center.
- (4) Lane departure prevention control: When the driver chooses to initiate the “lane departure prevention control” function, the vehicle automatically switches to “automated steering” control if the driver keeps ignoring the warning signal. The

vehicle will be automatically steered back into the lane after the vehicle has driven into the adjacent lane, i.e., when the lateral deviation reaches 1.1 meters.

- (5) Manual/Automatic steering transition: The driver can smoothly switch between manual, guidance, and automatic steering control at any location or time he chooses. This function was developed through the California Bus Docking Project.

2.4 HMI description

This section describes the display screen design as shown in Fig. 2.5. In the center of the display are two white lines simulating the lane width on the road. At the top is a small blue square, showing where the vehicle will be in 20 meters. At the bottom is a blue rectangle showing the current location of the vehicle in the lane. A message can be displayed below this rectangle. It shows information such as the service begin, service end, end of magnets, fog, water surface; the distance left before a right or left turn; the time left before an obstacle.

On the top left corner of the screen is a single letter, showing the current status of the steering system: M for manual driving, G for guidance, A for automated, and D for lane departure prevention control. On the top right corner of the screen is the vehicle speed (in km/h), and on the bottom right corner the distance traveled (in m) since the beginning.

The color of the white lines and red squares change according to the system status. When the system starts, the screen is blank. Once some magnets are read, the road lines and the vehicle positions become yellow. Once a “service-begin” marker is passed, the road lines become white and the vehicle positions red. If too many magnets are missed, the road lines and the vehicle positions turn gray. Finally, if the system is in automated steering, the road lines are always white and the vehicle positions always blue, as in the example in Fig. 2.5.

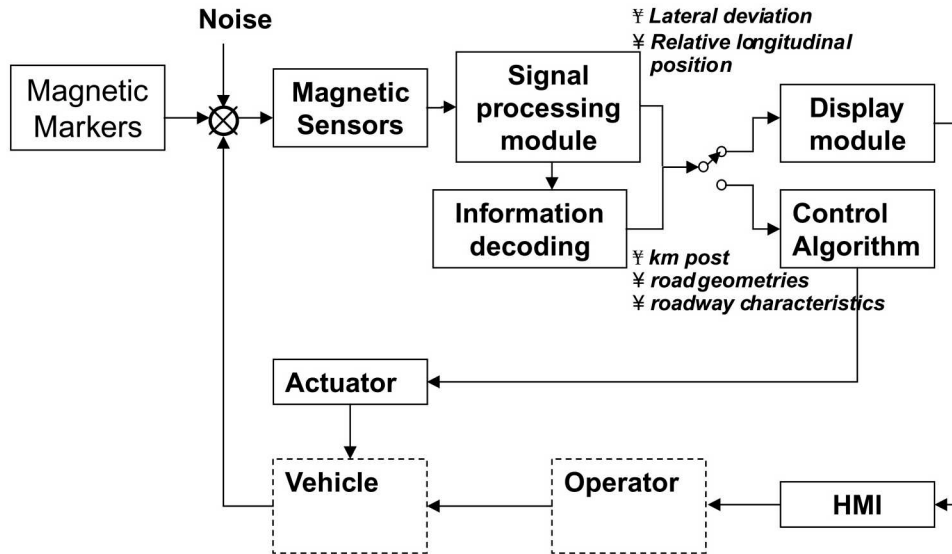


Fig. 2.1 PATH Advanced Steering Functionality

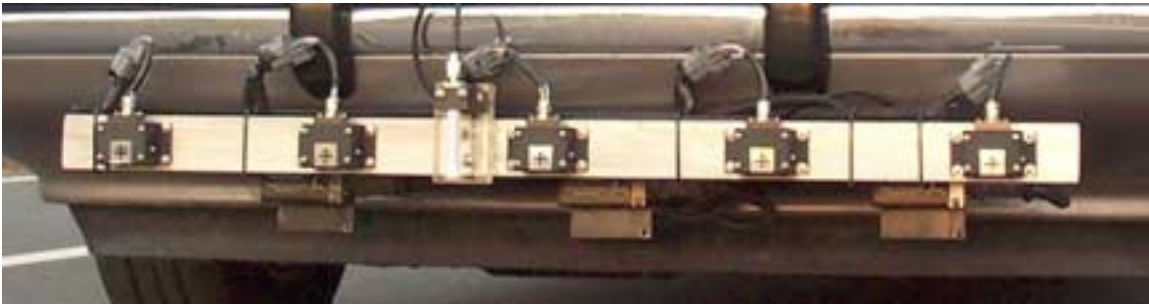


Fig. 2.2 PATH Dual Magnetic Sensor Configuration

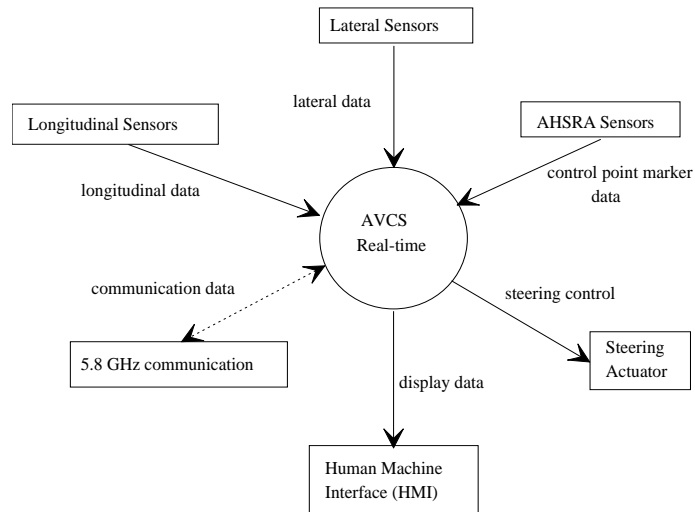


Fig. 2.3 Software Structure for Buick LeSabre

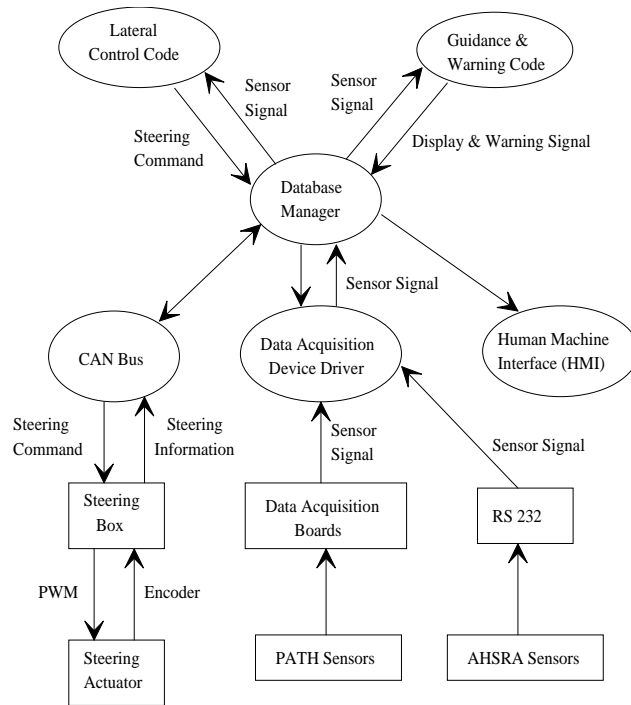


Fig. 2.4 Software Components Interaction



Fig. 2.5 Example of HMI Guidance Display

3 Benchmark Proving Tests

This section contains the basic proving test results based on the 2-meter spacing magnetic markers for the following services:

- (1) Support for prevention of overshooting on curve.
- (2) Support for prevention of lane departure under expressway speed condition.

(3) Support for prevention of lane departure under fog condition.

These services involve infrastructure support and in-vehicle support. The infrastructure provides messages such as incoming road information to the moving vehicle. The vehicle then responds to those messages by providing either a warning or guidance to the driver or by initiating appropriate automatic control functions. As described in Section 2, the PATH vehicle acquires its absolute longitudinal position on the test track by reading any “service-begin” radio wave lane marker. By combining the “service-begin” with the counting of the magnetic lane markers, the PATH vehicle knows its location on the test track at all times. Using the map of the test track stored in the on-board computer, the vehicle has the knowledge of the test track infrastructure, such as current or incoming road curvatures. In the aspect of not using the 5.8 GHz communication equipment, as far as the proving tests go, the results presented in this report can be interpreted in the same way as using a simulated 5.8 GHz communication system. The only difference is whether the infrastructure information is coming from the 5.8 GHz antenna or from the information stored in the on-board computer.

After receiving the infrastructure information (such as an incoming sharp curve), the vehicle responds with longitudinal speed control and lateral lane-keeping control. In the case of these proving tests, the driver controls the vehicle speed since PATH main focus is on the issues of steering control based on the magnetic markers. In particular, the driver adjusts its speed to the appropriate speed based on the warning message displayed by the HMI. Such speed adjustment is not part of PATH focus for these proving tests, and thus will not be discussed in this report. The three services described above are addressed by four steering control mechanisms based on the magnetic markers:

(1) Automated steering control.

The driver switches the vehicle into automated steering control any time he chooses.

(2) Driver steering guidance display.

The driver uses the “predictor” in the display for steering guidance to maintain the vehicle in the road center, even when he can not see anything through the windshield.

(3) Lane departure warning.

The HMI displays and sounds a lane departure warning signal to the driver when the vehicle is one second away from reaching the lane divider. This is accomplished by calculating the predictor at a location of one-second headway. The lane departure warning starts as the predictor reaches 0.85 meter of lateral deviation to the lane center.

(4) Lane departure prevention control.

When the driver chooses to initiate the “lane departure prevention control” function, the vehicle automatically switches to “automated steering” control if the driver keeps ignoring the warning signal. The vehicle will be automatically steered back into the lane center after the vehicle has driven into the adjacent lane, i.e., when the lateral deviation reaches 1.1 meters.

Because of the limited time available for collecting the proving test data, PATH devised three benchmark tests to efficiently demonstrate the effectiveness of the above system in fulfilling the three aforementioned services. These tests were performed on a 1.8-km stretch of test track in the North Loop totaling 900 magnetic markers. For convenience, marker #0 was assigned to the first magnetic marker after the North Loop “service-begin” control point marker. The benchmark test track starts 350 meters before the “service-begin” marker (at marker #-175) and ends 1450 meters after the “service-begin” marker (at marker #725), just before the final straight section of the North Loop. This designated track for the benchmark proving tests starts with a 400-meter straight section and then encompasses all the curve sections in the North Loop. Fig. 3.1 shows a typical benchmark test speed profile with the associated test track curvature based on the magnetic marker numbers. The driver controls the vehicle speed according to the following speed profile:

- (1) Slowly speed up to 50 km/h during the first 100 meters (straight section).
- (2) Maintain 50 km/h for the next 100 meters (straight section).
- (3) Quickly increase speed to 90 km/h and then slow down to 70 km/h during the next 400 meters (on the straight section before the first curve).
- (4) Maintain 70 km/h into the right-turn curve (radius of curvature of 137 meters) for 200 meters (curve transition and curve section).

- (5) Gradually slow down to 20 km/h within the next 400 meters (curve section and curve transition).
- (6) Speed up to 80 km/h in 300 meters (left-turn curve transition).
- (7) Slow down and stop after 300 meters (left-turn curve section and stop just before the final straight section in the North Loop).

To demonstrate the effectiveness of the PATH lateral control/guidance system with respect to the three services described above, three different basic benchmark scenarios are tested according to this speed profile. The benchmark tests are: (1) automated steering control, (2) driver steering control based on HMI guidance display alone, and (3) driver steering control based on lane departure warning alone. Due to the limited time available for the proving tests as well as the consistency of the performance, only two data sets with one driver are recorded for each basic scenario and discussed in the following subsections. These data together with the data recorded for the demonstration scenario (discussed in Section 4) illustrate the strong performance capabilities of the PATH system. The lateral guidance/control/warning system based primarily on the magnetic markers is effective to support the three services discussed in this report: support for prevention of overshooting on curve, support for prevention of lane departure under expressway speed condition, and support for prevention of lane departure under fog condition. The spacing between the magnetic markers for all the tests described in this section is 2 meters. Since all benchmark tests follow the same target speed profile, figures presented in this report are plotted against magnetic marker numbers for both simplicity and clarity.

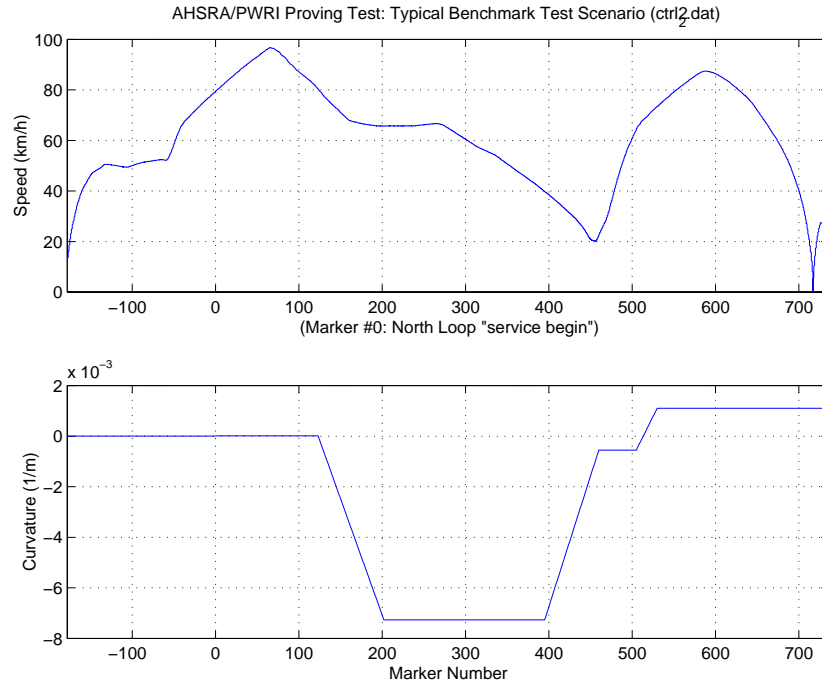


Fig. 3.1. Proving Test Typical Benchmark Speed Profile and Curvature

3.1 Automated steering control

In this basic benchmark proving test scenario, the driver switches on the “automatic steering” control function as soon as the vehicle starts moving. The driver then controls the vehicle speed and follows the speed profile described above using the predetermined landmarks along the test track. The “automatic steering controller” determines the steering wheel angle based on the lateral displacements calculated from the magnetic marker signals as well as the curvature information stored in the computer and matched by the radio control point marker.

Since the system performance is extremely consistent, data from only two test runs are recorded and presented in this report. Fig. 3.2.1 shows the vehicle lateral deviation from the road center as well as the vehicle departure angle from the road center lane for these two tests. Fig. 3.2.2 shows the vehicle speed and the associated road curvature. Using these two figures, one can observe the following about the automatic steering control system:

- (1) Small lateral deviation and vehicle departure angle are consistently maintained. The lateral deviation is kept within 5 cm maximum on the straight road and 15 cm maximum on curves regardless of the vehicle speed. The vehicle departure angle is kept within three-quarters of a degree during the tests at various speeds and curvatures (less than a third of a degree on straighter roads).
- (2) Small curve transition error is shown for all six curve-transitions of the test track. Very small steady state lateral deviation (bias) is observed on the curves because the curvature information is known.
- (3) The steering control system also works for stop-and-go situations as illustrated at the end of the tests.

The above benchmark tests demonstrate the effectiveness of the automatic steering control based on the magnetic markers. Since the PATH automatic steering control can be switched on any time the driver chooses, this system can effectively support all the services discussed in the report by switching the vehicle into automatic steering control whenever needed. Such switching can be initiated either by driver's demand or by the automatic system (such as in the case of automatic lane-departure-prevention control).

3.2 Driver steering control based on guidance display alone

For this basic benchmark test scenario, the driver uses the specific designed "driver steering display" to steer the vehicle without any visual information from outside the windshield. To prevent the driver from looking outside, the windshield in front of the driver is blocked by a one foot-square cardboard. The 5.7-inch flat panel screen located on the dashboard in front of the driver displays a "steering guidance system" as explained in Section 2.4. The driver controls the steering wheel to maintain the "predictor" in the display at the "future road center" in order to keep the vehicle close to the lane center.

For this basic benchmark proving test scenario, the driver steers the vehicle using only the "guidance display". He controls the vehicle speed based on the verbal commands given by the test assistant to follow the speed profile. The "guidance controller" determines the displayed "predictor" based on the lateral displacements calculated from the magnetic

marker signals, the curvature information stored in the computer matched by the control point marker, as well as the current steering wheel angle.

Since the system performance is also very consistent, data from only two test runs are recorded and presented in this report. Fig. 3.3.1 shows the vehicle lateral deviation from the road center as well as the vehicle departure angle from the road center lane for these two tests. Fig. 3.3.2 illustrates the vehicle speed and the associated road curvature. In addition, Fig. 3.5 compares the vehicle lateral deviation and the vehicle departure angle between the guidance and the automatic steering controls. Using these three figures, one can observe the following about the driver steering guidance system:

- (1) Small lateral deviation and vehicle departure angle are consistently maintained despite the fact that the vehicle is manually controlled. The lateral deviation is kept within 15 cm maximum on the straight road and 30 cm maximum on curves at various speeds. The vehicle departure angle is basically kept within one degree at various speeds and curvatures (it is less than half a degree on straighter roads).
- (2) Although curve transition errors are visible, they are still relatively small as shown for all six curve-transitions of the test track. For the curve transitions in and out of the curve of 137-meter radius of curvature, the transition error is about 30 cm maximum at speeds up to 70 km/h. Small steady state lateral deviation (within 10 cm) is observed on the curves because the curvature information is known.
- (3) Fig. 5.3 reveals surprisingly similar dynamic behavior between the performance of guidance and automatic steering controls. The differences mainly lie on the larger transition error and slightly more oscillations on the sharp curve for the case of “display-guided” manual steering.
- (4) The driver steering effort on the curve increases more significantly with respect to speed than that on the straight road.

