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Longitudinal Control – Phase 1

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LONGITUDINAL CONTROL -PHASE 1

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Chapter 1. Introduction

1.1 Objective

The objective of the project is to assess the feasibility of vehicle-follower control with high accuracy and good ride quality, using a Doppler radar as the primary sensor (See Appendix A.1 - A.3).

1.2 Overview of the longitudinal control research at PATH

The PATH work on longitudinal control has emphasized the concept of vehicle-follower control. Using inter-vehicle communication links as well as direct measurements, a *platoon* of closely-spaced vehicles can be precisely controlled to provide the desired spacing. The communication links are used to transmit to each vehicle the speed and acceleration of the vehicle in front of it and also that of the lead vehicle of the platoon. The measurements transmitted from the lead vehicle are used to cancel the accumulated effect of time delays and lags on the inter-vehicle spacing control.

In order to assess the feasibility of applying currently available technology for the platoon concept, studies were first made on vehicle modeling, controller design and simulation. The vehicle modeling was developed to achieve a realistic mathematical representation of the power-train including internal combustion engine dynamics. Considering that the vehicle model is nonlinear, a nonlinear controller was designed to compensate the vehicle plant over a wide range of nonlinearities. Sliding control theory was chosen as the nonlinear controller design approach for the automatic vehicle following. Following satisfactory results in simulations, experiments were conducted to test and prove the implementation of the controller on vehicles. The assessment of the longitudinal control system Will be made based on the assumption that no radically new technology will be needed to implement the system; the system has been developed using essentially existing technology and components. The hardware components of the experimental setup are, in fact, off-the-shelf products that were purchased or provided by private companies.

A number of publications have documented the PATH longitudinal control research either in the form of PATH technical reports or journal (conference) papers. The idea of the platoon control originated from the work performed by Shladover in the late 1970's [1,2]. In these publications, Shladover demonstrated the feasibility of a vehicle-follower control system with short-headway platoons via analysis and simulations. Based on this concept of the vehicle platoon, PATH researchers started to design the controllers in 1989. Sheikholeslam and Desoer conducted a series of analyses of the vehicle dynamics and controller [3,4,5,6,7,8]. In this work, the controller was designed using exact linearization methods to linearize and normalize the input-output behavior of each vehicle in the platoon. The research also examined various effects such as vehicle-to-vehicle communication delay, vehicle mass variations, noise in measurements, etc. The design demonstrated simulations of stable platoon behavior which does not exhibit oscillations, but maintains good ride comfort.

In parallel with the study by Sheikholeslam and Desoer, McMahon and Hedrick developed another control law [9,10,11]. This control algorithm was developed using a modified sliding control method which compensates for the inherent nonlinearities that exist in the automobile plant. The sliding control method is a method which basically transforms an n-th order tracking problem by a first order stabilization problem. This method provides a systematic approach to the problem of maintaining stability in the face of modeling imprecisions. For the controller design, the vehicle was modelled with three state variables: mass air flow rate in the intake manifold, engine speed and brake torque, with some assumptions for simplification. This is the control algorithm which was actually implemented for experiments on the test vehicles in San Diego.

The difference between the Sheikholeslam/Desoer controller and the McMahon/Hedrick controller is that the Sheikholeslam/Desoer controller design is based on. assumptions which enabled simplifications in the modeling and analysis of long platoons, permitting rapid study of the large-scale platoon dynamics issues. On the other hand, the sliding controller is based on a nonlinear model of the vehicle power train, which produced a more complicated and realistic controller from the implementation point of view. Using the sliding control, there were numerous iterations between the experiments and the analysis and simulations for the control gain adjustments and practical algorithm development.

As was investigated in Shladover's work [1], the asymptotic stability of the platoon control is guaranteed only when using the lead vehicle's information in addition to the preceding vehicle's information. Hence the vehicle-to-vehicle communication algorithm was developed by Varaiya [12,13,14]. These references present the detailed experimental setup, operating program, test results and analysis in addition to the communication algorithm developed based on shared use of a radio channel. The papers focus on the regulation and platoon layers in the overall communication architecture. A protocol is proposed to allow the exchange of messages by vehicles performing cooperative maneuvers. In the middle of the project, there were two publications summarizing the status of the AVCS research at PATH [15,16]. These papers describe the accomplishments to date on the development of both longitudinal and lateral control.

Chapter 2. Collision Warning Test Program

2.1 Outline

This test was performed by Systems Technology, Inc. (STI) as an independent subcontractor to PATH from April 1990 to August 1990 using the Ford LTD test vehicle. The objective of this program was to evaluate the radar-based collision warning system developed by RCS. In this configuration, the system is intended to provide a warning to the driver when the equipped vehicle is in danger of being involved in a collision with another vehicle or object. This is achieved by reflecting a radar signal from vehicles or objects ahead and using this information to calculate range. Changes in range over time (closing rate), range to the object, and vehicle speed are then used to activate the alarms.

The field test was conducted with two segments. The first segment analyzed *quantitative* measures of the system. These tests involved verification of the system's displayed speed and range; obtaining repetitive alarm activation data at various closing rates on several types of vehicles; testing the system's sensitivity to pedestrians, bicycles and motorcycles; testing the interference resistance of the unit itself; and testing the system's capability under degraded atmospheric conditions.

The second segment involved the *qualitative* evaluation of the anti-collision system under normal driving conditions. Varying traffic, roadway, and surrounding environmental conditions were chosen to provide a thorough analysis of the system. The purpose of this test was to determine how the RCS system functioned in the "real world". The evaluation took place on various types of roadways in Southern California.

2.2 Test results

Since the final report submitted by STI [17] includes extensive test data, results, discussions and conclusion, only a summary of the results will be included here. The more detailed discussions can be found in the STI final report.

Range verification

The accuracy of the RCS radar range measurements was tested in this experiment. The results showed that the system provided sparse measurements at closing speeds higher than 17.8 m/s, and *no* measurements at closing speeds higher than 26.8 m/s. This phenomenon may cause .a missed alarm when a stalled vehicle is sitting in the middle of the freeway lane. The second problem noted was the large variability in the range data; for example, the radar range deviation was about 15.2 m at 61.0 m true range when the closing speed was 13.4 m/s. Finally, the radar system indicated a range which was further away than the true distance from the target. This range bias could create problem in providing a timely warning.

Closing rate verification

This experiment was conducted by having the test vehicle approaching another test vehicle travelling at a constant speed. Independent measurements were taken with a radar gun. The closing rate of the RCS system showed good accuracy; at most, the error was within 0.22 m/s in the range between 1.34 m/s and 7.15 m/s of closing rate.

System Interference test

When the system was tested with a police radar gun and another RCS radar system approaching the unit under experiment from the opposite direction, no interference was noted. Some occasional interference was noted, probably due to AWACS operations at the adjacent Miramar Naval Air Station.

Qualitative test

The recorded events in the test fall into three categories: ***false alarms, appropriate events,*** and system misses. Although the RCS radar system performed better than previously existing similar systems in some aspects, it was still found to require further improvements.

The final report and video recordings were delivered to PATH, NHTSA and Caltrans by STI.

2.3 Discussions

The purpose of this task (Collision Avoidance Test Program) was to evaluate the RCS radar system from the view point of collision warning device, not as the range sensor for vehicle following [18]. It needs to be remarked that the active operating region of the radar range and radar closing rate is quite different for each case: collision warning vs. vehicle-following. The vehicle-following control is operated at low closing rate within short range while the collision warning device needs to cover higher closing rates and longer distances for proper activation. For the application of the vehicle-following system, the range verification data collected by STI showed reasonably good accuracy; for example, 0.44 m standard deviation with a mean value of 34.8 m for 30.5 m of true distance and 4.5 m/s closing rate. With the range bias compensation, the 1.5% range error would be acceptable for the spacing control.

This range accuracy, however, is completely lost when the closing rate is very low (0.22 m/s) due to the loss of Doppler effect. The range measurement is invalid in this case, which will occur most of the time during the vehicle following control mode. Therefore, the question of '***how to remove the range drop-out period***' has been a continued problem throughout the project. The way to solve this problem will be described later in the range estimation section of this report (Section ***4.4).***

Chapter 3. System Characterization Test Program

This test program was designed to characterize the test vehicles, evaluate the RCS radar system and test actuators for the application to the vehicle platoon control system. The test data file list is available in the Appendix as a reference. For most of the tests conducted in this task, a flat segment was selected. on the 1-15 HOV (High Occupancy Vehicle) lane: a section from Miramar Way to Pomerado Road in San Diego (Fig. A. 1 in Appendix). The upgrade/ downgrade tests were conducted at the section from Mercy Road to Poway Road, which has a constant grade of 3%. This particular section runs about a mile.

3.1 Vehicle performance characterization test (Table A.2)
The objective of this test was to collect experimental data in order to utilize them in designing controllers for the platoon system. The data can be used as typical inputs to the vehicle dynamic model or can be used to determine parameters associated with the control algorithm. In Table A.2, the measured distances denote the calculated distance using the integration of vehicle speed for braking tests, and the reading from the trip odometer for coast down and cruise control tests of which accuracy was in units of 0.1 miles.

3.1.1 Red Lincoln Town Car
Maximum Acceleration Tests

Tests were conducted on a level section of the 1-15 HOV lane from 0 to 26.8 m/s (60 mph) (Fig. A.2), 2.24 m/s (5 mph) to 26.8 m/s, 6.7 m/s (15 mph) to 26.8 m/s, 13.4 m/s (30 mph) to 26.8 m/s, 20.1 m/s (45 mph) to 26.8 m/s (Fig. A.3), and 26.8 m/s to 31.3 m/s (70 mph) using full throttle. Some of the tests were also conducted with partial throttle openings determined either by the human driver or the throttle actuator controlled by a computer command. When the manual operation was executed for partial throttle, the test driver tried to maintain the constant throttle opening by feeling the pedal movement. The actual throttle angle profiles can be observed in the plots. In addition, an acceleration test from 20.1 m/s (45 mph) to 26.8 m/s (60 mph) was performed on an upgrade and downgrade hill using full throttle (Fig. A.4, Fig. A.5). The acceleration time from 0 to 26.8 m/s (60 mph) was found to be 12 seconds with manual throttle, and 16 seconds with the original RCS DC motor throttle actuator. The instantaneous peak acceleration achieved from the test on a flat road was found to be about 0.55 g. The peaks appearing in the acceleration profiles represent gear shiftings during the acceleration period (Fig. A.2 - AS) (Note that the time scale for Figs. A.4 and A.5 is different from that for A.2 and A.3, accounting for some of the differences in appearance of these plots.).

Partial throttle acceleration tests were performed on a level roadway from 0 to 26.8 m/s (60 mph) and from 20.1 m/s (45 mph) to 26.8 m/s (60 mph) using throttle actuator or manual throttle (Fig. A.6 - Fig. A.9). The throttle angle plots in Fig. A.6, Fig. A.7 indicate a slow throttle actuation response of 32 deg/sec while the ones in Fig. A.8 and Fig. A.9 show much faster human actuation movement of 450 deg/sec.

	Full Throttle	Partial Throttle
0 to 26.8 m/s	0.55 g (Fig. a.2)	0.45 g (Fig. A.8)
20.1 to 26.8 m/s	0.2 g (Fig. A.3)	0.08 g (Fig. A.9)

Table 1. Peak acceleration by manual throttle operation

Braking Distance Tests

Braking distance tests were performed on a dry level roadway for 100%, 70%, 50% and 30% braking from cruise speeds of 6.7 m/s (15 mph), 13.4 m/s (30 mph) (Fig. A. 10 -Fig. A.11), 20.1m/s (45 mph), 26.8 m/s (60 mph) (Fig. A.12-Fig.A.13) and 31.3 m/s (70 mph) to a complete stop. The braking tests were conducted only using the manual braking, not the brake actuator. Percentage of braking in this report refers to the travelling distance of the brake pedal. In addition, the 20.1 m/s (45 mph)-to-stop braking test was performed on an upgrade and downgrade with 100% (Fig. A. 14, Fig. A. 15), 70%, 50% and 30% braking. The partial braking was maintained using stopping blocks positioned underneath the brake pedal.

It was found that the brake pressure sensor limit (1800 psig) is lower than the maximum brake pressure actually applied during the tests. This limit resulted in the cutoff at the top of the brake pressure profiles in some data plots. After this finding, the pressure sensor was replaced with a new one with a higher pressure limit (3000 psig). The maximum deceleration was found to be about -1.0 g. In general, this maximum acceleration was achieved with at least 50 % of braking. Large oscillations right after the braking tests when the vehicle stops completely represent the car body suspension rocking which is estimated about 2 Hz. The large fluctuations or temporary drop-out period in the brake pressure profiles may result from the brake pressure sensor incorrectly functioning in the operation range exceeding its maximum pressure limit, combined with cycling of the anti-lock braking system (ABS) and some inadvertent “pumping” of the brake pedal by the driver.

Coast Down Distance Tests

Coast down tests were performed on a level roadway from 3 1.3 m/s (70 mph) to 8.9 m/s (20 mph) and from 22.4 m/s (50 mph) to 8.9 m/s (20 mph). In addition, the 22.4-8.9 m/s (50- 20 mph) coast down test was repeated on an upgrade and downgrade.

The modified aerodynamic drag coefficient defined as $0.5^*p^*Cd^*A^*V^2$ was found to be 0.576 from the test results; this number is 0.534 based on Ford’s spec (Cd = 0.36). The coefficient was calculated using regression curve fitting based on the correlation between the deceleration and the drag coefficient which were collected from the test data file. The deceleration in coast down depends on aerodynamic drag and rolling resistance, which can be assumed to be constant. Hence from the data on deceleration and vehicle speed, the drag coefficient can be calculated. This coefficient, however, was checked just for verification purposes. In the actual platoon control experiments, Ford’s spec value was used.

3.1.2 Grey Lincoln Town Car

The objective of this test is to check the difference in vehicle dynamics for different vehicles. For this experiment, only one additional vehicle of the same model was tested due to time constraints. In general, to draw any conclusive statement, we need to conduct more field tests dedicated to the purpose of understanding the differences between vehicles.

Maximum Acceleration Test

Acceleration tests were conducted for the second car on a level roadway from 0 to 26.8 m/s (60 mph) with full or partial throttle (Fig. A. 16).

Fig. A. 16 shows that the initial profile of velocity is different between the two vehicles. This difference caused the second car (Grey) to take 0.3 sec longer in reaching 26.8 m/s (60 mph) from stationary position, despite throttle inputs that appear very similar.

Coast Down Distance Test

Coast down distance tests were conducted for the second car on a level roadway from 22.4 m/s (30 mph) to 8.9 m/s (20 mph) (Fig. A.17, A.18). The second car showed faster deceleration than the first car in the tests. In one test (Fig. A. 17), the instantaneous deceleration for the second car differs from the first car by 0.01 g when reaching 8.9 m/s (20 mph) from 22.4 m/s (30 mph) initial speed. This result may be due to the different aerodynamic drag and/or different rolling resistance (which could have been caused by different tire pressure).

3.2 Radar system range measurement test (Table A.3)

The purpose of this test is to evaluate the RCS radar range measurement. The accuracy of measurements was estimated by conducting calibration of range measurements using a distance measuring tape (61 m) placed on the pavement. A video camera was attached on the outside of the driver's door, facing the pavement to focus on the tape. The car (Red Lincoln) was driven from 61 m away from a stationary target vehicle (Grey Lincoln) while the driver was trying to steer the car to ensure the alignment of the video camera sight with the measuring tape by observing a TV screen connected to the video camera. In this way, the image of the tape was recorded in real time while the car was approaching the stationary target vehicle. At the same time, the radar range measurement was overlaid on the video screen for later comparison with the tape measure. In this test, we were able to drive the car up to a maximum speed of 10.3 m/s (23 mph), before the scale measures started to appear blurred due to the motion. The test was repeated with vehicle speeds of 3.1 m/s (7 mph), 3.8 m/s (13 mph), 8.3 m/s (19 mph), 10.3 m/s (23 mph). The minimum speed was determined based on the speed that could be maintained at engine idle, without applying the brakes

After a number of tests, the video recordings were analyzed by reviewing each video frame. The true closing rate was also estimated by reading the distance interval from tape measure while advancing to the next frame using the exact time interval of 1/30 second of video frame recording rate.

Test results are shown in Table A.3 in data file format and Fig. A: 19 - Fig. A.24 in graphic representation. As the results show, the range measurements are reasonably good within the measuring distance of 18.3 m (60 feet) with the error of + 1.22 m (4 ft) (bias). Beyond this distance, the radar range data do not seem to provide as accurate measurements: ± 3 m (10 ft) error in the range of 18.3 m (60 ft) to 36.6 m (120 ft) and ± 15.2 m (50 ft) error in the range over 36.6 m (120 ft). This trend was noticeable repeatedly for all the testing speeds from 3.1 m/s (7 mph) up to 10.3 m/s (23 mph). It is to be noticed that, at distances of less than 18.3 m (60 feet), all the range measurements are biased above the actual range; this result is consistent with what STI observed in their tests. This bias is about 1.22 m. When the radar is improved to offset this bias, the short range measurements provided by the radar should be satisfactory. In Fig. A.20, A.21, the broken data line indicates no measurements available in that interval of range. In other words, the radar system was unable to provide range data.

The closing rate data showed that the measurements are accurate, with about +0.22 m/s error in all closing rates covered in the tests. The radar seems to provide fairly good measurements in closing rate. It is also to be noticed that the radar closing rate is lagged behind the tape measured distance especially when the test vehicle approaches to the target near the end of the test (Fig. A.23, Fig. A.24). The lag between those measurements is about 90 ms, which represents the radar signal processing and data storage time for obtaining closing rate using RCS' AMIGA computer with RS232 connection. Due to the very slow data transfer rate through the RS232 connection which was not used in feedback control experiments, this lag data does not provide any information to be addressed in the field tests.

3.3 Closing/opening rate characterization test

This test is to evaluate the performance of the RCS radar closing rate sensor. The closing rate test was performed by setting the lead vehicle in a stationary position and having the following vehicle approach the target with 0.1 g, 0.2 g and 0.4 g deceleration.

Test results are shown in Fig. A.25 - Fig. A.27. At the time of these tests, the RCS radar signal processing software had a range hold feature as can be seen in range profiles. This feature holds the previous range information whenever the radar signal is invalid. The range is reset to a new value when the radar recovers normal operation. As was mentioned before, the range is fluctuating substantially beyond about 21.3 m (70 ft). The closing rate profile shows good correspondence with the vehicle speed which should represent the closing rate since the target vehicle was in stationary position. It is to be remembered that since the time of these tests, the radar system has been modified substantially. For example the current radar system does not have the range hold function, and the closing rate signal is always functioning regardless of the radar flag. The detailed description regarding the current radar system characterization test will follow later.

3.4 Actuator performance tests

3.4.1 Throttle actuator

RCS installed a DC motor as a throttle actuator for the purpose of vehicle-following spacing control. After a variety of static and dynamic tests using this motor, it was found that the response of the motor was too slow to maintain proper control performance.

Fig. A.28 shows the time response of the DC motor. The response showed the rate limit of 16 degrees per second during static tests. In dynamic tests, the rate limit was 24 degrees per second. This slow throttle actuator was replaced with a fast stepping motor later in the project.

3.4.2 Brake actuator

RCS designed a brake actuator for the platoon control system. This actuator consists of a compressed air tank, a pressure regulator and a solenoid valve, all of which are in the car trunk, and a pneumatic cylinder located near the brake pedal on the engine compartment side of the firewall (Fig. A.29). It should be noted that this RCS brake actuator is designed so that the human brake pedal movement would never affect the pneumatic cylinder. The human brake pedal action can make its influence only on the regular hydraulic braking system of the car. The slot in the mechanical linkage will do the job. That way it can be ensured that the human braking action does not make any influence on the pneumatic cylinder. The movement of the pneumatic piston, however, pulls down on the brake pedal so that the hydraulic pressure can be built up in the regular braking lines. It should also be noticed that this particular solenoid valve is working with a pulse-width-modulated pulse train signal. The brake pressure to be applied can be varied with a variation of the width of the active pulse trains, which can be viewed as a duty cycle adjustment.

Several tests have been performed to obtain the characteristics of the brake actuator. The test variables include the pulse width: 30 ms and 70 ms; test vehicle's starting speed: 13.4 m/s (30 mph) and 26.8 m/s (60 mph); and the regulated air pressure: 30 psig and 60 psig. These test results are shown in Fig. A.30 - Fig. A.33.

The time constant was turned out to be varied too much depending on the level of the air regulated pressure. For 30 psig case, the time constant was in the range of 100 ms and 200 ms again depending on the starting speed and the pulse width. For 60 psig case, the time constant was found to be between 30 ms and 50 ms. In general, the response of the actuator was dependent on various environmental conditions: air tank regulation pressure, vehicle speed, temperature, etc. This inconsistency was not acceptable for the application of the vehicle-following automatic braking and this system was abandoned in the course of the project, to be replaced by a hydraulic system. The detailed description regarding the new brake actuator will be followed later in this report.

Chapter 4. Experimental Setup for Vehicle following Tests

4.1 Overall configuration of IPCS system

The platoon control system developed in this project is named an Intelligent Platoon Control System (IPCS) [12]. The IPCS installed on the test vehicles consists of the following components (Fig. 1) *used part of test:

- Radar system provided by VORAD to measure range and closing rate
- 80386 based 23 MHz personal computer
- Data acquisition unit
- Communication digital radio transceiver
- Communication interface unit
- Sensors to measure vehicle speed, acceleration, throttle angle, *brake pressure, engine speed and intake manifold pressure
- Throttle and *brake actuation systems

4.2 Selection of equipments

Test vehicles and radar system: These selections were made based on the interests of the manufacturers in cooperating with Caltrans and PATH on this research program.

Computer: In order to provide real time control, it was important to have sufficient processing power. After a careful consideration of the price and performance ratios, we decided to use an 80386 based AT-compatible computer as our central controller. Using this setup has several advantages:

a. We have chosen a model of IBM PC/AT compatible computer from Zendex Corporation. This model comes in a fully integrated, ruggedized enclosure which is designed to prevent damage due to shock and vibration normally found in harsh environments, such as within a moving vehicle.
b. The price of the model was acceptable in the project budget.
c. The 80386 processor was the fastest microprocessor at the time of selection.
d. The popularity of the ATs enabled us to have a large selection of peripheral boards we needed to choose; the communication board and the data acquisition board were thus obtained.
e. There are many fast data storage options available only for the AT.
f. A variety of software development systems are available on the ATs.

Data acquisition system: A multifunctional data acquisition board from National Instruments (Model AT-MIO-16) was selected for the data acquisition unit. The board satisfied the following criteria:

a. The board must be able to sample the output from sensors at an acceptable rate and accuracy. For the most demanding control scheme, the sampling rate was 2 kHz. The maximum sampling rate of the AT-MIO-16 board was 43 kHz.
b. The on-board FIFO ensured, to a good extent, the host will receive samples without loss.
c. There are status and error registers on the board for error recovery features.

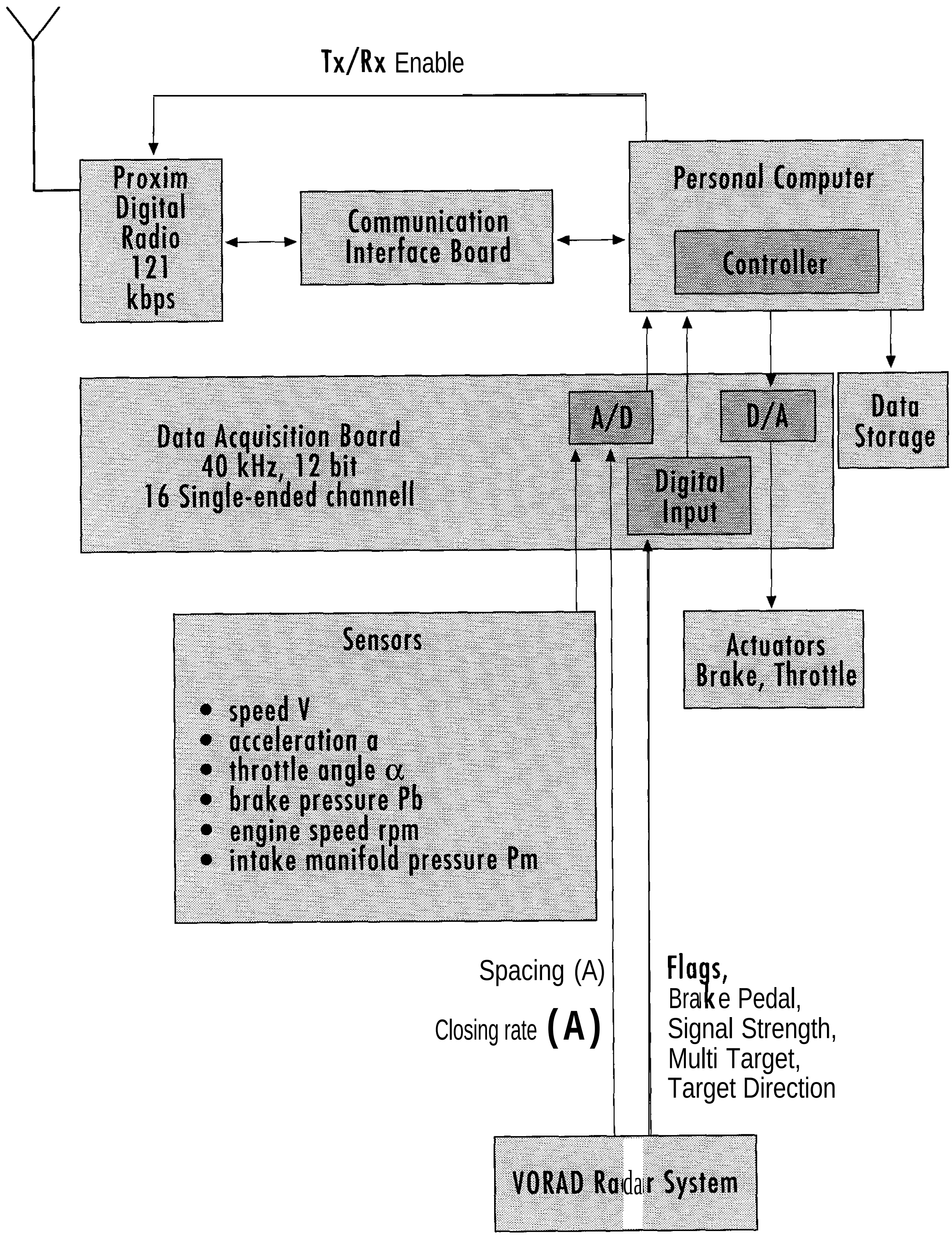


Fig. 1 Overall System Configuration

d. The board is AT compatible.

Digital radio transceiver: In order to provide reliable and high speed digital communications between vehicles, we decided to use the PROXIM digital radio transceivers. These radio transceivers have the following properties:

a. The PROXIM radio has spread spectrum support. This technology ensured us of an almost error-free data communication.
b. The radio provides high speed data rate up to 121 kbits/sec.
c. The radio is capable of error-free transmissions in a range of quarter-mile.
d. The PROXIM transceiver can be easily interfaced with a host communication controller.
e. The size of the board is small, and the power consumption is relatively small, which can be supplied by a typical AT-compatible computer's power supply.

Communication interfacing board: While it was possible to construct our own communications interface between the host controller and the PROXIM transceiver, a great deal of time would have been spent on its development and construction. Thus, in order to meet the project deadline, an off-the-shelf alternative was selected for this purpose. The METACOMP ATcomm2 board was selected for its power and features at a reasonable price.

a. The ATcomm2 board can be easily interfaced between the host processor and the PROXIM transceiver. In addition, the board provides an extensive set of programming options, which can be used to realize the full potential of the PROXIM transceiver.
b. The board provides a separate communications coprocessor that is dedicated to the digital communications between the ATcomm2 and the PROXIM board. Because of the addition of the coprocessor, the host processor is relieved of the burden to provide control to the PROXIM board, and more time can be spent on the control calculation and other aspects of the operation. The dedicated coprocessor also increases the throughput rate between the ATcomm2 and the PROXIM board, and provides a most flexible environment for this communication interface project.
c. ATcomm2 comes with buffer memory for incoming communication data. This ensures the host not to miss any incoming data.
d. A comprehensive set of error signals to alert the host in the case of error. This leads to a quick error recovery.
e. The board is AT compatible.

4.3 Sensors

Sensors	Manufacturer	Input Range
Vehicle speed (transmission axle)	Ford	signal conversion from 8 pole pulse generator to analog voltage (0 m/s to 45 m/s)
Vehicle acceleration	ICSensors, Milpitas, CA Model 3 1 10-001 (Fig. A.34)	-1.og to +1.0 g
Range	VORAD	0 m to 152.4 m
Closing rate	VORAD	0 m/s to 28.6 m/s
Engine speed (rpm)	Ford ignition coil	0 to 7500 rpm
Throttle angle	Ford	0 deg to 85 deg
Brake pressure	OMEGA Model PX603-3KG5V	0 to 3000 psig
Intake manifold pressure	GM	0 atm to 1 atm

Table 2. Sensors installed in test vehicles
(All the sensors provide analog voltage between 0 and 5 V)

4.4 Radar system

As a sensor to measure the distance and relative speed between two adjacent vehicles, the radar system designed by VORAD (formerly RCS) has been used for this project. RCS originally designed the radar system (RCS Ml000 model) for the purpose of collision warning to increase driving safety rather than directly for the use of vehicle-following spacing control. This radar's major functions are to maintain necessary driver awareness, identify hazardous driving conditions, and warn the driver to take corrective action before it is too late to avoid a serious problem. This radar is a continuous wave Doppler target detection system operating at a frequency of 24 GHz. Radiated power is 0.5 mW, and FCC approval has been granted for use. The range of the target is derived by measuring the Doppler phase shift, and the relative speed is provided by the Doppler frequency shift. The radar system also provides various operational condition flags (Signal Strength, Multipath, Interference) for the use of corrective action, adjustment or recovery from improper operation.

Later this RCS Ml000 model has been evolved to VORAD T100 model using a different modulation scheme. Both these models were installed in the test vehicles for this project: three Lincoln Town Cars are equipped with the M1000 models and the LTD is equipped with the T100 model. For the purpose of this project, there is no fundamental difference between the two models.

The current radar system has some problems to be resolved for application to vehicle-following control.

- Due to the use of the Doppler effect in obtaining range, the range measurements become invalid whenever the closing rate is very low (0.22 m/s or less).
- The radar range measurements are unreliable; the data jump too much (Fig. A. 35 - Fig. A.37).
- The radar measurements are not consistent between units (Fig. A.38 - Fig. A.42). For example, one unit shows spikes in the closing rate (Fig. A.38) while another unit shows unacceptable jumps in its closing rate (Fig. **A.39).**

In addition to the problems listed above, it will be important to identify the delay in processing radar signals in the next phase of the project, because longer delays would degrade controller performance. It is also necessary to pay attention to the radar interference problem; the radar units may interfere with each other in multicar platoon formations when the transmitting channel frequencies are close together. The channel frequencies of the current units were set far enough apart to avoid this problem, but that will not always be possible when larger numbers of vehicles are equipped.

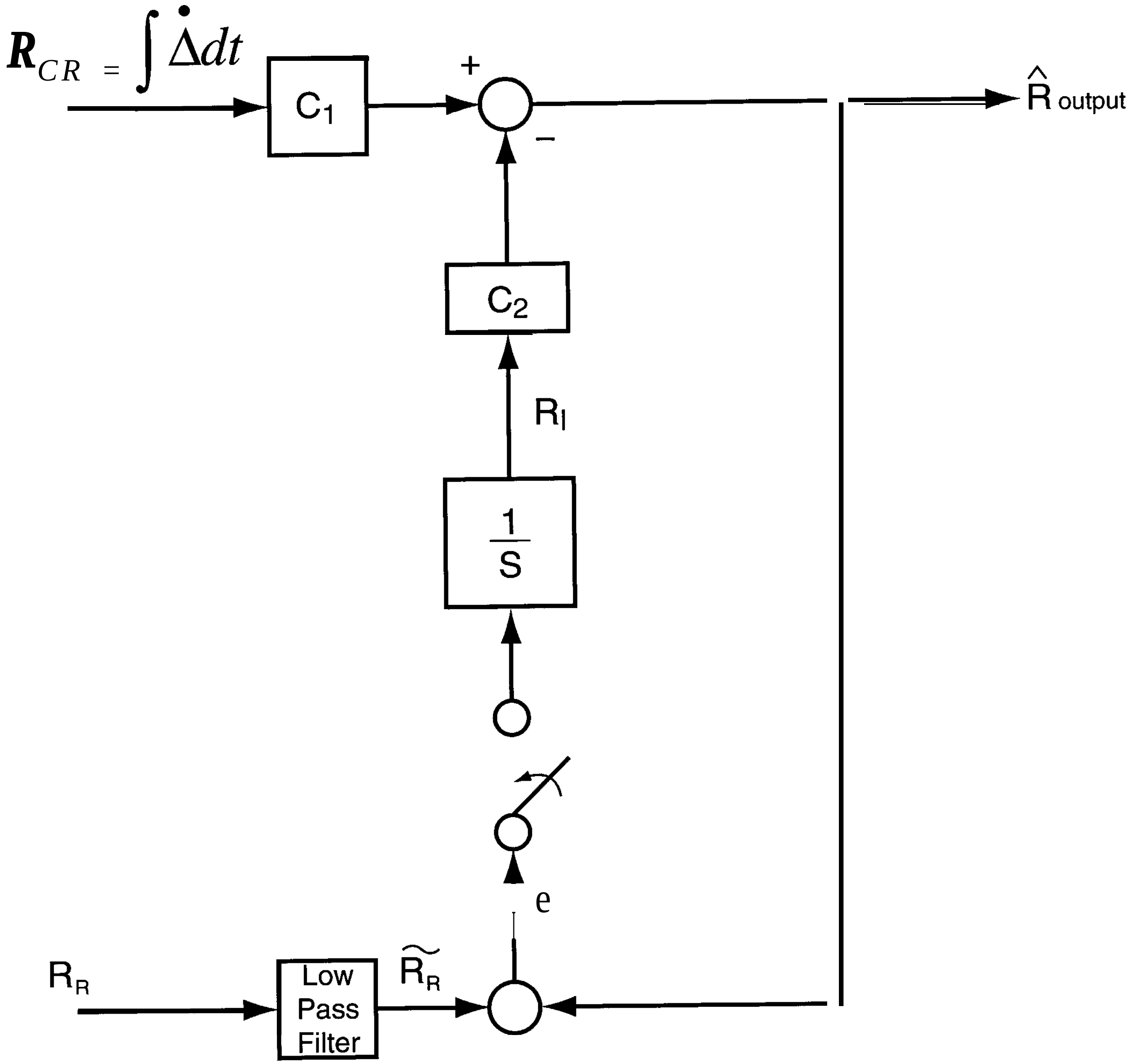
The opposite signs in the speed measurement and the raw radar closing rate variation as shown in Figures A.38, A.39, A.4 1, result from the vehicle direction incorporation on the raw radar closing rate, but not on the speed measurement.

In order to avoid the problems produced by the inconsistent raw radar range during drop-out periods, a range estimation scheme was developed by VORAD and PATH [19]. In this scheme, the estimated range is calculated from two inputs (Fig. 2): raw radar range and raw radar closing rate. The estimated range is derived by integrating the closing rate. At the output, the estimate is compared to the filtered radar range. The difference is passed through an integrator to obtain an average range error. The range error is used' to cancel the drift of the integrated closing rate.

4.5 Control algorithm

The control algorithm used for this project was designed by Professor Hedrick's Vehicle Dynamics group in the Department of Mechanical Engineering at the University of California, Berkeley [9,10,11]. Two vehicle models; a complex model and a simplified model, were developed based upon the Ford Lincoln Town Car, which was the test vehicle used in this project. The control algorithm was developed using a modified nonlinear sliding control method which compensates for the inherent nonlinearities that exist in the automobile plant. This modified method uses multiple sliding surfaces. The objective of the controller design is to make the closed loop system asymptotically stable to disturbances,

Fig. 2 Range Estimation Scheme



$$\hat{R}_k = R_{CR_k} - R_{I_k}$$

$$e = \hat{R}_{k-1} - \tilde{R}_{R_k}$$

R_R : Raw Radar Range
$\tilde{R}_R$: Filtered Radar Range
R_{CR} : Range from Integration of Radar Closing Rate
$\hat{R}$: Estimated Range

which means that the spacing errors between successive following vehicles in a platoon should converge to zero asymptotically. Furthermore, the ride quality in the automatically controlled vehicles should be comfortable, without jerky motions. The control algorithm development is fully documented in reports [9,10,11].

4.6 Communication scheme

Radio Transceiver

The control algorithm requires data (vehicle speed and acceleration) to be transmitted from one car to another. To accomplish this, a communication link among the test vehicles has been designed using off-the-shelf components, including a radio transceiver, a communication interface board, and a host computer. Over-the-air communications are made possible by the PROXIM spread-spectrum digital radio transceivers (1 W output power) [20]. The radio is operated synchronously and serially using the PROXIM onboard clock at a fixed rate of 121 Kbits per second. In synchronous mode, the PROXIM transceiver clock controls the clock on the interface board, and enables the PROXIM to operate at the fast rate. When the PROXIM's clock is independent of the interface board's clock (asynchronous mode), the transfer rate is limited to 19.2 Kbaud. In this project, the PROXIM radio is set up to communicate in the synchronous mode. Since the radio cannot 'transmit and receive at the same time, it must operate in a half duplex mode. The radio operates in the 902-928 MHz Commercial/Industrial band which has been assigned by the Federal Communications Commission (FCC) for unlicensed use by spread spectrum systems. From the four independent frequency channels in the band, a fixed frequency channel of 918 MHz (channel #4) has been used in this project. To enhance the range of communications, an extension antenna is installed with each of the radio transceivers in the system. Each of the radios, in turn, is controlled by an ATcomm communications interface board, made by Metacomp, installed in an 80386 based computer. The host computer in each vehicle controls all aspects of the system's operations.

Communication Interface Board

The radio is controlled by a METACOMP communications board [21] that contains: an 80186 microprocessor, on-board memory (Dual Port RAM), and a serial communications controller (85C30). When the PC in each IPCS vehicle transmits any data, the information is placed in the RAM of the METACOMP communication board. The 80186 microprocessor then instructs the communications controller to format the data for serial communications and. activates the PROXIM radio. The processor can also be interrupted by the radio to handle incoming information. The computer main processor (80386) and the communication unit share the Dual Port RAM (512 K bytes) over the AT bus.