The benchmark tests in this subsection demonstrate the effectiveness of the driver guidance steering control system based on the magnetic markers. The driver can use the PATH guidance system any time he wants since the computation is done all the time as long as the magnetic markers are read. This system can effectively support all the services

discussed in the report. The driver can simply move the “predictor” on the display using the steering wheel to support the lane keeping function. This system is particularly useful in the situations of poor visibility conditions such as under heavy fog, rain, or snow. Section 4 will present the results of the demonstration scenario about the support for prevention of lane departure under fog condition. The similarity of the system dynamics under automatic steering control and driver-guidance steering (as illustrated in Fig. 5.3) facilitates the easy transition between these two modes.

3.3 Driver steering control based on lane departure warning alone

The PATH lane departure warning system based on the magnetic markers is derived from the PATH “steering guidance” system. A modified predictor computation triggers the departure warning signals. A lane departure warning sounds when the modified predictor reaches the left or right lane boundaries at one-second headway. Although spatially separated warning speakers (right side for right lane departure warning, and left side for left lane departure warning) are the preferred audible warning system configuration, due to the limited preparation time, different sound patterns from one speaker are used for the left and right lane departure warning in these tests.

Special steering maneuvers are designed to test the performance of this lane departure warning system. For the basic benchmark scenario discussed in this report, the driver is advised to steer the vehicle in a specific manner using the lane departure warning signals. He tries to keep his current steering angle until the lane departure warning starts. At that point, he reacts to the pending departure situation and over-steers the vehicle back into the lane. The driver freezes the steering correction as soon as the lane departure warning stops. Such steering maneuvers create an oscillatory vehicle trajectory as well as stringent operating conditions for any lane departure warning system. The goal is to demonstrate a reliable lane departure warning system under various departure conditions.

As the driver steers the vehicle based on the method described above, he also controls the speed according to the verbal commands given by the test assistant to follow the specific speed profile. Similarly, the “lane departure warning controller” determines the modified

“predictor” based on the lateral displacements calculated from the magnetic marker signals, the curvature information stored in the computer matched by control point marker, as well as the current steering wheel angle.

Although the detailed system performance of this proving test scenario is not in the same level of consistency as those of the automatic or guidance control systems described in Sections 3.1 and 3.2, the performance characteristics for the same driver exhibit remarkably similar behavior. Therefore, only two data sets are recorded and presented in this report. Fig. 3.4.1 shows the vehicle lateral deviation from the road center as well as the vehicle departure angle from the road center lane for these two tests. Fig. 3.4.2 illustrates the vehicle speed and the associated road curvature. Fig. 3.4.3 shows the detailed warning signals from marker #300 to #700 for test 2. By examining Fig. 3.4.3, one can observe that the warning signals are reliably generated under a wide range of departure conditions: different speeds, lateral deviations, as well as low to high departure angles (2 to 5 degrees). Even with large departure angles, the vehicle is controlled within the lane boundary most of the times (the outer ring of the tire touches the lane dividers at 0.85 cm and the inside of the tire touches them at 1.15 cm).

Using these three figures, one can observe the following about the lane departure warning system:

- (1) The vehicle is consistently maintained close to the lane boundaries even under severe departure conditions. The excursions into the adjacent lane, which usually happen on sharp curves at higher speeds, are generally kept within the width of a tire.
- (2) The error attributed to the curve transition is not significant as illustrated by plots for all six curve-transitions. The maximum lateral deviation is smaller (by up to 50 cm) on the straighter road than on sharp curves. Higher vehicle speed also creates larger error; however, sharp curves create even larger error.
- (3) No significant steady state lateral deviation is observed on the curves because the predictor is computed using the curvature information.

(4) Because the magnetic lateral sensing system is very accurate, the computation of the lane departure warning is reliable and precise. No false alarms or missing alarms are ever observed in the data sets.

The benchmark tests in this subsection demonstrate the effectiveness of the lane departure warning system based on the magnetic markers. This warning system provides a very reliable lane departure warning for the driver at all times as long as the magnetic markers are read. This system can also effectively support all the services discussed in the report.

By combining the capabilities of automatic steering control, driver steering guidance display and the lane departure warning system, the PATH lateral system based on the magnetic markers creates a high performance lateral guidance/control system for the vehicle. With such capabilities, the driver as well as the vehicle possess a wide range of possibilities, from warning to full automation, for prevention of lane departure under various curves and visibility conditions. The lane departure prevention control is one such example that will be illustrated in Section 4 with the demonstration scenarios.

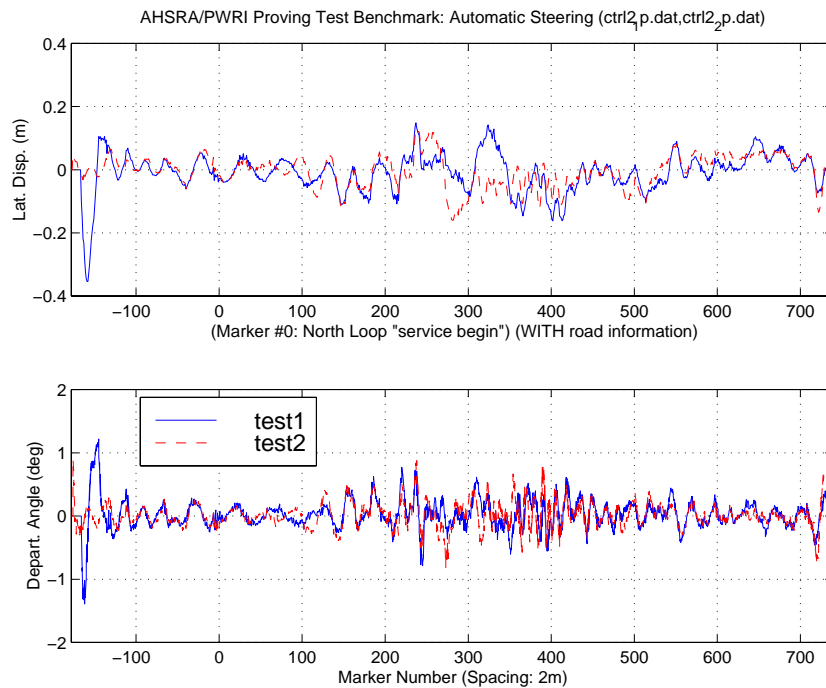


Fig. 3.2.1. Proving Test Benchmark: Automatic Steering (2m marker spacing, using road information) (lateral deviation and vehicle departure angle)

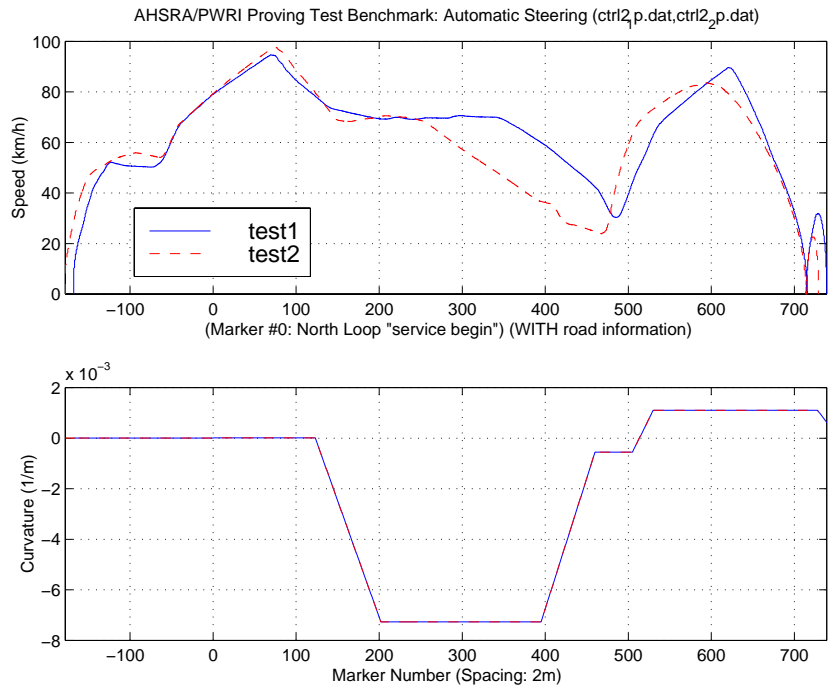


Fig. 3.2.2. Proving Test Benchmark: Automatic Steering (vehicle speed and road curvature)

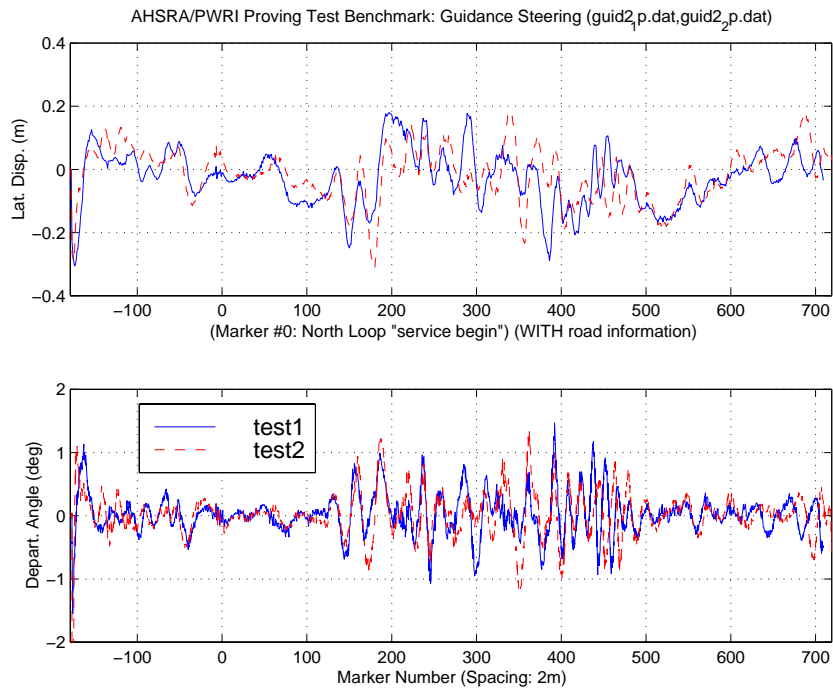


Fig. 3.3.1. Proving Test Benchmark: Steering Guidance based on HMI alone (2m marker spacing, using road information) (lateral deviation and vehicle departure angle)

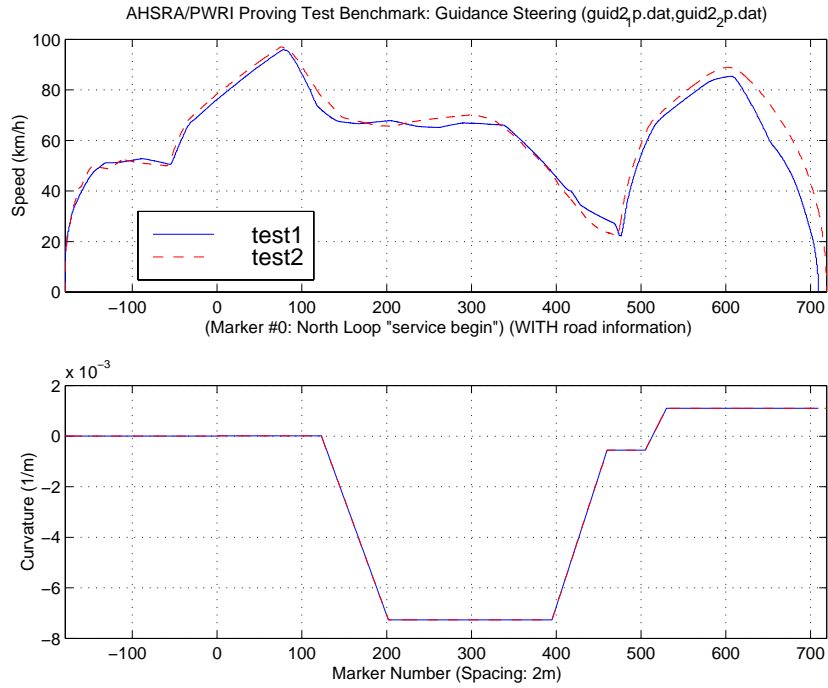


Fig. 3.3.2. Proving Test Benchmark: Steering Guidance based on HMI alone (vehicle speed and road curvature)

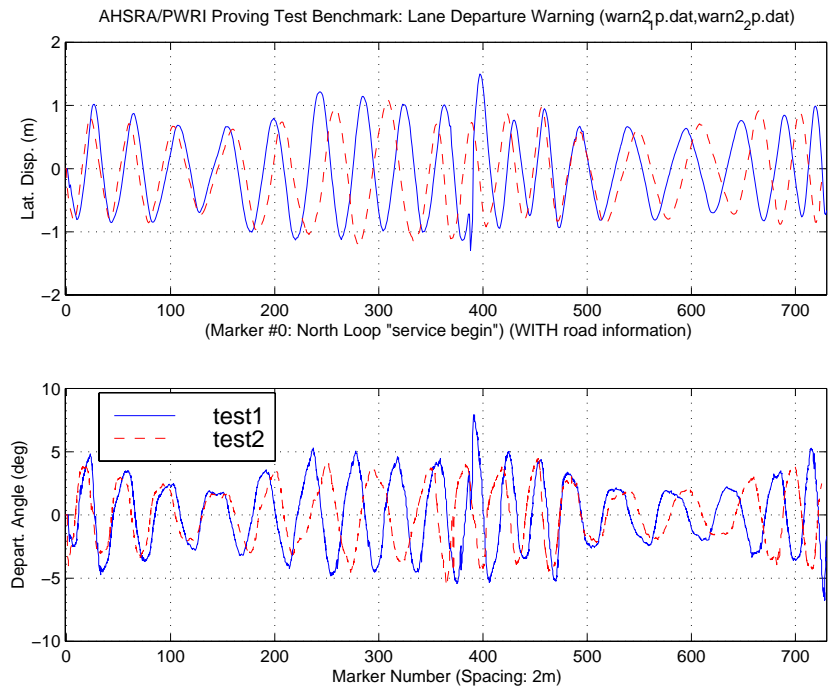


Fig. 3.4.1. Proving Test Benchmark: Driver Steering based on Lane Departure Warning alone (2m marker spacing, using road information) (lateral deviation and vehicle departure angle)

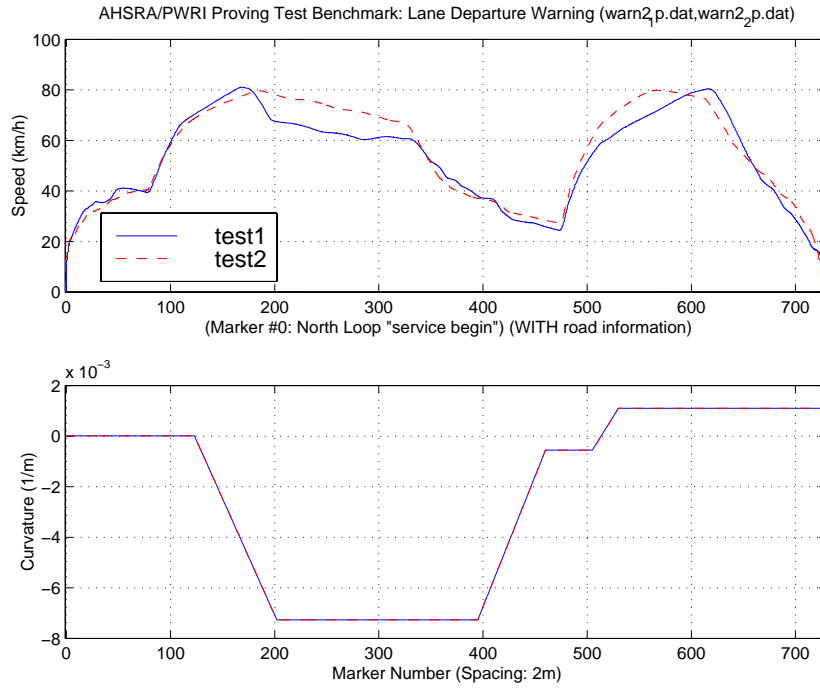


Fig. 3.4.2. Proving Test Benchmark: Driver Steering based on Lane Departure Warning alone (vehicle speed and road curvature)

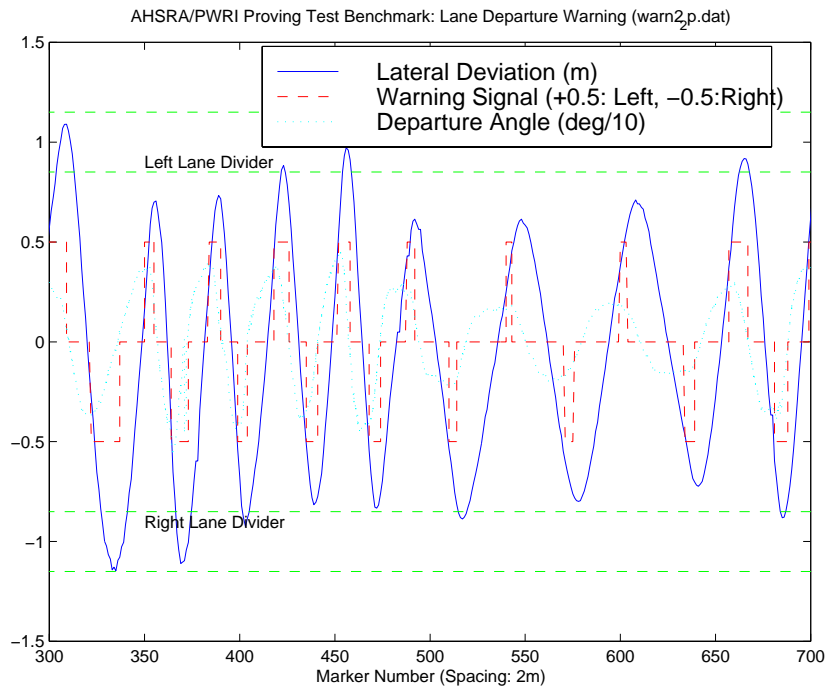


Fig. 3.4.3. Proving Test Benchmark: Driver Steering based Lane Departure Warning (lateral deviation and warning signals)

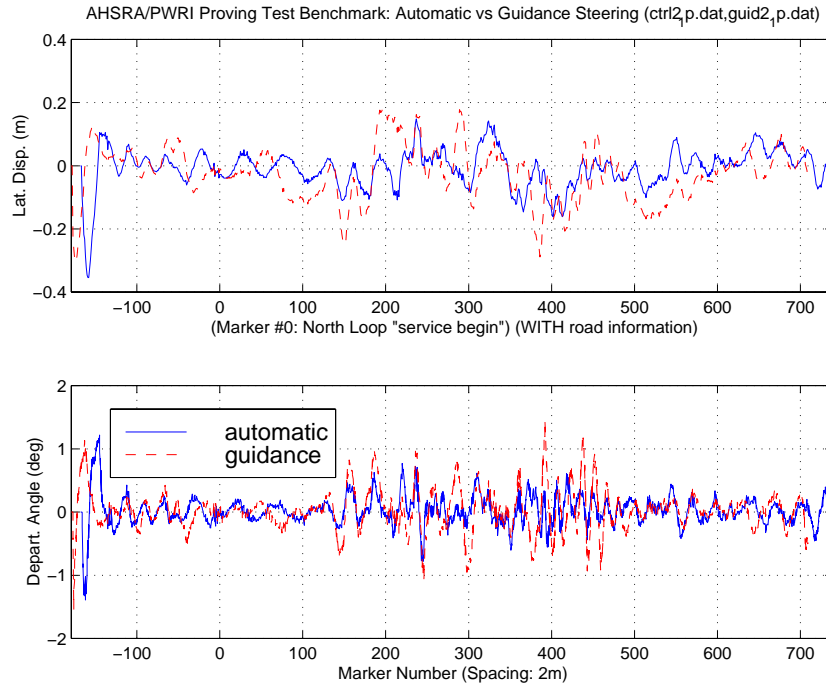


Fig. 3.5. Proving Test Benchmark: Automatic vs Guidance Steering (2m marker spacing, using road information) (lateral deviation and vehicle departure angle)

4 Demo2000 Scenarios

The PATH test vehicle (Buick LeSabre) demonstrated three scenarios during Demo2000 at the PWRI test track in Tsukuba City, Japan. The PATH lateral sensing system reads the magnetic field of the magnetic markers (position markers) and generates accurate lateral deviations every 2 meters. AHSRA’s radio antenna receives information from the control point markers (“service-begin” and “service-end” markers), and transmits them to the PATH on-board computer. Using the test track map stored in the computer and counting the magnetic markers, the PATH system has the knowledge of both the curvature information and the obstacle location. PATH successfully demonstrated the functions of “automatic steering control”, “driver guidance display”, “lane departure warning”, “lane departure prevention control”, as well as “manual and automatic transition”. These functions proved to be the effective in supporting the three services described in Section 3. These services are prevention of overshooting on curve, prevention of lane departure under expressway speed condition, and prevention of lane departure under fog condition.

The demonstrations were very successful. Not a single failure occurred during the 4-day demonstration and 5-day rehearsal.

The capabilities demonstrated for the three scenarios are listed below:

(1) North loop:

Smooth switching between manual and automatic steering at any vehicle speeds and at any road curvature conditions, automatic steering control on sharp curves at high speeds, reliable lane departure warning on curves, and automatic lane departure prevention control.

(2) Whole Loop (i.e. north loop and outer loop):

Same as above, and obstacle warning.

(3) Fog Tunnel:

Steering guidance in zero visibility conditions (fog), automatic steering control, lane departure warning, smooth switching from manual to automatic, and obstacle warning.

4.1 General Demo Scenarios Description

The goal of the PATH demonstration is to show the effectiveness of the lateral “warning/guidance/control” systems based on the magnetic markers to support various driver steering functions. The main purpose of this demonstration is to show the system’s capabilities. Since most functions demonstrated can be initiated at any time or location either by the driver (e.g., switching in and out of automatic steering control) or by the automatic system (e.g., lane departure prevention control), the “demo scenario” described in this section is only a “guideline” for demonstration. The driver often modified the scenario during the demonstration, for example driving up to 100 km/h on the South Loop curve, or continuously switching between manual and automatic control at very high speeds.

The main demonstration is the Whole Loop. It starts at the main garage. On the first straight, steering guidance, steering control and switching at low speed are demonstrated. Then the vehicle speeds up to 110-130 km/h while doing some fast switching. Just before

the “service-begin” marker, the vehicle slows down to 80-90 km/h and is switched back to steering guidance. After the North Loop “service-begin” marker, lane departure warning followed by lane departure prevention control are shown. At the beginning of the big curve (137 m radius), the vehicle is switched back to automatic steering control to drive the curve at 65-75 km/h. At the end of the curve, the vehicle accelerates to 80-90 km/h and is switched back to steering guidance. Curve overshooting and lane departure warning are shown on both sides. On the straight by the fog tunnel, lane departure warning and lane departure prevention control are shown. From the North Loop “service-end” marker to the South Loop “service-begin” marker, steering guidance, steering control and switching are demonstrated. After the South Loop “service-begin” marker, curve overshooting, as well as lane departure warning and prevention control, and obstacle warning, are shown. After the obstacle and through the South Loop “service-end” marker, the vehicle is switched back to automatic steering control and speeds up to drive the curve at 90 km/h. At the warning for the end of the track, the vehicle slows down and is switched back to manual driving.

The second demonstration is the Rain and Fog Tunnel. Steering guidance in the fog is demonstrated up to 50 km/h. A few demonstrations happened in almost zero visibility. At the obstacle warning (5 seconds before reaching the obstacle), the vehicle slows down and overtakes the obstacle. Once it is back into the lane, lane departure warning is shown on both sides. After the “service-end” marker and once the magnets start again, the vehicle is switched to automatic steering control and driven at 70 km/h. At the end of the tunnel, the vehicle is switched back to manual driving.

Since the North Loop demonstration is part of the Whole Loop demonstration, it will not be explained separately.

4.2 Detailed Demo Scenario Examples

Two data sets, one for the Whole Loop scenario, the other one for the Fog Tunnel scenario, recorded during the rehearsal period of Demo2000, are presented in this section as examples of the demo scenario. As explained in the previous section, these data serve

as examples to illustrate the system’s capabilities. Some demonstrations during Demo2000 were even more “aggressive” than those presented in this report.

Figs. 4.1.1, 4.1.2 and 4.1.3 show the lateral deviation, control and warning states, as well as speed and curvature, respectively, for the Whole Loop Demo example. Similarly, Figs. 4.2.1, 4.2.2, and 4.2.3 show the same information for the Fog Tunnel Demo example. Figs. 4.1.1 and 4.2.1 provide a rough description of the capabilities used during the particular demo examples. Figs. 4.1.2 and 4.2.2 plot the corresponding control and warning states of the “warning/guidance/control” system during the demonstration. There are three control states: (1) manual/guidance steering, (2) automatic steering control, and (3) lane departure prevention control. The driver uses buttons on the steering wheel to switch back and forth between the control states (1) and (2). Lane departure prevention control is a feature that the driver can select. Once activated by the driver, the vehicle automatically switches to “automatic steering control” if the driver continuously ignores the lane departure warning and the vehicle begins to drift into the adjacent lane. Three warning states are involved in these two examples: left and right lane departure warnings and obstacle warning. Finally, Figs. 4.1.3 and 4.2.3 mark the positions of the “service-begin” marker, “service-end” marker, and the obstacle’s location for reference. Cross-examining the above figures gives a clear picture of the demonstration. The key capabilities of the two examples are listed in the tables below.

Time(s)	Demo Scenario	Speed(km/h)	Curvature
10-94	60 manual/automatic switches	0-137-86	straight
94-105	2 lane departure prevention control (<50cm)	86-76	straight – right transition
105-135	automatic control on curve (error<10cm)	76-70	transition-right curve (137m)
135-150	4 lane departure warning (within boundaries)	70	right curve – left curve
150-175	22 manual/automatic switches on curves	70-80	left curve – straight (sharp)
175-210	5 lane departure prevention control (<45cm)	80	straight
210-250	30 manual/automatic switches	80	straight –left-right curve
250-262	obstacle avoidance	80-40	right curve (213m)
262-299	automatic control on curve (error<8cm)	40-85	right curve (213m)

Table 4.1. Whole Loop Demo Example (Figs. 4.1.1, 4.1.2, and 4.1.3)

Time(s)	Demo Scenario	Speed(km/h)	Curvature
15-24	guidance steering in heavy fog (error<20cm)	0-46	straight
24-30	obstacle avoidance	46-20	straight
30-46	guidance/manual steering	20-55	straight
46-67	automatic control (error<6cm)	55-57	straight

Table 4.2. Fog Tunnel Demo Example (Figs. 4.2.1, 4.2.2, and 4.2.3)

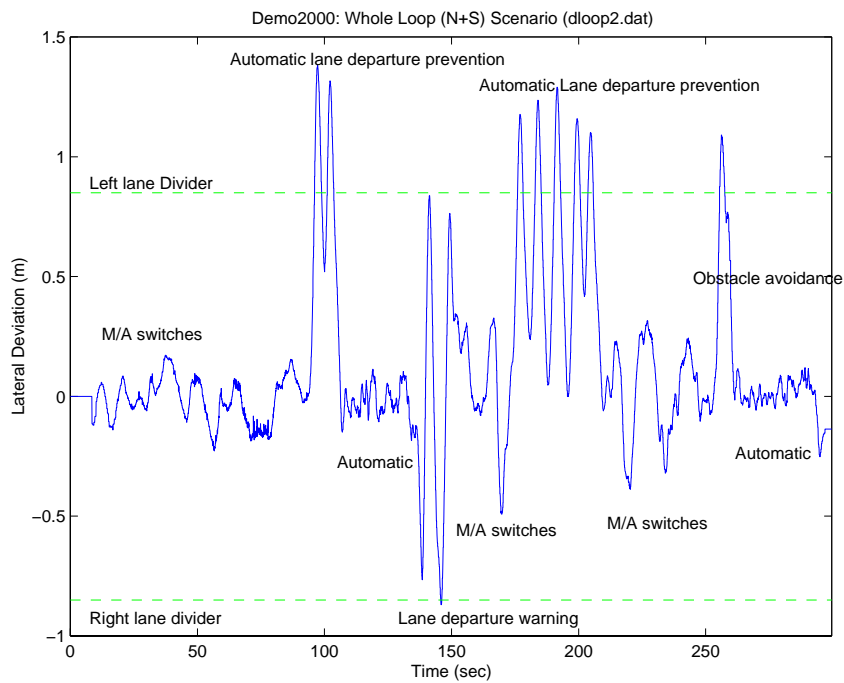


Fig. 4.1.1. Demo2000 Whole Loop (North + South Loops) Scenario (lateral deviation)

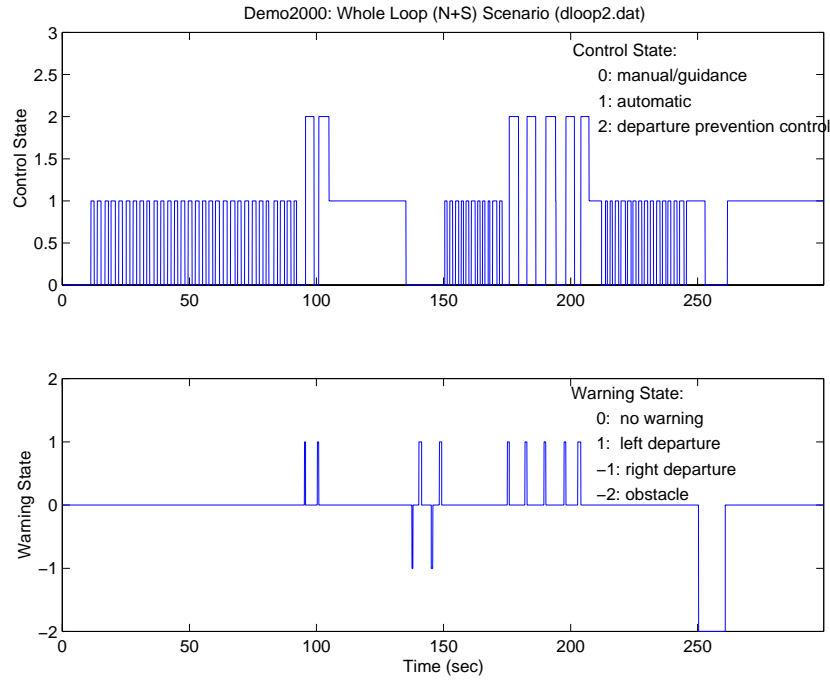


Fig. 4.1.2. Demo2000 Whole Loop (North + South Loops) Scenario (control and warning states)

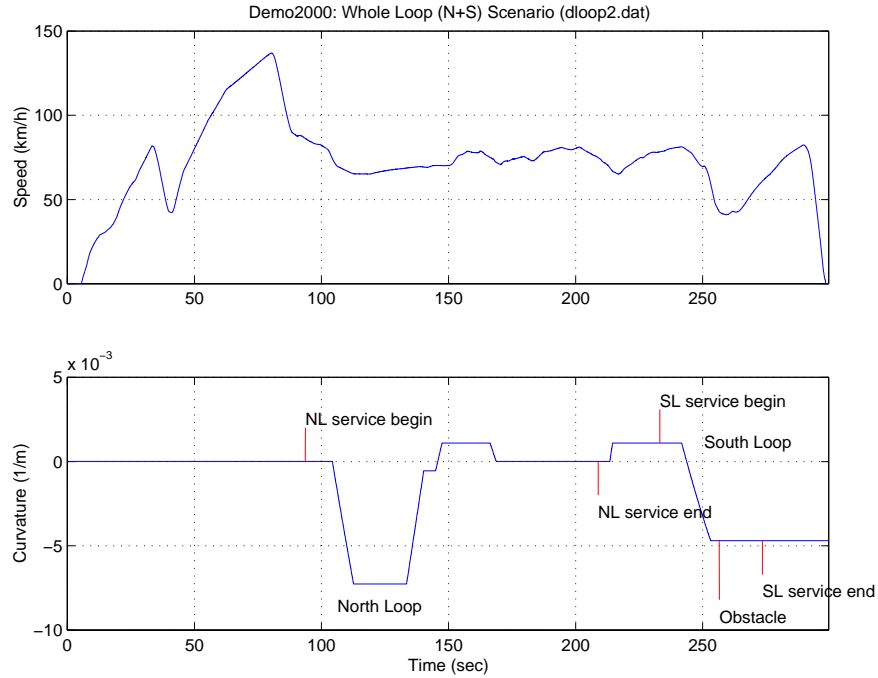


Fig. 4.1.3. Demo2000 Whole Loop (North + South Loops) Scenario (speed and curvature)

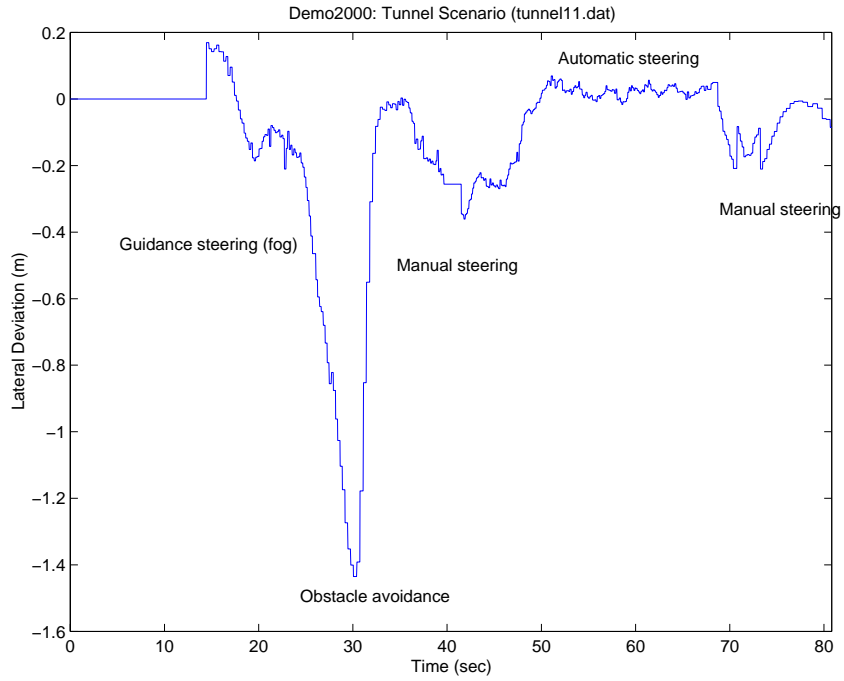


Fig. 4.2.1. Demo2000 Fog Tunnel Scenario (lateral deviation)