In this project, the drivers for the ATcomm board and the 85C30 are downloaded from the host to the memory local to the ATcomm board. However, since the communication programs remain relatively static throughout the development of this project, placing them in firmware like PROM, EPROM or EEPROM will remove the need for the time-consuming downloading process, reducing the experimental setup time for the communications link.

Most of the communications software development time was spent in getting familiar with the functionalities of the various devices on the ATcomm board, particularly the 85C3O communications controller.

Communication Scheme Outline

Performing coordinated maneuvers with automatically controlled vehicles requires a communication link [12,131. The link is required to support the broadcast of the speed and acceleration of each of the coordinated vehicles. In the two car platoon case, the transmitting/receiving role is fixed depending on the car position in the platoon; the leading vehicle transmits its speed and acceleration, and the following vehicle receives them all the time without any role switching. Due to the simplicity of the scheme in the two car case, the channel control was not needed once it was initialized at the start of each test. In the four car platoon case, the vehicles in the middle of the platoon need to transmit their information also to the following vehicle (Fig. 3). This scheme requires the design of communication channel control.

The radio in each vehicle can either transmit or receive data. The radio cannot do both simultaneously. Since the radio also cannot monitor transmissions, if two radios transmit at the same time, the messages collide and are lost. A channel allocation scheme had to be developed to avoid collisions and to allow all the vehicles to communicate over a single channel.

A multi-vehicle scheme assumes a fixed number of vehicles in the platoon. Each vehicle relies on data to be received within a specified amount of time. Thus, a deterministic communications protocol is desired. Channel access is granted in a round-robin fashion by a form of distributed polling. The lead vehicle maintains a timer and synchronizes its transmissions at 55 ms intervals, which was as fast as it could be made to go. Each following vehicle broadcasts only after it receives broadcast data from the vehicle in front of it. All vehicles transmit and receive at a common radio frequency. A vehicle monitors all radio broadcasts when it is not transmitting. Each vehicle has an address that corresponds to its position in the platoon relative to the lead vehicle. When a vehicle detects a broadcast by the vehicle in front of it, the vehicle behind receives the message containing the sender's address, stores the data, and assumes it has transmit privilege. The broadcast of the last vehicle serves as an acknowledgment to the lead vehicle that a complete transmission cycle has occurred. The lead vehicle will wait for this form of acknowledgment before it can start to transmit again in the 55 ms fixed interval. If the acknowledgments is not received within 55 ms, the lead vehicle considers this condition a negative acknowledgment and will start a new transmission cycle immediately. Thus, all vehicle transmissions are synchronized [13].

Although this communication scheme is fine with the four vehicle case, it is not realistic to apply this approach when we have larger scale deployment due to the communication delay built up from the lead vehicle to the last vehicle in the platoon and the limited available channel capacity. Hence it may be necessary to use a line-of-sight communication

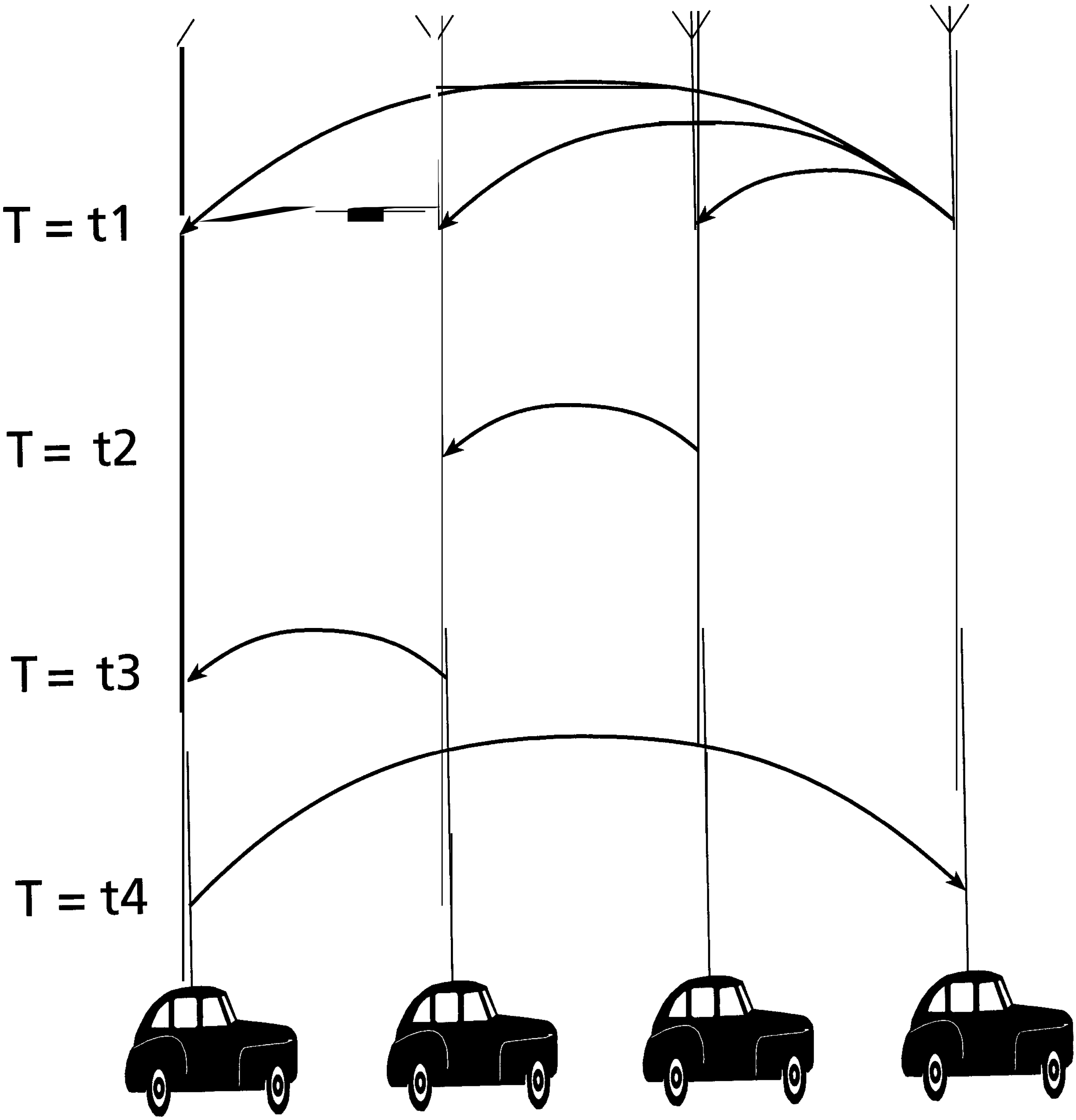


fig. 3 Communication Link (Time Progresses from tl to t4)

link between adjacent vehicles perhaps along with the radio broadcasting from the lead vehicle to following vehicles. The line-of-sight communication will enable us to avoid communication collisions between vehicles so that we can achieve simultaneous data transmission/reception among multiple pairs of adjacent vehicles.

4.7 Data acquisition

The data acquisition unit is a National Instrument IBM PC board [22] that contains nine 12-bit AID converters (to acquire data from the sensors on the vehicle) and two 12-bit DIA converters (to drive a throttle and a brake actuator). The analog inputs can be scanned and stored in a 16-word FIFO. The sampling rate of the sensors is about 18 Hz (55 ms loop time). In simulations, a slower sampling rate than this was found to degrade the platoon system performance.

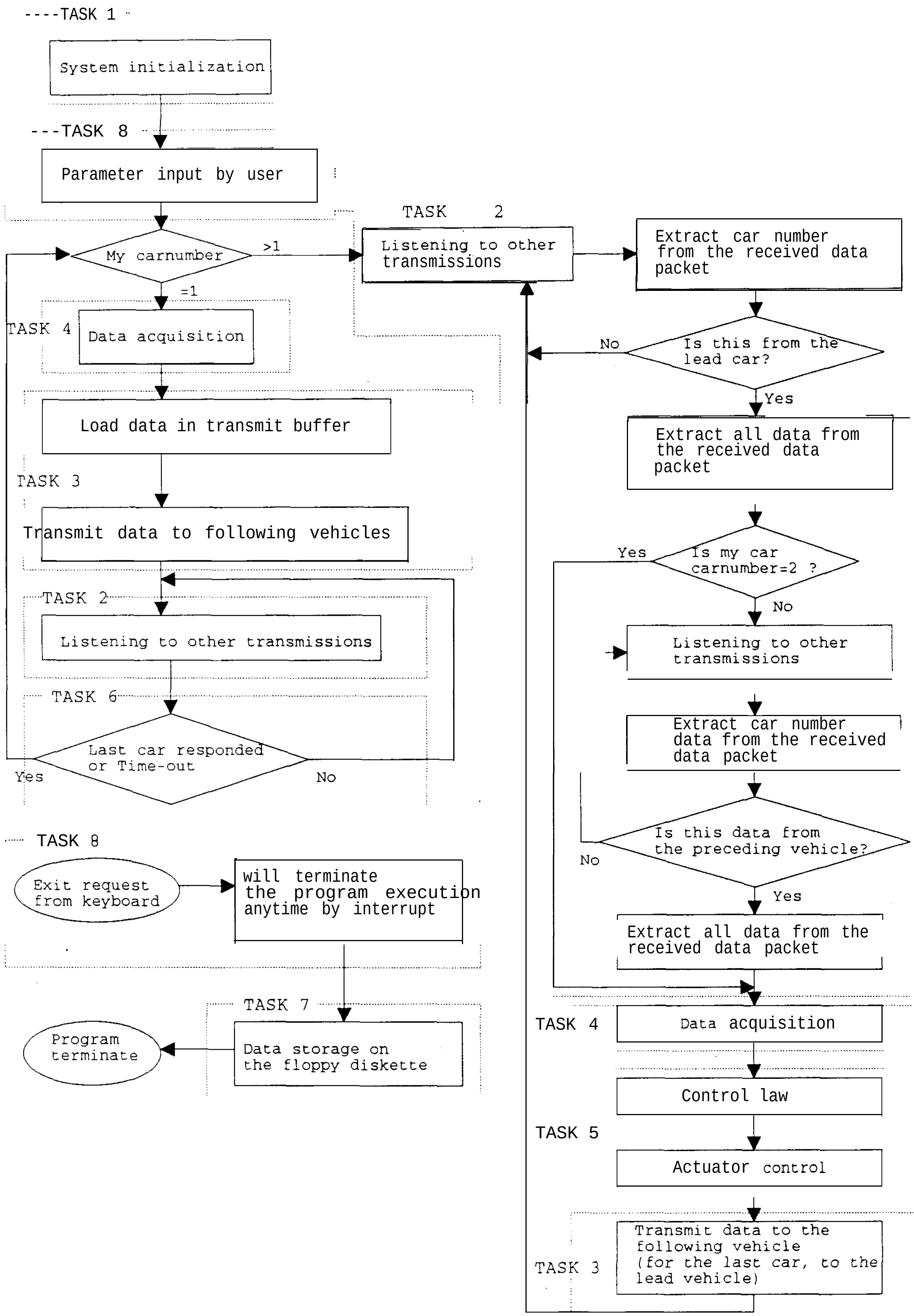
4.8 Operating program

Because of the complexity involved in performing various tasks (control, communication, data acquisition, data storage, etc.) under real time constraints, the timing scheme and priority allocation for each task turned out to be crucial in this project. The multi-tasking operating system, VRTX-PC [23] was chosen since it allows tasks to run under different priorities and with various scheduling policies. VRIX-PC offers convenient facilities, including mailboxes and queues, for inter-task communication. At the time of the selection of the software, VRIX-PC had advantages to the other operating kernel in that the software was already used by faculty and graduate students involved in the project, which certainly reduced the development time of the operating program. In addition to that, Ready Systems initially offered use of the VRTX86 software at no cost. The operating program written in C language using the Microsoft C compiler and the VRTX-PC kernel is organized into several key tasks (Fig. 4):

1. Initialization
   This task initializes different components in the system for proper operation.
2. Data Reception
   This task is performed through radio link or data acquisition. The software is organized to receive data with enough accuracy and time slicing to prevent any data loss.
3. Data Transmission
   The communication interface board must switch to transmit mode and start sending data.
4. Data Acquisition
   This task reads in analog voltages from sensors via AID converter at about 18 Hz sampling rate, and outputs the actuation signal via DIA converter.
5. Control Law Calculation
   This task performs control law calculations based on collected data. Performing this task should not cause any problem in receiving new data by not delaying the controller.
6. Error Handling
   Different errors might occur during the operation of the system and peripherals. Software should be equipped with routines for proper and fast response to these errors.
7. Data Storage
   This task is needed for off-line evaluation of system performance.

Fig. 4

FLOW CHART OF THE OPERATING PROGRAM



8. User Interface
This task provides the user the ability to type in input Parameters, or to stop the execution of the program.

Although we used the multi-tasking program environment, the only multi-tasking feature we used was the user interface for data display on the screen and the 'ESCAPE' key execution to terminate the test. The original idea of using multi-tasking was to execute the communication and data acquisition (including control routine) at the same time to reduce the control actuation delay which would otherwise be longer for the following vehicles in a platoon. It turned out that the four car platoon was not so demanding in timing. Therefore, throughout the project, the tasks were configured to run in sequence rather than multi-tasking. This approach, however, needs to be changed with an increased number of vehicles in a platoon, when the timing becomes a more critical issue.

4.8.1 Restructuring of the code

Throughout this phase of the project, the structure of the operating code was not really of interest; the cede was written to simply verify that the IPCS performed as desired. Toward the end of the project, this approach had to be changed due to the remarkably increased number of task functions and complexities involved with the inter-task relationships. The restructuring and organization of the code is also needed to ensure reliability of the program functioning and to enhance the compilation process; for example, by making task functions as portable as possible, only the function to be modified needs to be compiled to be linked with other libraries. The code also needs detailed comments for other researchers to read without any difficulties. This task has already begun at the time of this writing, and this effort will continue into the next phase of the project probably by a newly hired software engineer.

4.9 Improved actuators

4.9.1 Throttle actuator

After conducting a number of tests with the DC motor as the throttle actuator, it was found that the response time of the motor is too slow. Because of this slowness in the actuation, the test results showed that the following car had oscillatory motion under automatic control (Fig. 5). From static actuator characterization tests, the response time of the DC motor was about 16 deg/sec (degree refers to the throttle valve angle). Given the maximum throttle angle as 85 deg, this response means that it takes more than 3 seconds to open completely from zero. This slow bandwidth of the actuator contributed to poor performance in the vehicle following control (Fig. 5) (highly oscillatory following vehicle acceleration and large throttle angle excursions).

To solve this problem, the actuator specification was refined by use of simulations. The minimal required throttle actuator bandwidth was found to be 5 Hz, and the required throttle saturation rate was greater than 400 deg/sec. As a new throttle actuator, the SLOSYN stepping motor (Model M063-CE, Fig. A.43) manufactured by Superior Electric was selected based on these simulation results. The throttle actuator unit was fabricated by VORAD to include a dedicated microprocessor with encoder position feedback. The motor is driven in full steps with a rate of 1,000 steps/sec. Fig. 6 shows the control performance using the faster throttle actuator. Figures 5 and 6 are included in this report just to present the control performance differences due to the effect of the response speed of two different throttle actuators. A totally fair comparison of the control performance in terms of spacing control cannot be made in this context due to the different test maneuvers used in Figs. 5 and 6. It can be, however, concluded that the large oscillatory motion in the following vehicle acceleration and throttle angle shown in Fig. 5 does not appear in Fig. 6 with the faster throttle actuator. This represents a very typical example of an excessively slow actuator in a control loop degrading the stability of the closed loop system and causing oscillatory performance. (The intermittent "spikes" in the speed and range plots in particular represent spurious readings by the radar system, not real speed and range excursions)

4.9.2 Brake actuator

The original pneumatic brake actuator installed by RCS was also found to be slow and unreliable to varying input conditions (static/dynamic). After performing simulations, the minimum needed brake actuator bandwidth was defined to be 5 Hz. The maximum bandwidth of the on-off pneumatic brake actuator was 1 Hz. According to the simulation, the minimum brake actuator saturation rate was (Maximum Torque)/0.1 sec. It was also found that the pneumatic brake actuator was very dependent on the air tank pressure, temperature and vehicle speed. It also had slow response time. Due to these kinds of problems, a hydraulic actuator was selected and is under development as the new brake actuator. This new actuator appears to have faster bandwidth than the pneumatic actuator. Static and dynamic tests of the actuator will be performed in the months subsequent to the writing of this report to verify its performance.

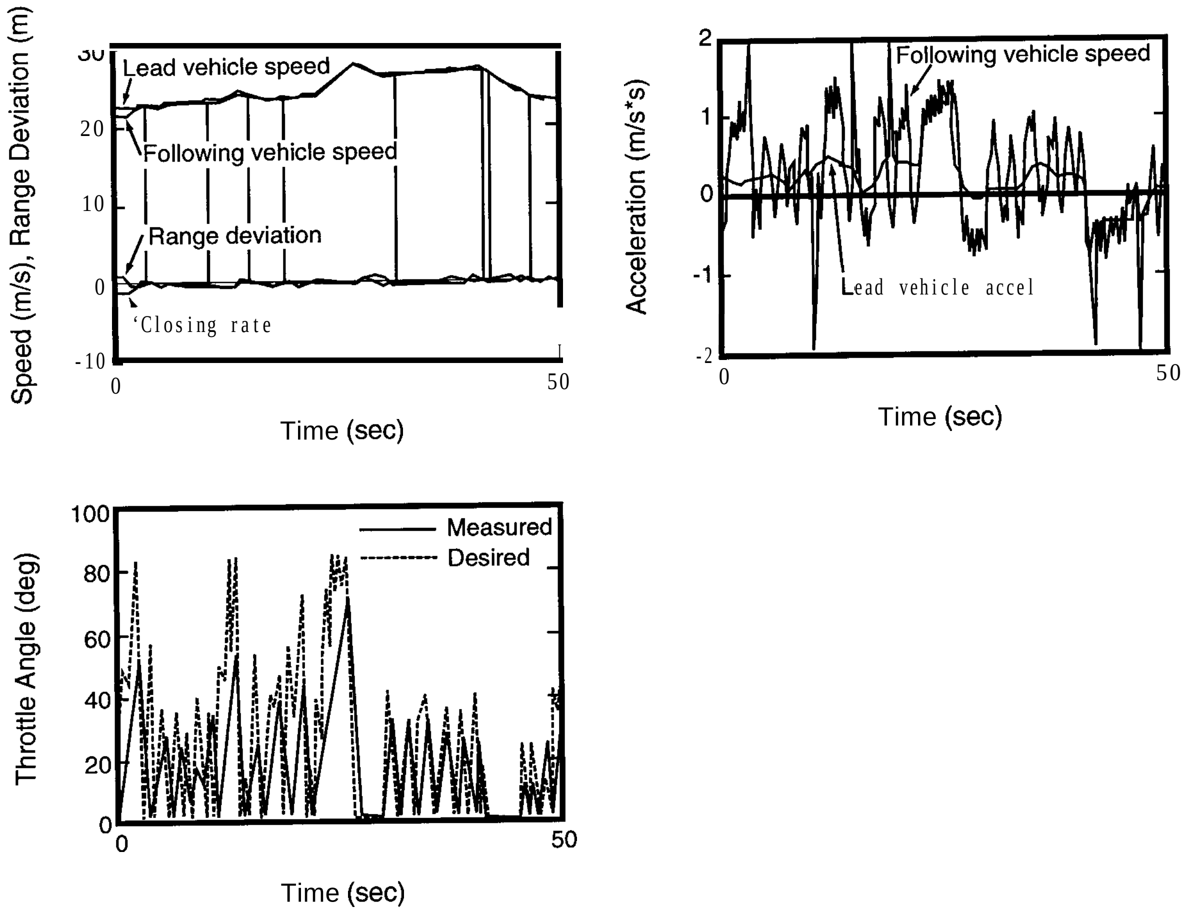


Fig. 5 Example of Control Performance Using Slow Throttle Actuator

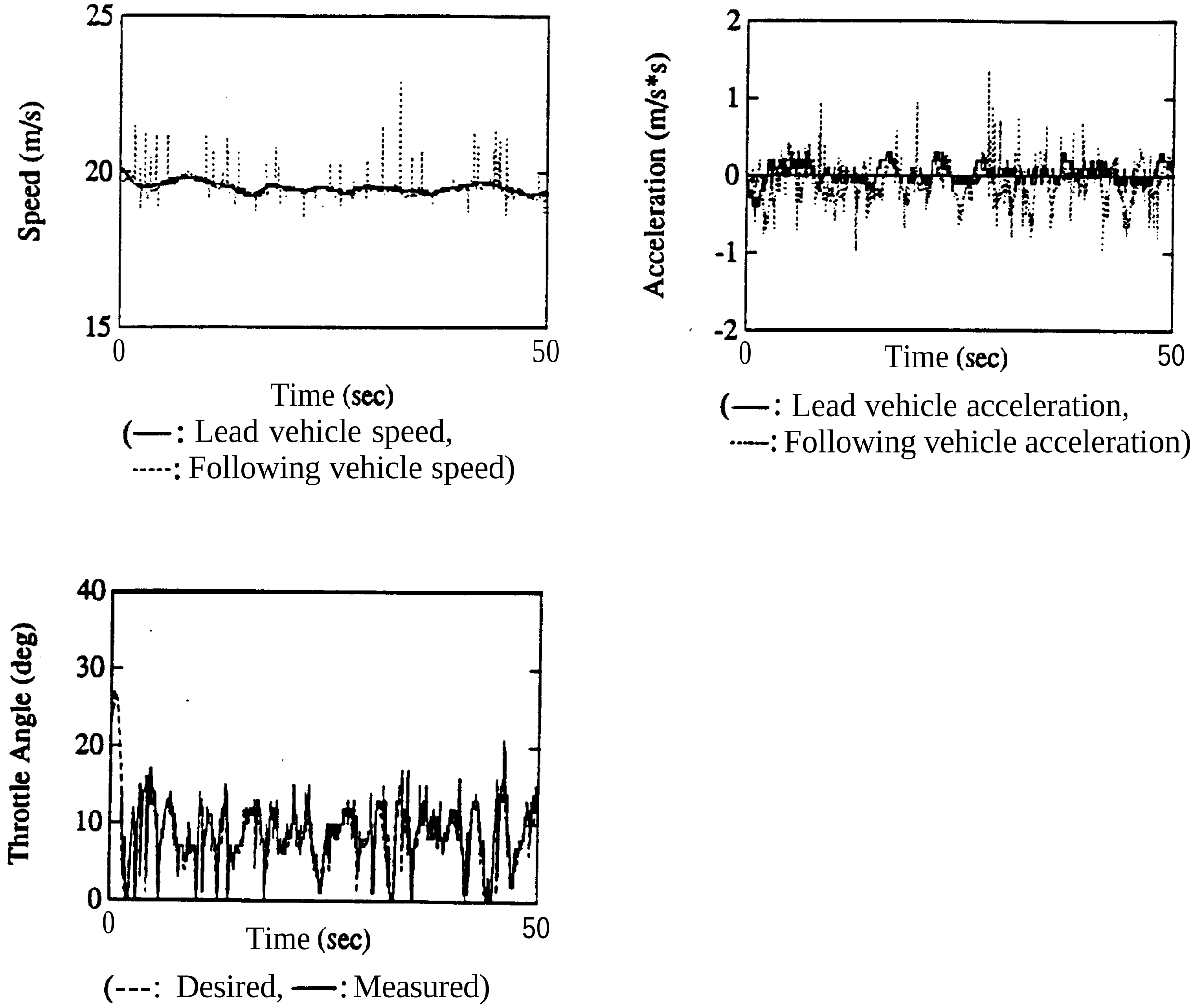


Fig. 6 Example of Control Performance Using Faster Throttle Actuator

Chapter 5. Two Car Experiments

5.1 Experiments

Full-scale testing was performed in January 1992 to verify the model, design, and analysis of the vehicle-follower control system [14,16]. Before full-scale testing, there were many preliminary tests at the University of California's Richmond Field Station and the California Highway Patrol Academy test track in Sacramento to iterate on the designs. These tests were especially performed using the speed sensor to estimate the range between two vehicles; the estimation was obtained by integrating the radar closing rate or the speed sensor measurement differences. This phase of experiment was needed since the radar system was not ready at that time. The estimated range was sufficient to verify the performance of the control law and the communication scheme. The test results using the integration of the radar closing rate are shown in Fig. 7 and Fig. 8. The small spikes in vehicle speed plots were due to the noise in the speed sensor. The large spikes in the following vehicle speed plot were due to the communication loss at this early stage of the project. This frequent communication loss problem was fixed later by adjusting the waiting time between the transmission and reception control on the transceiver. The large deviations shown in both figures in the early parts of the tests are due to the initial (manual) mismatching of the range and speed between the two test vehicles. These initial condition errors decrease under closed loop control as the test continues.

The full-scale test was conducted on an eight-mile section of high-occupancy-vehicle (HOV) lane in the median of Interstate 15 to the north of San Diego. The HOV facility contains two twelve-foot lanes, with ten-foot shoulders on both sides, separated from the rest of 1-15 by full Jersey barriers. The facility is a one-way freeway (inbound in the morning, outbound in the evening) with two lanes to be open to the commuting public only during the morning and evening commuting hours. For the rest of the day, the HOV lane is closed at both ends using orange cylindrical markers and cross bars. Our experiments are conducted when the facility is closed to the general public in order to ensure safety.

For the first phase of the platoon experiments, only two cars (Lincoln Town Cars) were used with only throttle control (no automatic brake actuation). Both vehicles are equipped with air-bags and were driven by highly trained test drivers provided by the Automobile Club of Southern California. The lead vehicle was manually driven while the following vehicle was under automatic control in the longitudinal direction. The following vehicle had a test driver on board to provide steering control only, but also to take over longitudinal control if necessary. The reduced number of cars simplified some of the tasks involved in platoon control, in particular that of communications. In the two car platoon, the lead car always performed the transmission task while the following car always performed the reception task. In a four car platoon, cars in the middle of the platoon must switch between the transmission and reception tasks for inter-vehicle communication, which is more complicated.

After checking the functioning of various components of the IPCS, both cars were

Fig. 7 Two car experiment using integration of speed sensor (steady cruising condition)

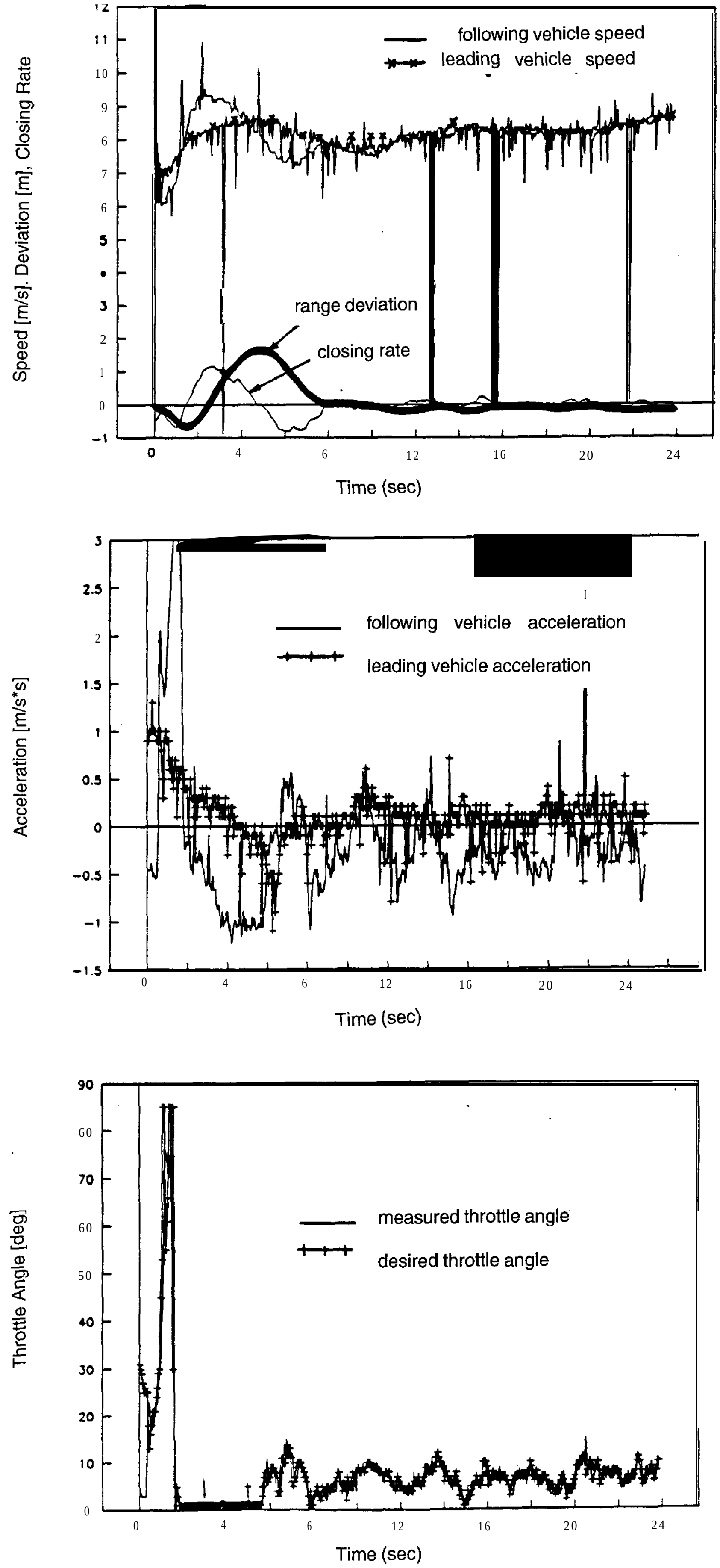
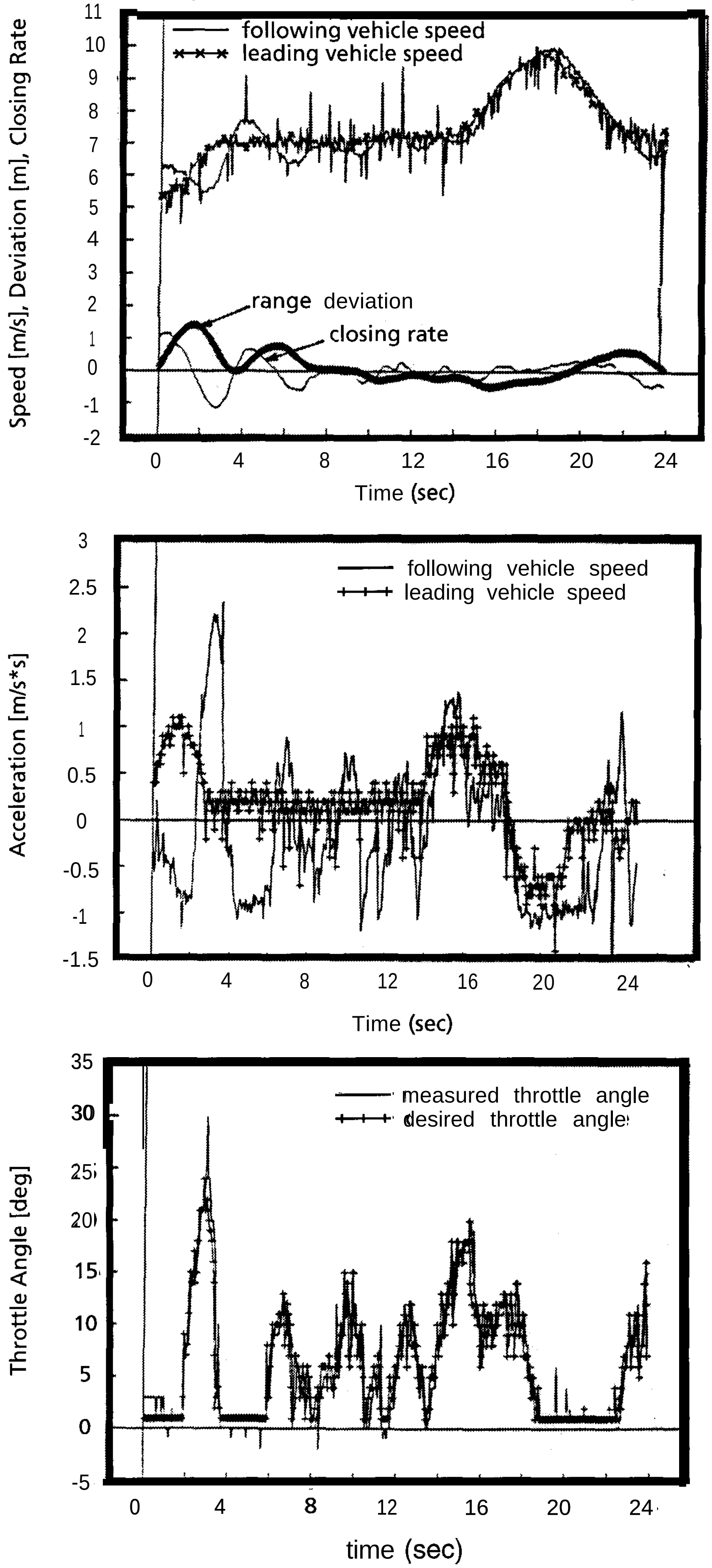


Fig. 8 Results of Two Car Experiment using Integration of Speed Sensor (acceleration/deceleration condition)



accelerated under manual control to a steady-state speed close to the desired test speed, at approximately the desired spacing. At this point, by test personnel's (driver and computer operator) operations, the computer in the lead car began conducting data acquisition and transmission and the computer in the following car began conducting reception, data acquisition and automatic control in the longitudinal direction. During the test, test personnel used extreme caution to guard against potential emergency conditions. The brake pedal has a tap switch on the pad to deactivate automatic throttle movement as soon as the driver pushes the brake pedal. After running through a preplanned test section on the HOV lane, the data set collected in the RAM was stored in a floppy disk for later analysis. The test scenes were also recorded using two video cameras, one for each vehicle.

5.2 Experimental results

5.2.1 Lead vehicle at constant speed (25 m/s)

With the lead vehicle cruising at a constant speed, the following vehicle moved up behind and the radar locked on to follow it. The lead vehicle speed was controlled by the standard factory-installed cruise control and the following vehicle controlled by the platoon control system. Although automatically controlled in the travelling direction, the drivers in both vehicles were still in charge of control of the steering wheels.

Three different desired spacings (21 m, 15 m, 9.14 m) were used in three different sections of HOV lane. The sections used were:

1) the Southern section of HOV lane having straight and mild curves
2) the section having grades, i.e. downhill (-3 %) and uphill (+3 %)
3) the whole stretch of I-15 HOV lane

In this report, only results from the test with 9.14 m of desired spacing are presented as shown in Fig. 9. The car-following performance can be evaluated by investigating three variables: the actual vehicle spacing deviation from the desired spacing, the closing rate (relative speed) between two vehicles, and the acceleration differences between the vehicles. When the following vehicle maintains the desired spacing, the closing rate should be zero for perfectly matching its maneuver with the leader. The figure includes these variables to show satisfactory performance of the test. The actual spacing deviation was maintained less than 1 m from the desired. Acceleration data obtained from both vehicles (leader and follower) is also shown in the figure. The small magnitude of acceleration (0.025 g) in the following vehicle represents smooth and comfortable riding performance. The plot of this throttle angle variable shows the actuation signals: actual and desired, applied to the throttle valve of the following vehicle for automatic control.

5.2.2 Lead vehicle varying speed (25 m/s - 34 m/s)

The lead vehicle was driven with a sequence of speed change maneuvers by the driver at two levels of severity instead of using the cruise control. Typical maneuver of the lead vehicle for this test consists of:

1) a constant speed maintained for about 15 seconds
2) mild acceleration and deceleration at 0.05 g (4.9 m/s in 10 sec)
3) moderately heavy acceleration and deceleration at 0.1 g (9.8 m/s in 10 sec)

This testing mode was performed only in a flat section again with three different desired spacings.

Example test results are shown in Fig. 10. The velocity profile shows how the lead vehicle driver conducted the acceleration/deceleration and also how the following vehicle successfully followed the lead vehicle maneuver. The spacing data again represents good performance of the car-following. As shown in the figure, the deviation of the following vehicle acceleration from the lead vehicle acceleration is maintained below 0.005 g. The actual spacing deviation was maintained less than 1 m from the desired. The actual throttle angle and the desired throttle angle match very well. The actual riding quality was so smooth and impressive that the following car gave the impression of being rigidly linked with the leader. Considering the rate of acceleration and deceleration change in the lead vehicle, a human driver's manual control cannot match these speed changes closely enough to keep the space deviation within 1 m.

System performance needs to be evaluated in terms of both tracking accuracy and ride quality. Tracking accuracy is needed to ensure that spacings between vehicles remain close to the desired values so that the vehicle occupants cannot perceive spacing changes, as well as to minimize the likelihood of vehicles approaching each other close enough to touch. The tracking accuracy indicators are the similarity of the velocity profiles of the vehicles and the smallest possible values of spacing changes (which must remain a small fraction of the desired nominal spacing). The ride quality indicators are acceleration and jerk variability. The acceleration measurements were not "clean" enough to produce useful estimates of jerk (which cannot be measured directly). The most widely used existing standard for passenger ride comfort (ISO 2631) is oriented toward applications to transit or rail system riders, rather than automobile drivers and passengers. It is based on measures of rms acceleration in 1/3 octave bands for steady-state operation. The test data acquired here are not suitable for comparison with that standard because of the different operating conditions and insufficient data quantity and quality.