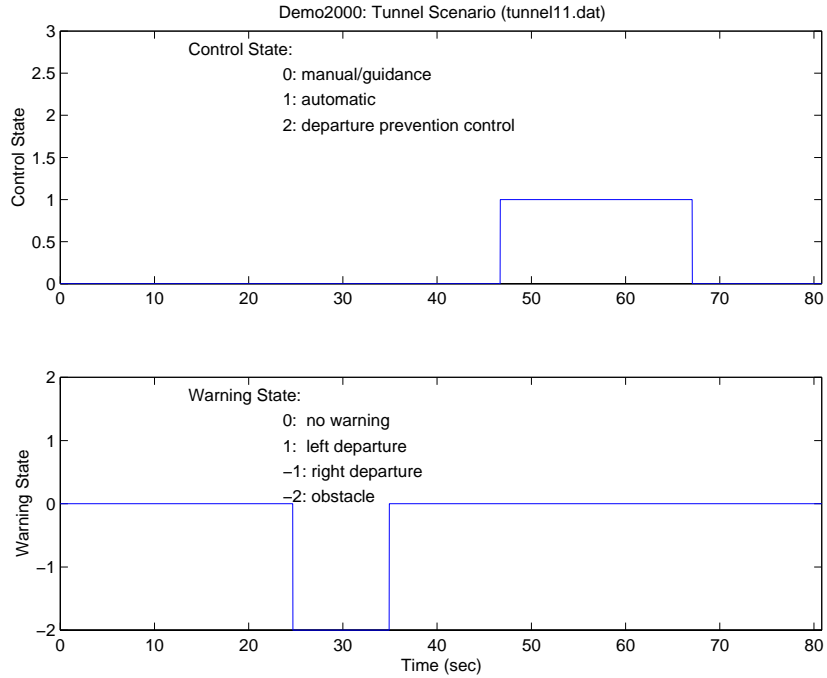


Fig. 4.2.2. Demo2000 Fog Tunnel Scenario (control and warning states)

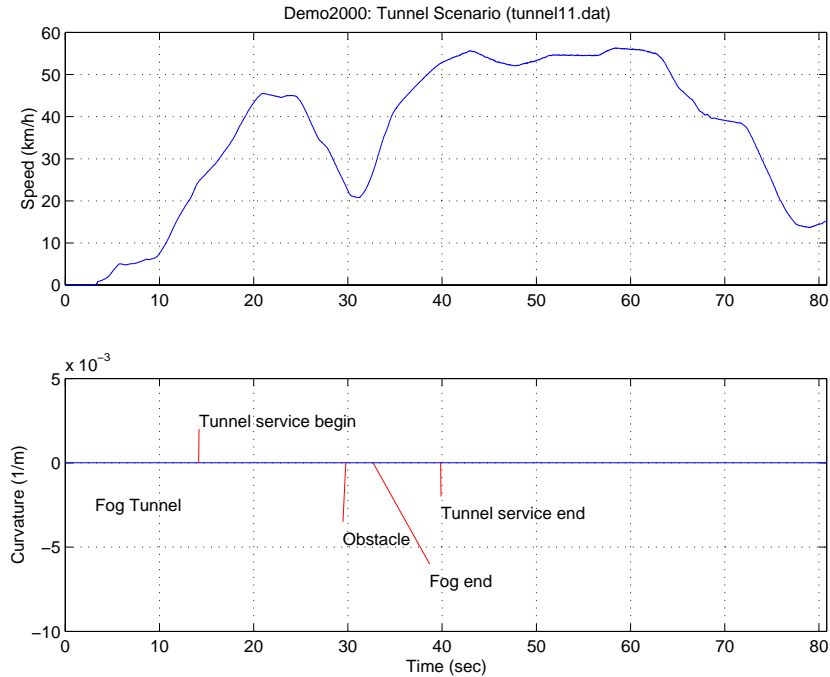


Fig. 4.2.3. Demo2000 Fog Tunnel Scenario (speed and curvature)

5 Proving Tests Without Curvature Information

An infrastructure based vehicle information and control system requires infrastructure to either provide messages such as incoming road information to the moving vehicle or to synchronize the signal for the vehicle to use the appropriate map information. The vehicle then responds to those messages by providing either a warning or guidance to the driver or by initiating appropriate automatic control functions. One important question in applying the magnetic marker sensing technology to vehicle lateral guidance and control is how crucial the curvature information is to the integrity of such “steering control” system. Conventional wisdom suggests that “preview” curvature information is extremely important to the performance and robustness of a lateral control/guidance system. The use of the “curvature information” is particularly critical to the lateral control system based on the magnetic marker measurements because such system is a “look-down” lateral sensing system. However, it has been shown that a well-designed steering control configuration and algorithm can alleviate such limitation. Since “road curvature”

information supplies “feed-forward” input to the control algorithm, the key to a good design is a high performance feedback algorithm. The basic objective of this section is to demonstrate the survivability of a well-designed steering control system under the situation of loss of road curvature information.

The PATH test vehicle acquires its curvature information either by direct magnetic marker coding scheme, or by combining a map with counting magnets, or by radio transmission. For the proving tests in PWRI, the PATH system simulated the 5.8 GHz communication system by counting magnetic markers from the absolute position of the “service-begin” radio wave lane marker. By using the map of the test track stored in the on-board computer, the PATH vehicle has the knowledge of the test track infrastructure information, such as incoming and current road curvatures. In this section, the PATH vehicle ignores the curvature information in all its algorithms. All signal processing, filters, guidance, warning, and control algorithms assume no knowledge of any curvature information.

Similar benchmark tests to those described in Section 3 are used in this section on the same 1.8-km (900 total magnetic markers) test track in the North Loop. The only difference is that the road curvature information is unknown. The three benchmark test scenarios are: (1) automated steering control, (2) driver steering control based on HMI guidance display alone, and (3) driver steering control based on lane departure warning alone. The same speed profile was adopted for easy comparison with the previous test results. Similarly, because of the limited time available for the proving tests as well as the consistency of the performance, only two data sets with one driver are recorded for each basic scenario and discussed in this section. The magnetic marker spacing for all tests in this section is 2 meters.

The test results in the following subsections will help to conclude that:

- (1) The dynamic performance of the PATH guidance/control/warning system is very similar with or without the knowledge of road curvature.

- (2) The performance degradations due to the lack of road curvature information are: (a) larger transient lateral deviation at curve transition, and (b) larger steady state lateral deviation (bias) in the sharp curve section.

5.1 Automated steering control without road curvature information

The tests presented in this section are identical in every aspect to those in Section 3.1 except that there is no curvature “preview” control in the steering control algorithm. The “automatic steering controller” determines the steering wheel angle based solely on the lateral displacements calculated from the magnetic markers.

Since the performance of automatic steering control without curvature preview is found to be extremely consistent, only two test runs are recorded. The data are compared to one of the data sets of Section 3.1 (with curvature preview). Fig. 5.1.1 shows the vehicle lateral deviation from the road center with and without the curvature information. Fig. 5.1.2 plots the vehicle departure angle with respect to the road center as well as the associated vehicle speed. The data are plotted against the marker number (from marker #175 to #725). Using these two figures, one can observe the following about the automatic steering control system with and without the road curvature information:

- (1) Relatively small lateral deviation and vehicle departure angle are consistently maintained. The lateral deviation is kept within 5 cm maximum on the straight road and 30 cm maximum on curves at various testing speeds. The vehicle departure angle is kept within three-quarters of a degree at various speeds and curvatures (less than a third of a degree on straighter roads), which is similar to the case with curvature information.
- (2) By looking at the vehicle departure angle, one can observe that the dynamic lateral behavior of the “controlled” vehicle is remarkably similar with and without the use of the road curvature information. Slight variations occur only during the sharp curve transition (at marker #125).
- (3) The most noticeable difference between the performance with and without road curvature shows up on the plot of the lateral deviation during the curves and curve

transition (from marker #125 to #650). The major differences are the transitional tracking error and the steady state error (for example 20 cm during the curve of 137 m radius of curvature) that is required to generate the feedback steering command for maintaining the curve without prior road curvature information.

The above benchmark tests demonstrate the effectiveness of the automatic steering control based on the magnetic markers with and without the knowledge of the road curvature information. The curvature information, although reducing the transient and steady state error on curves, does not jeopardize the integrity of the steering control system when it is not available. This ability significantly increases the robustness of such lateral control system.

5.2 Driver steering control based on guidance display alone without road curvature information

The benchmark test scenario in this section is the same as the one described in Section 3.2. The driver uses the predictor in the “guidance steering display” mounted on the dashboard to steer the vehicle with the windshield blocked. The driver controls the vehicle speed based on the verbal commands given by the test assistant according to the speed profile. The only difference in this setup is that the “guidance controller” has no information of the road curvature, both current and future. The guidance “controller” determines the “predictor” based on the lateral displacements calculated by the magnetic markers and on the current steering wheel angle. With no road curvature information, the “guidance display” assumes that the road is always “straight”.

Since the system performance is also very consistent, two data sets, one with and one without road curvature, are plotted for clarity. Fig. 5.2.1 shows the vehicle lateral deviation from the road center. Fig. 5.2.2 shows the steering wheel angle and the associated vehicle speed. Using these two figures, one can observe the following about the driver steering guidance system with and without road curvature information:

- (1) Similar lateral deviation is observed on the straight section in Fig. 5.2.1, whereas a significantly larger bias (steady state error) is found on the sharp curve for the system without the curvature knowledge (e.g., 50 cm from markers #150 to #400).
- (2) Fig. 5.2.2 depicts a very interesting phenomenon. The driver steering angles from two different tests (following the same speed profile) exhibit almost identical steering behavior despite the fact that noticeable lateral deviation is observed in Fig. 5.2.1.

The benchmark tests in this subsection demonstrate the stability of the driver guidance steering control system based on the magnetic markers with respect to the road curvature information. The driver can still operate the “guidance system” to maintain the vehicle in the lane when the road curvature information is incorrect. Steady state lateral deviation is the result of the incorrect curvature information, since the guidance system assumes the vehicle is travelling on a road with a different curvature than the true one.

5.3 Driver steering control based on lane departure warning without road curvature information

The test procedure presented in this section is identical to the one used in Section 3.3. The driver steers the vehicle in a specific manner using the lane departure warning while controlling the speed according to the speed profile. The driver keeps his current steering angle as long as no lane departure warning is issued. He reacts to the pending departure situation and over-steers the vehicle back into the lane during the period when the departure warning sound is on. The only difference in the setup in this section is that the “departure warning system” has no information of both current and future road curvatures. The warning signal is determined based on the lateral displacements calculated from the magnetic markers and the current steering wheel angle. With no road curvature information, the “lane departure warning” assumes that the road is always “straight”.

Since the PATH lane departure warning system based on the magnetic markers is derived from the PATH “steering guidance” system, the performance difference between with and without curvature information is expected to be very similar to that from the “steering

guidance” system described in Section 5.2. Two data sets, one with and one without road curvature, are plotted using the same format as in Section 5.2. Fig. 5.3.1 compares the vehicle lateral deviation from the road center for these two cases. Fig. 5.3.2 shows the steering wheel angle and the associated vehicle speed. Using these two figures, one can observe the following about the lane departure warning system with and without road curvature information:

- (1) Similar lateral deviation is observed on the straight section in Fig. 5.3.1, whereas a significantly larger bias (steady state error) is found on the sharp curve for the system without the curvature knowledge (e.g., 40-50 cm from markers #150 to #400).
- (2) As shown by Fig. 5.3.1, although the driver is able to drive the vehicle back into the lane consistently, several 50 cm excursions into the left lane occur on the sharp curve. Those excursions result from the fact that the warning system assumes the road is straight instead of a 137 m radius right turn.
- (3) Fig. 5.3.2 reveals an observation very similar to the steering guidance case as discussed in Section 5.2. The driver steering angle from two different tests (following the similar speed profile) exhibit the same steering pattern despite the fact that noticeable lateral deviation is observed in Fig. 5.3.1.
- (4) In general, the results of the cases with and without curvature in the lane departure warning tests (as in Figs. 5.3) show slightly more discrepancy than those in the steering guidance tests (as in Figs. 5.2). Fig. 5.3.2 shows that the testing speed is not consistently controlled in the case of the lane departure warning. By carefully examining the vehicle speeds during testing, it can be found that most discrepancies can be explained by the differences in speeds between the two tests.

The benchmark tests in this subsection present a conclusion very similar to the steering guidance case in Section 5.2. They demonstrate the stability of the lane departure warning system based on the magnetic markers with respect to the road curvature information. However, “excursions” into the adjacent lane are possible when the road curvature information is incorrect, since the lane departure warning system assumes the vehicle is travelling on a road with a different curvature than the true one.

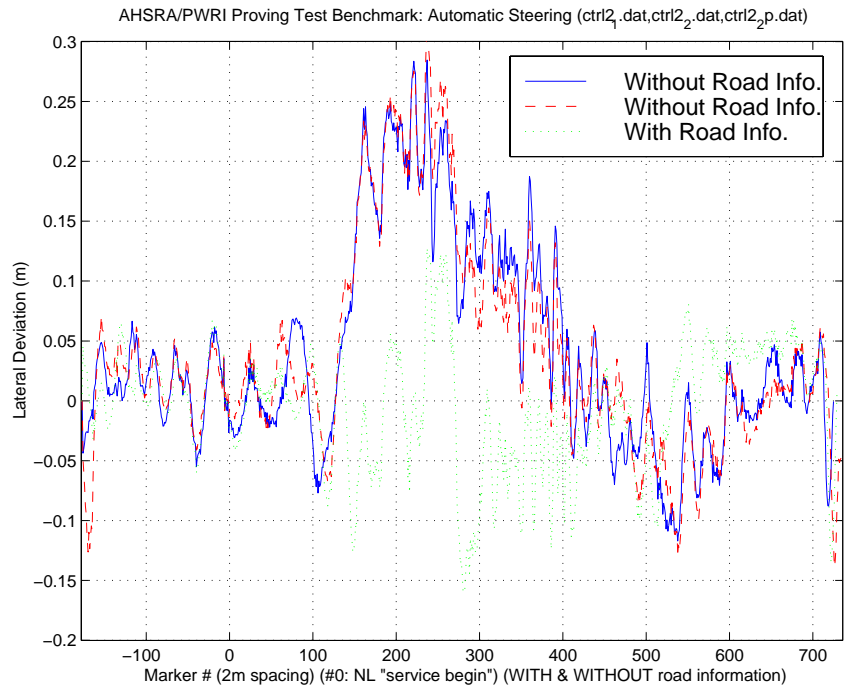


Fig. 5.1.1. Proving Test Benchmark: Automatic Steering (2m marker spacing, with and without road information) (lateral deviation)

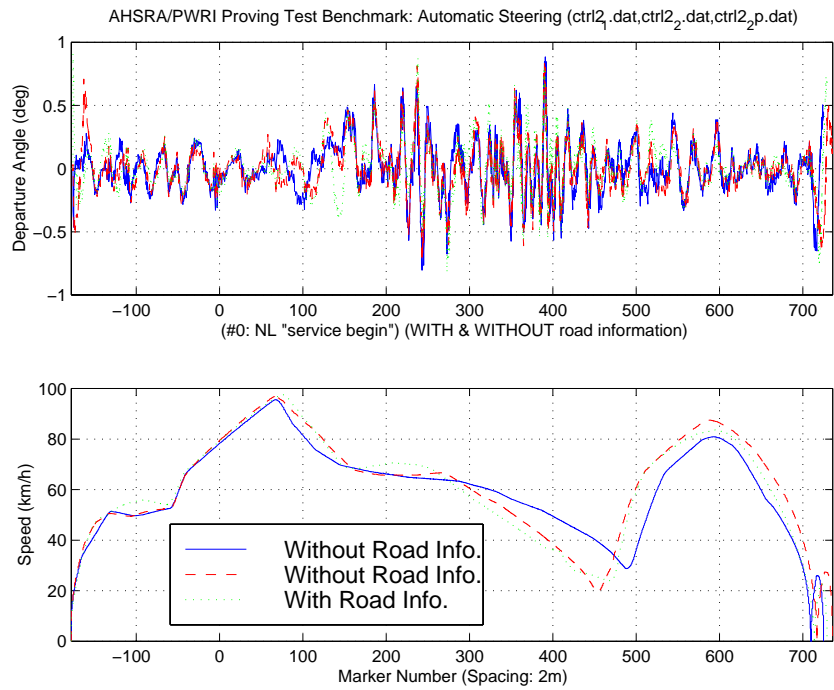


Fig. 5.1.2. Proving Test Benchmark: Automatic Steering (w & w/o road information) (2m marker spacing) (vehicle departure angle and speed)

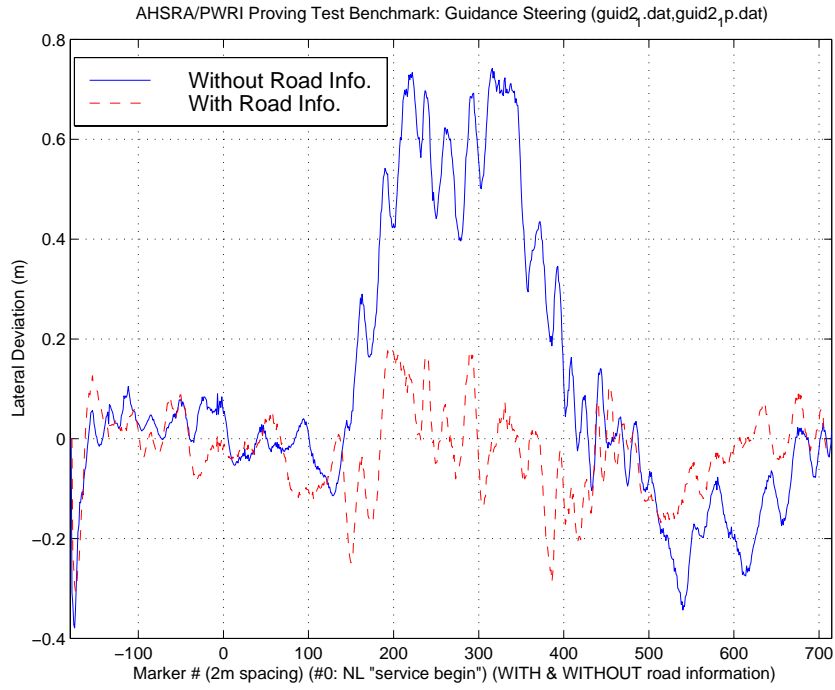


Fig. 5.2.1. Proving Test Benchmark: Driver Guidance Steering (2m marker spacing, with and without road information) (lateral deviation)

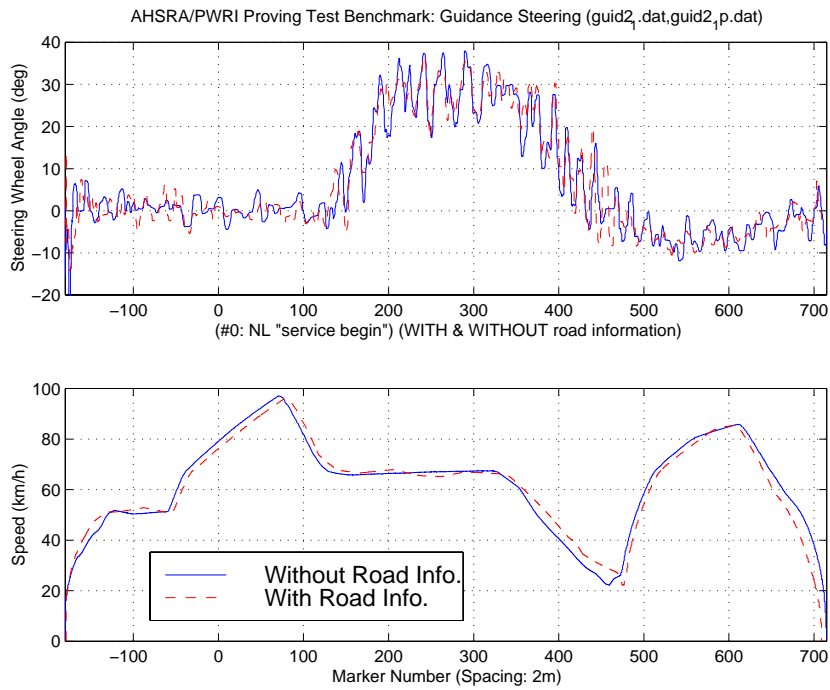


Fig. 5.2.2. Proving Test Benchmark: Guidance Steering (w & w/o road information) (2m marker spacing) (steering wheel angle and speed)

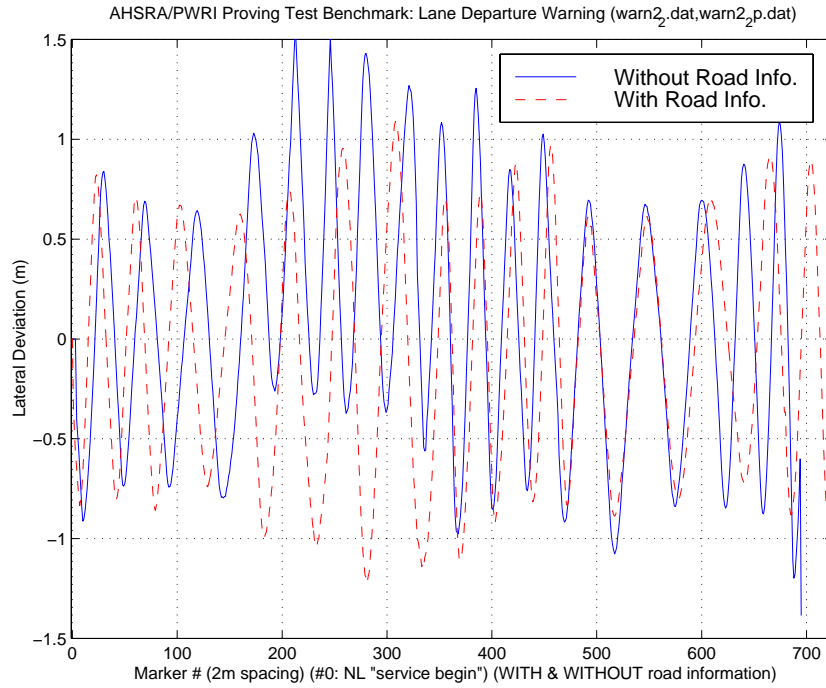


Fig. 5.3.1. Proving Test Benchmark: Lane Departure Warning (2m marker spacing, with and without road information) (lateral deviation)

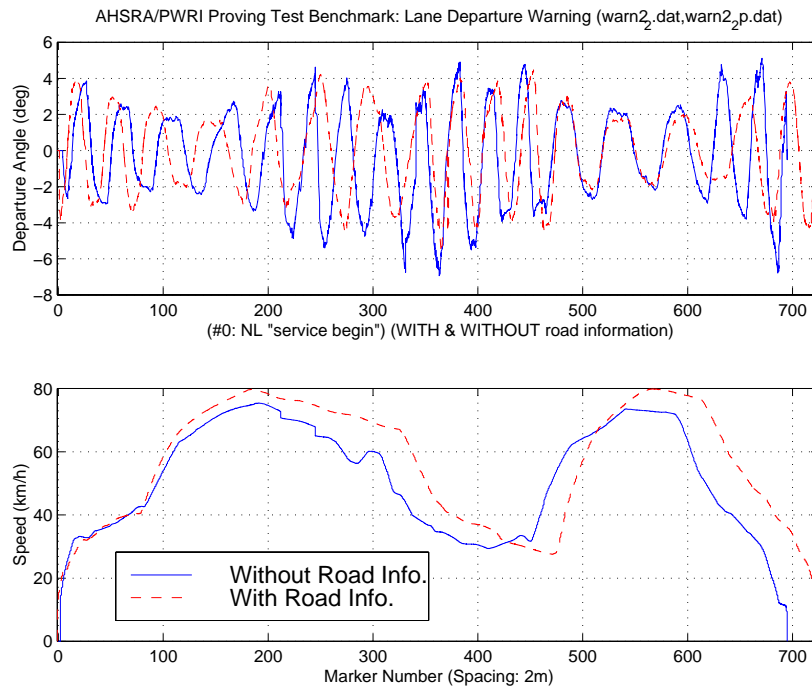


Fig. 5.3.2. Proving Test Benchmark: Lane Departure Warning (w & w/o road information) (2m marker spacing) (steering wheel angle and speed)

In conclusion, the PATH guidance/control/warning system exhibits very similar dynamic behavior with or without the knowledge of road curvature. The primary performance degradation due to the lack of road curvature information is the larger transient and steady state lateral deviation on curves.

6 Proving Tests with Magnetic Marker Spacing of 2, 4, 6 meters

Accuracy and reliability are two important advantages of the lateral sensing system based on the magnetic markers. However, these advantages are based on the fact that magnetic markers are carefully installed under the roadway. Therefore any reduction in the number of magnetic markers required for safe operation will improve both the infrastructure installation cost and the maintenance complexity. This section investigates the effects of the system performance with respect to various magnetic marker spacings, and in particular, to larger marker spacing.

PATH has extensive experience on lateral sensing systems based on the magnetic markers embedded on the roadway. The standard marker spacing used by PATH at various implementation sites is between 1 and 1.25 meters. Additionally, the test results in the previous sections clearly demonstrated that satisfactory performance can be obtained using 2-meter magnetic marker spacing. In order to get a first-hand experience about the performance reduction resulting from larger marker spacing, PATH devised a simple method to simulate the effects of larger marker spacing without physically reinstalling the magnetic markers.

A simple way to simulate larger marker spacing involves systematically skipping magnetic marker measurements as the vehicle travels over the magnetic markers. The magnetic sensors in the vehicle read the magnetic field strength of all the magnetic markers passing under the sensors. The on-board magnetic signal-processing algorithm processes these measurements and produces the lateral deviations with respect to every magnetic marker as usual. However, only the selected lateral deviations will be passed on to the rest of the vehicle applications, such as to the automatic steering controller,

guidance display controller as well as lane departure warning processor. The “standard marker spacing” is 2 meters for the test track in PWRI. If the magnetic signal-processing algorithm outputs every other marker measurements, the vehicle applications will consider the marker spacing to be 4 meters instead of 2. If the system skips two consecutive magnetic markers every time, the lateral sensing system will produce one lateral deviation every 6 meters. In all practical purposes, the magnetic sensing system can simulate any marker spacing that is an integer multiple of the standard marker spacing.

In order to provide a fair comparison to various performances of the steering control, driver guidance, and lane departure warning systems, the same algorithms are used for all the tests in this section. The only modification made is to the parameters that have a physical interpretation directly proportional to the marker spacing. No other change or re-tuning was made in any of the control, guidance, and warning algorithms.

Similar benchmark tests to those described in Section 3 and 5 (with and without curvature information, respectively) are used in this section for the case of various magnetic marker spacing. Those tests are conducted on the same 1.8-km test track in the North Loop. The three benchmark test scenarios are the same: (1) automated steering control, (2) driver steering control based on guidance display alone, and (3) driver steering control based on lane departure warning alone. The same speed profile was adopted for easy comparison with the previous test results. The magnetic marker spacing chosen for performance comparisons in this report is 2, 4 and 6 meters. Fig. 6.1 shows a typical example (extracted from the test data in Section 6.1) of the simulated lateral measurements. It clearly illustrates that the lateral measurements from 2-meter spacing have three times more marker readings than those from 6-meter spacing. However, all figures in this section are plotted against the “original” marker number for simplicity.

The main objectives of this section are to:

- (1) Examine the degree of performance degradation with respect to various larger marker spacing.

- (2) Investigate the critical operational factors that affect the performance sensitivity when large marker spacing is used.
- (3) Determine how strong are the effects of the curvature information on the performance sensitivity with respect to large marker spacing.

6.1 Automated steering control with curvature information

The tests presented in this section are identical to those in Section 3.1 except for the various marker spacing. The “automatic steering controller” determines the steering wheel angle based on the lateral displacements at the specific marker spacing as well as the curvature information.

Automatic steering control is used to collect one test run for each marker spacing (2, 4 and 6 meters). Fig. 6.2.1 compares the vehicle lateral deviation from the road center for the three cases. Fig. 6.2.2 plots the corresponding vehicle departure angle with respect to the road center. Fig.6.2.3 shows the respective vehicle speed and road curvature. Although the total number of “markers” is supposed to be different for different marker spacing, the data are still plotted against the “original” (2 m) marker number (from marker #-175 to #725) for easy comparison. Using these three figures, one can observe the following about the automatic steering control system under various magnetic marker spacing:

- (1) Lateral deviation and departure angle exhibit almost identical behavior in the 2m and 4m spacing cases at higher vehicle speeds. A slight increase of both lateral deviation and departure angle can be seen when the vehicle is on the curve with medium speeds. However, the final “stop and go” on the curve created a -0.6 m transient error for the case of 4m spacing.
- (2) The lateral deviation and departure angle in the 6m spacing case exhibit a somewhat degraded performance compared to the 2m spacing when the vehicle is on the curve at medium speeds. However, as the vehicle speed is reduced to below 25 km/h, the control system becomes unstable (at marker #440 such that the test is terminated).

The system performance is quite similar for marker spacing of 2, 4 and 6 meters when the vehicle is operated on the straight road at high speeds.

Above observations suggest the following conclusions for the automatic steering control system with respect to the marker spacing:

- (1) The performance degradation from 2m spacing to 4m spacing is quite small except at very low speeds.
- (2) Noticeable performance degradation, especially at lower speeds, can be observed from 4m to 6m marker spacing.
- (3) Lateral deviation slightly increases on the curve in the 6m marker spacing.
- (4) High speed on a straight curve is the least sensitive to the increase of the marker spacing.

6.2 Driver steering control based on guidance display alone with curvature information

The test scenario in this section is the same as the benchmark described in Section 3.2 except for the various marker spacing. The guidance “controller” determines the “predictor” based on the lateral displacements at the specific marker spacing, the current steering angle and the curvature information.

As in Section 6.1, data from one test run for each marker spacing (2, 4 and 6 meters) are used for performance comparison. Fig. 6.3.1 compares the vehicle lateral deviation from the road center for the three cases. Fig. 6.3.2 plots the corresponding driver steering wheel angle. Using these two figures, one can observe the following about the driver guidance steering system under various magnetic marker spacing:

- (1) Lateral deviation and departure angle exhibit similar behavior in the 2m and 4m spacing cases at higher vehicle speeds. Some increase of both lateral deviation and departure angle can be seen when the vehicle is on the curve at medium speeds. The most noticeable degradation appears in the 4m spacing case when the vehicle is on the curve at low speeds (marker #400 to #450).

(2) Examining Figs. 6.3, it can be observed that the only situation when the performance of the 6m spacing case is not degraded is when the vehicle is operated on the straight road with higher speeds (marker #-175 to #125). Otherwise, when the vehicle is on the curve (marker #150 to #400) or at low speeds (marker #400 to #500), the lateral deviation and departure angle in the 6m spacing case exhibit a very noticeable degraded performance compared to the 2m spacing case. The worst performance occurs when the vehicle is on curve at low speeds (from marker #400 to #500).

The above test results provide the following observations for the steering guidance system with respect to marker spacing:

- (1) The performance degradation from 2m spacing to 4m spacing is quite small; such degradation increases at low speeds and on curves.
- (2) Noticeable performance degradation can be observed when the marker spacing increases from 4m to 6m. Such degradation is very visible at lower vehicle speeds and on curves.
- (3) High speed on a straight curve is the least sensitive to the increase of the marker spacing.

6.3 Driver steering control based on lane departure warning alone with curvature information

The test scenario in this section is similar to the benchmark test described in Section 3.3, except that various marker spacings are used in this section. The lane departure warning “controller” determines the warning signals based on the lateral displacements at the specific marker spacing, the current steering angle and the curvature information.

As in Section 6.2, data from one test run for each marker spacing (2, 4 and 6 meters) are used for performance comparison. Fig. 6.4.1 compares the vehicle lateral deviation from the road center for the three cases. Fig. 6.4.2 plots the corresponding vehicle departure angles. Using these two figures, the following can be observed about the lane departure warning system under various magnetic marker spacing:

- (1) Lateral deviation and departure angle exhibit similar behavior in the 2m and 4m spacing cases at higher vehicle speeds. The only noticeable degradation appears in the 4m spacing case when the vehicle is on the curve at low speeds (marker #400 to #500).
- (2) Examining Figs. 6.4, it can be observed that the performance of the 6m spacing case is noticeably degraded compared to either the 4m or 2m spacing case. Even the situation with high speeds on straight road shows a significant degradation. This may be caused by the computation of large departure angles under the particular test maneuvers in this section. Fig. 6.4.2 also indicates the increase of the noise effect in the computed departure angle for the 6m spacing case. However, the combination of low speeds and curve still creates the largest degradation.

The above test results provide the following observations for the lane departure warning system with respect to marker spacing:

- (1) The performance degradation from 2m spacing to 4m spacing is quite small; such degradation increases somewhat at low speeds and on curves.
- (2) Noticeable performance degradation can be observed when the marker spacing increases from 4m to 6m at almost all vehicle speeds. Such degradation is particularly noticeable at lower speeds and on curves.
- (3) Large departure angle is suspected to increase the computational noise with respect to larger marker spacing.