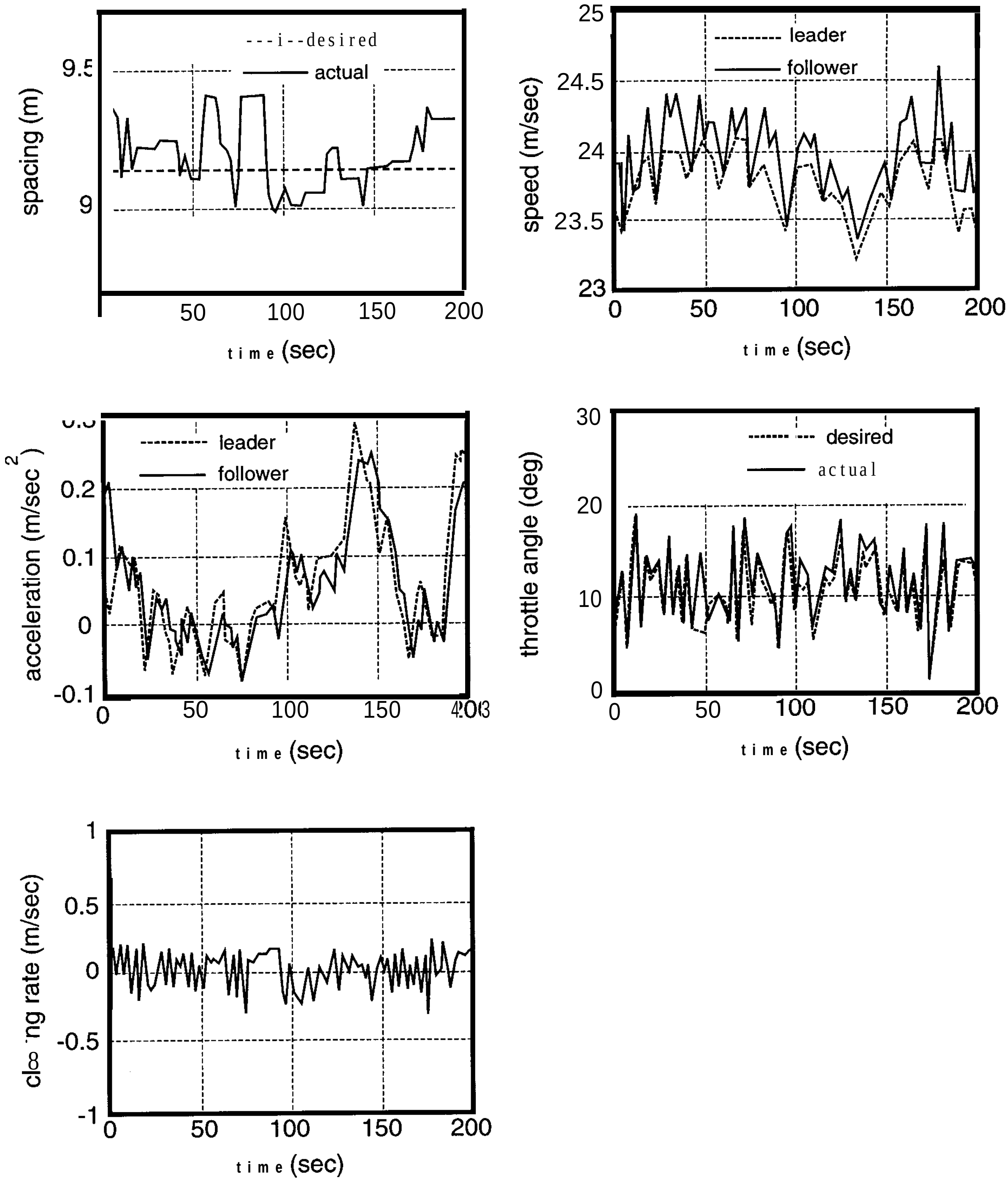


Fig. 9 Results of two car experiment using the radar
(lead vehicle at constant speed)

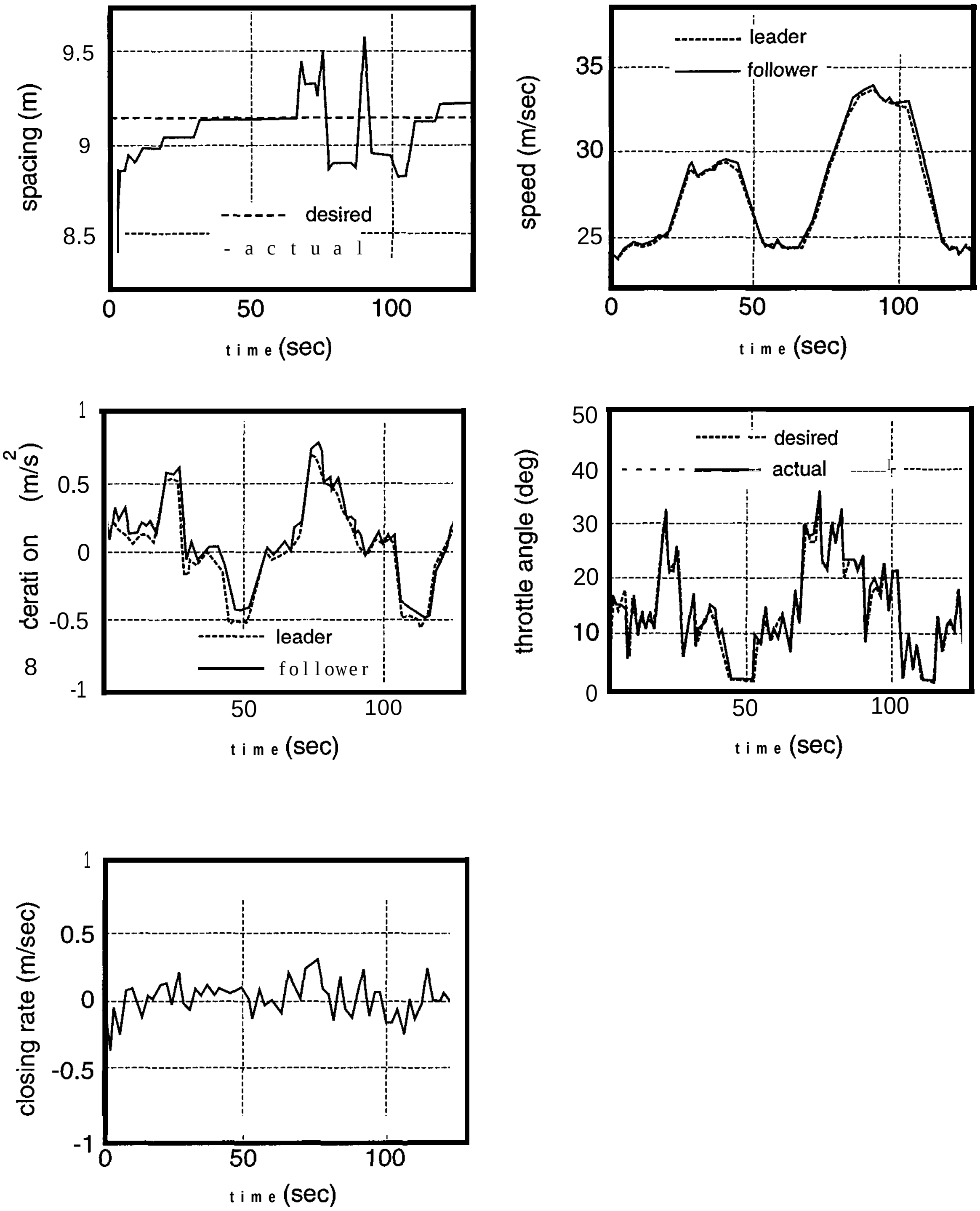


Fig. 10 Results of Two Car Experiment Using the Radar
(lead vehicle in acceleration/deceleration cycle)

Chapter 6. Four Car Experiments

6.1 Experiments

The full-scale testing was performed in May 1992 on the I-15 HOV lane in San Diego to verify the design of the multi-car platoon control system. In the actual test, four cars: one Ford LTD as a manually controlled leading vehicle and three Ford Lincoln Town Cars as automatically controlled following vehicles, were driven with the help of Caltrans and Automobile Club of Southern California who provided highly trained test drivers.

The lead vehicle was manually driven while all the other following vehicles were under automatic control in the longitudinal direction. The following vehicles had test drivers on board to provide steering control only, but also to take over longitudinal control if necessary. As in the two car experiments, only throttle control was used in the test since the brake actuation was not implemented yet.

The technological differences between the two car platoon system and the four car platoon system lie in both control and communication design. In its controller, the automatically following vehicle in the middle of the platoon uses vehicle information (speed and acceleration) of the leading vehicle (the first vehicle in the platoon) as well as the preceding vehicle in front of it (Fig. 3). This requirement was verified in simulations to stabilize the platoon string against any unsteady maneuver performed by the leading vehicle. Therefore, the controller contained two additional control gains to be selected: one associated with the lead vehicle speed feedback and another with the lead vehicle acceleration feedback. These control gains were determined from simulations and modified through tests. The second difference is the communication scheme, due to the requirement for the preceding vehicle information as was explained earlier in this report.

For demonstration purposes, gear position sensing was developed. Currently it is possible to detect transmission gear positions at second, third and fourth. All test vehicles start from stationary position by slowly moving forward (about 2 m/s) manually, and the lead vehicle announces the low steady speed status. Then the following vehicles turn on their actuators in sequence until the last vehicle is engaged. After confirming that every following vehicle is in automatically controlled status, the lead vehicle starts to speed up to the predetermined constant speed. During the transition period, the controller updates the gear position parameter based on the sensor information.

6.2 Experimental results

Lead vehicle at constant speed (25 m/s)

Three different desired spacings (21 m, 15 m, 9.14 m) were used throughout the whole section of the I-15 HOV lane.

Date performed	Test number of the day	Desired spacing	Figure Number
5/11/92	#5	9.1 m	Fig. 11
5/11/92	#7	9.1 m	Fig. 12
5/12/92	#1	9.1 m	Fig. 13
5/12/92	#2	15.2 m	Fig. 14
5/12/92	#3	21.3 m	Fig. 15
5/14/92	#2	9.1 m	Fig. 16
5/14/92	#3	9.1 m	Fig. 17

Note that the time scale for Fig. 16 is different from the time scale for the other figures, which can give the misleading impression of smoother performance.

Lead vehicle varying speed (20 m/s - 30 m/s)

The lead vehicle was driven with a sequence of speed change maneuvers by the driver at two levels of severity instead of using the cruise control. The maneuver was the same as in the two vehicle experiment case.

Date performed	Test number of the day	Desired spacing	Figure Number
5/12/92	#4	15.2 m	Fig. 18
5/12/92	#5	21.3 m	Fig. 19
5/14/92	#4	9.1 m	Fig. 20

6.3 Discussions

Filtering of the radar range measurements

It was found that the spacing deviations from the desired range were unacceptable in most of the tests. The deviation was within 50 cm for the second vehicle (± 0.5 m) and within ± 1 to 2 m (worst case) for the third and fourth vehicle. The average acceleration deviation from the lead vehicle acceleration is 0.3 m/s^2 (0.2 to 0.4 m/s^2) which equals 0.03 g. Compared to the very small acceleration deviation of 0. 1 m/s^2 at maximum from the lead vehicle acceleration in two car platoon tests, this level of acceleration was not smooth for riders in test vehicles.

Based on these observations, data analysis was performed to find the cause of this jerky/ surge motion occurring in following vehicles in the test platoon. It was found that the filtering of the radar range measurement was not conducted properly to obtain a smooth range profile. The radar range signal has drop-out periods due to the absence of Doppler effect when the closing rate between two vehicles is very low (less than 0.23 m/s). During that period, the range estimator calculates range information only based on the radar closing rate. As soon as the Doppler effect is recovered, the raw radar range starts to be fed into the estimation routine. The current second order filtering (Fig. A.44) which requires two previous data samples also starts working on these new values as initial conditions; in fact, the filtering algorithm just skips the first three data samples (raw radar range measurements) after the start of the valid period before starting filtering. However, it was found that the raw radar range samples were still in transition status changing from erroneous signal to a stabilized signal representing true distance although the radar flag already indicated a valid period (Fig. A.45). This transitional status should have been treated in filtering to avoid jumps in the filtered range signal. For example, in Fig. 14 and Fig. 19, the large surges at about 180 seconds in Fig. 14 and at 200 seconds in Fig. 19 were due to the current filtering scheme which was affected by the erroneous raw radar range after recovering from the fairly long radar invalid period.

The solution to fix this problem will be to skip three transitional data samples by replacing them with the previous range measurement being held from the drop-out period. This should produce a smoothly filtered range signal. It is also to be noted that the filtering frequency should be high enough to catch the actual spacing variation dynamics, but should be low enough to produce smooth data points.

Spacing drift during drop-out period

When the radar range becomes invalid (drop-out period), the range estimation scheme calculates the estimated range only based on the integration of the radar closing rate. During this period, which is usually fairly long when the spacing control reaches steady state, the test drivers felt their vehicles actually start to catch up to the preceding vehicle although the range data showed a constant spacing (flat section in the spacing deviation plot in Fig. 15). This is probably due to the drift effect from the integration of the radar closing rate. The actual spacing will be slightly different from the estimate. After a while when the catching-up rate becomes large enough to trigger valid radar range measurements, the range estimation makes a self-correction to adjust the estimate to the actual spacing, which may then cause a surge in the following test vehicles.

The VORAD company has been designing a so-called pseudo-pulse radar ranging system to measure range when the closing rate is very low such as less than 0.225 m/s. Unfortunately by the time the project concluded, the pseudo-pulse radar unit development was not completed by VORAD. When the system is implemented, the radar range measurement won't suffer any drop-out periods, which should produce more comfortable and smooth riding.

Steady state error in the controlled spacing

It is a repeated observation that stationary ranges for all vehicles have biases from the desired range. This is due to differences among the sensors such as vehicle speed, acceleration and radar closing rate between different vehicles. The desired engine torque is calculated as follows:

2nd vehicle

tnetdes = (lead_accel - 1.0*radar_closing_rate - 0.5 * (desired_range-radar_range)) *40 + 0.054*speed*speed + rolling_resistance

3rd, 4th vehicle

tnetdes = (lead_accel + preceding_accel - 1 .0*radar_closing_rate - 0.5*(desired_range-radar_range) - 1.0*(myvehicle_speed-leadvehicle_speed))*40 + 0.054*myvehicle_speed*myvehicle_speed + rolling_resistance

At steady state, *tnetdes* must be approximately equal to the actual engine torque required to move the vehicle at that steady state. The last two terms in the *tnetdes* calculation are the aerodynamic drag and tire drag, which together equal this torque. Thus, steady state is reached when the other terms sum to zero. Any measurement offset, such as nonzero lead vehicle acceleration measurement when lead vehicle acceleration is actually zero, is then compensated for by a range offset of the appropriate sign.

As a way of removing this problem, it is proposed to calibrate all the related sensors (speed, acceleration, radar closing rate) to be tuned to one of the test vehicles, for example, the lead vehicle.

Considering that the public platoon systems deployed in the future will probably be different system by system (although regular check-up should be instituted by the authority), the steady state error may be reduced either by using an integral term, which will compensate for the stationary error by using an accumulated error term, or by using an adaptive control law to be robust to parameter changes.

Which solution (or even both solutions) will be pursued should be decided in the next phase of the experimental project.

Stability of the platoon

A stable platoon system means that disturbances occurring in the preceding vehicles are reduced toward the end of the platoon. The acceleration/deceleration test mode was planned to understand the robustness of the controller to the maneuver disturbance input. Throughout all the tests conducted with four car platoon control system, it was found repeatedly that the spacing deviations of the third and fourth car were greater than expected. It was also noted that the performance was worst sometimes in the third vehicle (5/11/92 and 5/12/92 tests) and sometimes in the fourth vehicle (5/14/92 tests) with unknown reason. Apparently we did not have enough data collection to draw any conclusion whether the spacing deviation becomes smaller for the vehicles toward the end of the platoon or not. Especially for the comparison of the spacing deviations between vehicles in the 5/1 1/92 and 5/12/92 tests, the offset of the stationary spacing deviation should be compensated to make a fair comparison. For example, the offset in the third vehicle is higher than the offset in the fourth vehicle in Fig. 13. After compensating for the offset, it does not seem to be legitimate to conclude that the third vehicle performed worse than the fourth.

We need to conduct more field tests to draw conclusions about the stability of the platoon.

Grade effect

Although it is difficult to draw any conclusions about the effect of grades due to the limited number of results, at least it can be speculated that the performance was probably affected by the grade. The downhill/uphill (± 3%) section in the I-15 HOV lane is located near the end of the North section of the lane. From the time axis in the data plots in all figures, the grade section corresponds to the time about from 220 sec to 280 sec, which may vary a little test by test. The controller was designed based on the flat road assumption without any grade effect and the single axis accelerometer could not resolve the difference between a "true" longitudinal acceleration and the longitudinal component of gravity when operating on a grade.

Some of the test results show substantial changes in the performance during this grade section of driving. Especially, Fig. 15 shows noticeable differences between the flat section and the grade section. This is probably due to the grade effect. In order to draw conclusion from repeated phenomena, we need to conduct more tests.

Spacing control from stationary position

Some of the field tests were conducted with the test vehicles starting to be controlled from a stationary position; the manually controlled lead vehicle starts to pull the automatically controlled following vehicles to keep desired spacing. The sensor detecting the transmission gear position enabled this mode of operation.

Fig. 21 shows the test results conducted in this operational mode. The range and speed profile show good tracking performance, and the acceleration profile shows two gear shiftings during the initial transitional period. The large spacing deviation at the start is due to the initial condition offset of the actual spacing with the desired spacing (9.1 m) for each vehicle.

These results show the feasibility of the application of the vehicle-following control system for automatic stop-and-go maneuvers. The performance will be improved with the application of the torque converter model and control which is planned to be performed in the next phase of the project.

Fig. 11 Example Results of Four-Vehicle Platoon Test #5 of May 11, 1992 (9m Nominal Spacing)

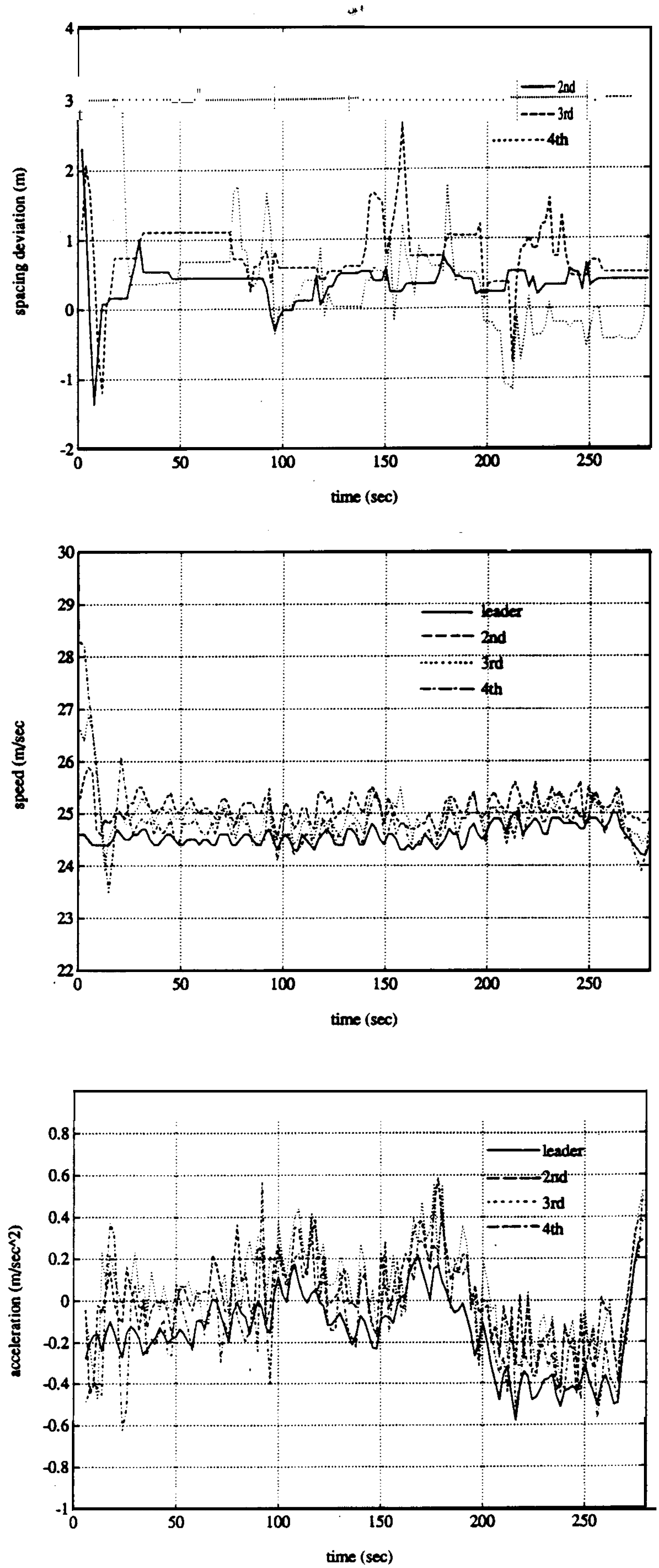


Fig. 12 Example Results of Four-Vehicle Platoon Test #7 of May 11, 1992 (9m Nominal Spacing)

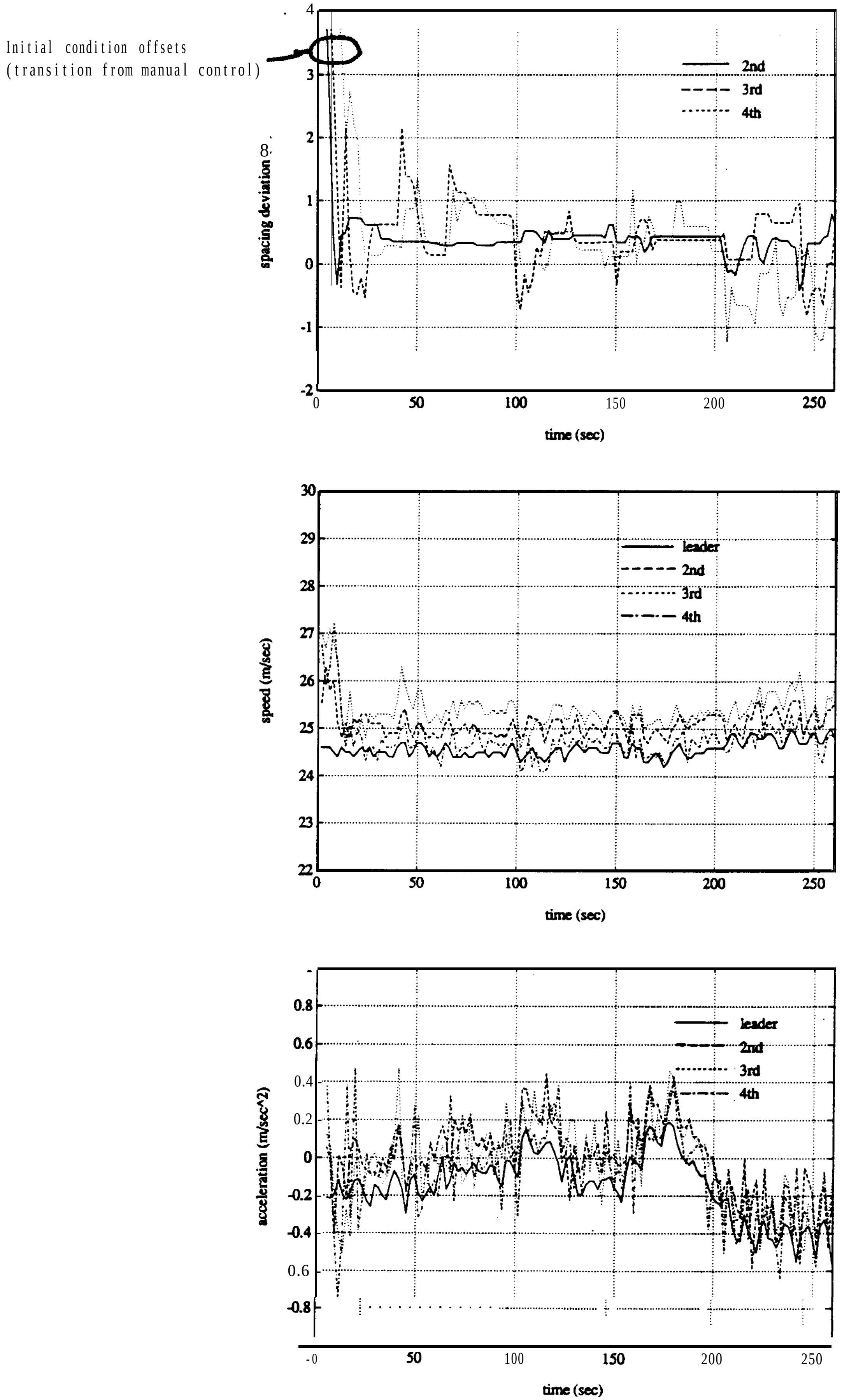


Fig. 13 Example Results of Four-Vehicle Platoon Test #1 of May 12, 1992 (9m Nominal Spacing)

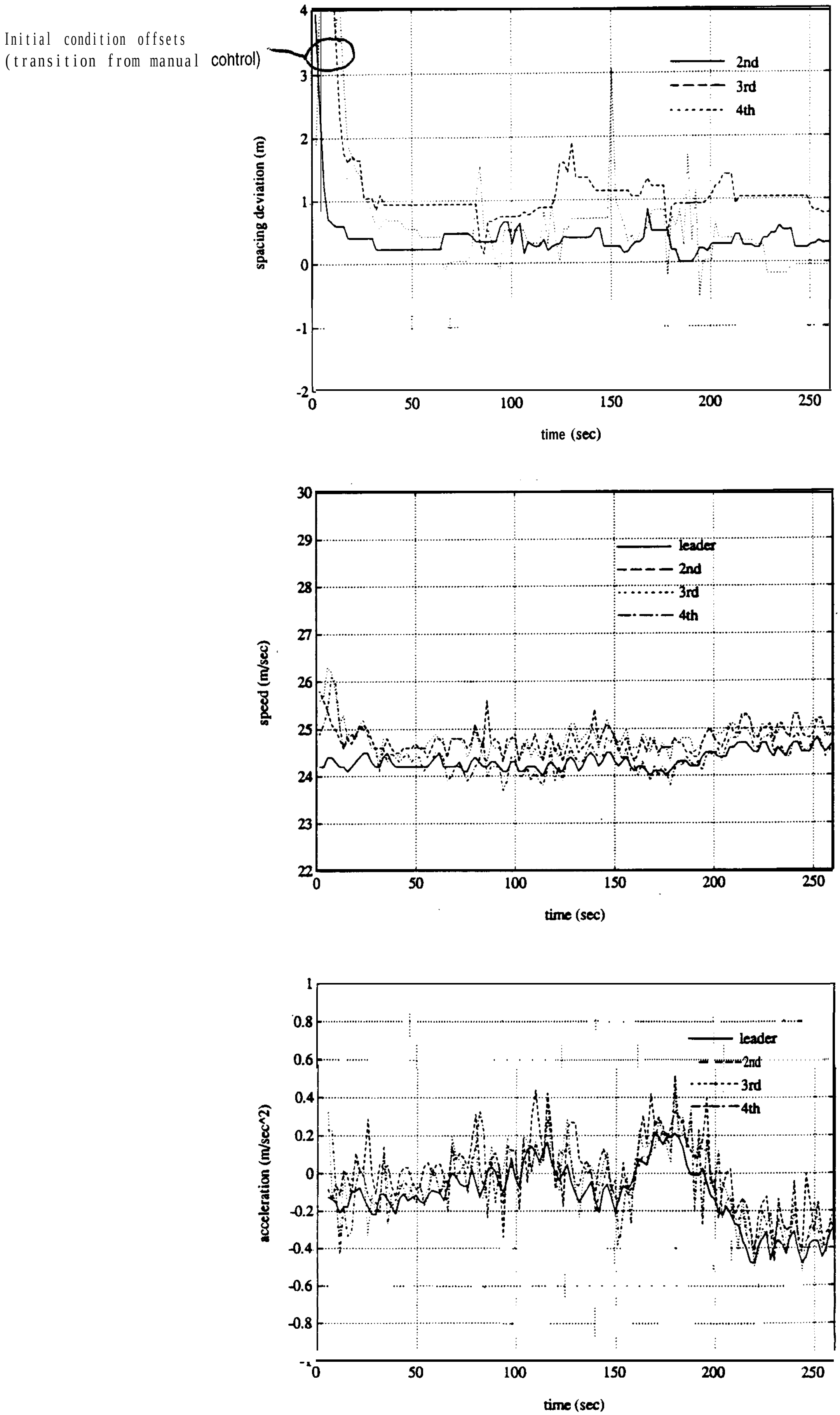


Fig. 14 Example Results of Four-Vehicle Platoon Test #2 of May 12, 1992 (15m Nominal Spacing)

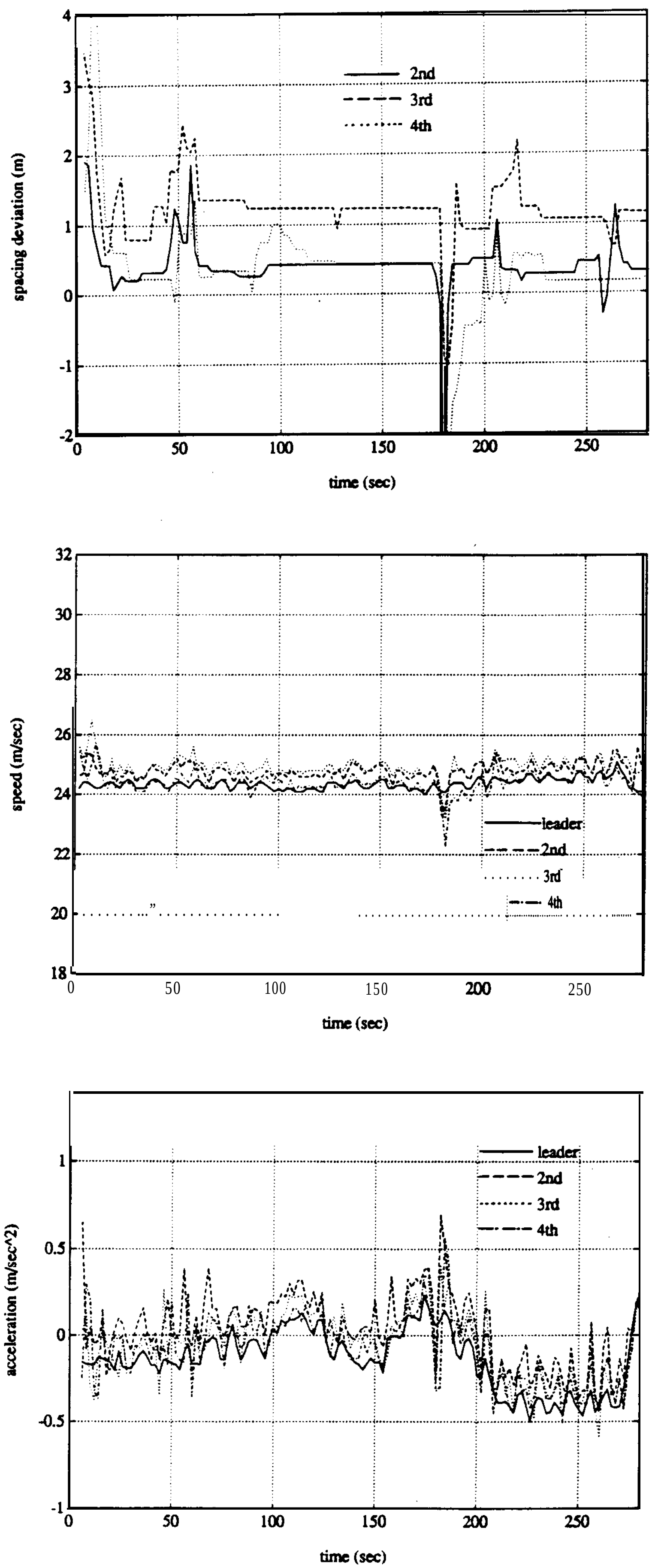
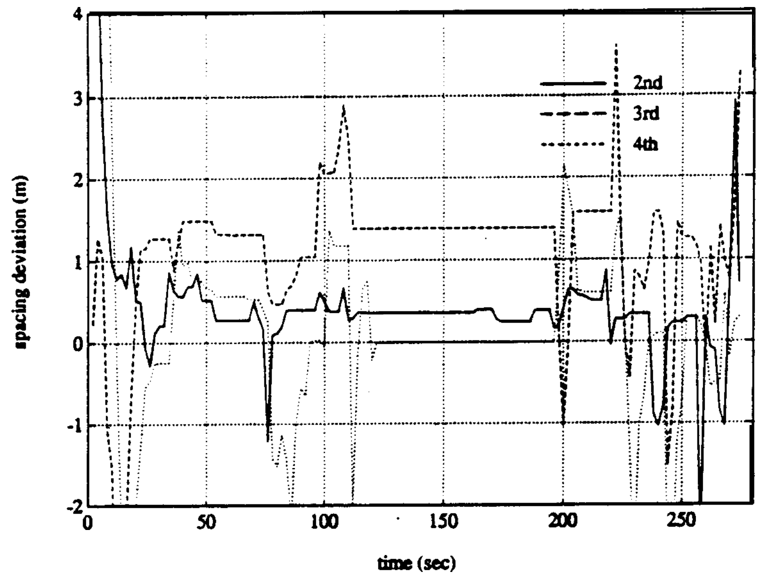
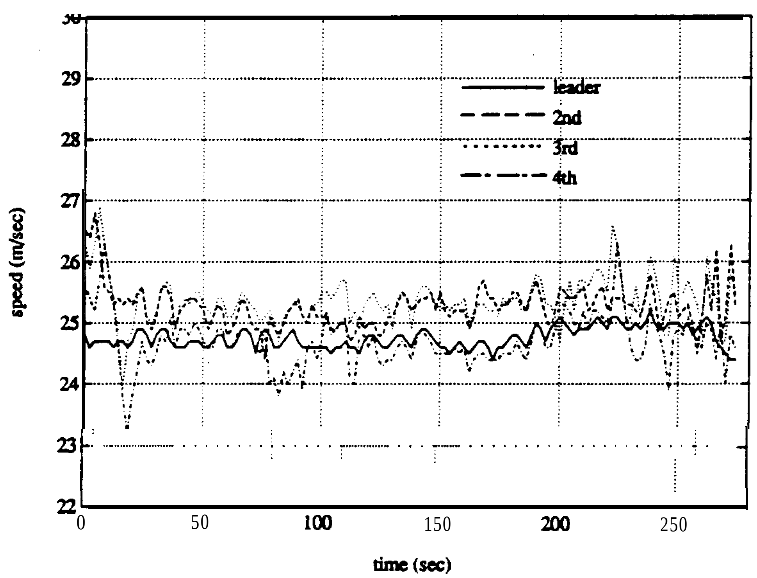


Fig. 15 Example Results of Four-Vehicle Platoon Test #2 of May 13, 1992 (21 m Nominal Spacing)





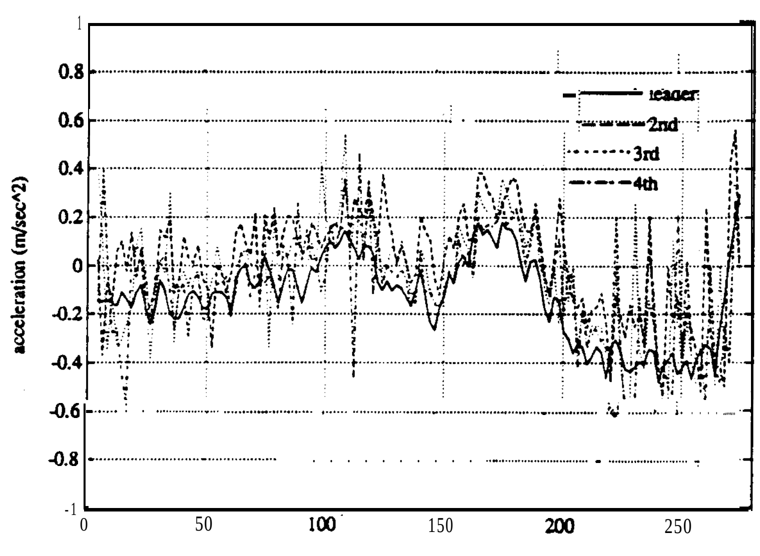


Fig. 16 Example Results of Four-Vehicle Platoon Test #2 of May 14, 1992 (9m Nominal Spacing)

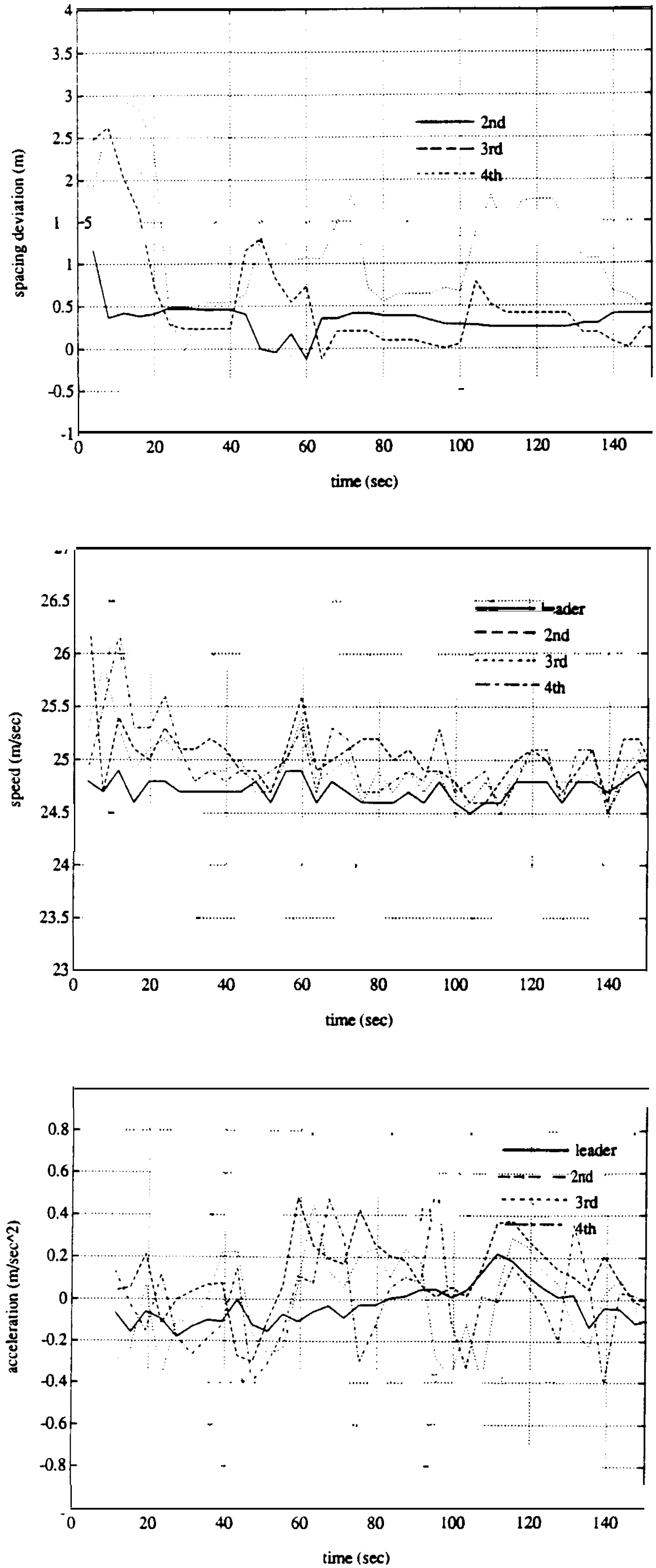


Fig. 17 Example Results of Four-Vehicle Platoon Test #3 of May 14, 1992 (9m Nominal Spacing)