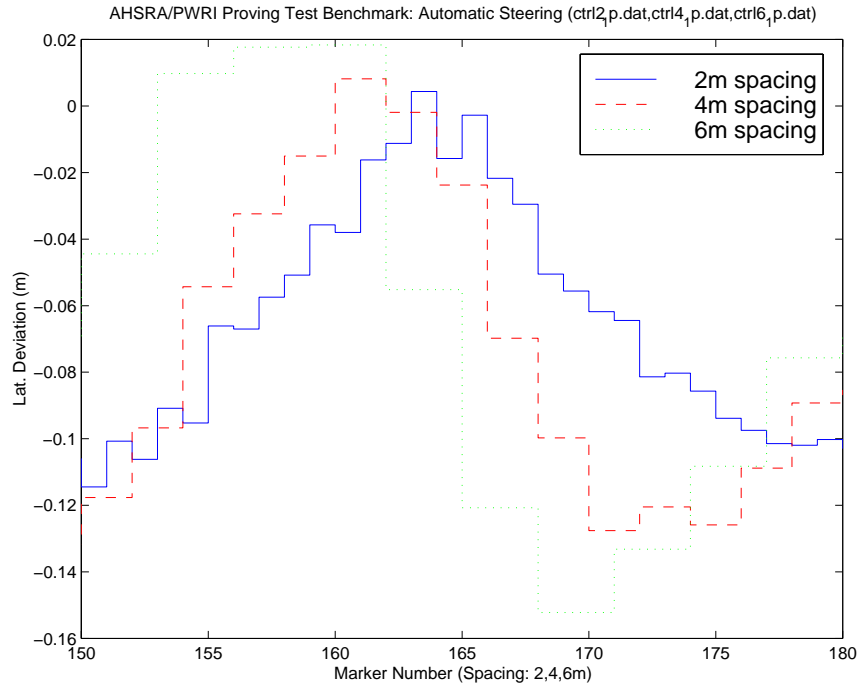


Fig. 6.1. Typical Example of Simulated Marker Spacings (2m, 4m , 6m)

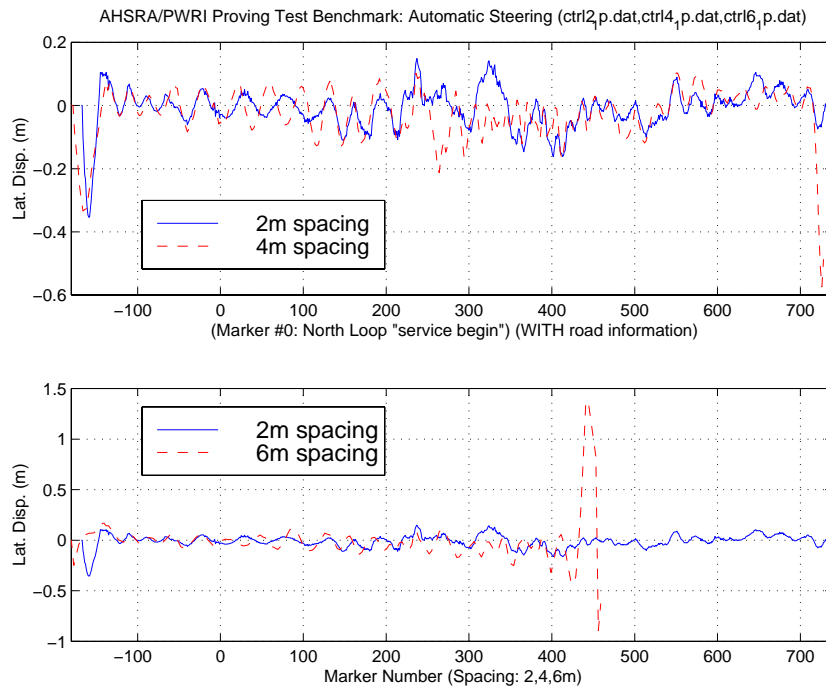


Fig. 6.2.1. Proving Test Benchmark: Automatic Steering (2, 4, 6 m marker spacing) (with road information) (lateral deviation)

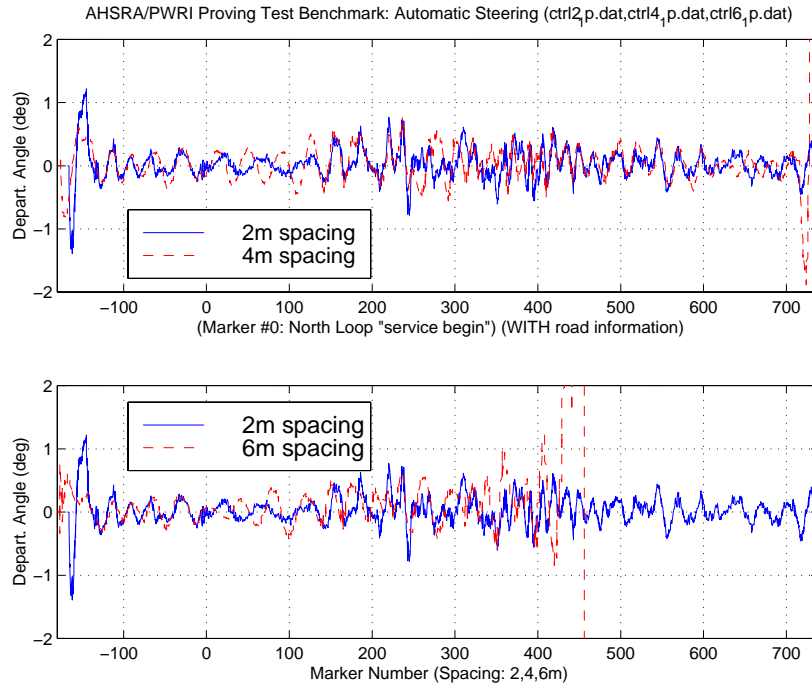


Fig. 6.2.2. Proving Test Benchmark: Automatic Steering (2, 4, 6 m marker spacing) (with road information) (vehicle departure angle)

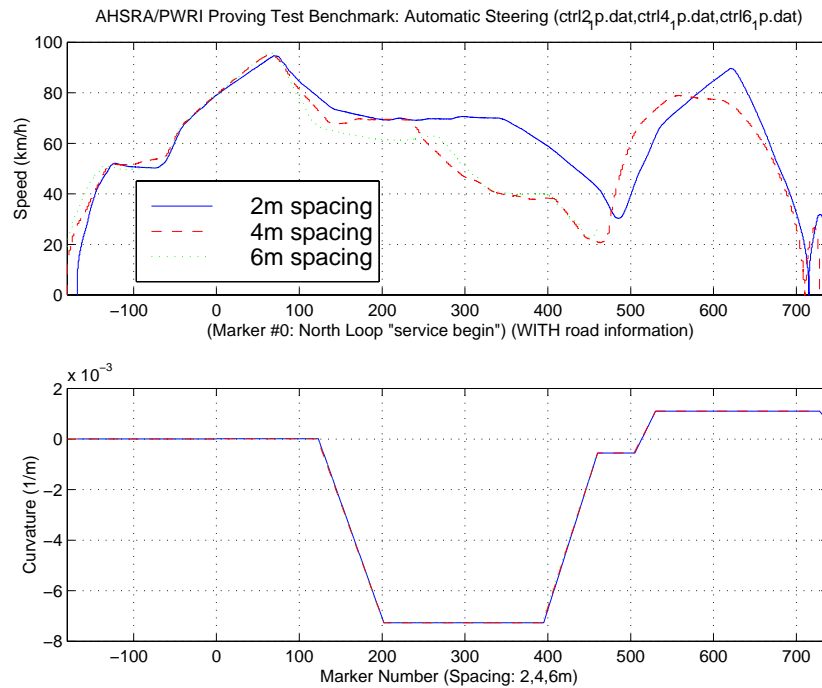


Fig. 6.2.3. Proving Test Benchmark: Automatic Steering (2, 4, 6 m marker spacing) (with road information) (vehicle speed and road curvature)

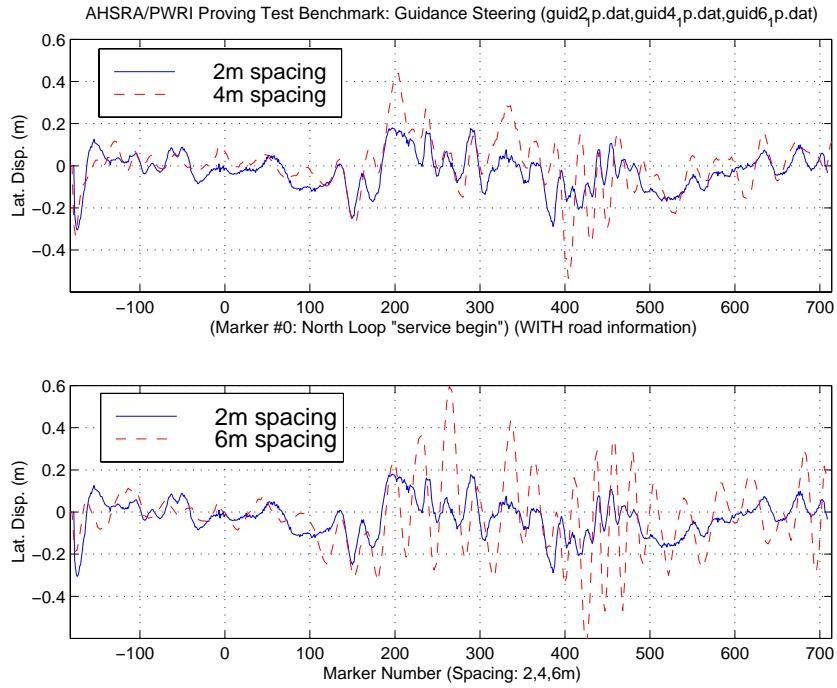


Fig. 6.3.1. Proving Test Benchmark: Driver Guidance Steering (2, 4, 6 m marker spacing) (with road information) (lateral deviation)

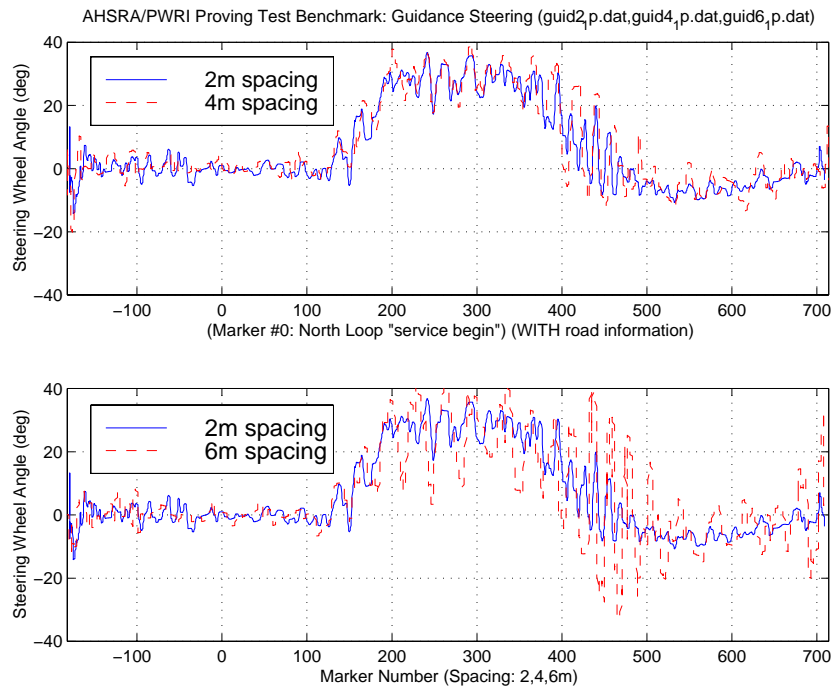


Fig. 6.3.2. Proving Test Benchmark: Driver Guidance Steering (2, 4, 6 m marker spacing) (with road information) (steering wheel angle)

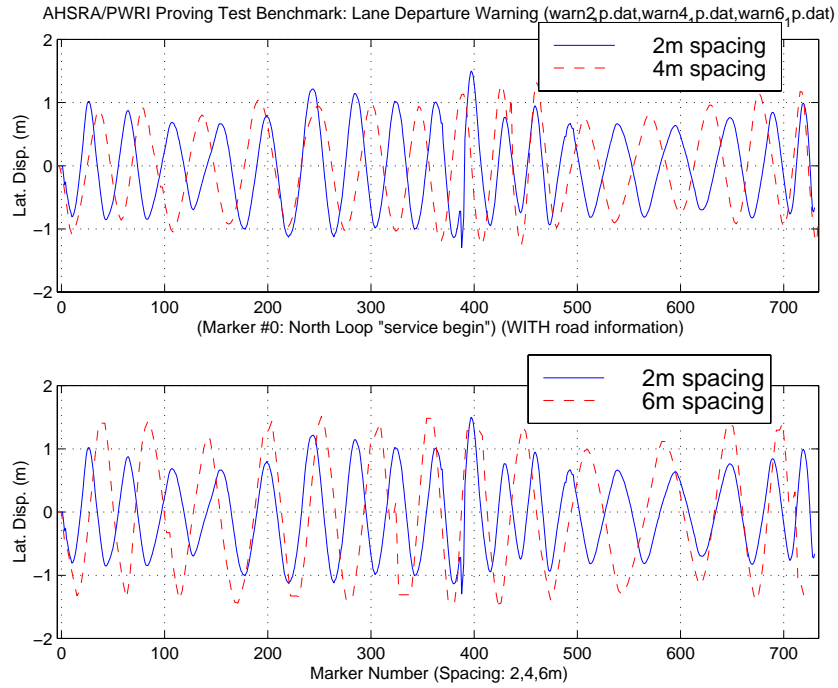


Fig. 6.4.1. Proving Test Benchmark: Lane Departure Warning (2, 4, 6 m marker spacing) (with road information) (lateral deviation)

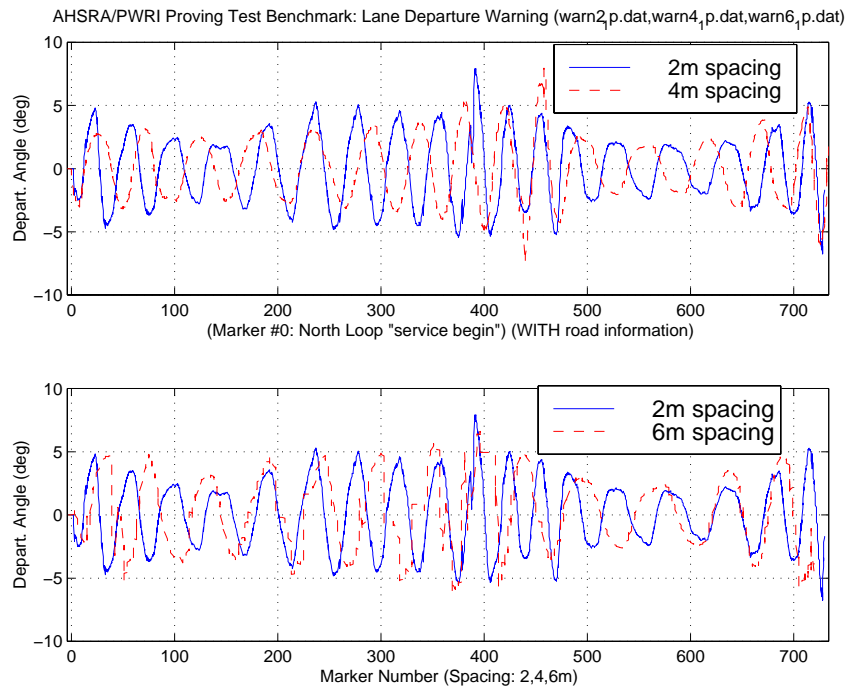


Fig. 6.4.2. Proving Test Benchmark: Lane Departure Warning (2, 4, 6 m marker spacing) (with road information) (lateral deviation)

6.4 Effects of marker spacing on warning/guidance/control without curvature information

The test scenarios in this section are the same as the tests described in Section 6.1 (for automatic steering control), Section 6.2 (for steering guidance) and Section 6.3 (for lane departure warning), except that no curvature information is available for those “controllers”. The controllers assume the road is “straight” in all their computations.

To illustrate the effects of road curvature information on the performance degradation with respect to different marker spacing, one data set for each scenario (automatic steering control, driver guidance steering, and lane departure warning), as well as for each marker spacing (2, 4, and 6 meters), are plotted in this section. Figs. 6.5.1, 6.6.1, and 6.7.1 compare the vehicle lateral deviation resulting from 2, 4 and 6 meters marker spacing for automated steering control, guidance steering control and lane departure warning, respectively. Figs. 6.5.2, 6.6.2, and 6.7.2 plot the corresponding vehicle departure angle or steering wheel angle for automated steering control, guidance steering control and lane departure warning, respectively. The observation of these six figures leads to virtually the same conclusions as those in Sections 6.1 to 6.3 and Sections 5.1 to 5.3. In short, the curvature information does not appear to affect the degradation from the increase of the marker spacing. The loss of curvature information only creates additional steady state lateral deviation regardless of what marker spacing is chosen (as also shown in Section 5). Detailed observations therefore will not be repeated in this section.

6.5 Preliminary summary about magnetic marker spacing

The preliminary summary of this section is:

- (1) The performance degradation from 2m spacing to 4m spacing is relatively small except at very low speed or sharp curves.
- (2) Noticeable performance degradation can be observed from 4m to 6m marker spacing especially at lower vehicle speeds.
- (3) High speed on a straight curve is the least sensitive to the increase of the marker spacing, except at very large departure angles.

- (4) Low speed on sharp curves is the most sensitive to the increase of the marker spacing.
- (5) The noise level of the angle estimate increases with larger marker spacing, especially at big departure angles.
- (6) The primary performance degradation due to the lack of road curvature information is the larger transient and steady state lateral deviation on curves regardless of the marker spacing.

The above initial summary is made based on the test situations and assumptions described in this section. The algorithms employed in the proving tests for 4 and 6 meter marker spacing were not optimized for the respective marker spacing; very-low speed and very-sharp curve scenarios were not tested; miss-reading of magnetic markers was not experimented; the “warning/guidance/control” systems designed for different vehicle platforms may not exhibit similar characteristics. Therefore, extreme caution should be taken before expending the interpretation of the above observations and summaries to other situations.

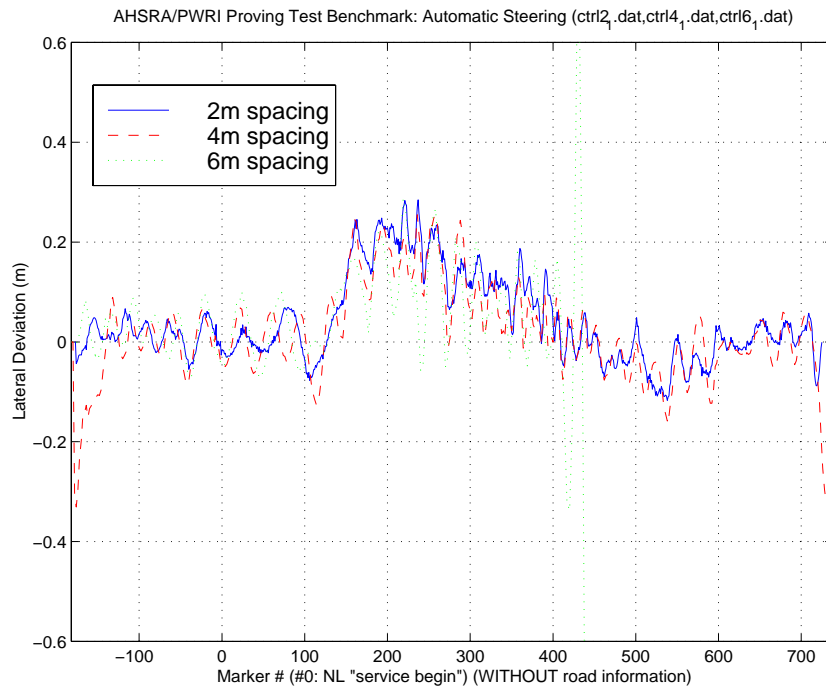


Fig. 6.5.1. Proving Test Benchmark: Automatic Steering (2, 4, 6 m marker spacing) (without road information) (lateral deviation)

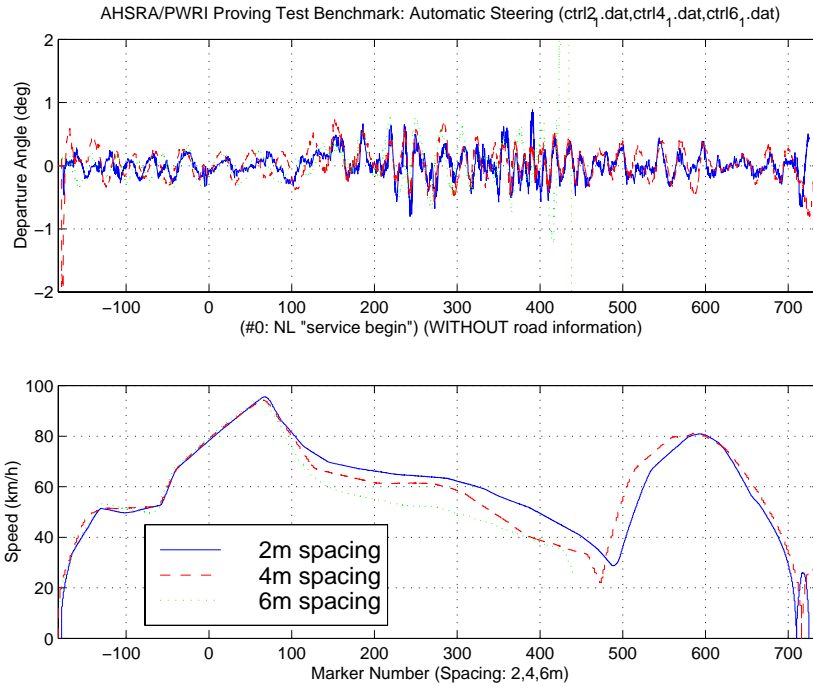


Fig. 6.5.2. Proving Test Benchmark: Automatic Steering (2, 4, 6 m marker spacing) (without road information) (vehicle departure angle and speed)

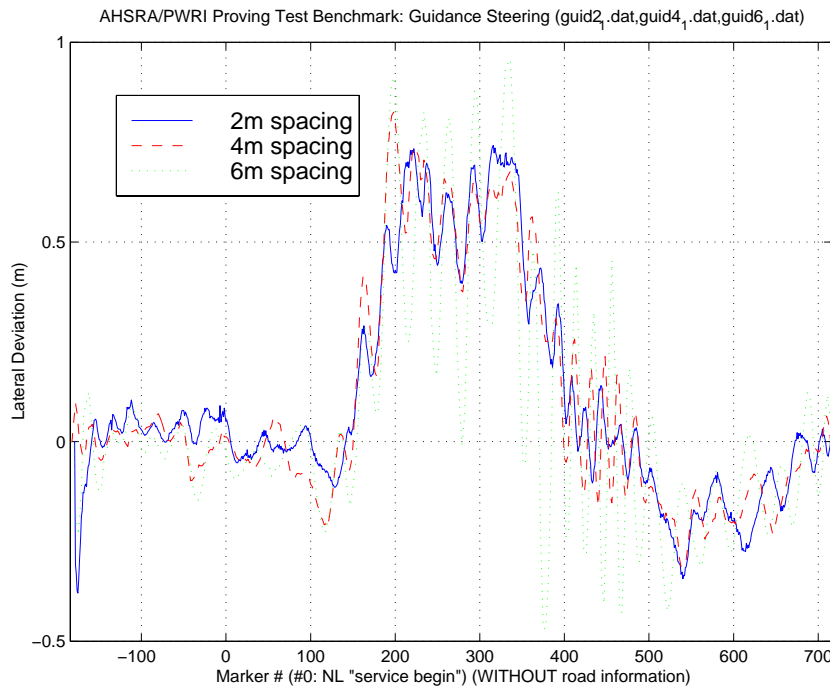


Fig. 6.6.1. Proving Test Benchmark: Driver Guidance Steering (2, 4, 6 m marker spacing) (without road information) (lateral deviation)

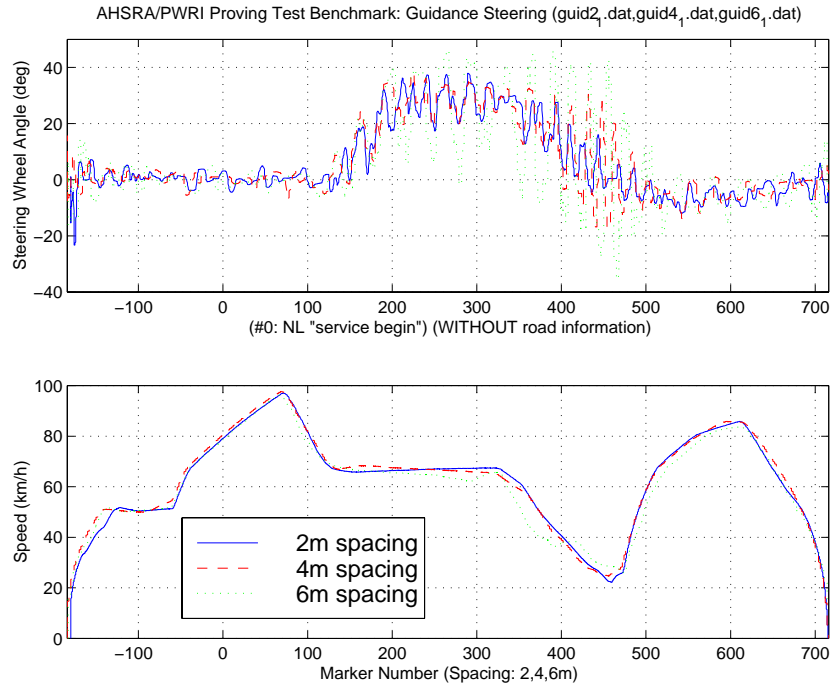


Fig. 6.6.2. Proving Test Benchmark: Driver Guidance Steering (2, 4, 6 m marker spacing) (without road information) (steering wheel angle and speed)

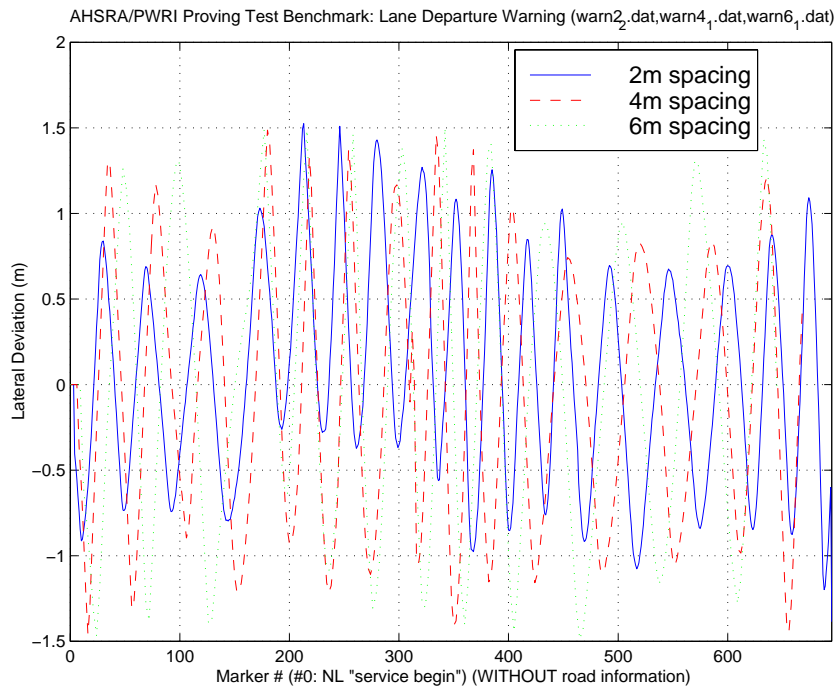


Fig. 6.7.1. Proving Test Benchmark: Lane Departure Warning (2, 4, 6 m marker spacing) (without road information) (lateral deviation)

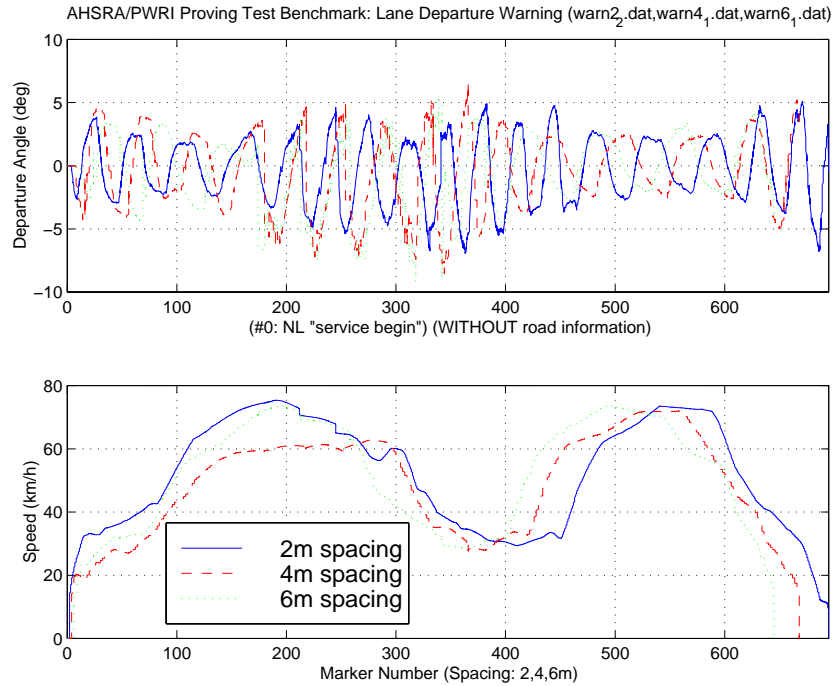


Fig. 6.7.2. Proving Test Benchmark: Lane Departure Warning (2, 4, 6 m marker spacing) (without road information) (vehicle departure angle and speed)

7 Observations on the Characteristics of the AHSRA/PWRI Magnetic Marker Sensing System

The following section contains the initial observations based on the magnetic marker characteristics of the PWRI test track based on the PATH vehicle measurements. The PATH vehicle is equipped with two types of magnetic sensors: 3 fluxgate magnetometers 30 cm apart located 29 cm above the ground under the front bumper; and 5 AHSRA magnetometers 20 cm apart located 30 cm in front of the front bumper. The PATH vehicle receives both raw magnetic field measurements from the 3 fluxgate sensors and the processed lateral deviation from the AHSRA sensors through a RS232 port. The PATH on-board computer processes the field strengths to obtain the lateral measurement. Since the PATH vehicle is equipped with automatic steering capability, lateral data are collected from both the PATH and AHSRA sensors under either manual or automatic steering control scenarios. Because only the nail type magnetic marker was available, the

entire signal-processing algorithm in the PATH vehicle is based on the nail type magnetic marker.

Since the North Loop and the Tunnel are the main areas where PATH performed testing, the following discussion focuses only on these two areas.

7.1 Basic magnetic marker map of the North Loop test track

The basic magnetic marker map of the North Loop starts 1280 meters south of the “service-begin” marker (control point marker 30) and ends at the “service-end” marker (control point marker 32). The starting point is the magnet marker immediately after the first over-pass bridge north of the separation traffic cones between the North and the South Loop cruise test areas. The first magnetic marker north of the control point 30 was set as magnetic marker number 1.

Marker number	Magnet Type	Comments
-640	Plate	First marker pass the 1 ST overpass on the north loop
-481	Plate	1 ST signal post (where the noisy section begins)
-468	Nail	Starts nail type (just before the 2 ND signal post)
-367	Plate	Starts plate type again
-349	Plate	After the light posts (after the area of noisy section)
1	Plate	First marker after the “service-begin” marker
76	Nail	Nail type starts
131	Nail	First CAN type
380	Nail	Last CAN type
1179	Nail	Just before the “service-end” marker

Table 7.1 Marker Number Definition in the North Loop

As shown in Table 7.1, the North Loop contains both types of magnets (nail and plate types). The PATH system observed a section in the North Loop that seems to have higher background noise characteristics. This section starts around the first signal post and ends just after the light posts. It also contains both types of magnets.

7.2 Noisy section

Fig. 7.1 is a typical plot of the lateral deviations on the straight section of the North Loop obtained from both PATH and AHSRA magnetic sensors. This particular set of data is obtained under automatic steering control. It can be observed that the section ranging from around marker number -475 to number -290 exhibits more noisy characteristics than any other part of the road.

Fig. 7.2 shows the lateral deviations obtained from the PATH and the AHSRA magnetic sensing systems from marker number -480 to -350 during manual driving. The measurements indicate that the vehicle is on the right side of the lane; therefore PATH left magnetic sensor basically records the earth field measurements as shown in Fig. 7.3. Fig. 7.4 exhibits the magnetic field measurements from the center magnetometer at the location just after the “service-begin” marker of the North Loop during manual driving. Although the sensor does pick up magnetic field from some magnetic markers, the earth field is still very visible in the figure. The earth field varies within 0.1 G. The comparison of the earth field in Fig. 7.3 with the earth field in Fig. 7.4 shows that the earth field “noises” in the “noisy section” are greater than those from the normal section.

7.3 Plate type and nail type magnets

Although two types of magnetic markers (nail and plate types) are used in the North Loop test track, no significant difference between these two magnets is observed. Since PATH did not get any plate type magnet for examination, all the signal processing was designed based on the nail type magnet. The results do not show clear distinctions between these two kinds of magnet. Fig. 7.5 shows the lateral deviation from both sensing systems starting at the North Loop “service-begin” marker. As indicated in Table 7.1, both types of magnet are installed within this data set. Plate type magnets are located from marker number 1 to 75, with the rest of the magnets being of nail type. However, as an unscientific observation, one can say that the nail type seems to produce a little bit smoother results. Fig. 7.6 shows similar result from an automated steering test.

7.4 Comparison between AHSRA and PATH magnetic sensing systems

As seen from both Fig. 7.5 and Fig. 7.6, AHSRA sensor measurement jumps when the sensor is in between two magnets. Fig. 7.7 shows the lateral deviations of the whole North Loop with the vehicle changing between manual and automatic steering control. It can be observed that, except for the two spikes of the AHSRA sensor, the measurements appear to be very similar for both systems. However, from a closer look, the difference in the data smoothness can also be observed, as in the blown-up plot in Fig. 7.8.