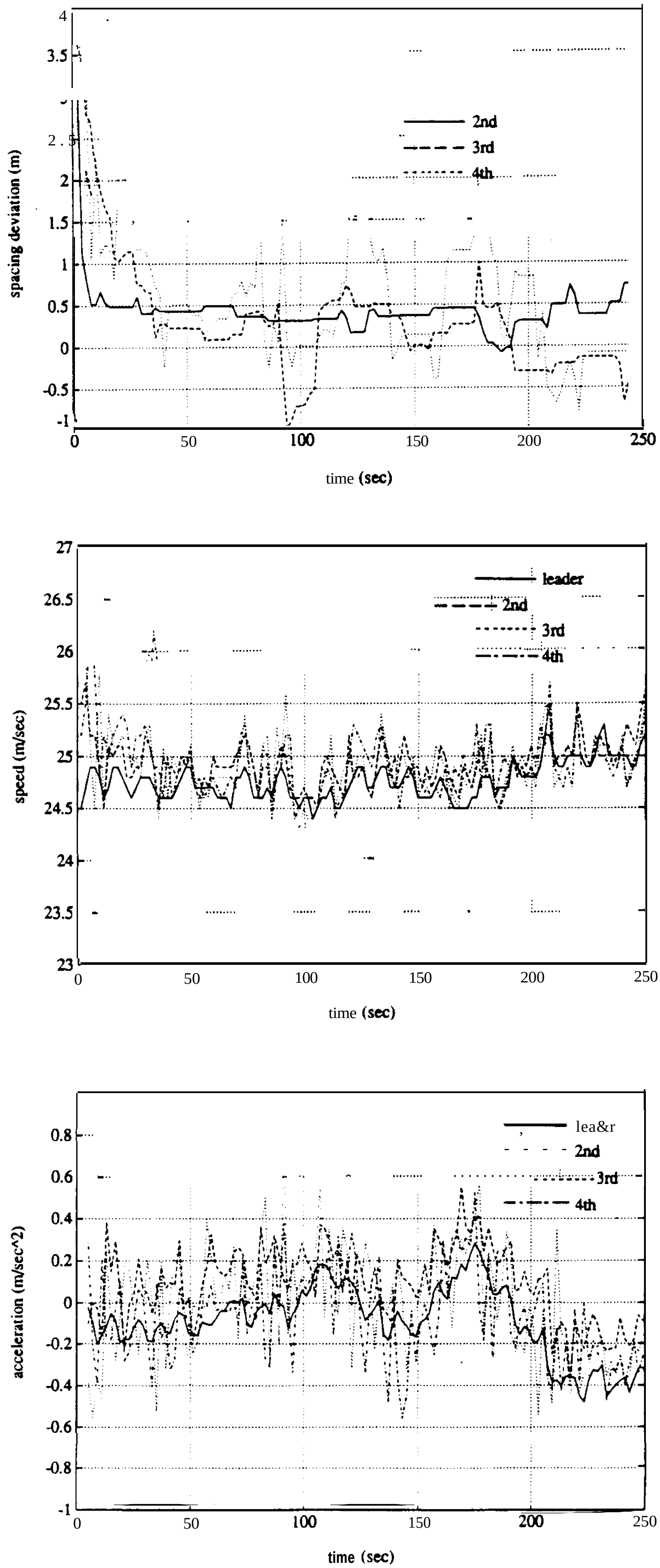


Fig. 18 Example Results of Four-Vehicle Platoon Test #4 of May 12, 1992, with Accelerate-Decelerate Cycles (16m Nominal Spacing)

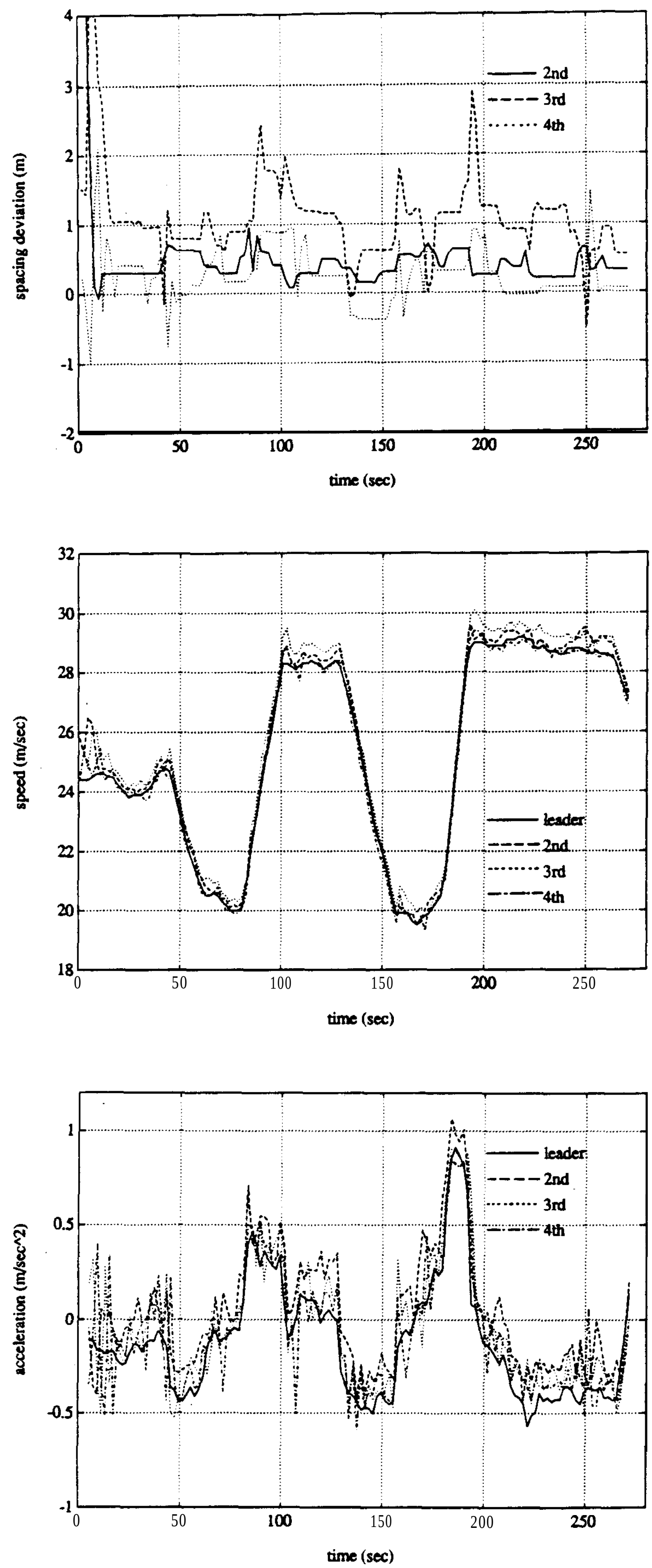


Fig. 19 Example Results of Four-Vehicle Platoon Test #5 of May 12, 1992, with Accelerate-Decelerate Cycles (21 m Nominal Spacing)

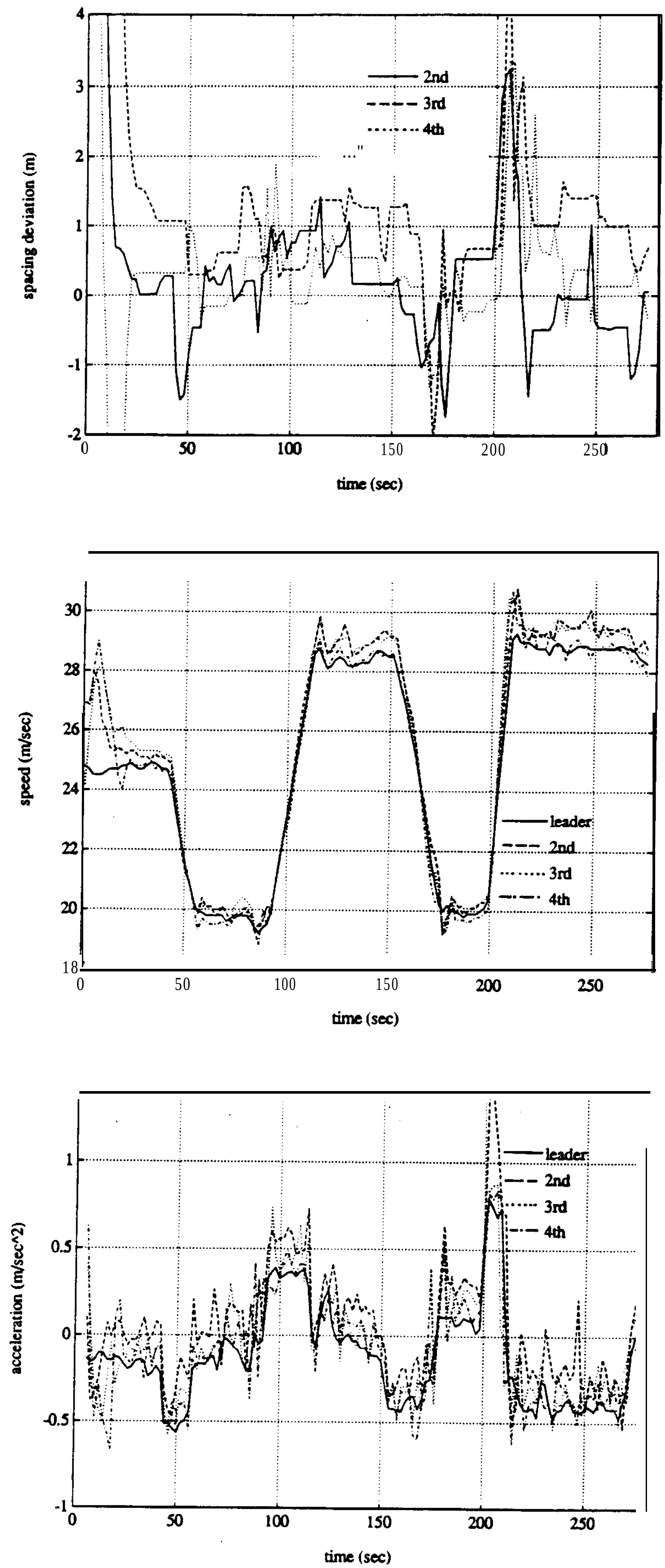


Fig. 20 Example Results of Four-Vehicle Platoon Test #5 of May 12, 1992, with Accelerate-Decelerate Cycles (21 m Nominal Spacing)

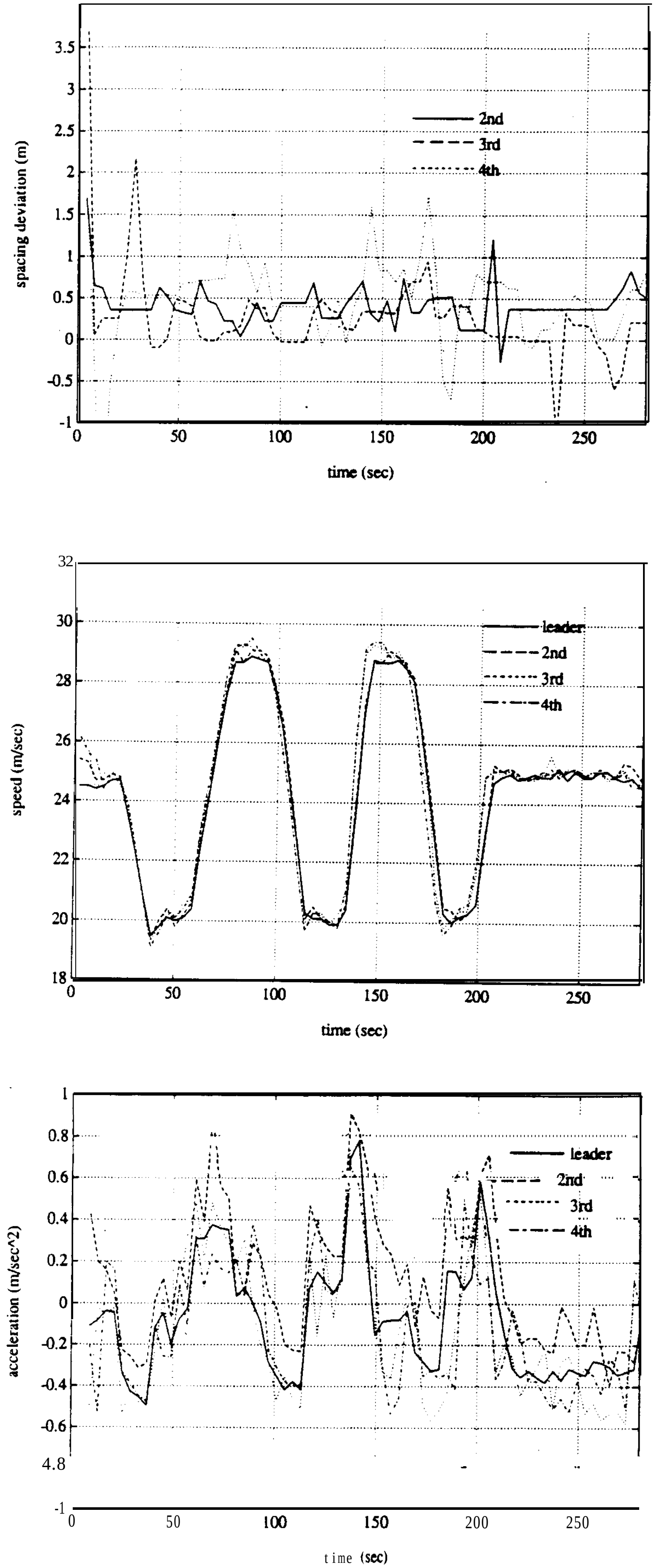
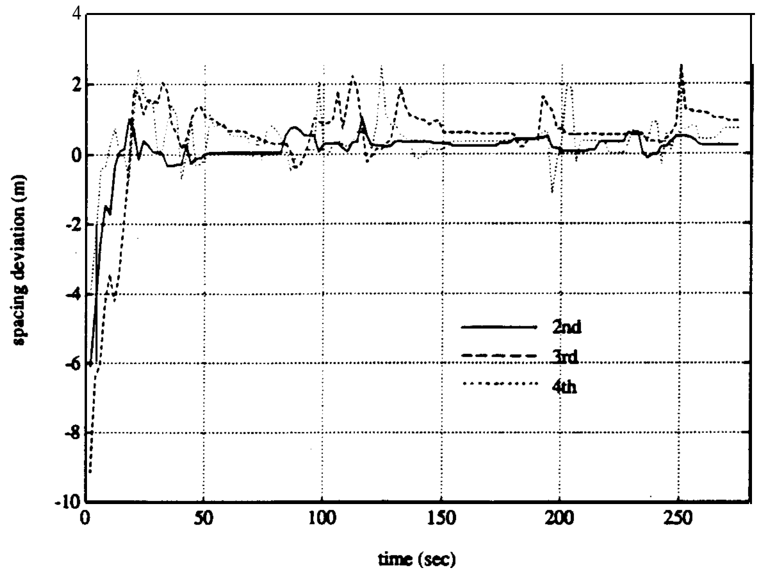
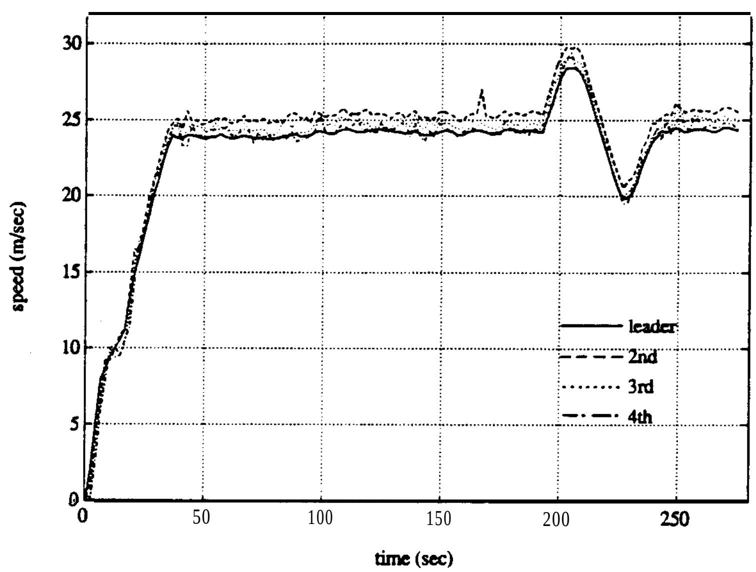
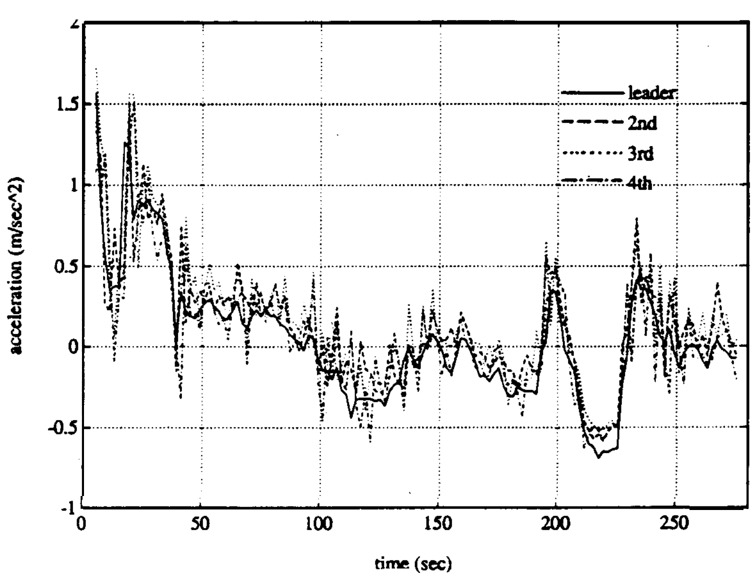


Fig. 21 Example Results of Four-Vehicle Platoon Test #9 of July 23, 1992, with Acceleration From Zero Speed (21m Nominal Spacing)







Chapter 7. Identified Problems

7.1 Hardware reliability improvement plan

Typically for experimental programs there were frequent failures of individual components and subsystems: for example, radar system, throttle actuator, communication radio, data acquisition board, etc.

In order to help solve these problems, the system rewiring/reharnessing is underway presently. The work includes:

- Replace all sensor and actuator wiring
- Design and build new interface circuit board
- Mount PC in trunk
- Change vehicle and engine speed sensing from F/V (Frequency to Voltage Conversion) circuits in VORAD box to pulse timing on board in PC
- Replace Ford 65 amp alternators with higher output alternators
- Relocate accelerometers from left rear floor to top of transmission tunnel under front seat
- Have cellular phone antennas permanently installed with cable to trunk
- Fix short service life of throttle actuators.

7.2 Unsolved Problems

Some problems which could not be solved in the course of this project need to be addressed with additional effort in the next phase of work.

These include:

- development and verification of automatic closed-loop brake control with the necessary bandwidth and accuracy
- enhancement of filtering of radar range rate measurements to obtain smooth yet fast response
- enhancement of radar ranging measurements so that range can be detected continuously, including at closing rates extending down to zero.

Chapter 8. Conclusions

Given the original goal of assessing the technical possibilities of the platoon control system based on the use of existing technology and components, this project proved successful.

Conclusions can be listed as follows:

1. The vehicle-following control system can be implemented with existing technology and hardware components;

2. The test results have demonstrated the basic feasibility of obtaining high accuracy vehicle following performance using an automobile with a fuel-injected spark ignition engine;

3. The current experimental setup (IPCS) provided reasonably acceptable control performance in terms of tracking accuracy and ride quality;

4. The test results provide clear indications of the technical changes needed to provide improved performance;

5. The most critical hardware issue to be resolved is the refinement of the sensor to measure the distance and closing rate between vehicles.

Acknowledgement

This work is a part of the Partners for Advanced Transit and Highways (PATH) Program, prepared under the sponsorship of the State of California, Business Transportation and Housing Agency, Department of Transportation (Caltrans). The Caltrans role extended substantially beyond financial sponsorship, to include important technical and procedural inputs by Randy Woolley, David Ashuckian and Charles Price of the New Technology and Research Program and the vital cooperation of the Caltrans District 11 (San Diego) Traffic Operations Center and highway maintenance staffs.The author also wishes to thank VORAD (especially John Olds), NHTSA, FHWA, Automobile Club of Southern California and Ford Motor Company for their support in this project. The work on this project was conducted by Professor J. Karl Hedrick, Professor Pravin Varaiya, Peter Devlin, and graduate students Donn McMahon, D. Swaroop, V. K. Narendran, William Li, Isaac Porche, Ahmad Shaikabahal and F. Assaderaghi with invaluable advice from Steven E. Shladover. The author also thanks Steven E. Shladover for his help in revising draft reports to make this final form.

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APPENDIX

A. 1 Project Period

Start Date: April 18, 1989
End Date: July 31, 1992

A.2 Participants

Organization	Work Scope
Caltrans	Project funding and monitoring Test facility Test procedures and safety plans
California PATH (University of California, Berkeley)	Project task coordination Research performed by U.C. Berkeley (Dept. of ME, Dept. of EECS) Experiments
VORAD (formerly RCS)	Radar system improvements Test support Actuator design/installation
Ford Motor Company	Test vehicles (one Ford LTD, three Lincoln Town Cards) and vehicle performance data
National Highway Traffic Safety Administration (NHTSA)	Funding of the tests conducted by STI to evaluate the RCS radar system and partial funding support of other experiments
Federal Highway Administration (FHWA)	Partial funding support of experimental work
Systems Technology Inc. (STI)	RCS radar system field evaluation
Automobile Club of Southern California	Test drivers for experiments in San Diego

Table A.1 Participants in the project

RCS TEST DATAFILE LOG

Kwang Soo Chang

Data Filename	File Date	Teat Mode	Test Speed(MPH)	Travel Dir	Data Rate	Test Vehicle	Measured Distance	Notes
134544	06/20/90	Acc 100% Level	0 - 60	N/A	100 ms	1	N/A	
134943	06/20/90	Acc 100% Level	5 - 60	N/A	100 ms	1	N/A	
135146	06/20/90	Acc 100% Level	15 - 60	N/A	100 ms	1	N/A	
134158	06/20/90	Acc 100% Level	30 - 60	N/A	100 ms	1	N/A	
134106	06/20/90	Acc 100% Level	45 - 60	N/A	100 ms	1	N/A	
133559	06/20/90	Acc 100% Level	60 - 70	N/A	100 ms	1	N/A	
94256	06/20/90	Acc 100% uphill	45 - 60	N/A	100 ms	1	N/A	
94438	06/20/90	Acc 100% Downhill	45 - 60	N/A	100 ms	1	N/A	
112353	08114190	Acc 100% Level	0 - 60	North	50 ms	1	N/A	
112620	08/14/90	Acc 100% Level	0 60	south	50 ms	1	N/A	
95411	08/09/90	Acc 70% Level	0 - 60	North	50 ms	1	N/A	Partial throttle by RCS actuator
95823	08/09/90	Acc 70% Level	0 -- 60	south	50 ms	1	N/A	Partial throttle by RCS actuator
100415	08/09/90	Acc 40% Level	0	North	50 ms	1	N/A	Partial throttle by RCS actuator
100633	08/09/90	Acc 40% Level	0 -- 6060	south	50 ms	1	N/A	Partial throttle by RCS actuator
100943	08/09/90	Acc 70% Level	45 - 60	North	50 ms	1	N/A	Partial throttle by RCS actuator
101154	08/09/90	Acc 70% Level	45 - 60	South	50 ms	1	N/A	Partial throttle by RCS actuator
101431	08/09/90	Acc 40% Level	45	North	50 ms	1	N/A	Partial throttle by RCS actuator
101658	08/09/90	Acc 40% Level	45 -- 6060	South	50 ms	1	N/A	Partial throttle by RCS actuator
100209	08/29/90	Acc 100% Level	0	North	23 ms	1	N/A	
100527	08/29/90	Acc 100% Level	0 -- 6060	South	23 ms	1	N/A	
102717	08/30/90	Acc 100% Level	0	North	23 ms	2	N/A	
102144	08/30/90	Acc 100% Level	0 -- 6060	South	23 ms	2	N/A	
100236	08/30/90	Acc 70% Level	0 - 60	North	50 ms	2	N/A	Partial throttle by RCS actuator
95947	08/30/90	Acc 70% Level		South	50 ms	2	N/A	Partial throttle by RCS actuator
100953	08/30/90	Acc 40% Level	0 - 60	North	50 ms	2	N/A	Partial throttle by RCS actuator
100728	08/30/90	Acc 40% Level	0 - 6060	South	50 ms	2	N/A	Partial throttle by RCS actuator
113504	11/08/90	Acc 70% Level	0		23 ms	1	N/A	Partial throttle by driver
113924	11/08/90	Acc 70% Level	45 -- 6060		23 ms	1	N/A	Partial throttle by driver
112049	11/08/90	Acc 40% Level	0		23 ms	1	N/A	Partial throttle by driver
112649	11/08/90	Acc 40% Level	45 -- 6060		23 ms	1	N/A	Partial throttle by driver
103424	06/20/90	Brk 100% Level	15 - 0	N/A	100 ms	1	4 ft 8 in	
103247	06/20/90	Brk 100% Level	15 - 0	N/A	100 ms	1	6 ft 0 in	
104102	06/20/90	Brk 100% Level	30 - 0	N/A	100 ms	1	26 ft 9 in	
103618	06/20/90	Brk 100% Level	30 - 0	N/A	100 ms	1	27 ft 4 in	
104330	06/20/90	Brk 100% Level	45 - 0	N/A	100 ms	1	66 ft 6 in	
100446	06/20/90	Brk 100% Level	45 - 0	N/A	100 ms	1	66 ft 11 in	
105541	06/20/90	Brk 100% Level	60 - 0	N/A	100 ms	1	135 ft 11 in	
105251	06/20/90	Brk 100% Level	60 - 0	N/A	100 ms	1	128 ft 9 in	
110221	06/20/90	Brk 100% Level	70 - 0	N/A	100 ms	1	180 ft 17 in	
95935	06/20/90	Brk 100% Uphill	45 - 0	N/A	100 ms	1	52 ft 16 in	
104611	06/20/90	Brk 100% Downhill	45 - 0	N/A	100 ms	1	in	
121716	08/10/90	Brk 100% Level	15 - 0	North	23 ms	1	ft	
122057	08/10/90	Brk 100% Level	30 - 0	North	23 ms	1	40 ft	
122429	08/10/90	Brk 100% Level	45 - 0	North	23 ms	1	92 ft	
122834	08/10/90	Brk 100% Level	60 - 0	North	23 ms	1	156 ft	
123218	08/10/90	Brk 100% Level	70 - 0	North	23 ms	1	204 ft	
115243	08/10/90	Brk 70% Level	15 - 0	North	23 ms	1	6 ft	
115800	08/10/90	Brk 70% Level	30 - 0	North	23 ms	1	37 ft	
120307	08/10/90	Brk 70% Level	45 - 0	North	23 ms	1	86 ft	

RCS TEST DATAFILE LOG

Kwang Soo Chang

Data Filename	File Date	Test Mode	Test Speed(MPH)	Travel Dir	Data Rate	Test Vehicle	Measured Distance	Notes
120654	08/10/90	Brk 70% Level	60 - 0	North	23 ms	1	153 ft	
121046	08/10/90	Brk 70% Level	70 - 0	North	23 ms	1	213 ft	
112650	08/10/90	Brk 50% Level	15 - 0	North	23 ms	1	5 ft	
113358	08/10/90	Brk 50% Level	30 - 0	North	23 ms	1	36 ft	
114008	08/10/90	Brk 50% Level	45 - 0	North	23 ms	1	86 ft	
114443	08/10/90	Brk 50% Level	60 - 0	North	23 ms	1	149 ft	
114824	08/10/90	Brk 50% Level	70 - 0	North	23 ms	1	205 ft	
104901	08/10/90	Brk 30% Level	15 - 0	North	23 ms	1	7 ft	
105954	08/10/90	Brk 30% Level	30 - 0	North	23 ms	1	45 ft	
110631	08/10/90	Brk 30% Level	45 - 0	North	23 ms	1	104 ft	
111160	08/10/90	Brk 30% Level	60 - 0	North	23 ms	1	164 ft	
111904	08/10/90	Brk 30% Level	70 - 0	North	23 ms	1	229 ft	
125547	08/10/90	Brk 100% Uphill	45 - 0	North	23 ms	1	91 ft	
132621	08/10/90	Brk 70% Uphill	45 - 0	North	23 ms	1	88 ft	
131752	08/10/90	Brk 50% Uphill	45 - 0	North	23 ms	1	89 ft	
130904	08/10/90	Brk 30% Uphill	45 - 0	North	23 ms	1	89 ft	
130229	08/10/90	Brk 100% Downhill	45 - 0	North	23 ms	1	90 ft	
132913	08/10/90	Brk 70% Downhill	45 - 0	North	23 ms	1	94 ft	
132122	08/10/90	Brk 50% Downhill	45 - 0	North	23 ms	1	93 ft	
131237	08/10/90	Brk 30% Downhill	45 - 0	North	23 ms	1	91 ft	
111702	06/20/90	Coast Down	70 - 20	N/A	100 ms	1	1.2 Miles	
112016	06/20/90	Coast Down	70 - 20	N/A	100 ms	1	1.2 Miles	
114555	06/20/90	Coast Down	50 - 20	N/A	100 ms	1	0.5 Miles	
114930	06/20/90	Coast Down Uphill	50 - 20	N/A	100 ms	1	0.2 Miles	
113329	06/20/90	Coast Down Uphill	50 - 20	N/A	100 ms	1	0.2 Miles	
112632	06/20/90	Coast Down Downhil	50 - 20	N/A	100 ms	1	1.2 Miles	
113812	06/20/90	Coast Down Downhil	50 - 20	N/A	100 ms	1	1.3 Miles	
101241	08/14/90	Coast Down	70 - 20	North	250 ms	1	1.3 Miles	Coast Down Time: 128 eec
103518	08/14/90	Coast Down	70		250 me	1	0.9 Miles	Coast Down Time: 87 sec
104247	08/14/90	Coast Down	50 - - 20 20	South North	250 ms	1	0.8 Miles	Coast Down Time: 101 sec
104735	08/14/90	Coast Down	50		250 ms	1	0.6 Miles	Coast Down Time: 68 sec
110254	08/14/90	Coast Down Uphill	50 - - 20 20	South North	250 ms	1	0.2 Miles	Coast Down Time: 31 sec
110809	08/14/90	Coast Down Downhil			250 ms	1	N/A	Never Reached 20 MPH
120156	08/14/90	Coast Down	50 - 20	South	250 ms	2	0.8 Miles	Coast Down Time: 93 sec
120653	08/14/90	Coast Down	50 - - 20 20	North South	250 ms	2	0.6 Miles	Coast Down Time: 66 sec
			50					
5101N	08/15/90	Cruise Control	20 MPH	North	5 cm/min	1	2.5 Miles	Stri Chart Recordings of
5101S	08/15/90	Cruise Control	20 MPH	south	5 cm/min	1	2.5 Miles	Spee8 and Throttle Position
5102N	08/15/90	Cruise Control	30 MPH	North	5 cm/min	1	2.5 Miles	for these Cruise Control Tests
5102S	08/15/90	Cruise Control	30 MPH	South	5 cm/min	1	2.5 Miles	
5103N	08/15/90	Cruise Control'	40 MPH	North	5 cm/min	1	2.5 Miles	
5103S	08/15/90	Cruise Control	40 MPH	South	5 cm/min	1	2.5 Miles	
5104N	08/15/90	Cruise Control	50 MPH	North	5 cm/min	1	2.5 Miles	
5104S	08/15/90	Cruise Control	50 MPH	South	5 cm/min	1	2.5 Miles	
5105N	08/15/90	Cruise Control	60 MPH	North	5 cm/min	1	2.5 Miles	
5105S	08/15/90	Cruise Control	60 MPH	South	5 cm/min	1	2.5 Miles	
5106N	08/15/90	Cruise Control	70 MPH	North	5 cm/min	1	2.5 Miles	
5106S	08/15/90	Cruise Control	70 MPH	South	5 cm/min	1	2.5 Miles	

RCS TEST DATAFILE LOG

Kwang Soo Chang

Data Filename	File Date	Test Mode	Test Speed(MPH)	Travel Dir	Data Rate	Test Vehicle	Measured Distance	Notes
101505	09/07/90	Closing Rate		North	23 ms	1	N/A	
103004	09/07/90	Closing Rate		North	23 ms	1	N/A	
104203	09/07/90	Closing Rate		North	23 ms	1	N/A	

Table A.3 Radar System Range Measurement Test Results

Red Lincoln
11/16/90 on HOV Lanes
Target: Lincoln

Timestamp-->	**11:11:03**	**11:11:03**	**11:11:03**	**11:15:20**	**11:18:00**	**11:20:40**	**11:22:40**	**11:25:47**	**11:29:29**	**11:35:28**	**11:35:28**	**11:35:28**
Max **Spd---->**	7			7	7	7	7	13	19	23		
Actual Range	Radar Range	Actual **Cl.** Rate	**Radar** **Cl.** Rate	Radar Range	Radar Range	**Radar** Range	Radar Range	Radar Range	Radar **Range**	Radar Range	Actual Cl. Rate	Radar Cl. Rate
200	194	2.0	2.2	220	201	204	210	236	191	214	23.2	23.7
195	186	2.9	3.1	198	176	198	205	239	172	195	23.3	23.7
190	199	3.4	3.8	205	181	178	193	225	184	189	23.2	23.5
185	188	3.9	4.2	203	185	163	179	200	165	202	23.3	23.5
180	172	4.3	4.6	1%	190	164	159	202	145	192	23.2	23.5
175	177	4.7	4.9	173	184	179	192	219	137	167	23.2	23.5
170	199	4.8	5.1	140	164	173	210	224	186	179	23.0	23.2
165	156	5.2	5.2	125	139	88				171	22.8	23.2
160	148	5.3	5.5	168	157	182	142		189	111	22.9	23.3
155	173	5.3	5.7	150	150	161	154	157	183	118	22.7	22.6
150	153	5.4	5.7	148	152	159	163	162	166	158	22.8	23.0
145	153	5.5	5.8	145	142	150	146	154	162	146	22.6	23.0
140	165	5.6	5.9	143	136	132	137	151	161	129	22.6	23.0
135	164	5.8	6.1	149	157	138	101	149	153	115	22.5	22.8
130	57	5.9	6.1	151	156	168	118	118	140	124	22.6	22.8
125	138	6.0	6.3	93	100	131	150	101	97	170	23.0	23.0
120	156	6.1	6.3	123	145	116	124	131	77	154	22.8	22.8
115	100	6.2	6.4	119	120	132	107	136	108	91	22.6	23.0
110	107	6.3	6.5	106	112	119	115	113	125	122	22.8	23.0
105	114	6.3	6.5	104	109	107	108	111	106	110	23.0	23.1
100	107	6.4	6.6	97	107	W	100	107	105	106	23.0	23.2
95	95	6.4	6.7	91	104	97	W	W	100	W	23.0	23.4
90	86	6.6	6.7	95	88	103	101	86	101	92	23.1	23.4
85	92	6.6	7.0	103	94	93	89	87	101	93	23.2	23.5
80	92	6.7	7.0	75	91	73	73	89	95	92	23.2	23.5
75	73	6.7	7.1	83	75	84	84	75	78	74	23.2	23.7
70	76	6.7	7.2	77	60	72	80	78	54	72	23.3	23.7
65	63	6.8	7.2	68	76	70	65	60	72	81	23.2	23.7
60	65	6.9	7.2	65	56	63	61	65	69	62	23.3	23.7
55	58	7.0	7.2	58	60	58	57	58	59	62	23.2	23.7
50	52	7.0	7.4	51	53	52	53	53	54	53	23.0	23.3
45	48	7.0	7.4	46	47	48	48	48	47	51	22.1	23.0

40	44	7.1	7.5	44	45	44	45	44	44	41	20.8	22.0
35	39	7.1	7.6	40	40	40	40	39	41	40	19.6	20.7
30	33	7.1	7.5	34	33	33	33	33	35	34	18.2	18.8
2s	29	7.2	7.6	29	30	28	30	28	28	28	16.6	17.3
20	24	7.4	7.6	24	23	23	23	24	24	24	14.5	15.7
15	19	7.4	7.6	19	19	19	19	19	19	19	12.4	13.1
10	14	6.3	7.0	15	15	13	15	14	15	15	9.4	10.8
5	11	3.9	4.4	9	8	7	8	10	8	11	5.2	6.5