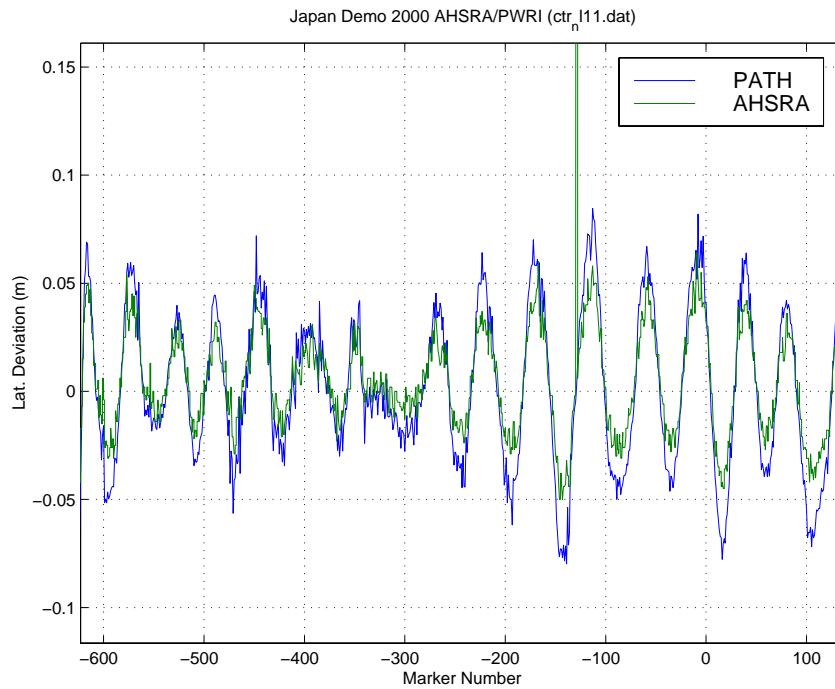


Figure 7.1 Straight Section Lateral Deviation

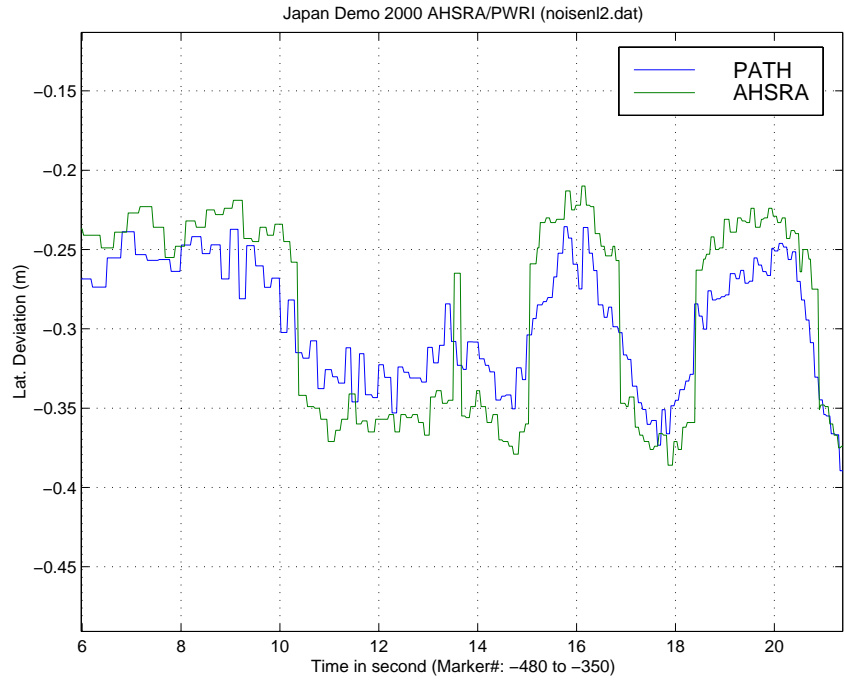


Figure 7.2. Noisy Section Lateral Deviation

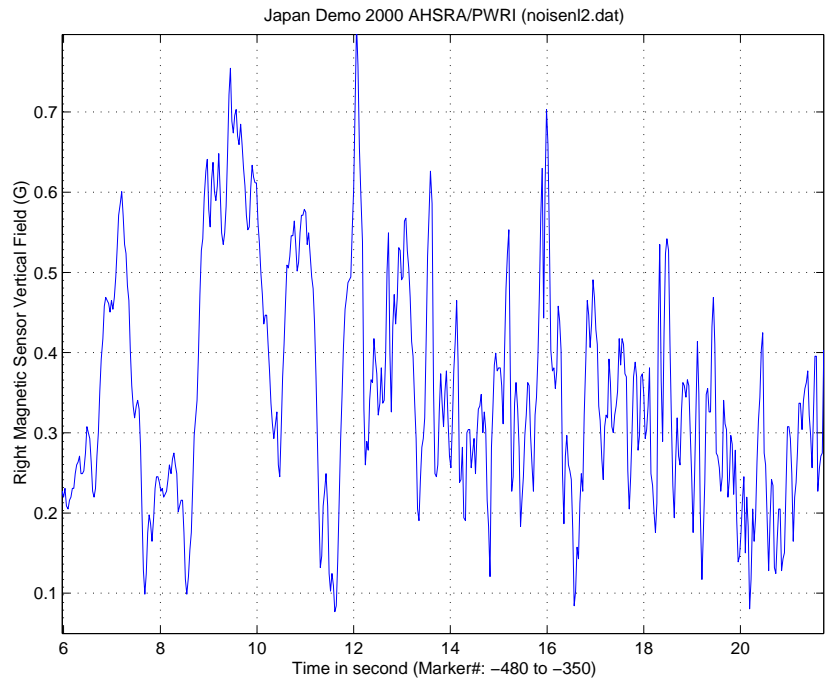


Figure 7.3. Noisy Section Earth Field

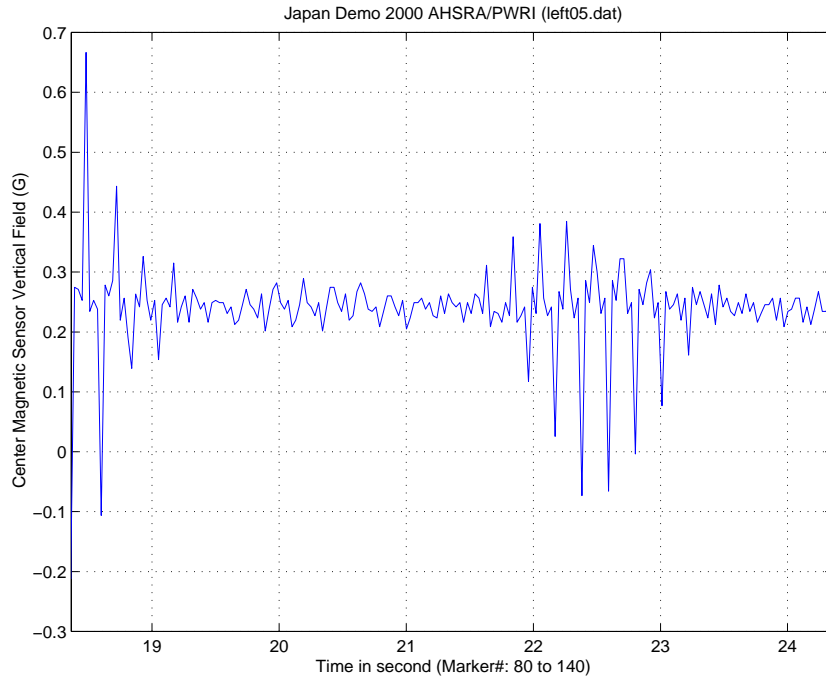


Figure 7.4. North Loop Earth Field after Service-Begin Marker

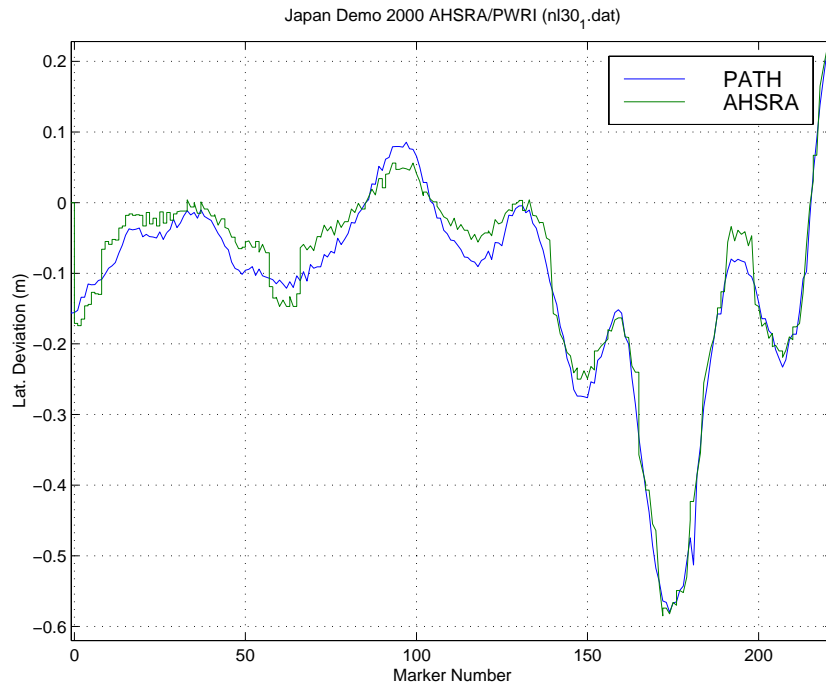


Figure 7.5. North Loop Two Types of Magnetic Markers (test 1)

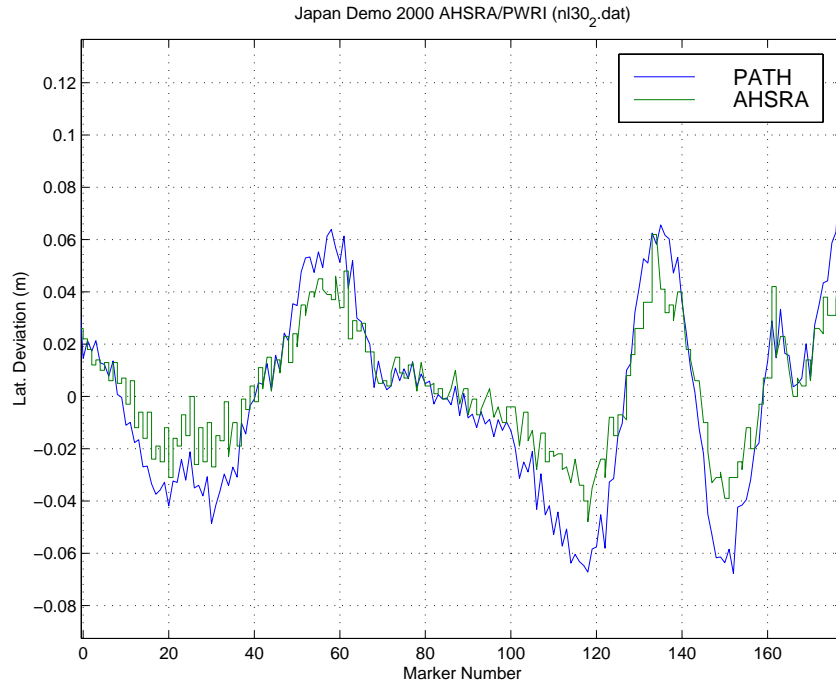


Figure 6. North Loop Two Types of Magnetic Markers (test 1)

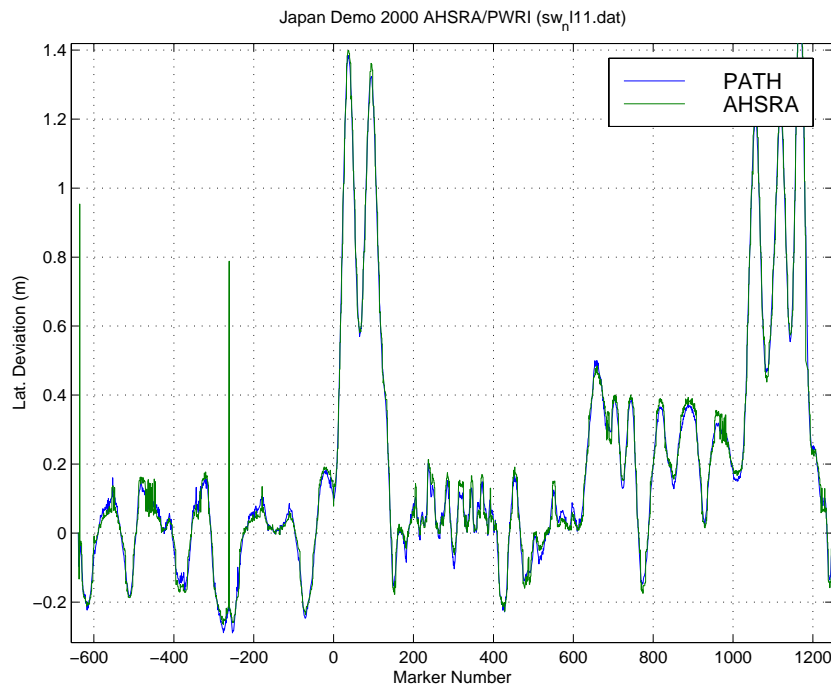


Figure 7.7. North Loop Sensor Comparison (test 2)

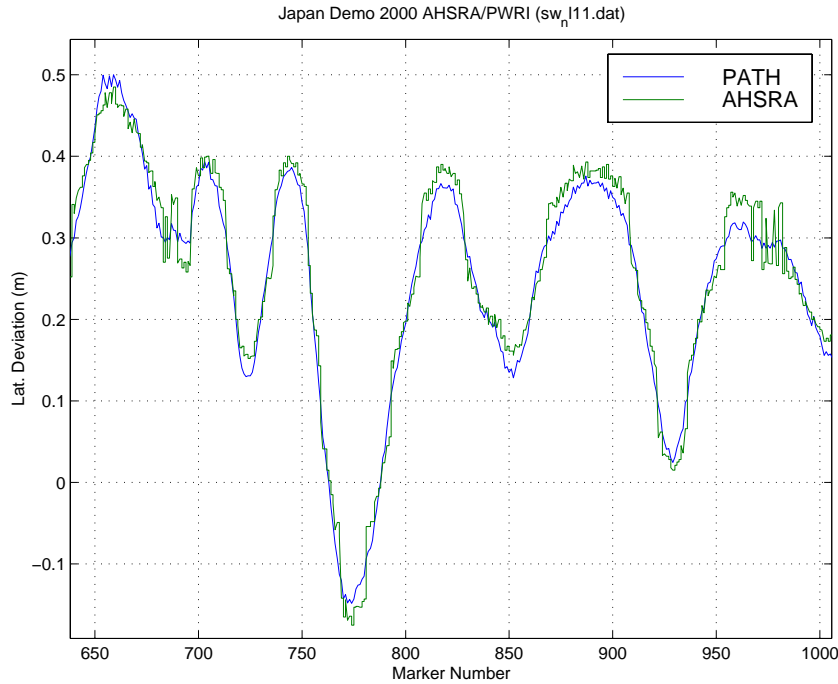


Figure 7.8. North Loop Sensor Comparison (test 2)

8 Other Discussions

Several issues related to the magnetic markers systems are briefly discussed in this section. Although PATH has on-going project focusing on the specifications and requirements issues of magnetic sensor and installation, no standard or conclusion has been made. The information provided in this section is preliminary and is to be used for reference only.

8.1 Current PATH magnetic sensing system

Since PATH is a research organization, it does not define standard specifications for the magnetic sensing system. Up to this point, most systems were developed based on the specific requirements of their respective projects. For example, snowplow guidance operation may not have the exact same requirements as a fully automated vehicle. Although there is on going PATH project focusing on the specifications of magnetic

sensor/installation, no conclusive results have yet been reported. The information provided in this section is therefore for reference only.

Most current PATH magnetic sensors are installed at the height between 23 to 30 cm from the ground. Multiple magnetic sensors are usually installed laterally in the vehicle to increase the lateral measurement range. The distance between two magnetic sensors is usually around 30 cm. This arrangement results in a total vehicle lateral range being a multiple of 30 cm. The current magnetic sensors installed in most test vehicles are fluxgate magnetometers with a range of 5 to 7.5 G. The accuracy of the PATH sensing system is generally better than 1.5 cm. However, this accuracy would drop if either the “background” noise level or spatial frequency increases, or if the field strength is reduced, as when the distance between the magnetic marker and the sensors increases.

Similarly, the strength and the shape of the magnetic marker, as well as the level of the background noise, determine the detection range. There are many tradeoffs in deciding the appropriate detection range, measurement accuracy, and height of the sensor. Even the cost of the sensor can be a significant factor in determining the appropriate detection range.

8.2 Magnetic marker installation requirements

A preliminary magnetic marker installation requirement prepared by PATH for snowplow marker installation is briefly described in this section for reference.

- Strength of the magnetic field:

The vertical magnetic field measured at 304.8 mm above the magnetic marker should be greater than 850 mG.

The vertical magnetic field measured at 304.8 mm above and 152.4 mm away from the magnetic marker should be greater than 500 mG.

- Magnetic marker placement accuracy:

Lateral position accuracy specifies the tolerance of the magnet location relative to the reference line. Lateral position tolerance is ± 15 mm.

Magnets shall be placed to within ± 100 mm longitudinally (parallel to centerline) of the designated location.

The top of the magnet stack shall be flush or less than 10 mm below the surface of the processed subgrade.

Magnets installation angle error is within 4.5 degrees.

Since the magnetic strength specified above is significantly lower than the magnetic markers used in the proving tests at PWRI, the cost of such magnets would be much lower in comparison with either the nail or and plate type magnets at PWRI.

8.3 Magnetic coding scheme

Since a magnet has either N or S polarity, it is an excellent media for binary coding. By placing magnetic markers according to some specific patterns along the roadway, it would not only provide lateral deviation, but also coded information to the vehicle. Therefore the magnetic binary coding creates a one-way infrastructure information transmission channel. This channel is relatively reliable as long as the vehicle is traveling within the sensor range to the magnets.

Normal considerations in the design of a magnetic coding scheme usually involve the type of information needed to be transmitted, information distribution, code-word structure and length, error correction capability, as well as encoding and decoding strategies.

Two types of coding have been experimented by PATH: information-coding and map-coding. The information-coding puts the “information” (such as road curvature) directly into the code, whereas the map-coding codes “milepost” and then the information is retrieved through a map and a corresponding data table. The information-coding method is more “generic” but uses more “bits”. On the other hand, the map-coding scheme is more flexible but requires a “map and table” in the vehicle. A combination of these two schemes has also been experimented with success.

The PWRI test track employs radio-wave control point markers to transmit information that are received by a radio-wave antenna in the vehicle. The system has been tested with high reliability. The 3-column magnetic pattern used at PWRI makes it very difficult to design a suitable coding scheme since specific polarity pattern has already been adopted to distinguish between different “column” of magnetic markers.

In general, the magnetic coding method is simple, inexpensive and reliable. But it is not as flexible as the radio wave “control point” marker method. Since both the magnetic marker coding and the radio based marker methods try to provide similar information to the vehicle, they are probably with similar reliability. The difference may lie in the areas of flexibility and cost. There will be some trade-off, which may even suggest the use of both systems for different purposes under the same highway system. However, it is presently difficult to make a fair comparison because of the lack of mature information.