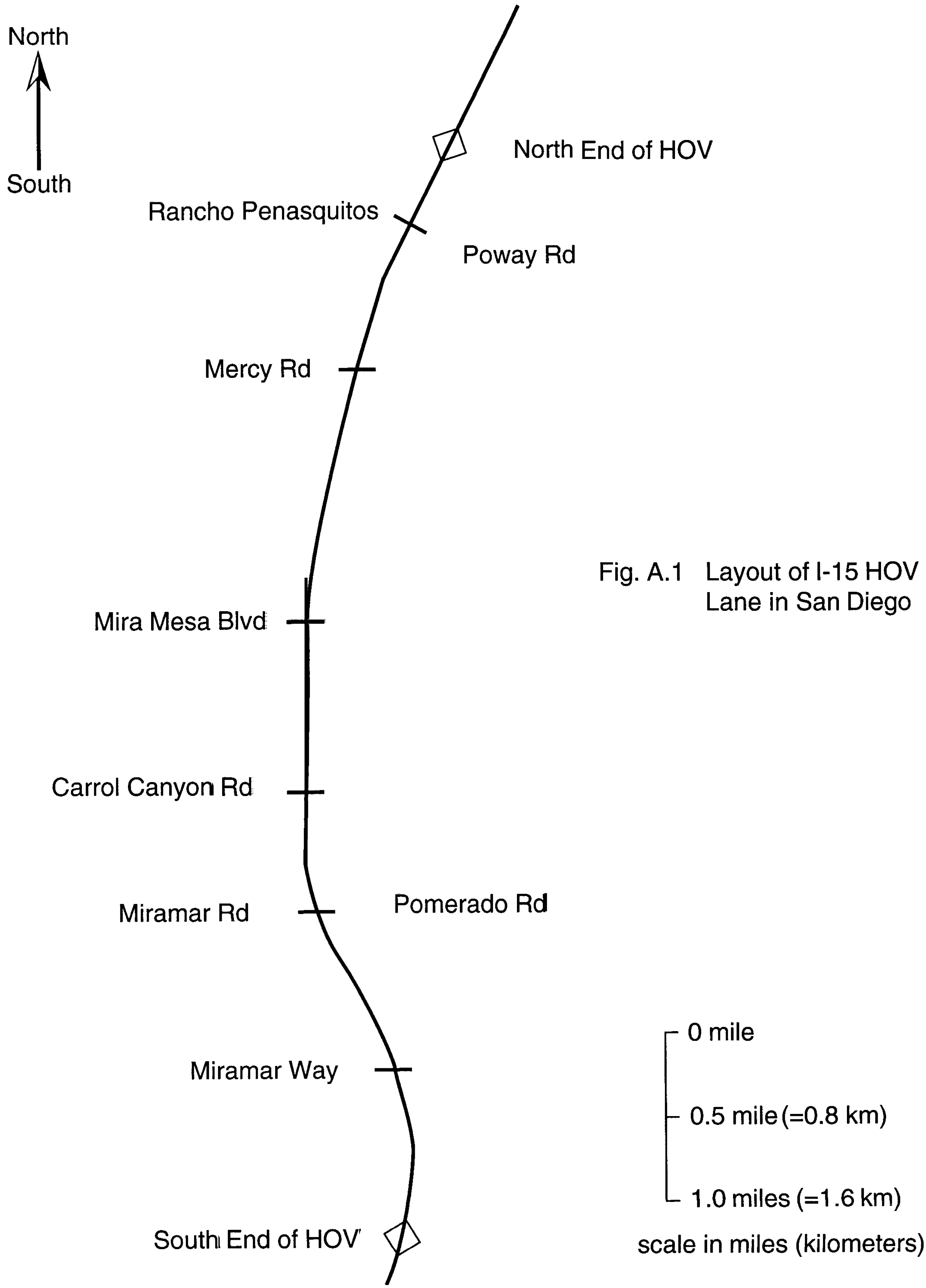


Fig. A.1 Layout of I-15 HOV Lane in San Diego

Fig. A.2 Open Loop Acceleration Test Results (0 to 26.8 m/s, Data File 134544) Using Manual Operation

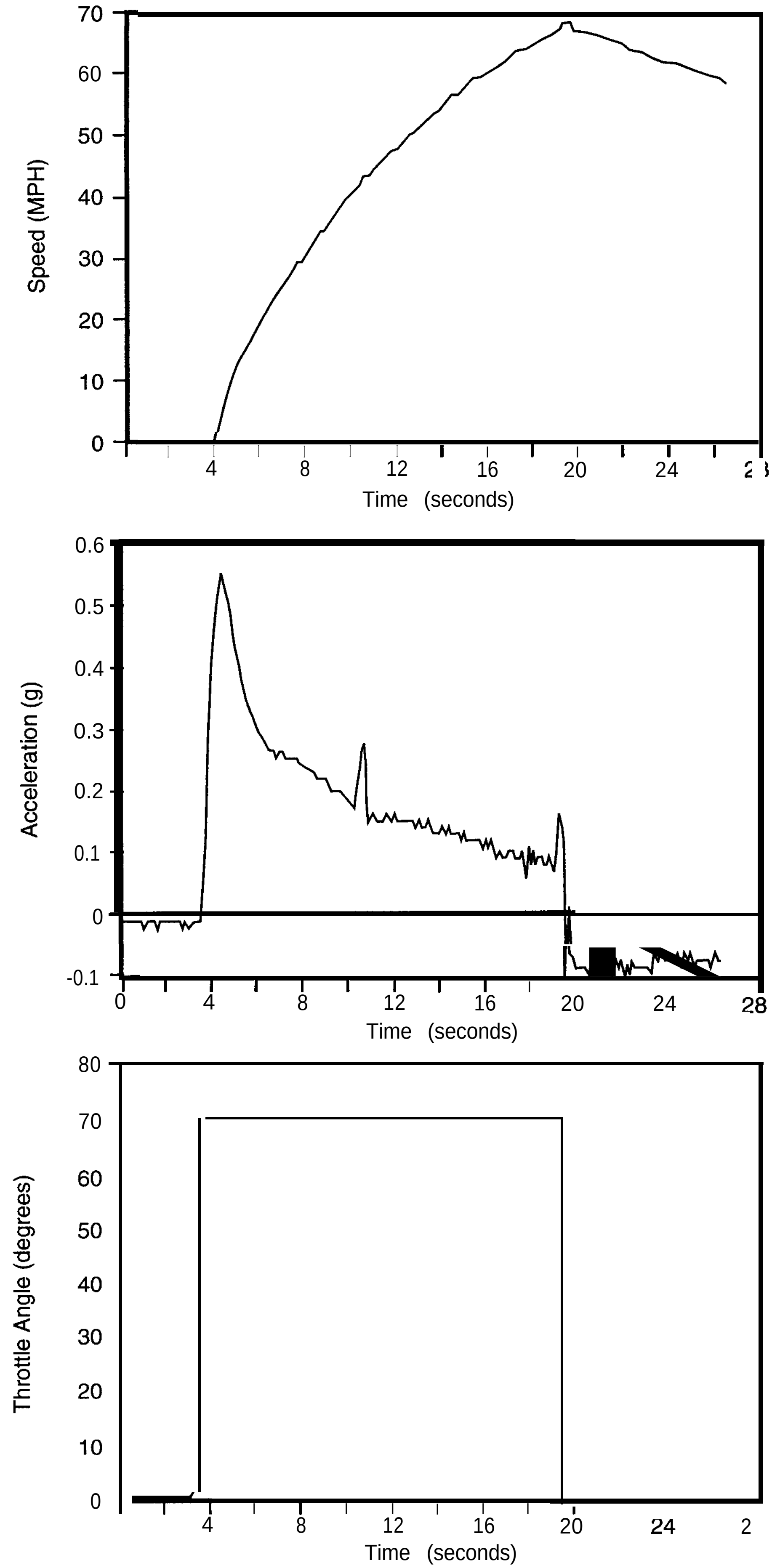
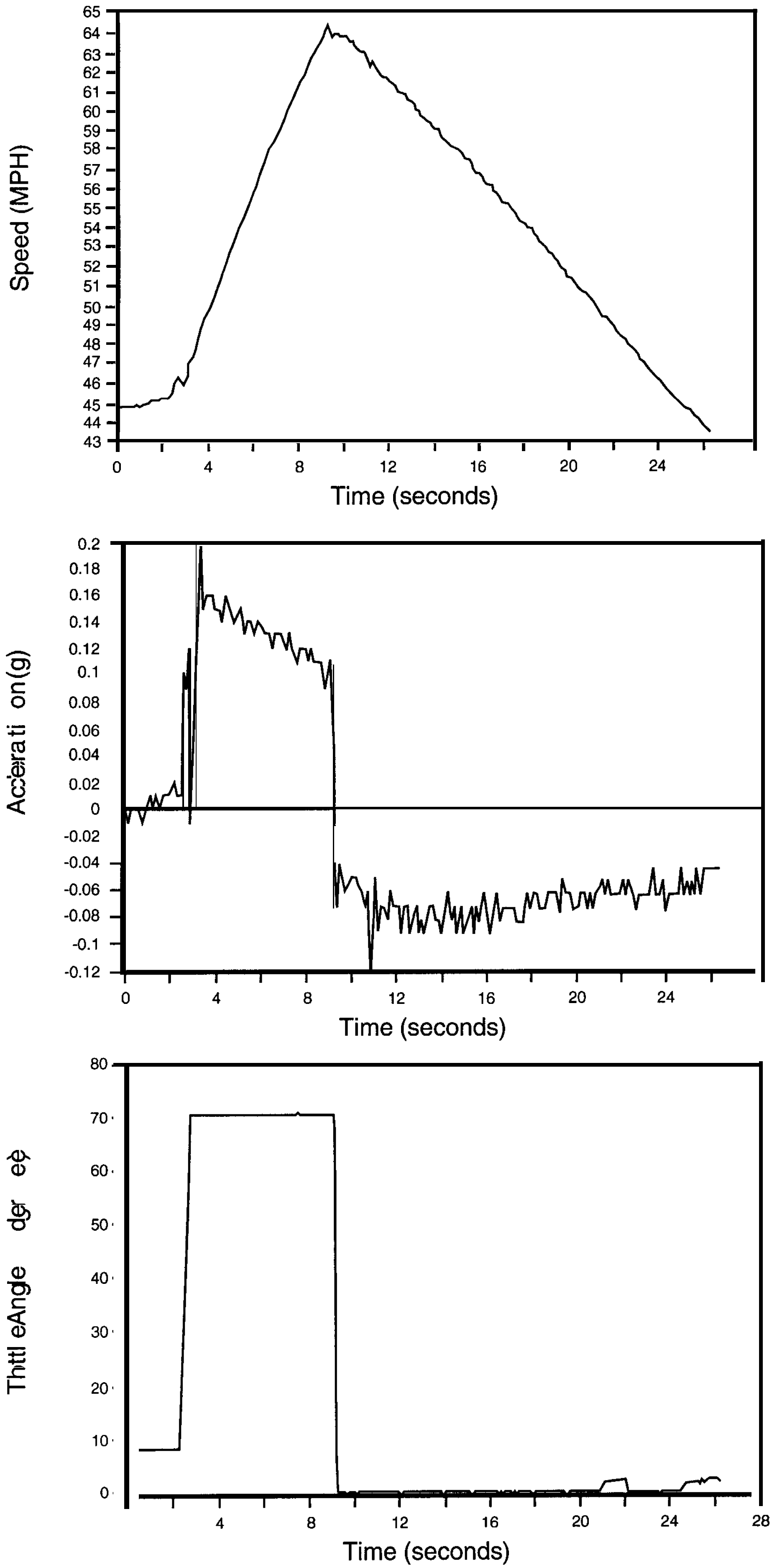


Fig. A.3 Open Loop Acceleration Test Results (20.1 to 26.8 m/s, Data File 134106) Using Manual Operation



A.3 Project Schedule History

Year	Month	Task
989	APR	◇ PATH contract with Caltrans & RCS
	MAY	
	JUN	
	JUL	
	AUG	
	SEP	◇ Start controller design and simulation
	OCT	
	NOV	
	DEC	◇ Test vehicles received from Ford
990	JAN	0 Start communication scheme design
	FEB	
	MAR	◇ RCS radar systems installed
	APR	
	MAY	◇ DC motor throttle actuator installed
	JUN	▷
	JUL	Vehicle performance tests RCS radar evaluation test by STI
	AUG	▷ 0 Equipment purchase (computer, communication board, radio, data acquisition board)
	SEP	
	OCT	Communication driver programming, VRTX programming
	NOV	◇ Radar change characterization test by RCS on i-l 5 HOV lane ◇ Name changed from RCS to VORAD
	DEC	▷
1991	JAN	Vehicle-following control tests using integration of speed sensor, without radar range measurement
	FEB	
	MAR	◇ Sensor installation on test vehicles
	APR	◇ First functioning of two-car-following system at Richmond Field Station
	MAY	◇ Radar range estimation scheme
	JUN	On-off pneumatic solenoid brake actuator tests
	JUL	▷
	AUG	Replacement of the DC motor with a faster stepper motor
	SEP	▷ ▷7
	OCT	4 car communication driver design & programming
	NOV	0 Radar adjustment for platoon purpose (adjustment of the radar closing rate limit)
	DEC	▷

1992	JAN	0 2 car platoon demo on I-1 5 HOV	'seudo-p se radar system design
	FEB		
	MAR		
	APR		
	MAY	◇ 4 car platoon demo on I-1 5 HOV	
	JUN		Bra e actuator selection/ de: jn/test
	JUL		Rewiring/reharnessing of test vehicles
	AUG		
	SEP	◇ Final Report	

Fig. A.4 Open Loop Acceleration Test Results (20.1 to 26.8 m/s, Uphill, Data File 94256) Using Manual Operation

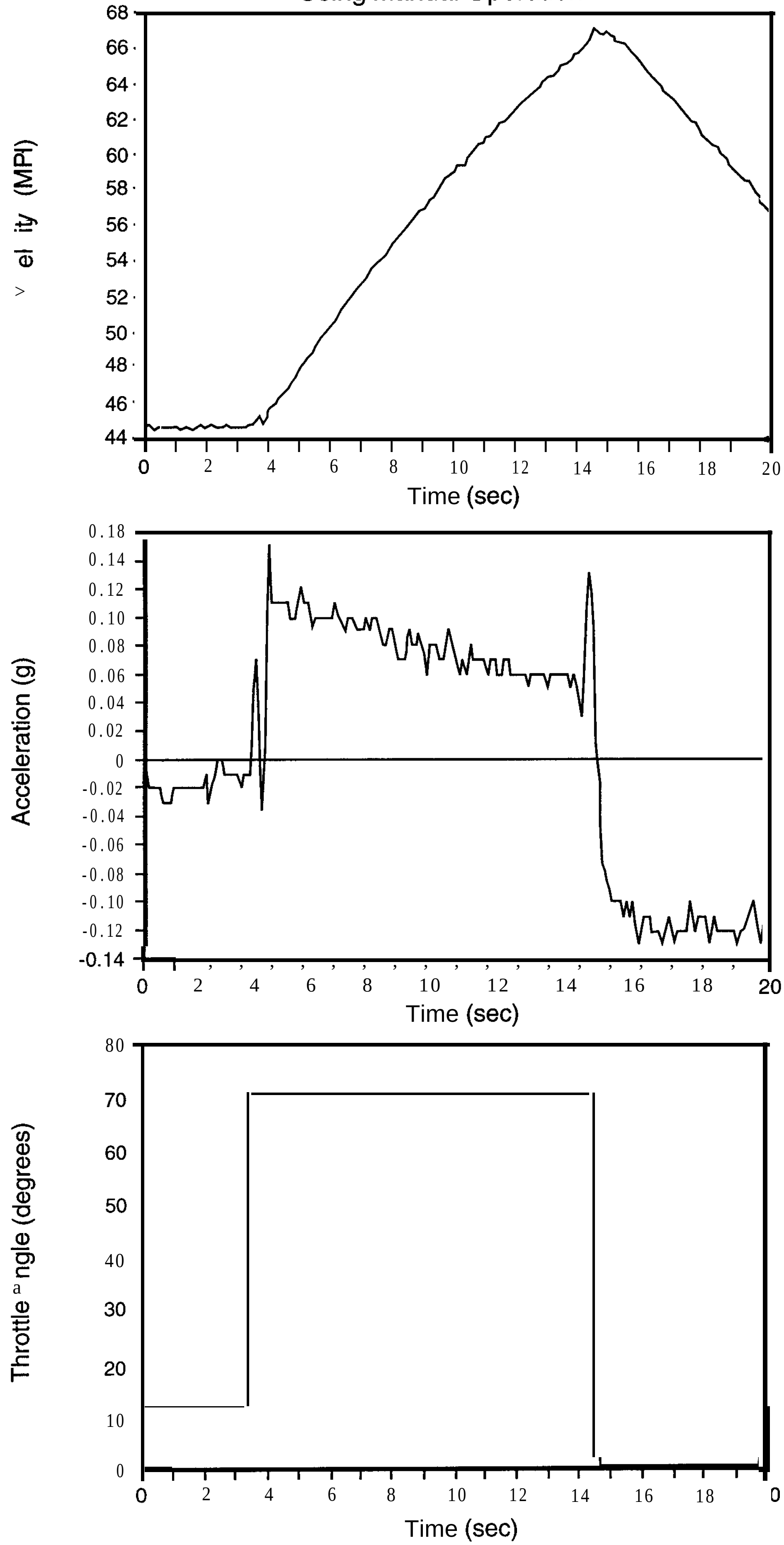


Fig. A.5 Open Loop Acceleration Test Results (20.1 to 26.8 m/s, Downhill, Data File 94438) Using Manual Operation

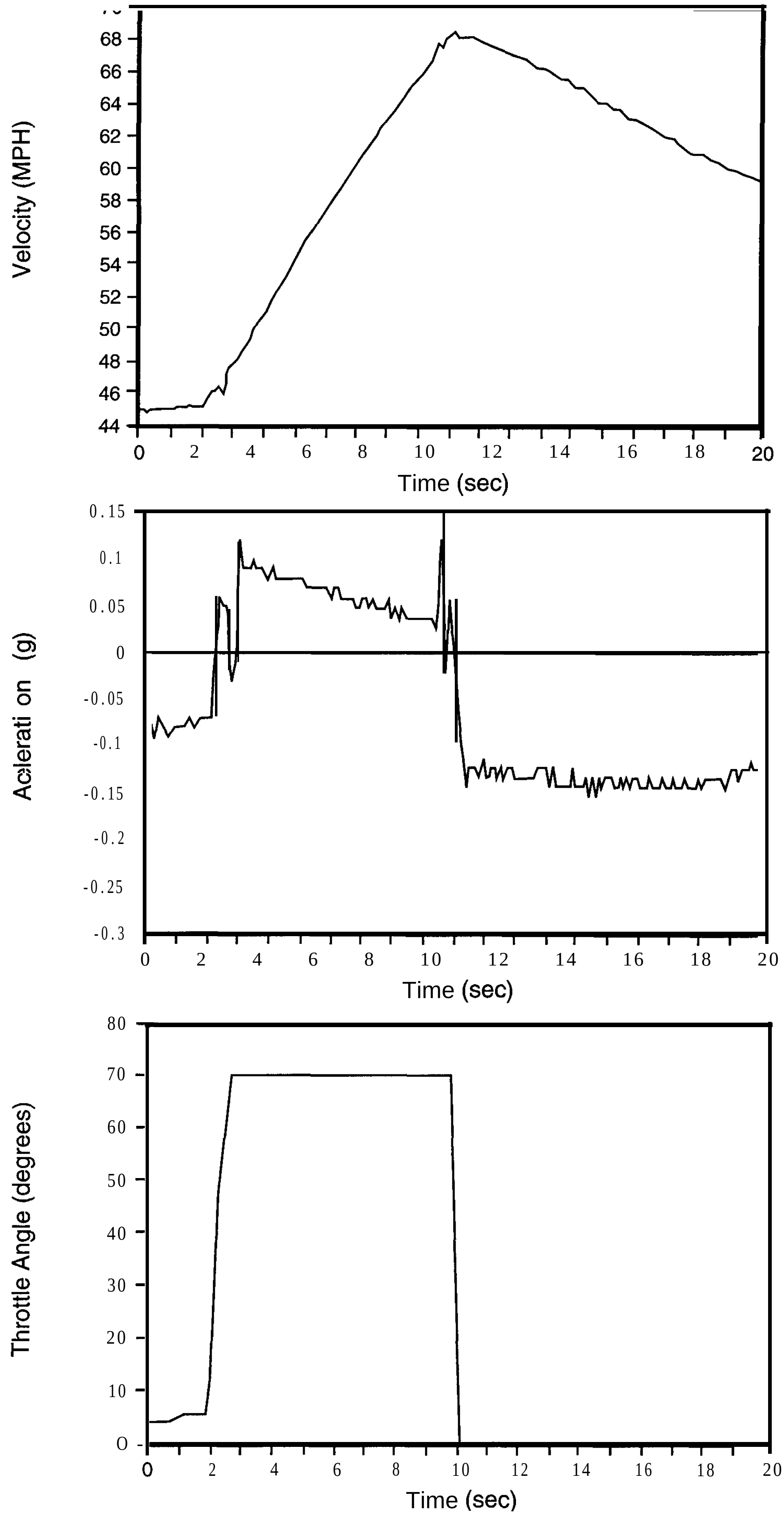


Fig. A.6 Open Loop Acceleration Test Results (0 to 26.8 m/s, Data File 100415)
Partial Throttle Actuation Test Using the Slow Throttle Motor

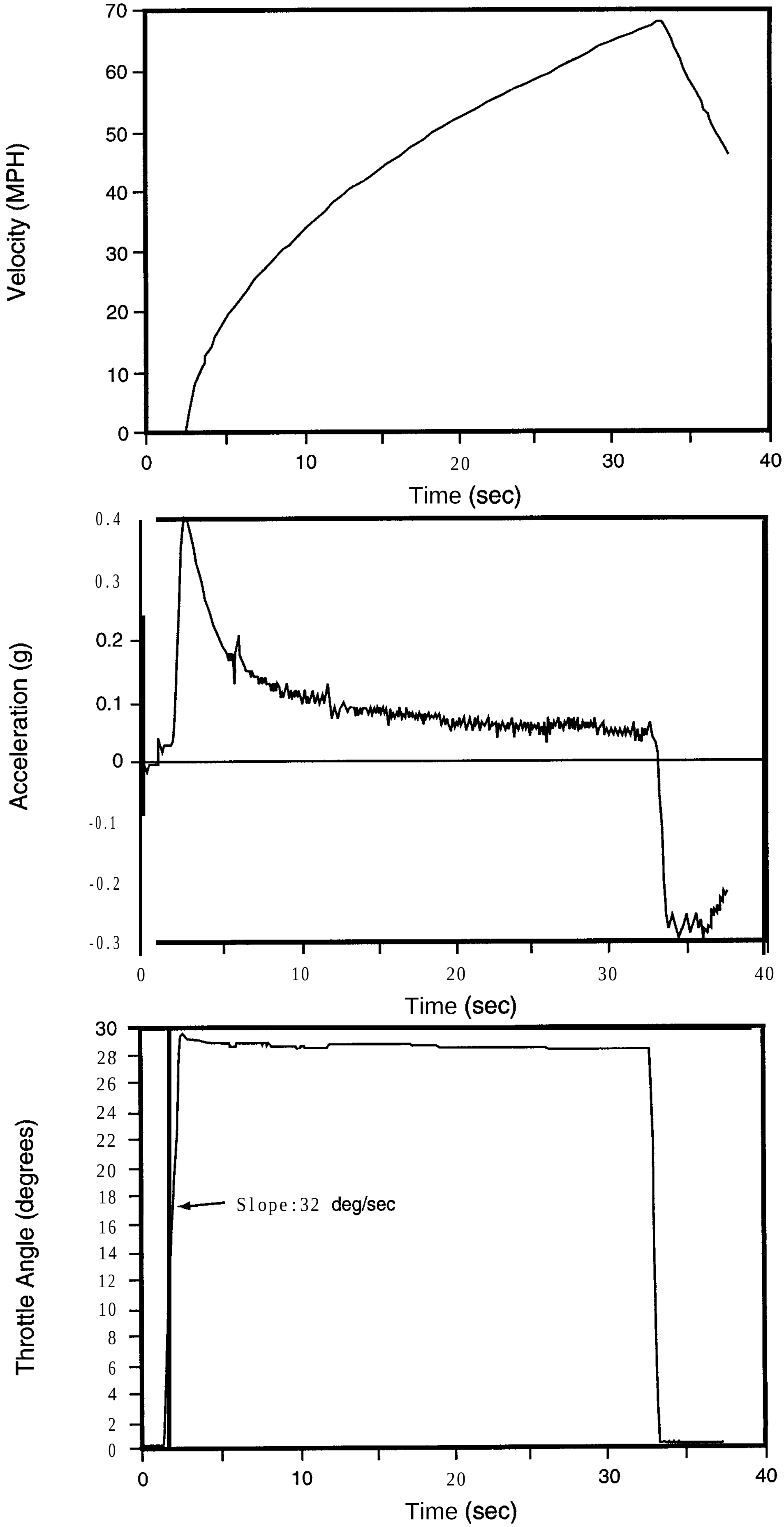


Fig. A.7 Acceleration Test (20.1 to 26.8 m/s, Data File 101431)
Partial Throttle Actuation Test Using the Slow Throttle Motor

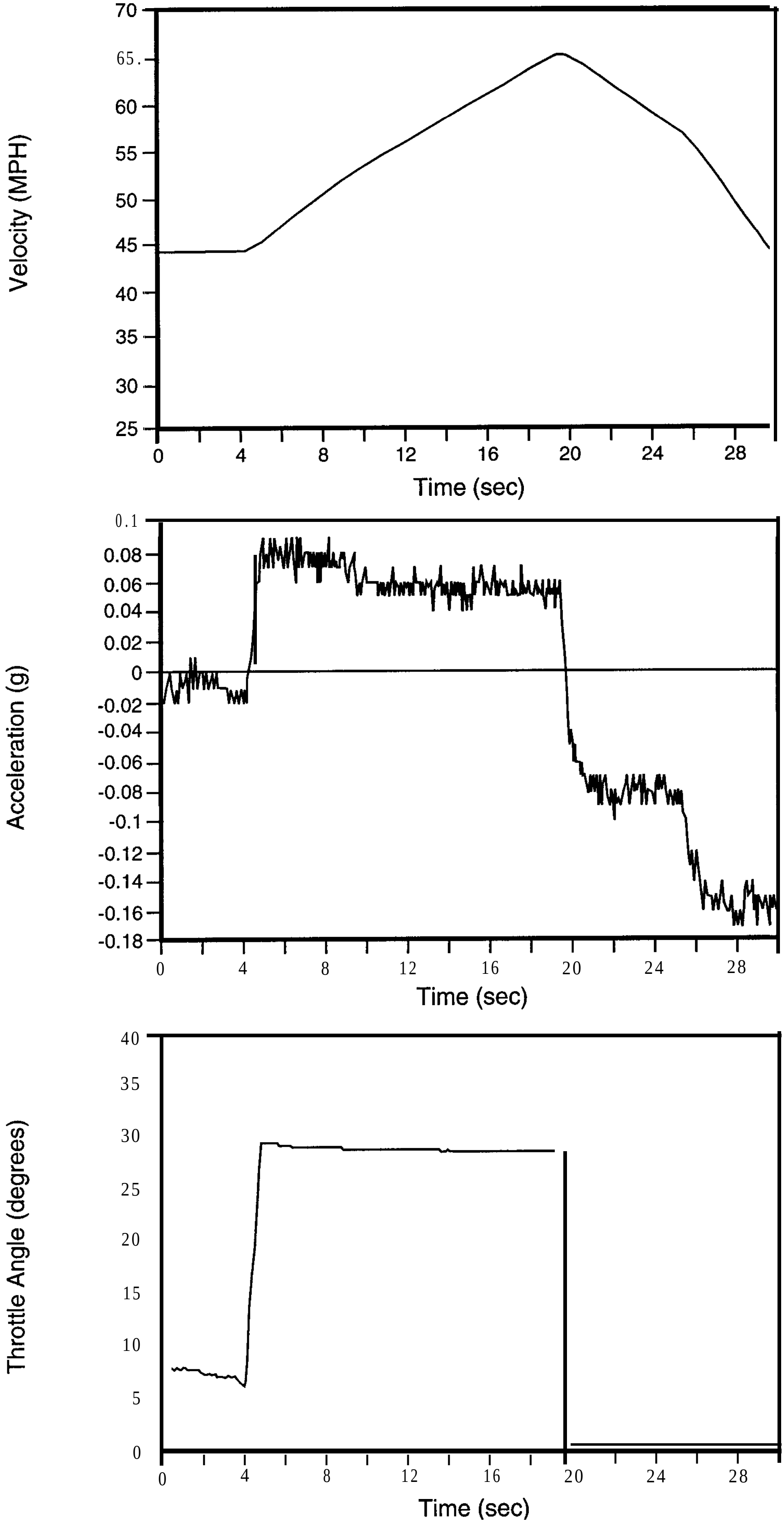


Fig. A.8 Acceleration Test (0 m/s to 26.8 m/s, Data File 112049)
Partial Throttle Actuation Test Using the Manual Operation

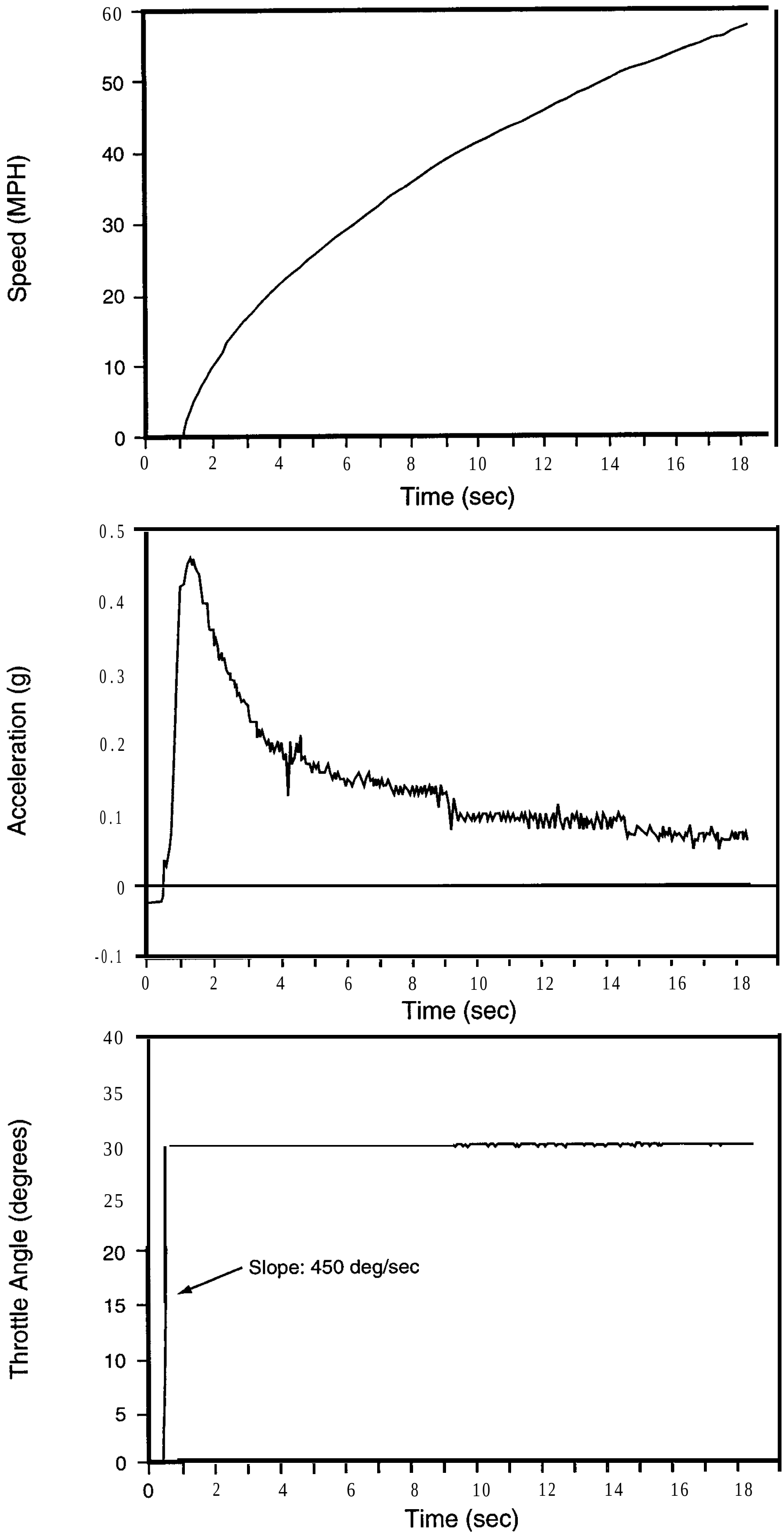


Fig. A.9 Acceleration Test (20.1 to 26.8 m/s, Data File 112649)
Partial Throttle Actuation Test Using the Manual Operation

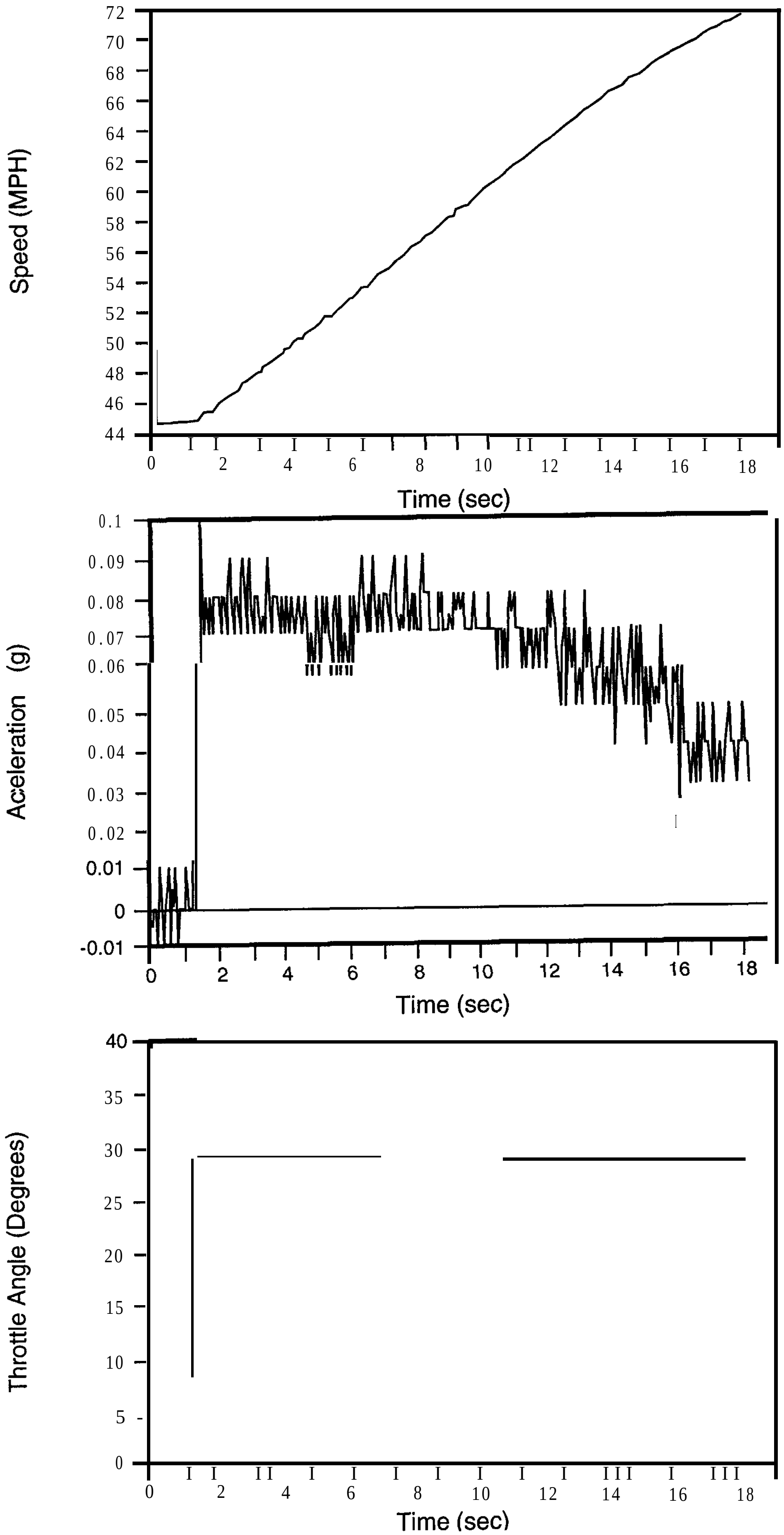


Fig. A. 10 Open Loop Braking Test (13.4 to 0 m/s, 100% Braking Effort, Data File 122057)

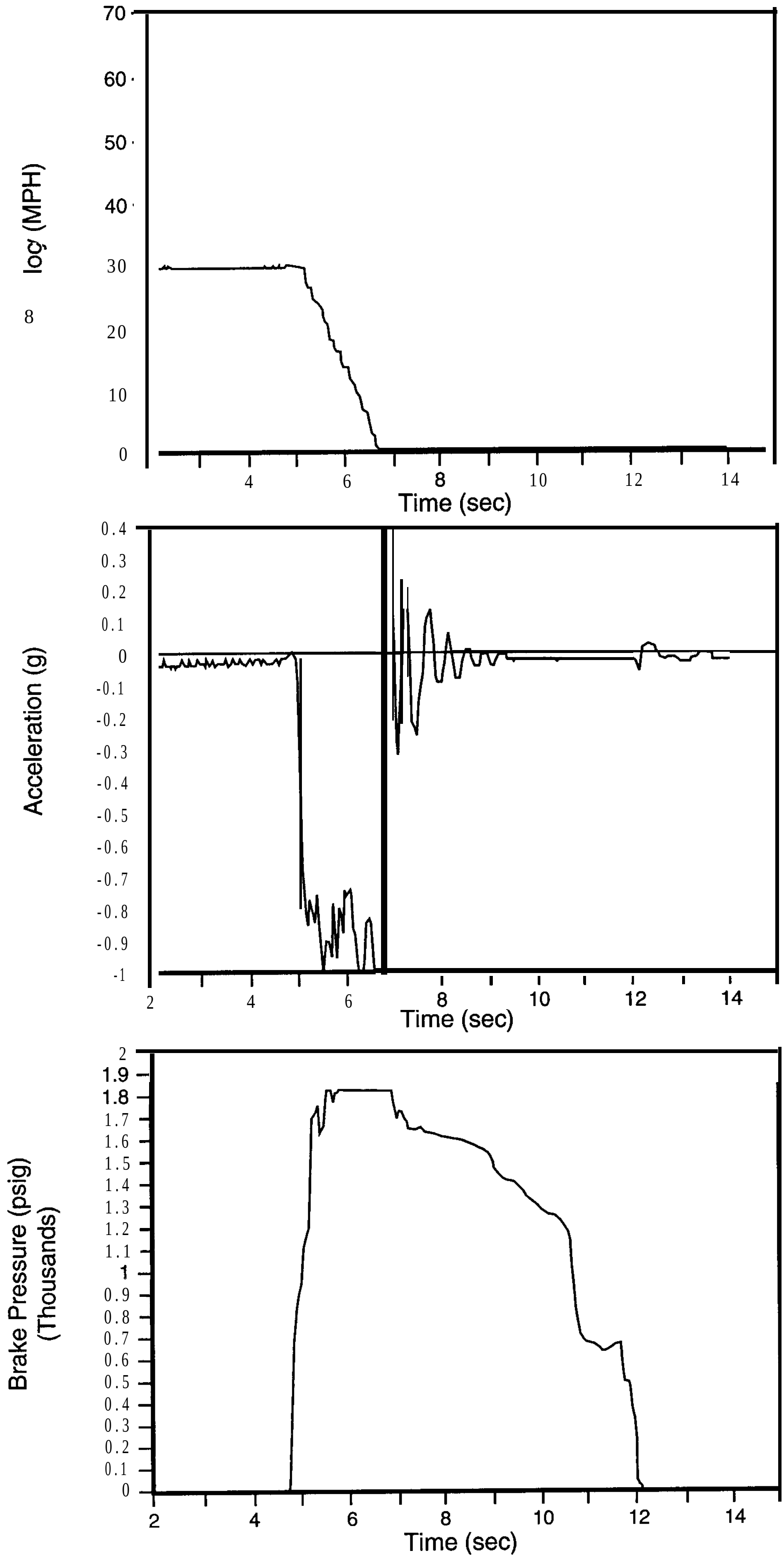


Fig. A.11 Open Loop Braking Test (13.4 to 0 m/s, 30%Brake Effort, Data File 105954, Partial Brake)

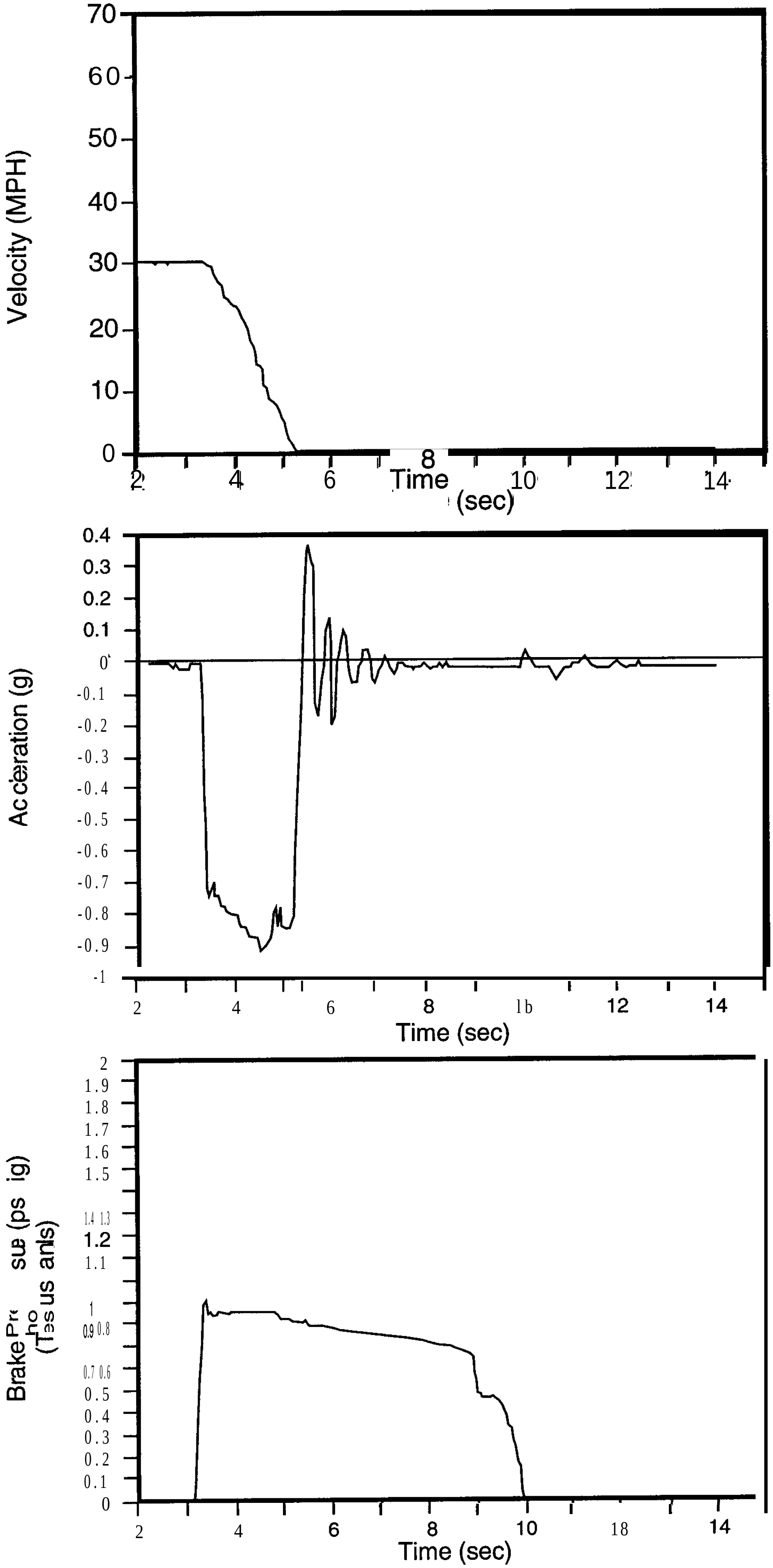


Fig. A.12 Open Loop Braking Test Results (26.8 m/s to 0 m/s, 100% Braking Effort , Data File 122834)
(Full Brake Including ABS Action and Driver "Pumping" of Brake)

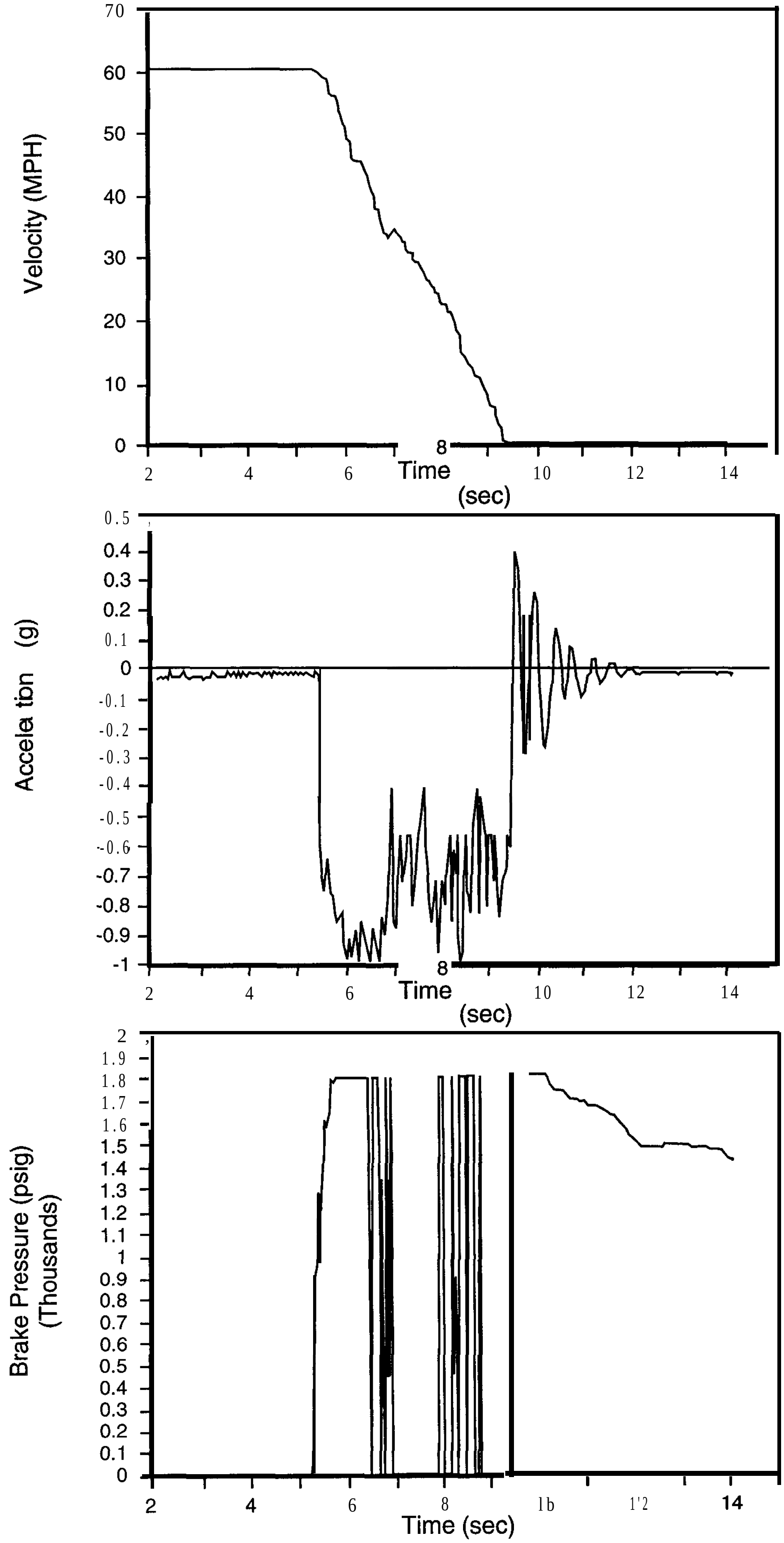


Fig. A. 13 Open Loop Braking Test Results (26.8 to 0 m/s, 30% Brake Effort, Data File 111160)

Partial Brake

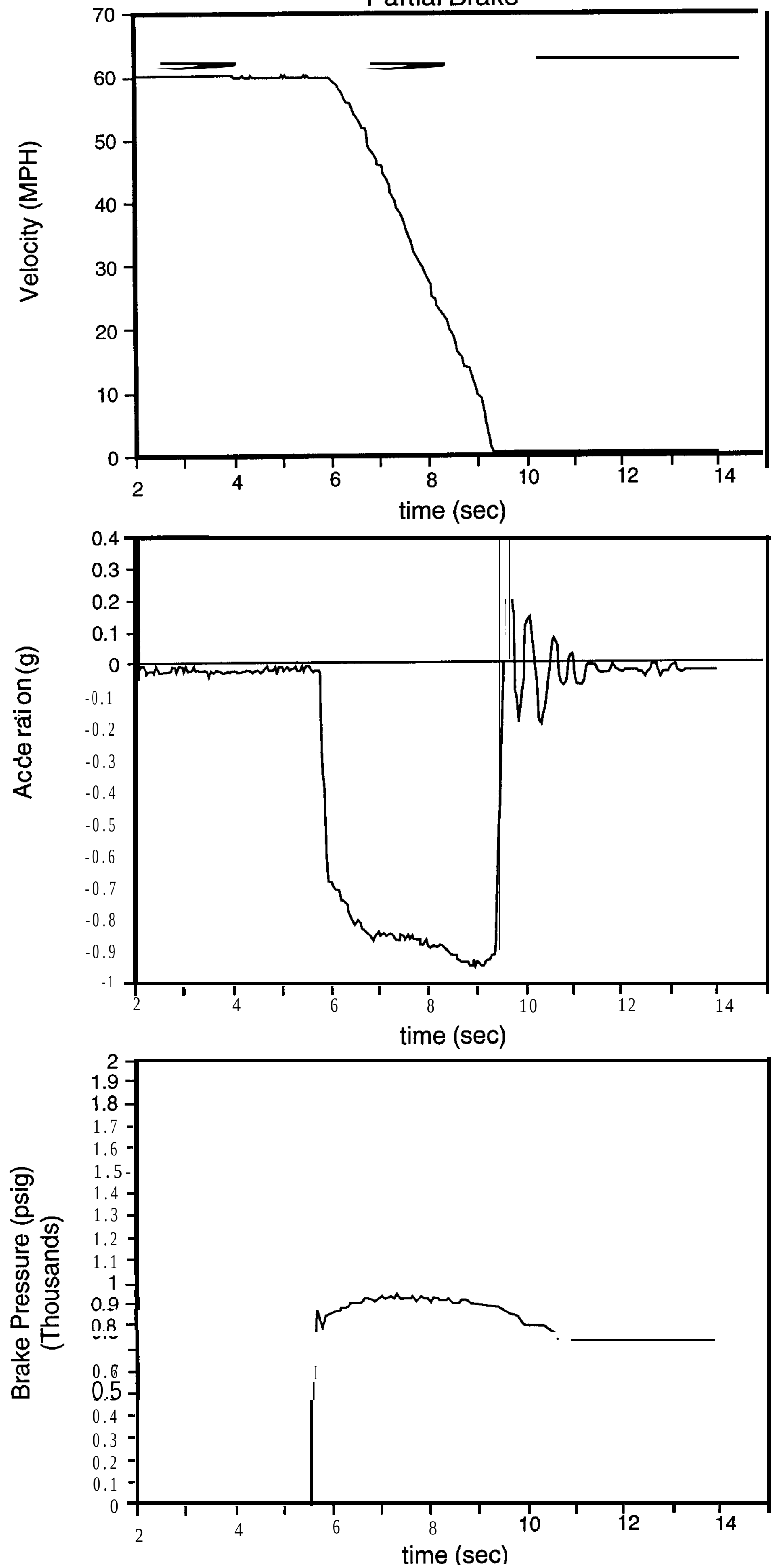


Fig. A.14 Open Loop Braking Test Results (20.1 to 0 m/s, Uphill 100% Brake Effort, Data File 125547)

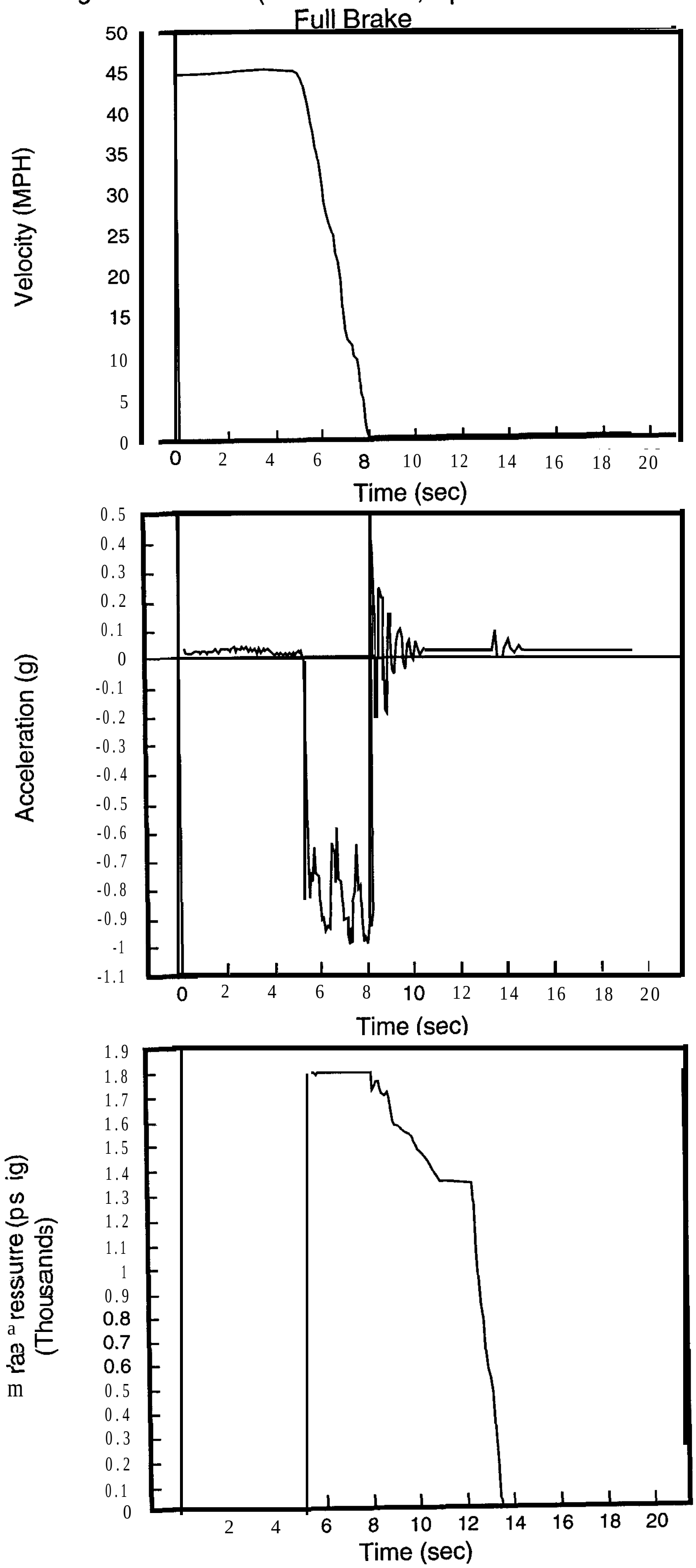


Fig. A.15 Open Loop Braking Test Results
(20.1 to 0 m/s, Downhill, 100% Brake Effort, Data File 130229) Full Brake

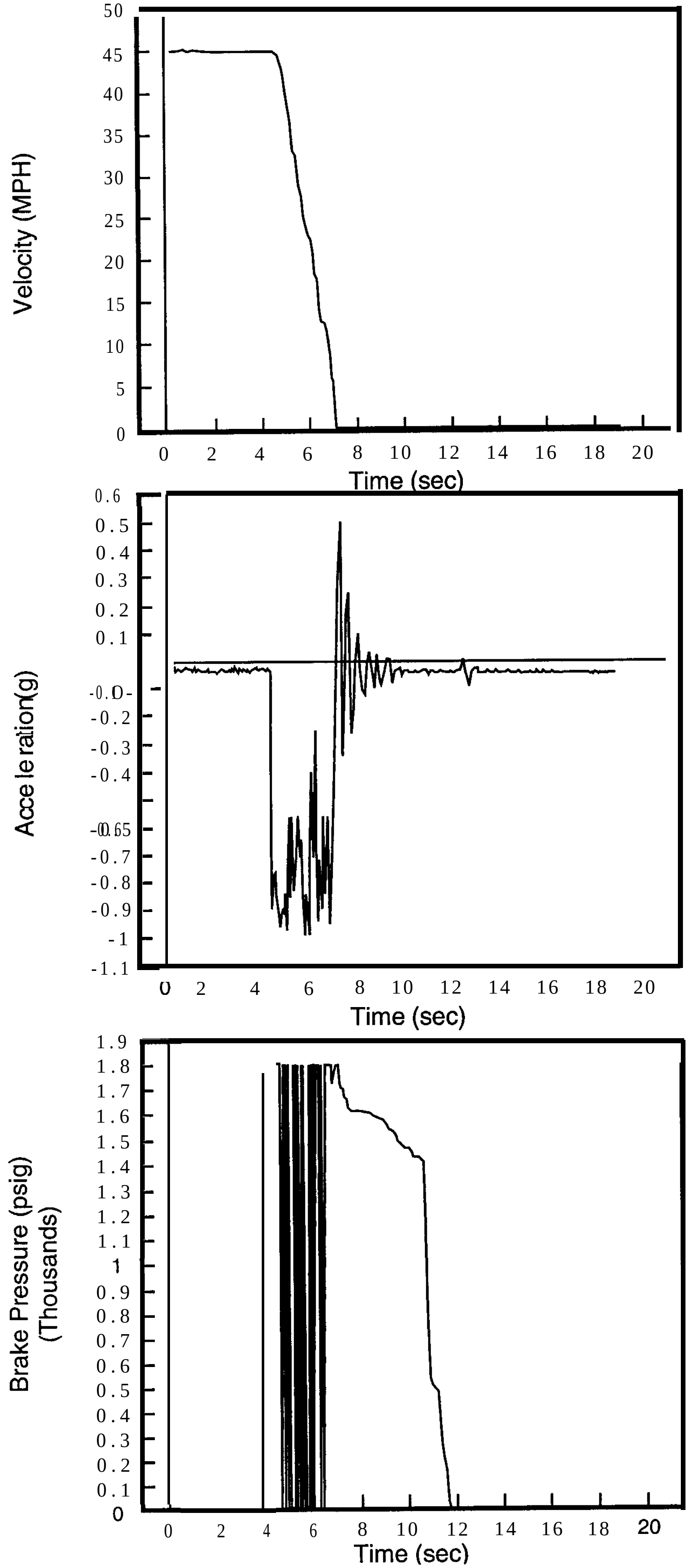


Fig. A.1 6 Maximum Acceleration Test for Comparison Between Two Test Vehicles
(Data Files 112353, and 102717)

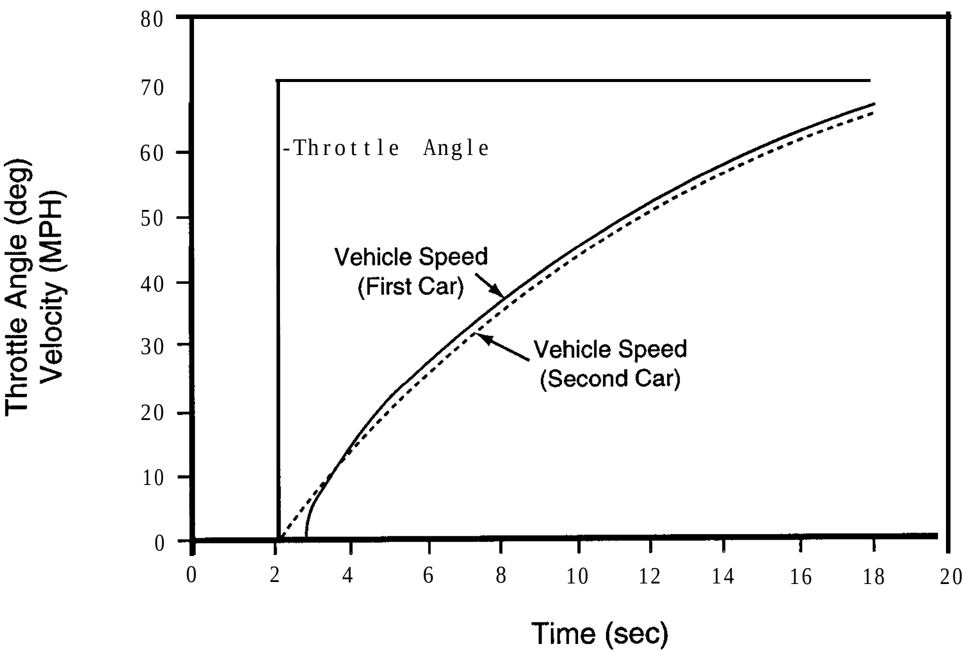


Fig. A.1 7 Coast Down Distance Test
North Direction (Data Files 104247 and 120156

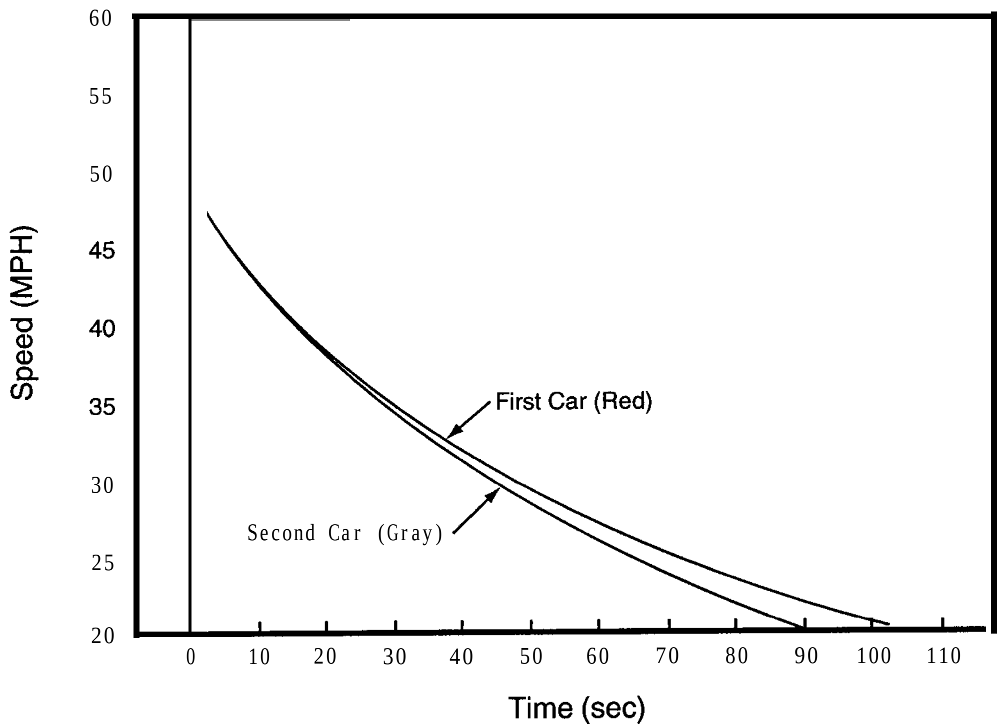


Fig. A.1 8 Coast Down Distance Test
South Direction (Data Files 104735 and 120653)

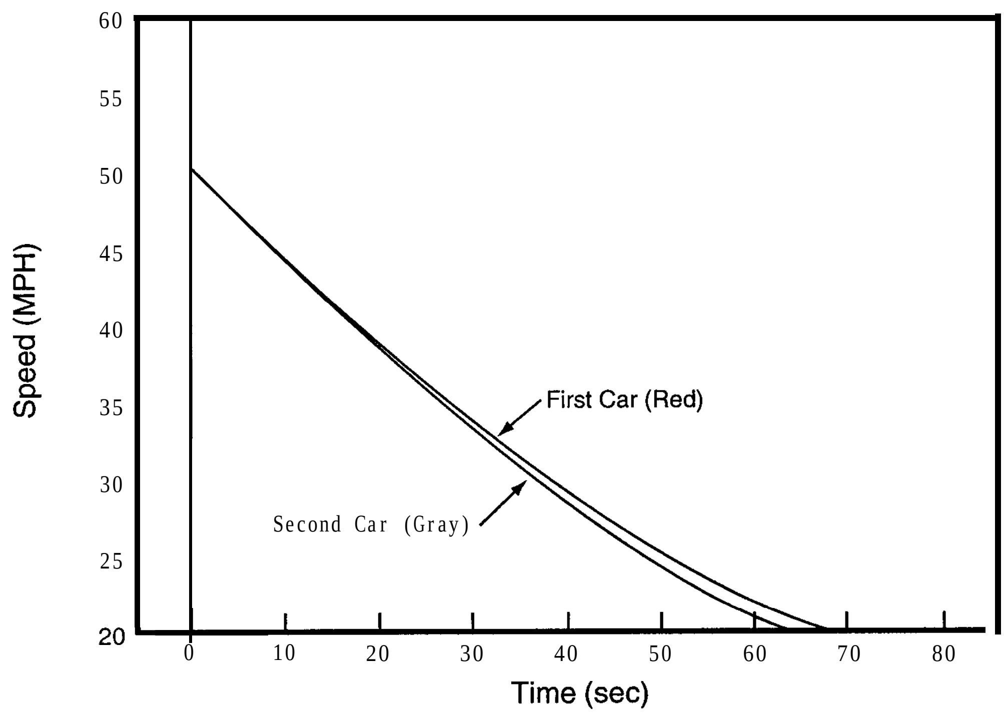


Fig. A.19 Radar Range Test at 3.1 m/s Closing Rate

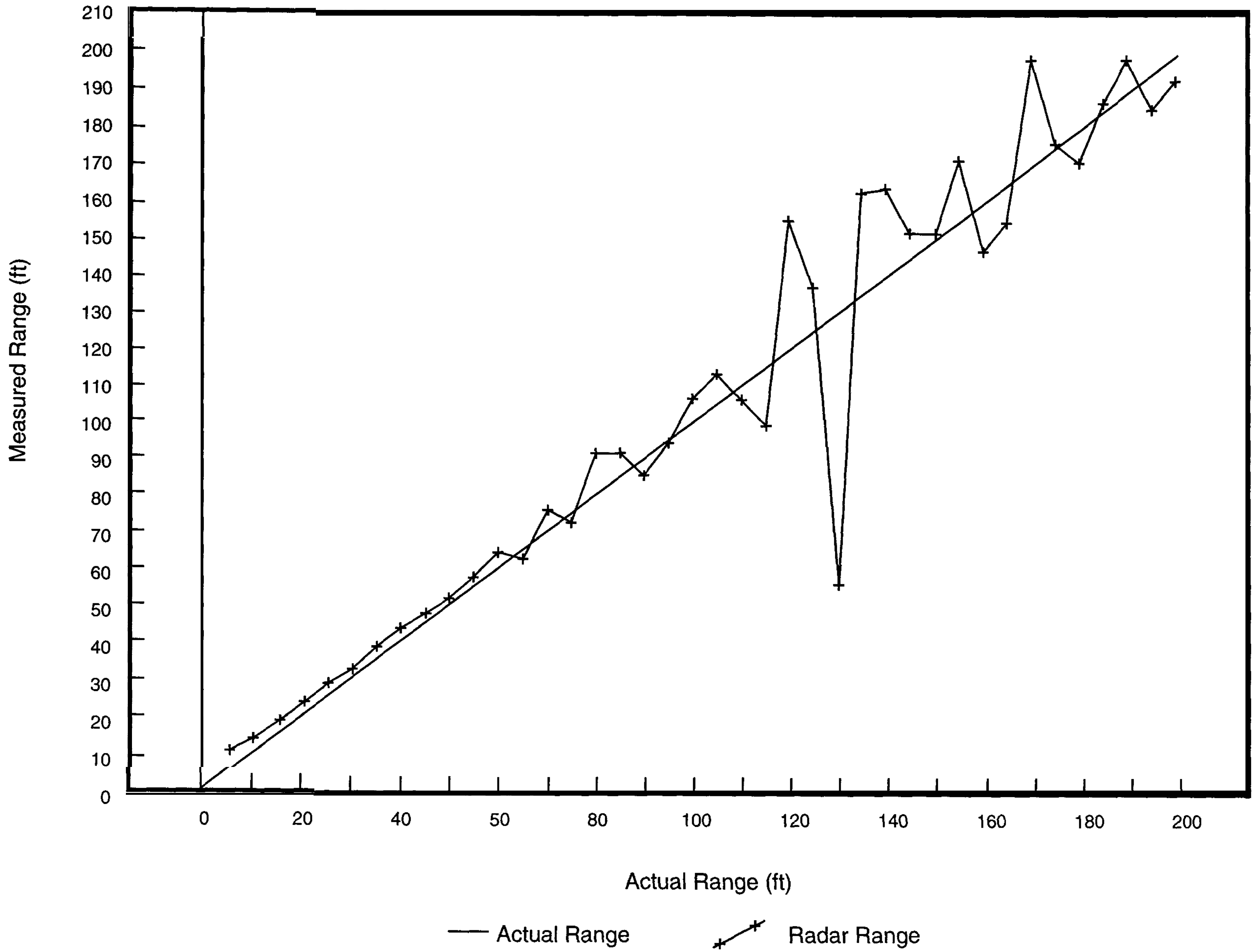


Fig. A.20 Radar Range Test at 5.8 m/s Closing Rate

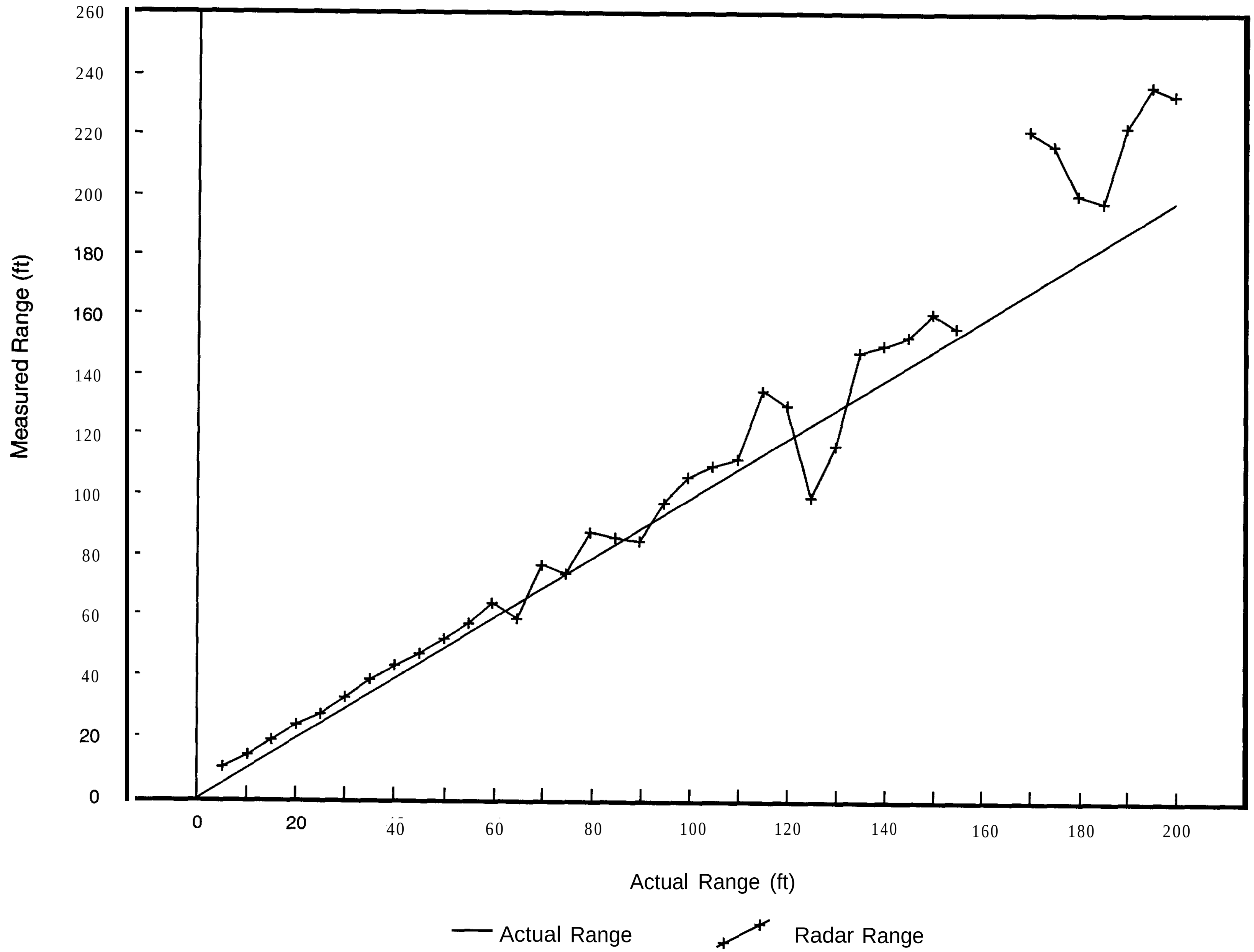


Fig. A.21 Radar Range Test at 8.5 m/s Closing Rate

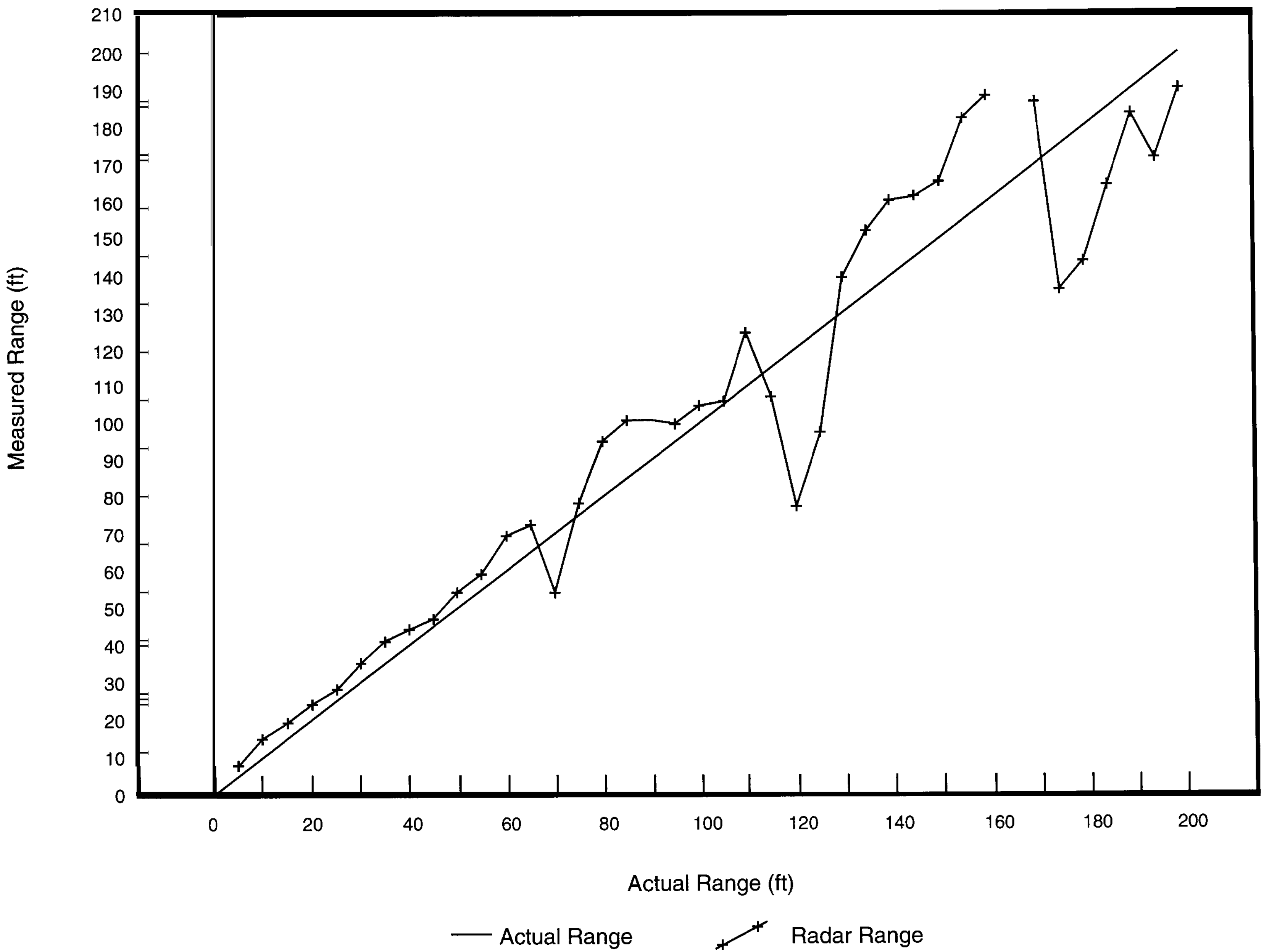


Fig. A.22 Radar Range Test at 10.3 m/s Closing Rate

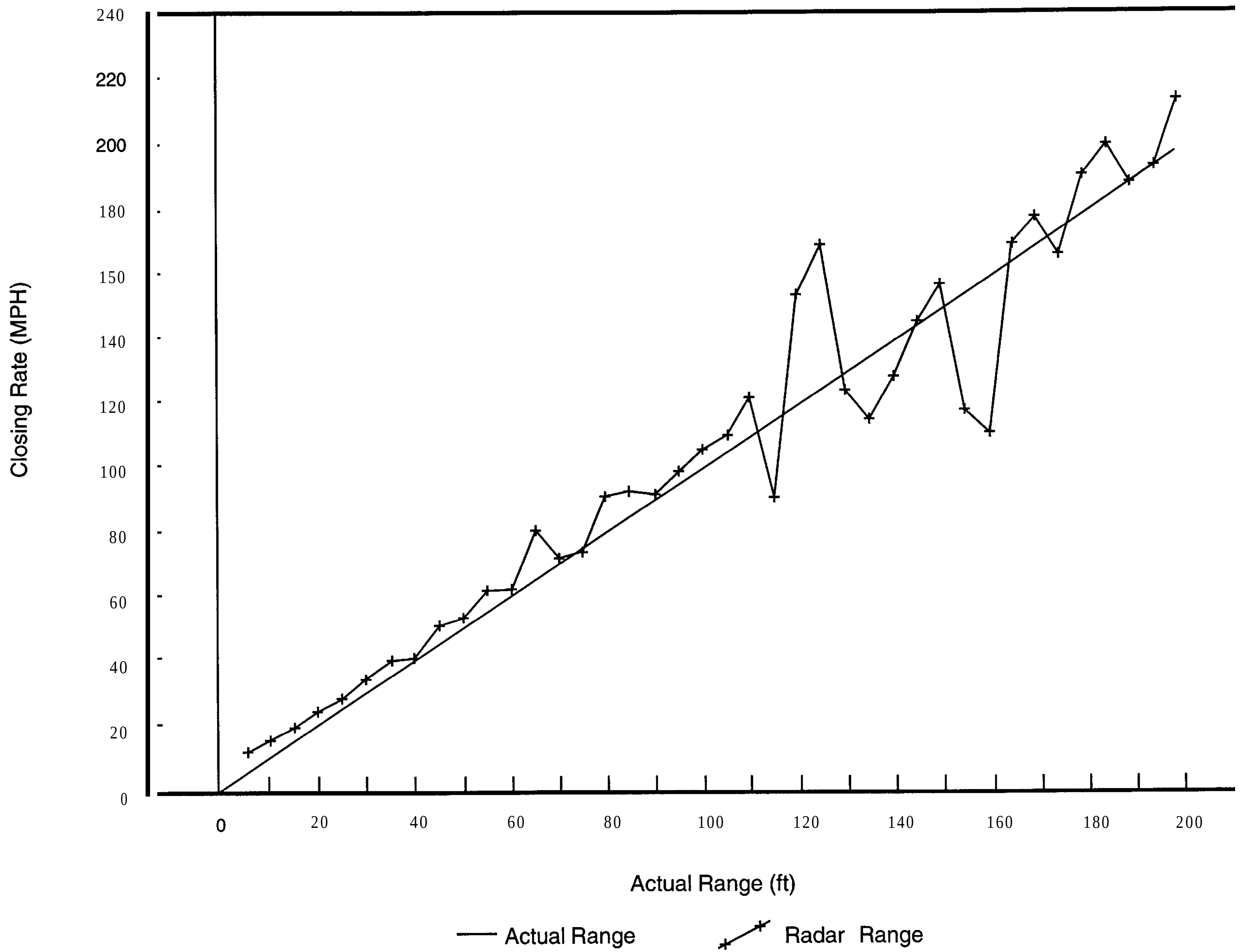


Fig. A.23 Radar Closing Rate Test with Acceleration At Low Speed

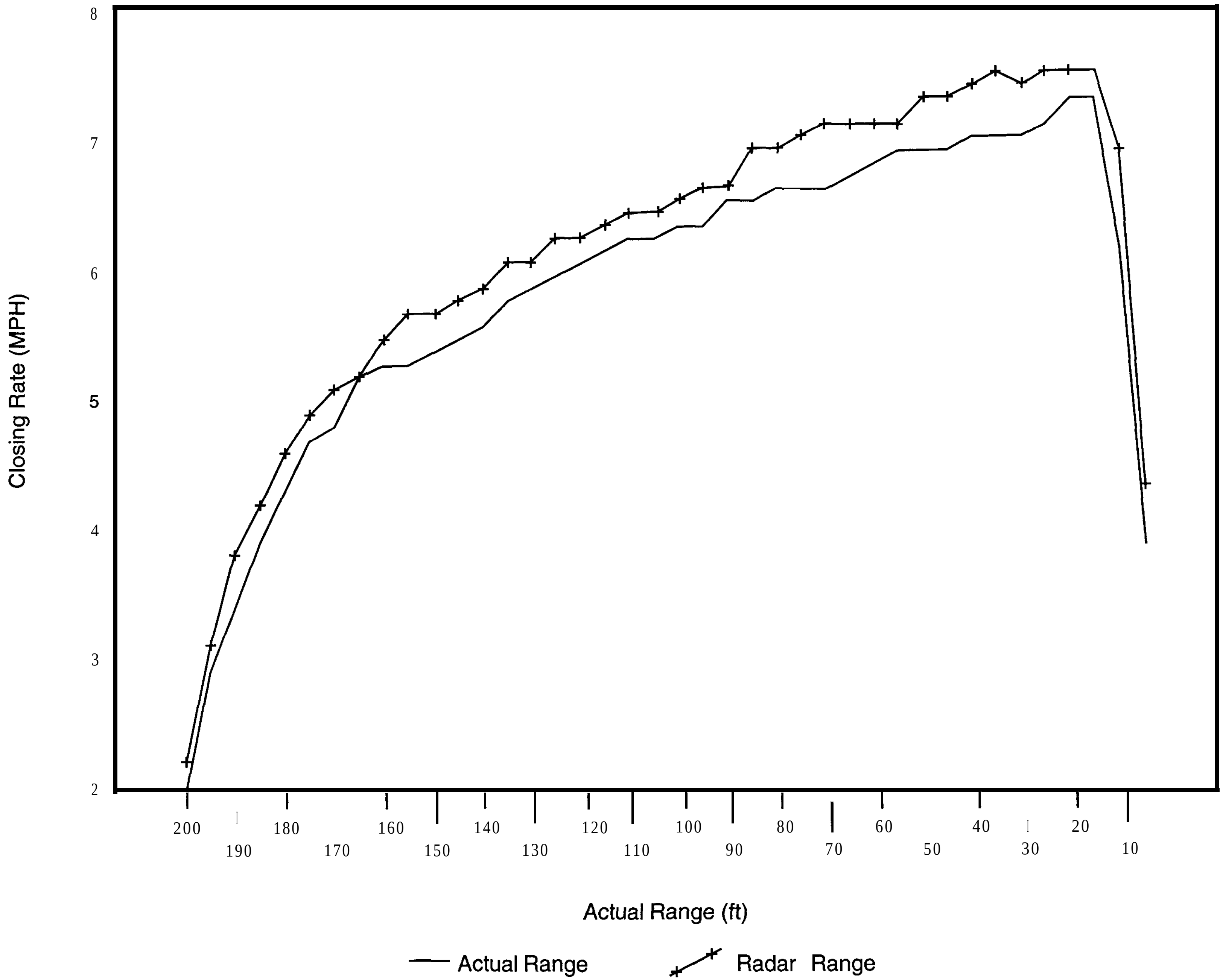


Fig. A.24 Radar Closing Rate Test from Constant Cruise Speed

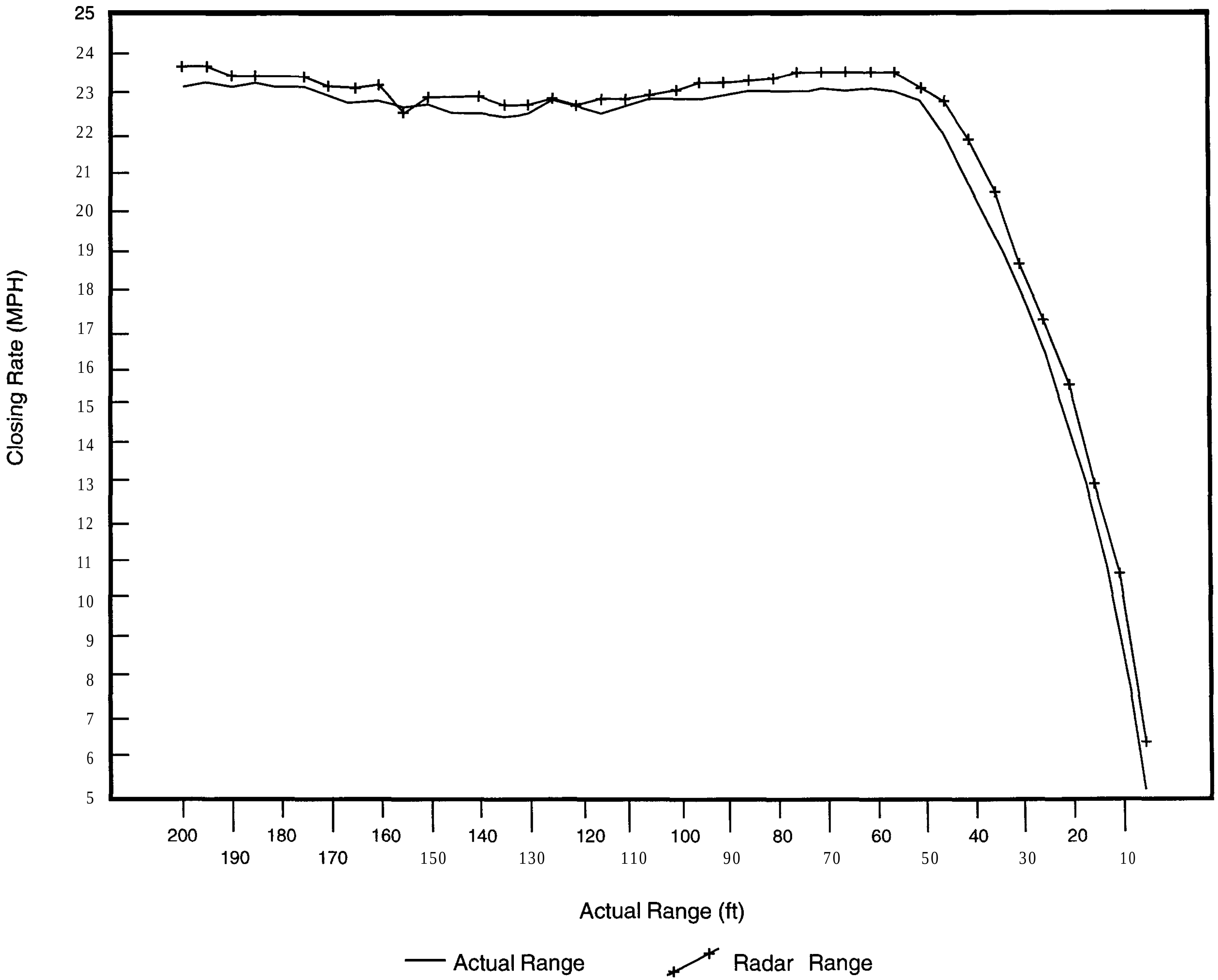


Fig. A.25 Radar Closing Rate Test (0.1 g)

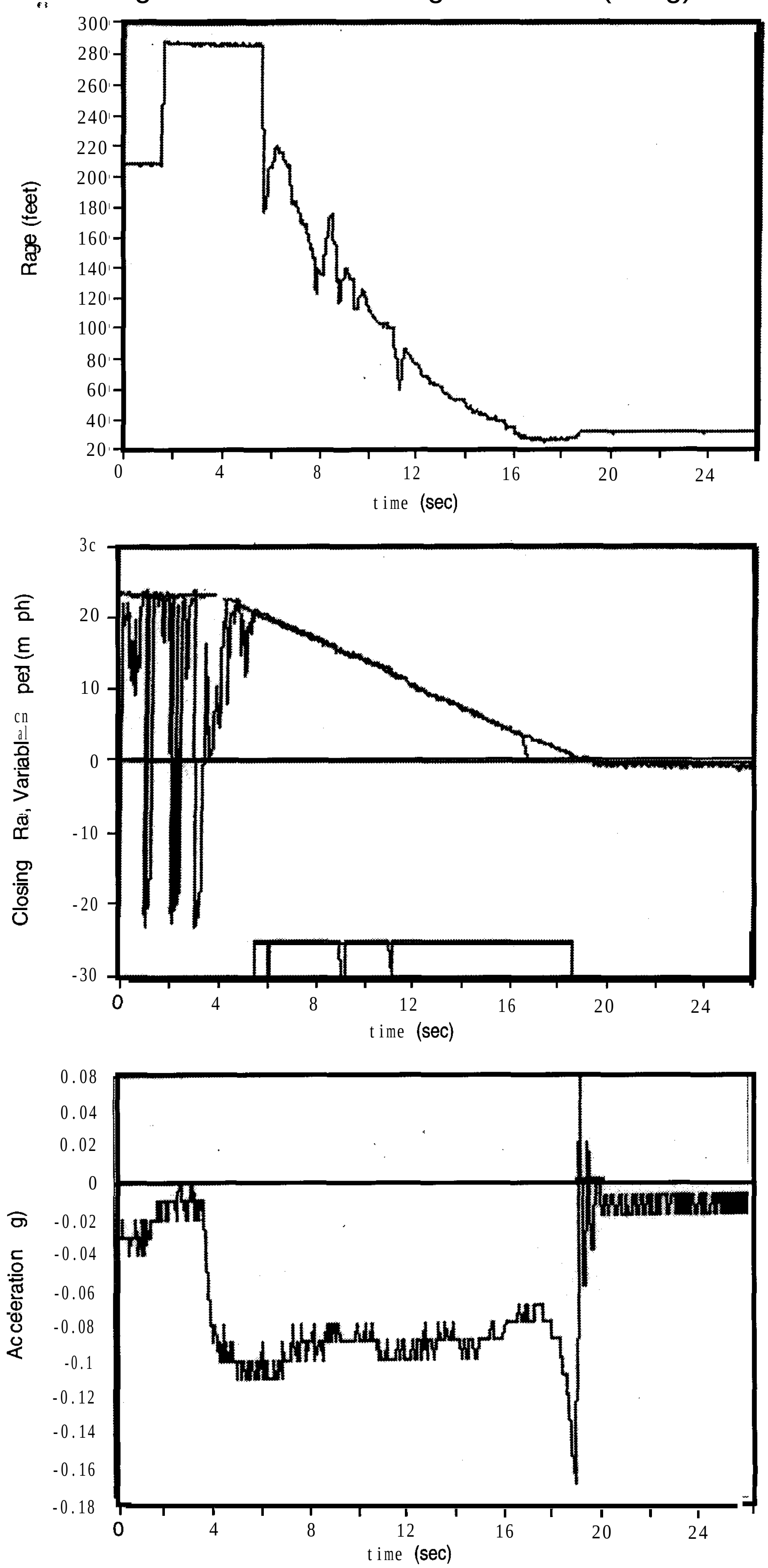


Fig. A.26 Radar Closing Rate Test (0.2g)

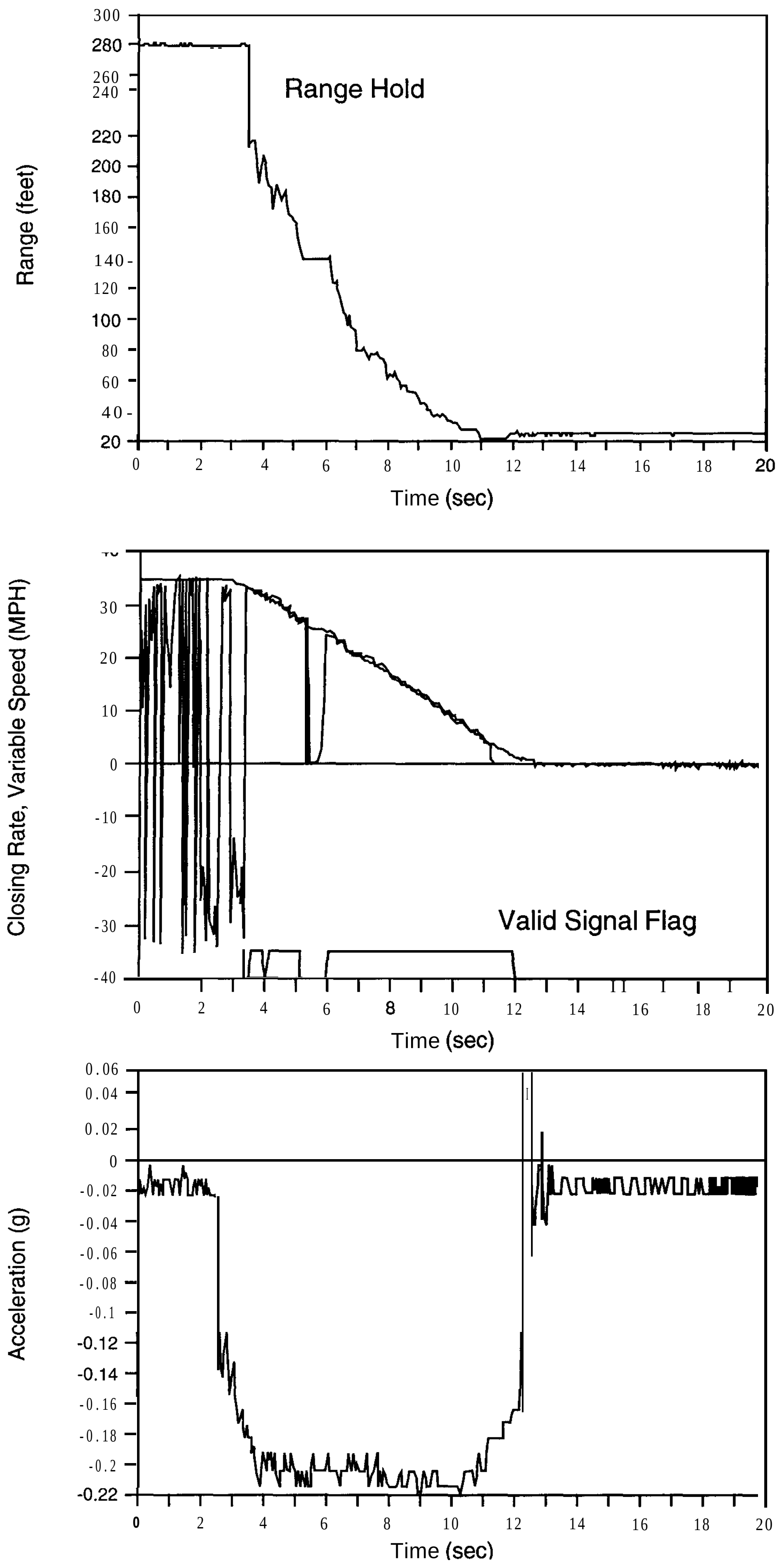
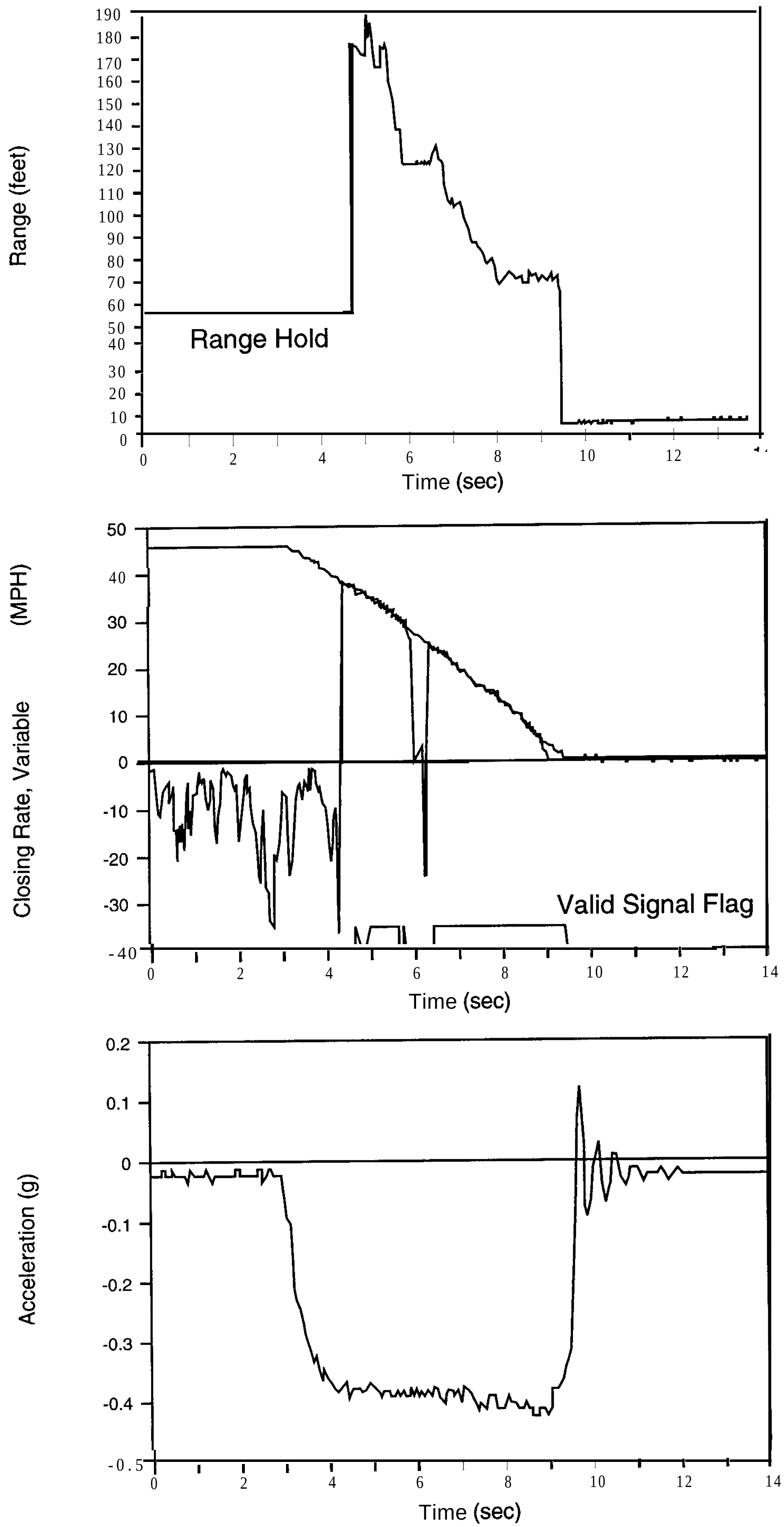


Fig. A.27 Radar Closing Rate Test (0.4g)



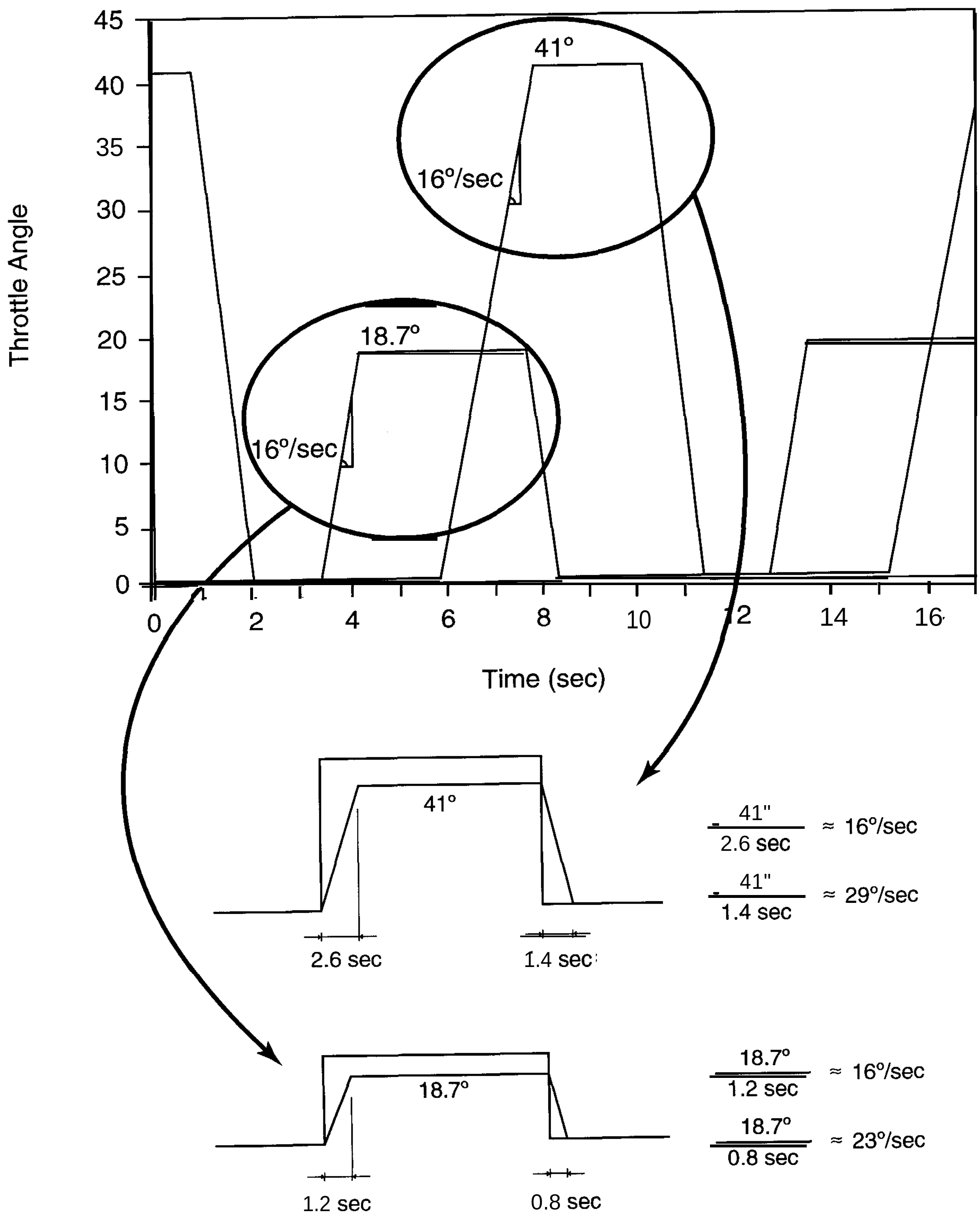


Fig. A.28 Old Throttle Actuator Response

Fig. A.29 RCS Braking Actuator Block Diagram

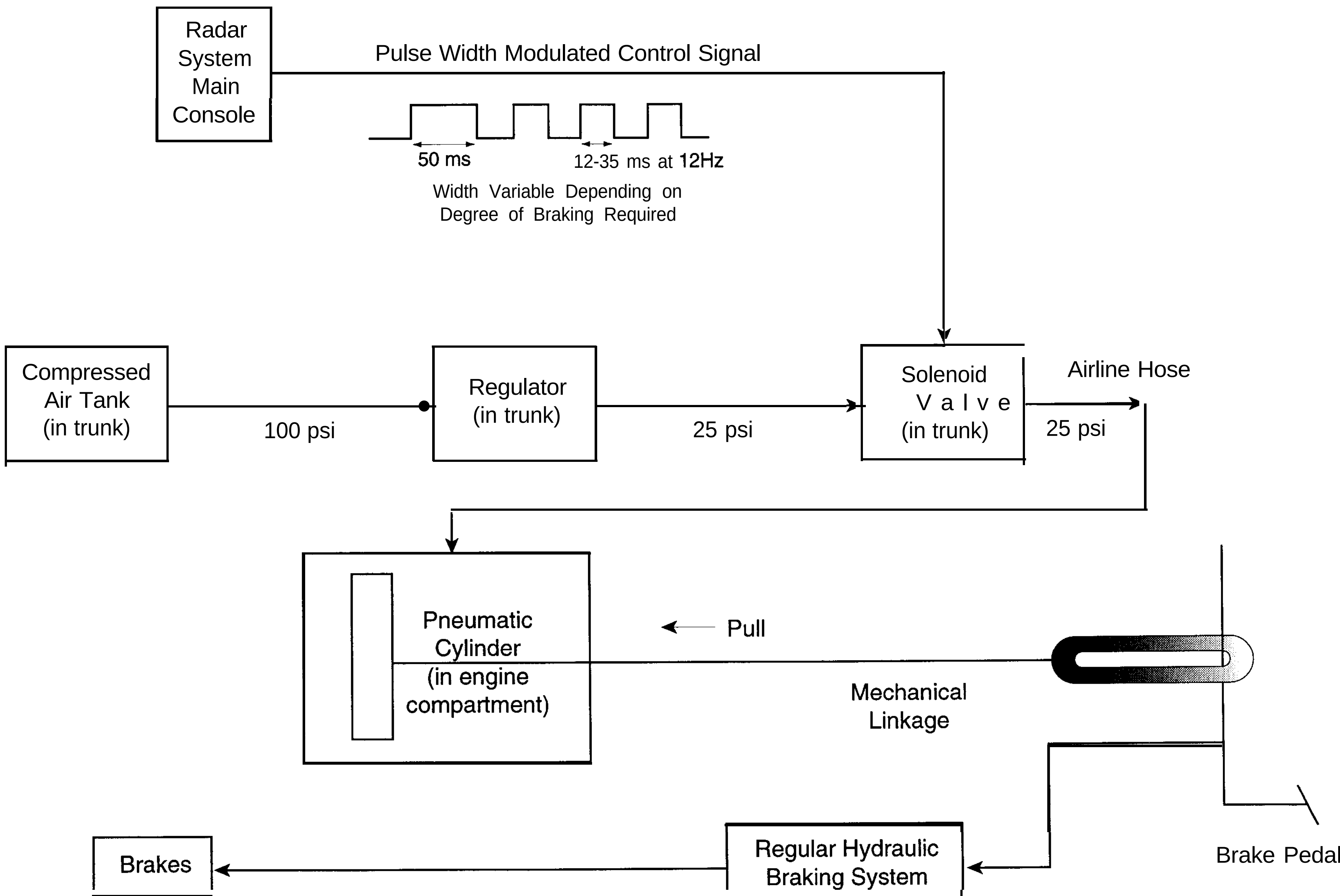


Fig. A.30 Pneumatic Brake Actuator Test (30ms pulse width 26.8 m/s, 30 psig air pressure)

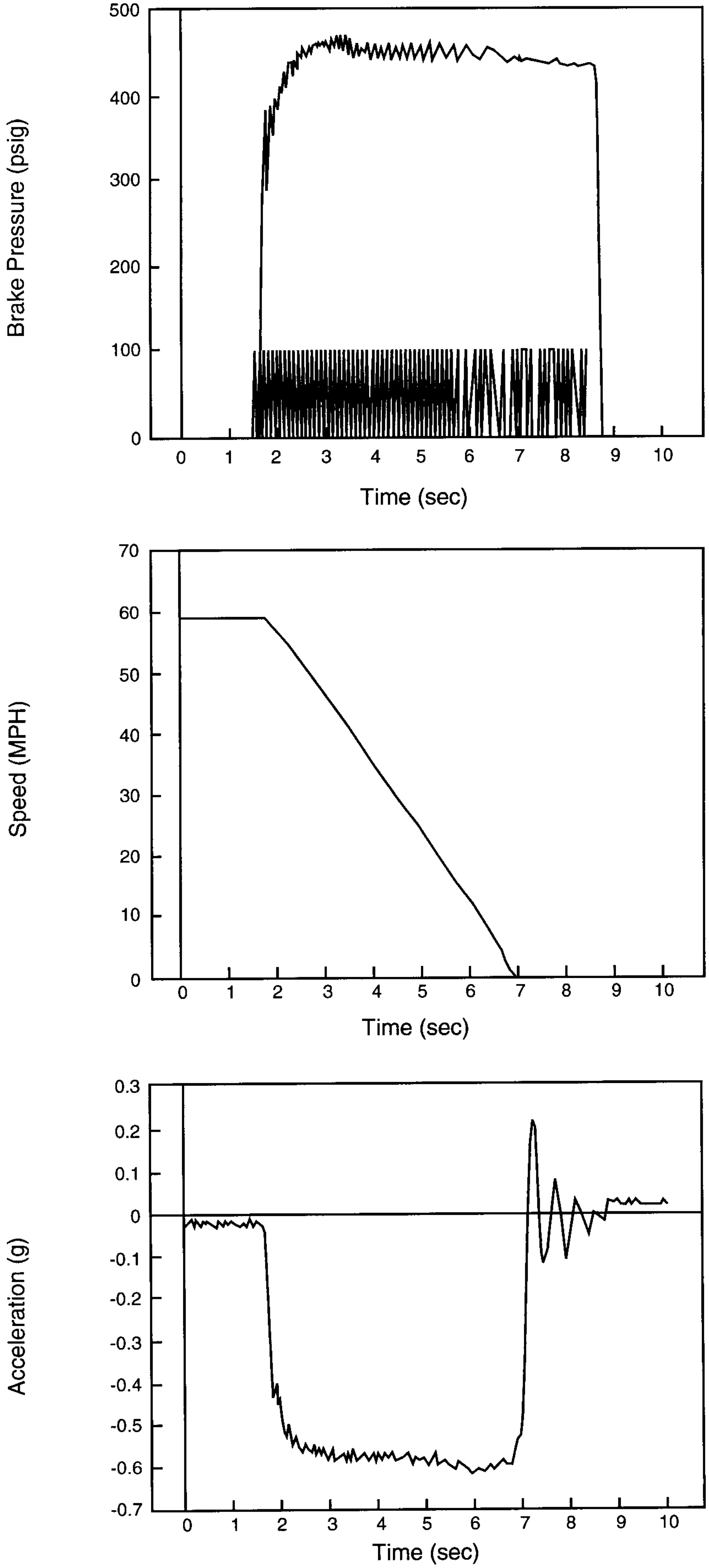


Fig. A.31 Pneumatic Brake Actuator Test (30ms pulse width '26.8 m/s , 60 psig air pressure)

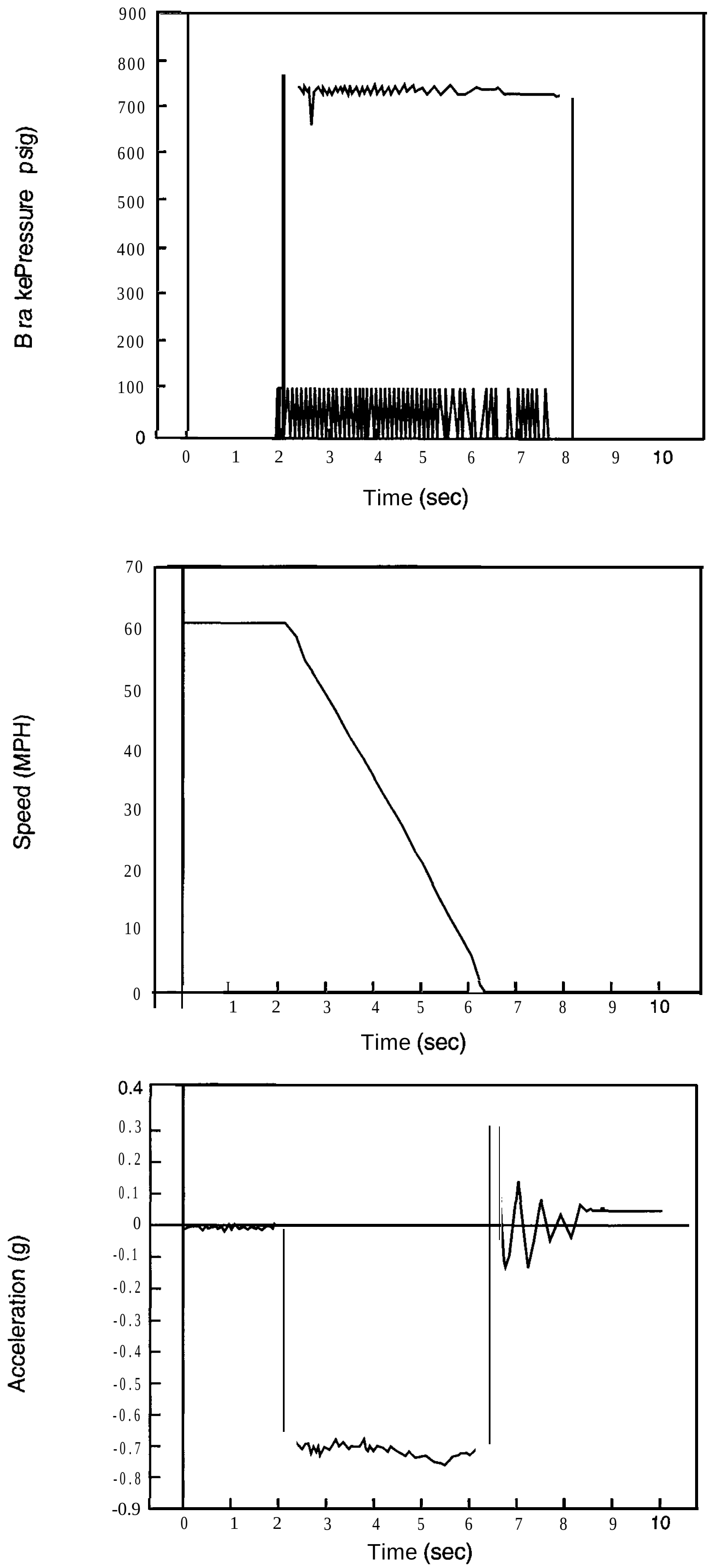


Fig. A.32 Pneumatic Brake Actuator Test (70ms pulse width 26.8 m/s, 30 psig air pressure)

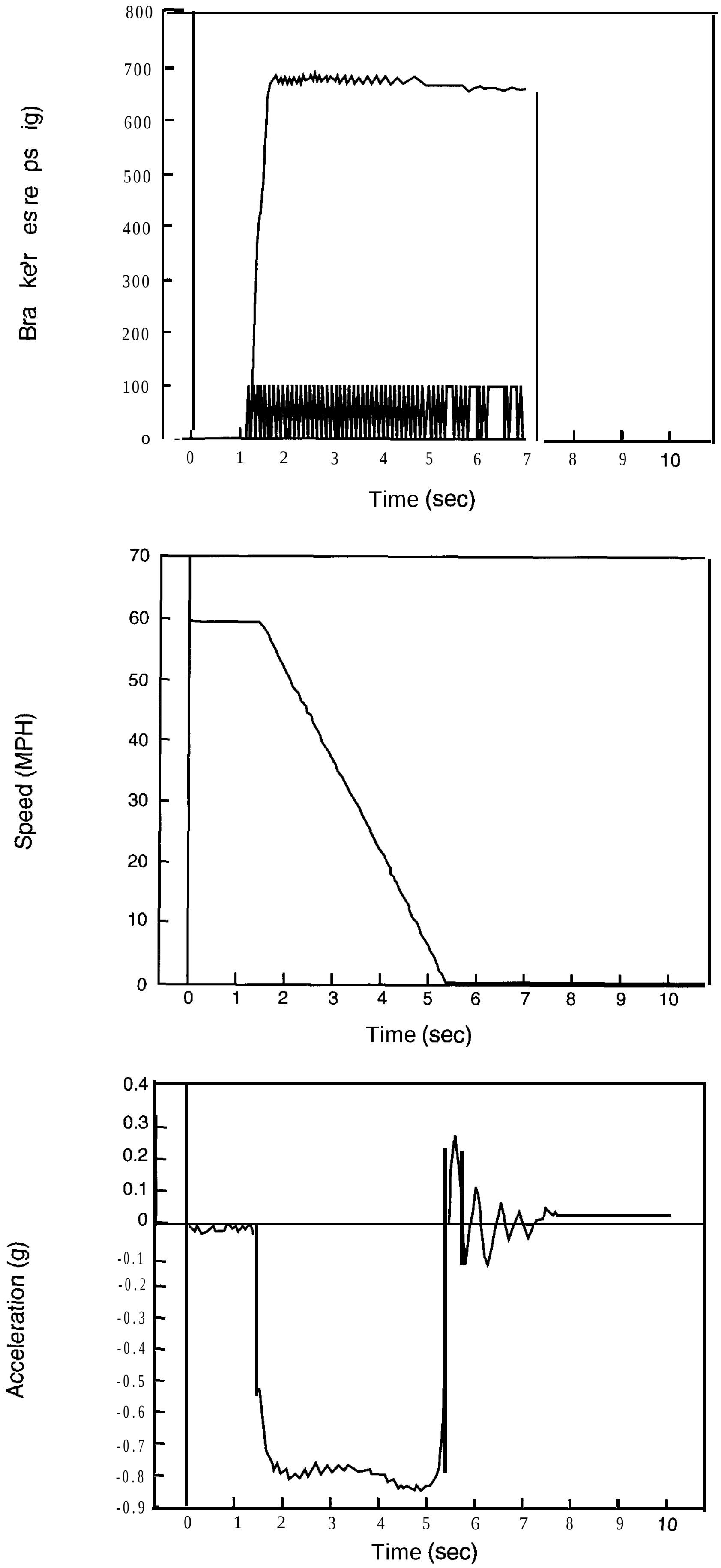
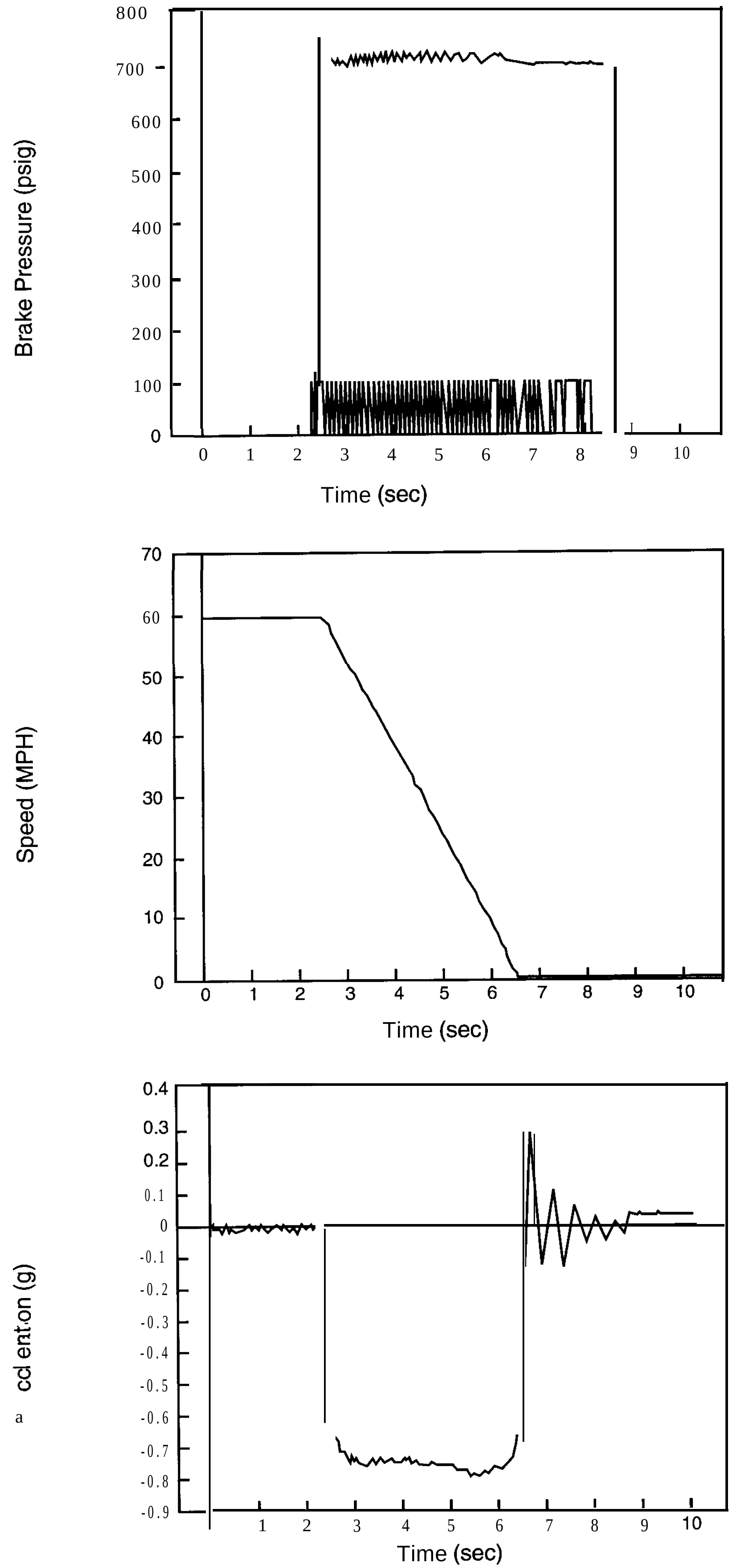
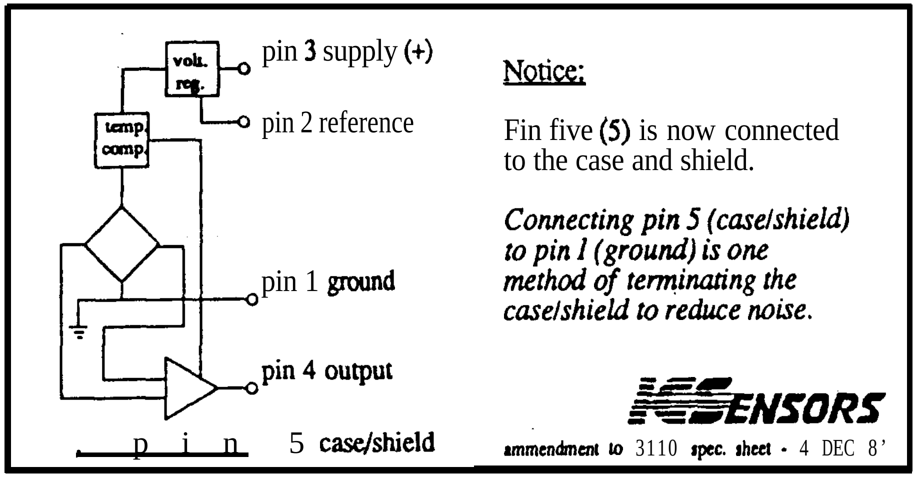


Fig. A.33 Pneumatic Brake Actuator Test (70ms pulse width 26.8 m/s, 60 psig air pressure)





Accelerometer Calibration
(Platooning Project)
RCS Corp - 11/19/90

Vehicle	Accel S/N	Label Up (VDC)	Label Down (VDC)	Span (VDC)	Span Error from Nominal (%)	Mid-Span (VDC)	Mid-Span Reading if 2.5 VDC is Scaled as 0g (g)
Grey	3A10112	4.454	0.532	3.922	-2.0%	2.493	-0.004
Red	3A10116	4.521	0.437	4.084	2.1%	2.479 =0.439+(4.521-0.437)/2	-0.010
Blue	3A10115	4.169	0.034	4.135	3.4%	2.102	-0.199
LTD	3A10114	4.534	0.443	4.091	2.3%	2.489	-0.006

Fig. A.34 Accelerometer Circuit and Calibration

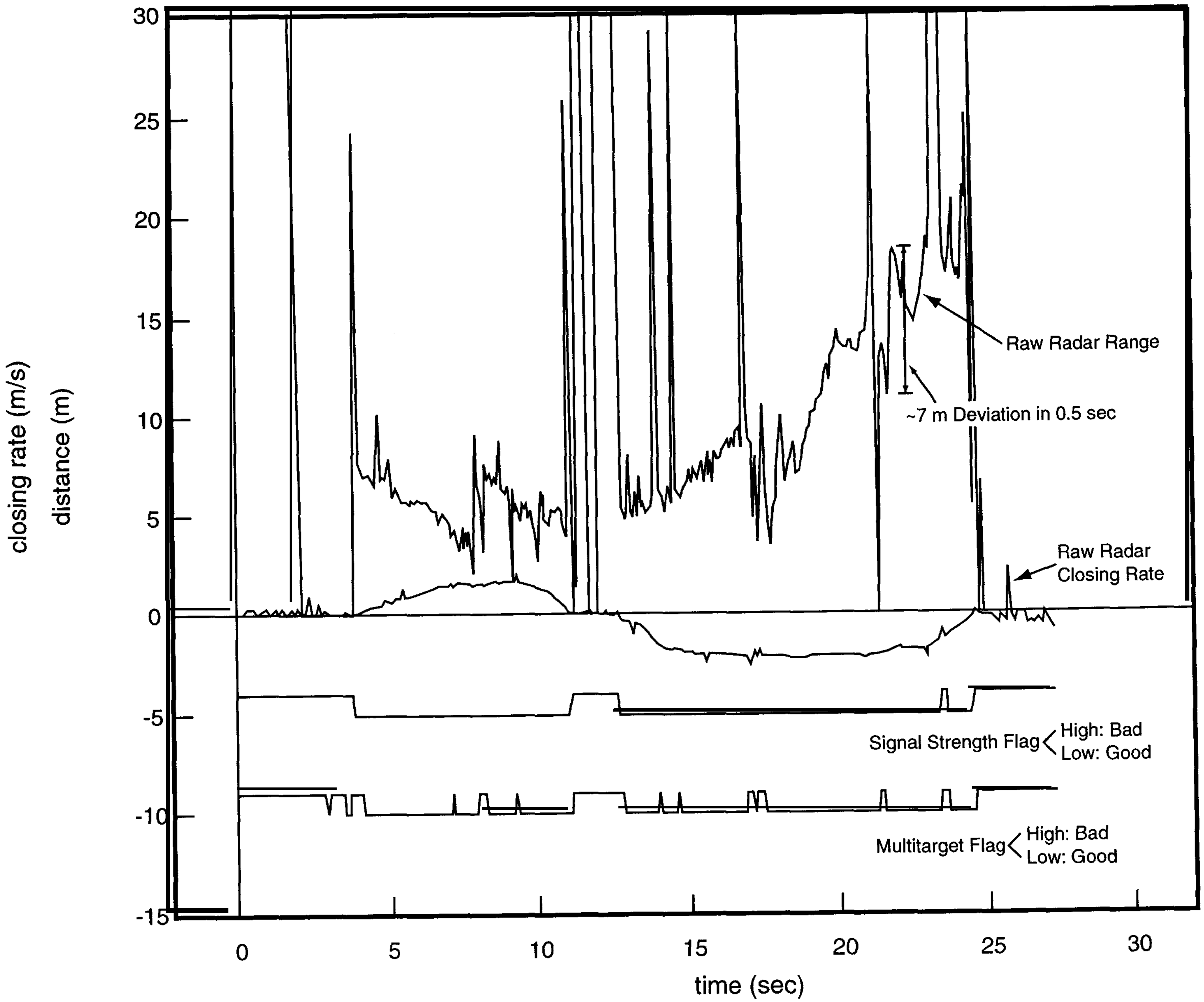


Fig. A. 35 Example Radar Test With a Stationary Vehicle as a Target (Blue LTC, 7/7/92)

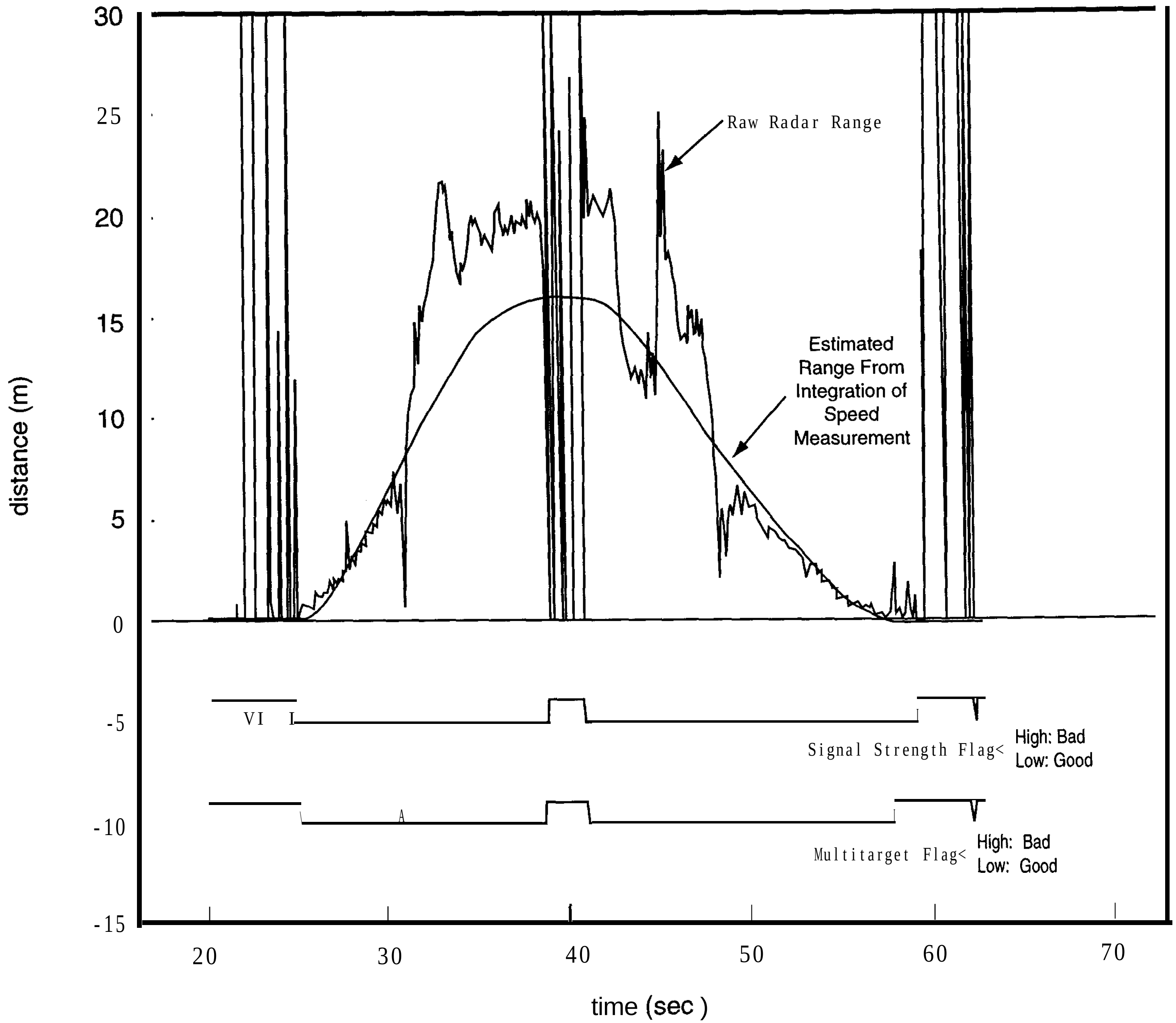


Fig. A 36: Example Radar Test With a Wall As A Target (Blue LTC, 7/7/92)

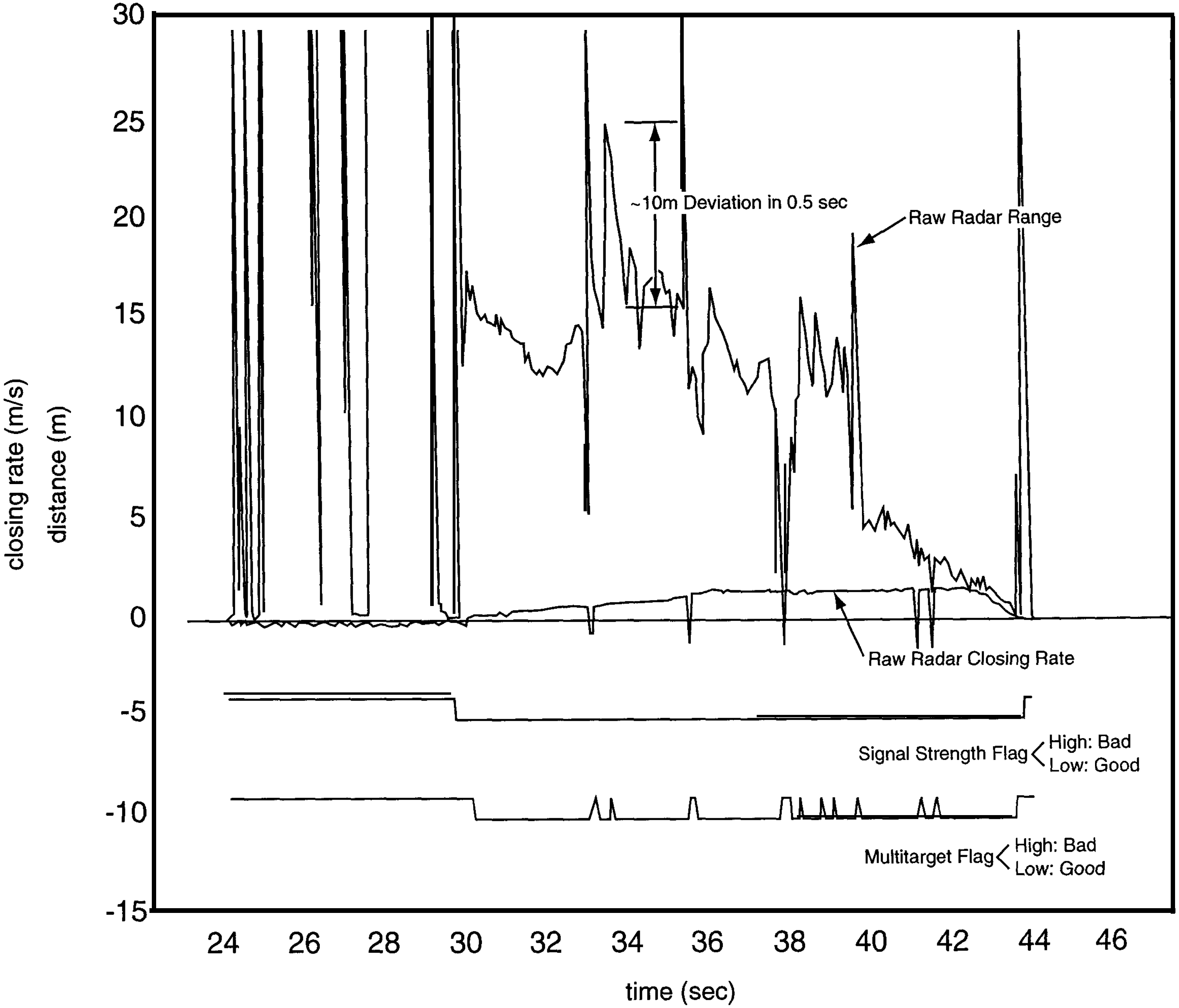


Fig. A.37 Example Radar Test With a Stationary Vehicle as a Target (Red LTC, 7/7/92)

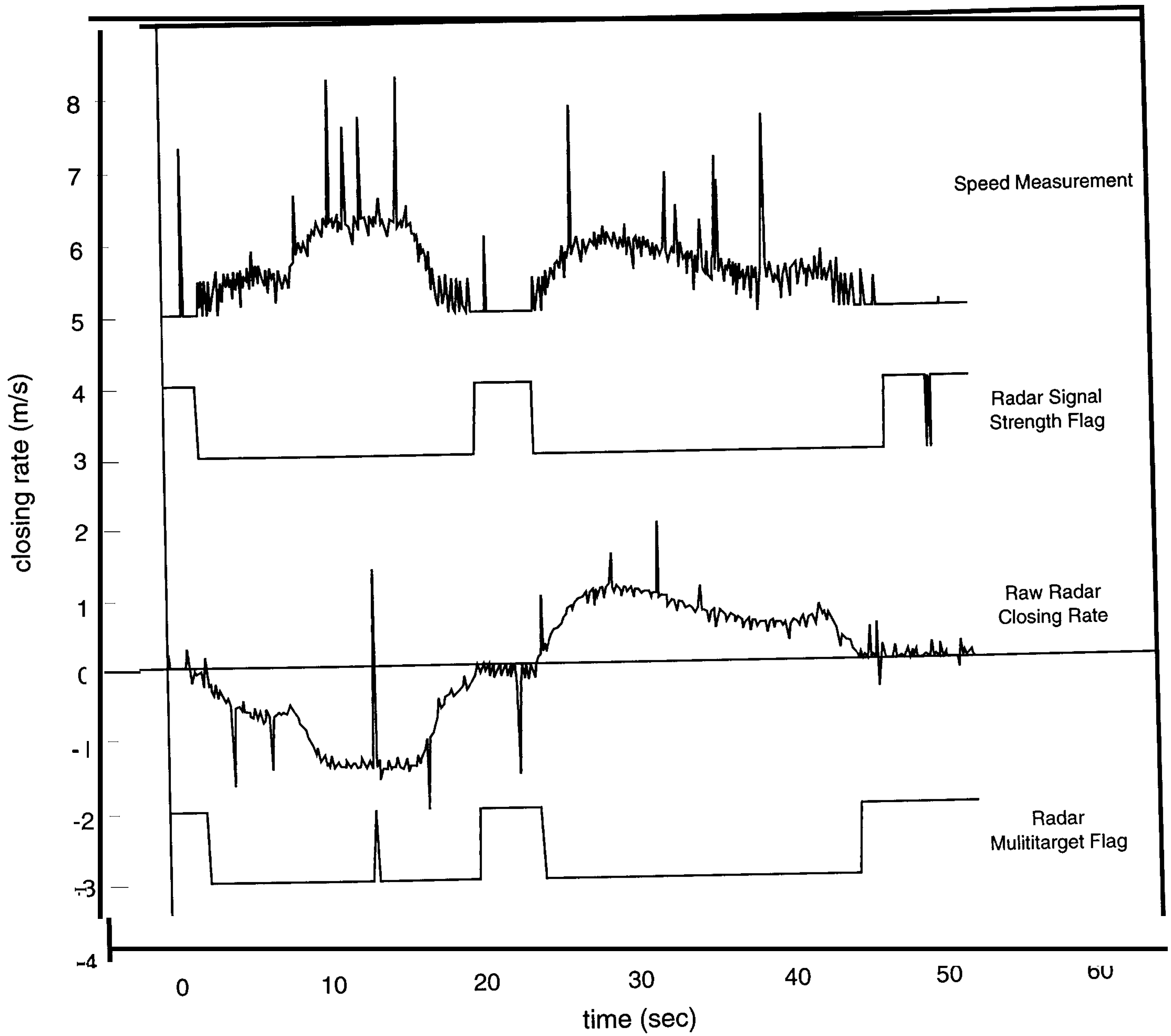


Fig. A.38 Example Radar Test Showing the Closing Rate (Blue LTC, 7/20/92)

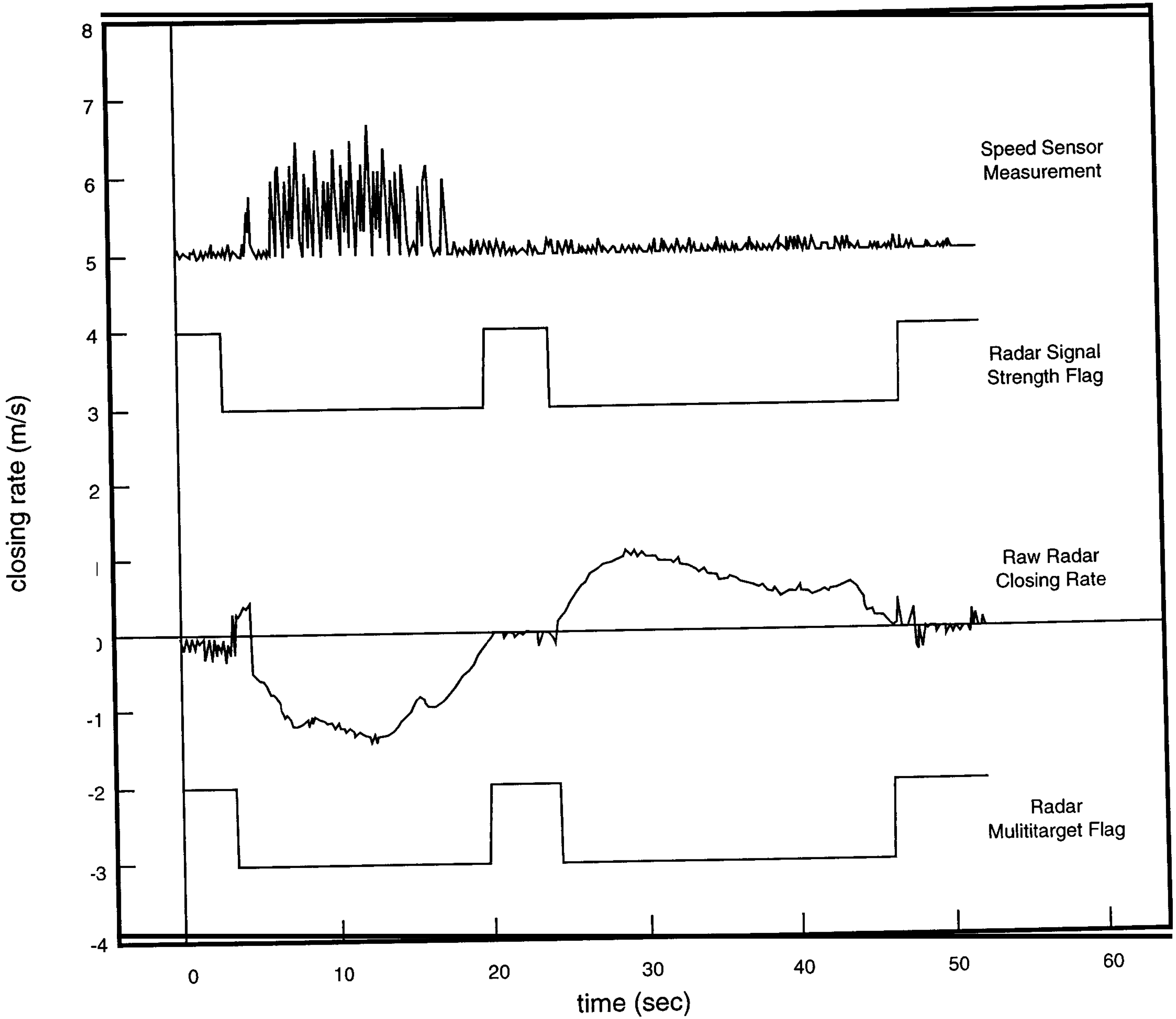


fig. A.39 Example Radar Test Showing the Closing Rate (Red LTC, 7/20/92)

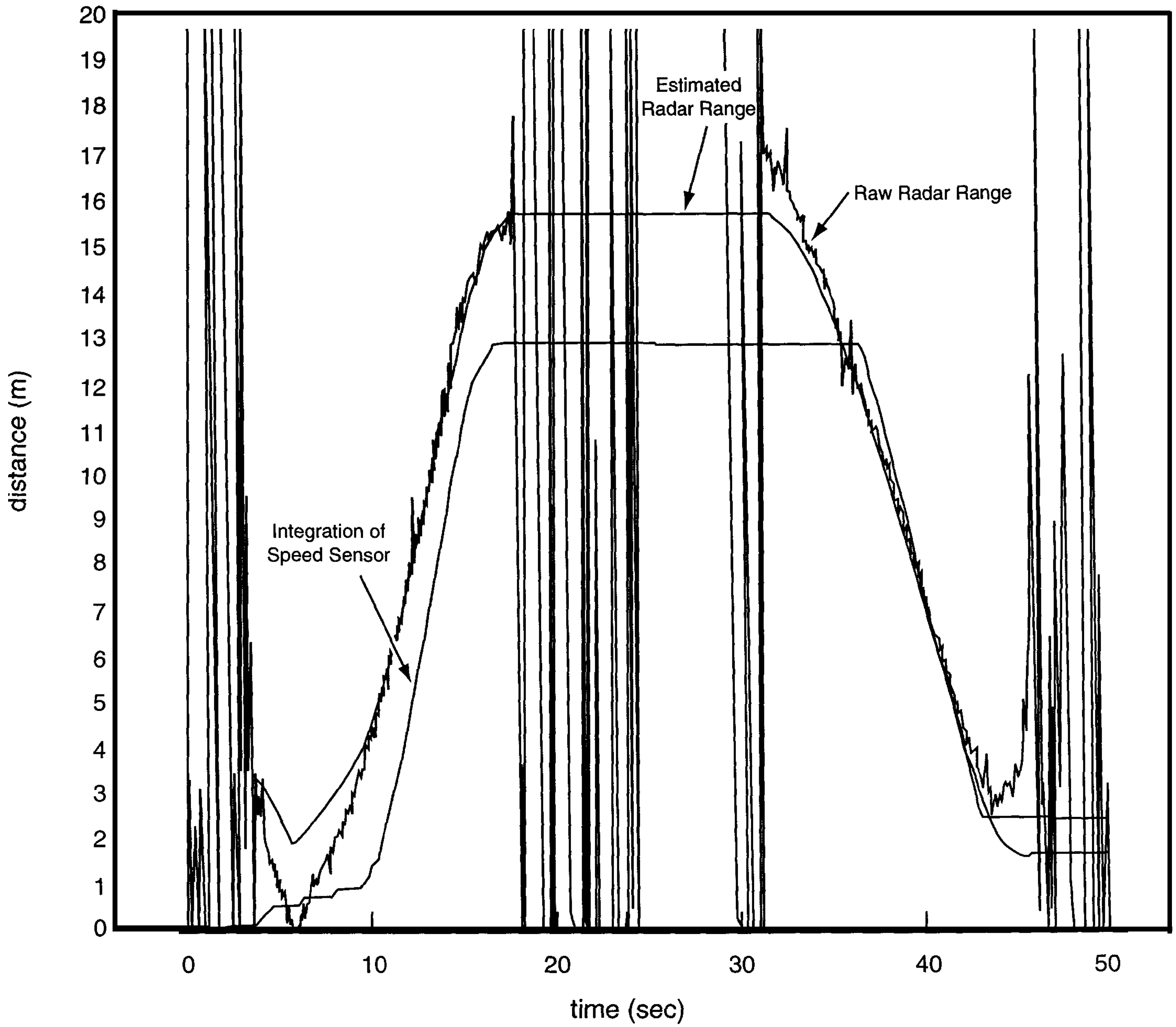


Fig. A.40 Example Radar Test For Comparison Between Different Range Data and Estimates (Red LTC, 7/21/92)

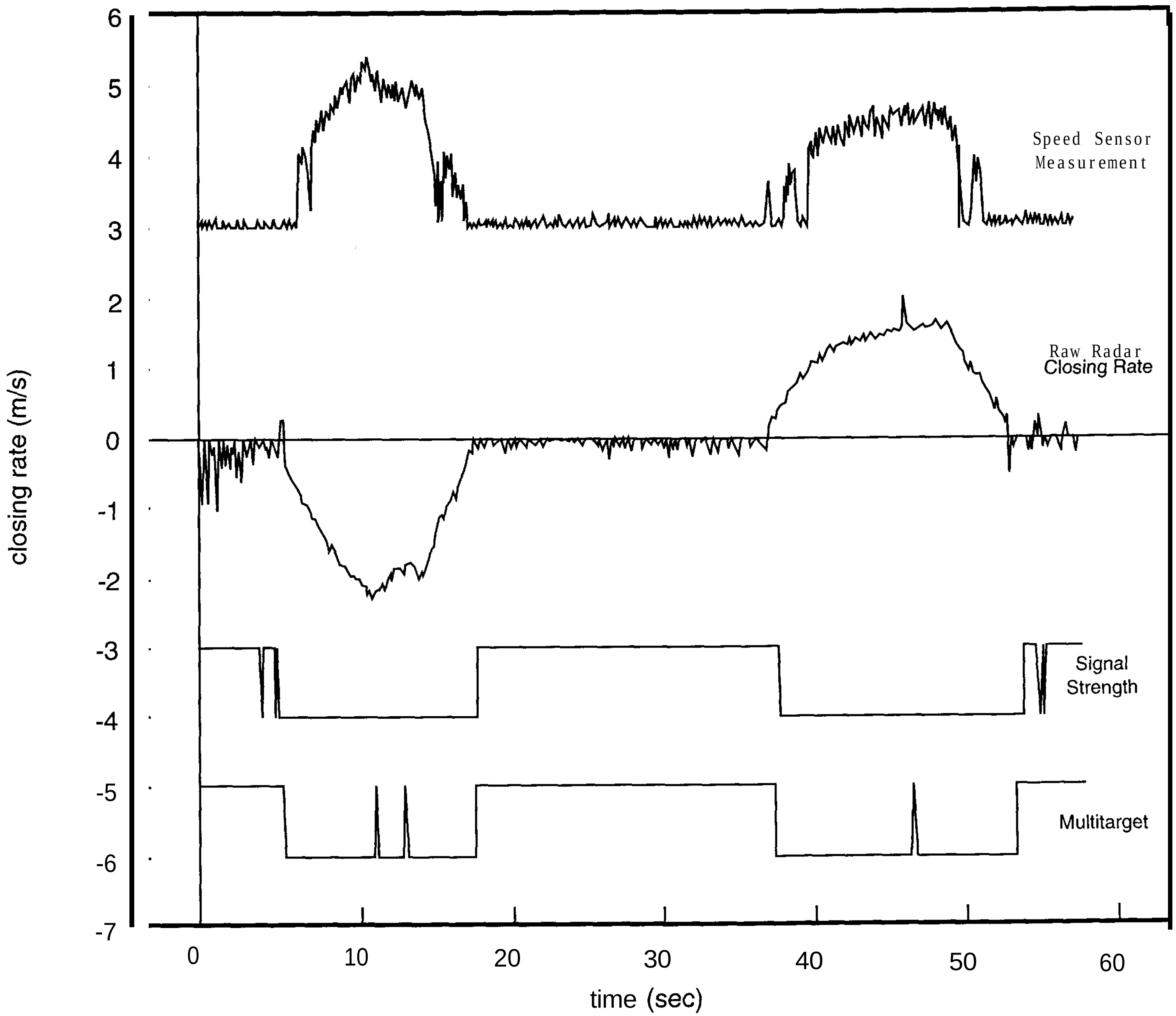


Fig. A.41 Example Radar Test Showing the Closing Rate (Gray LTC, 7/21/92)

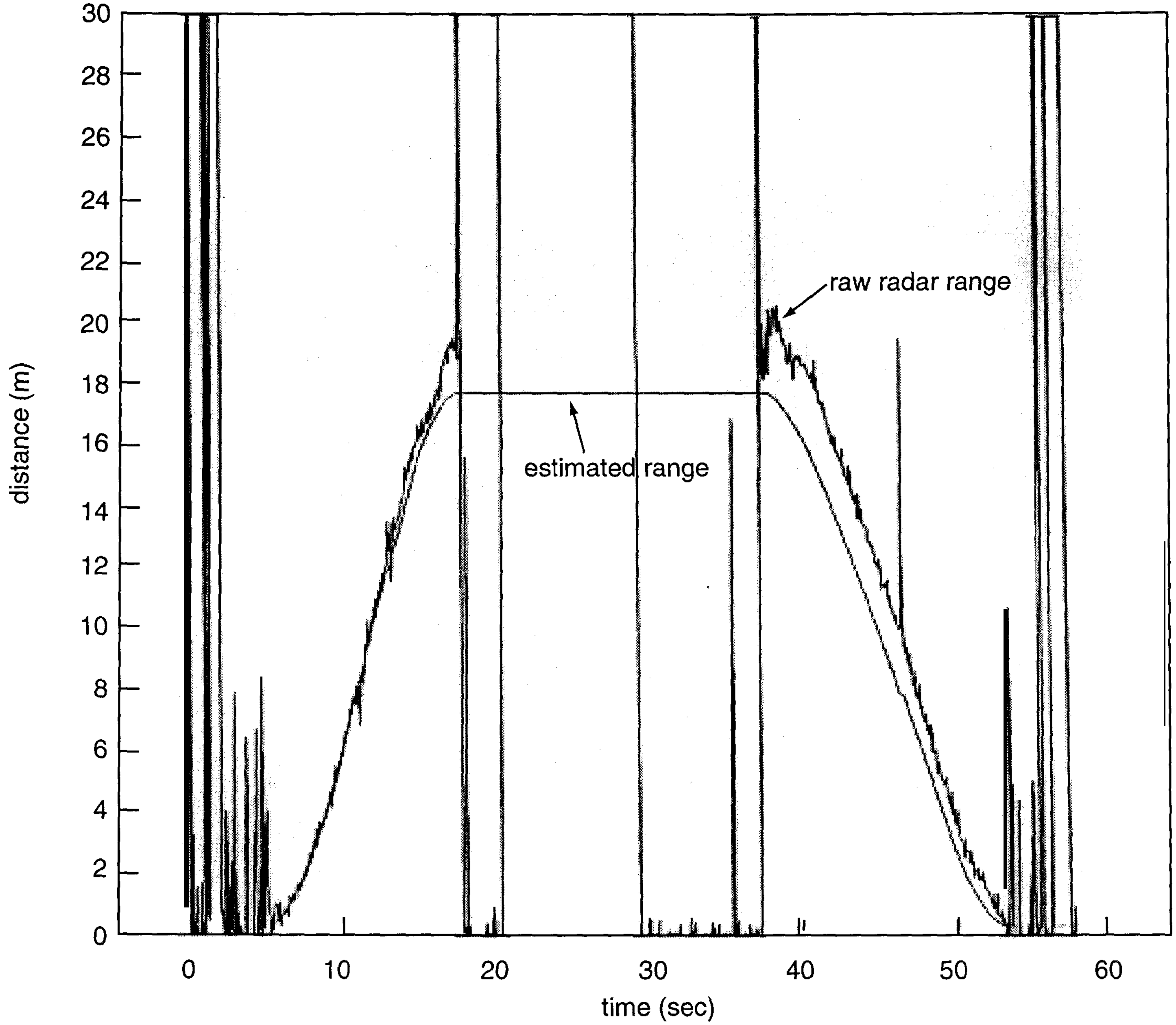
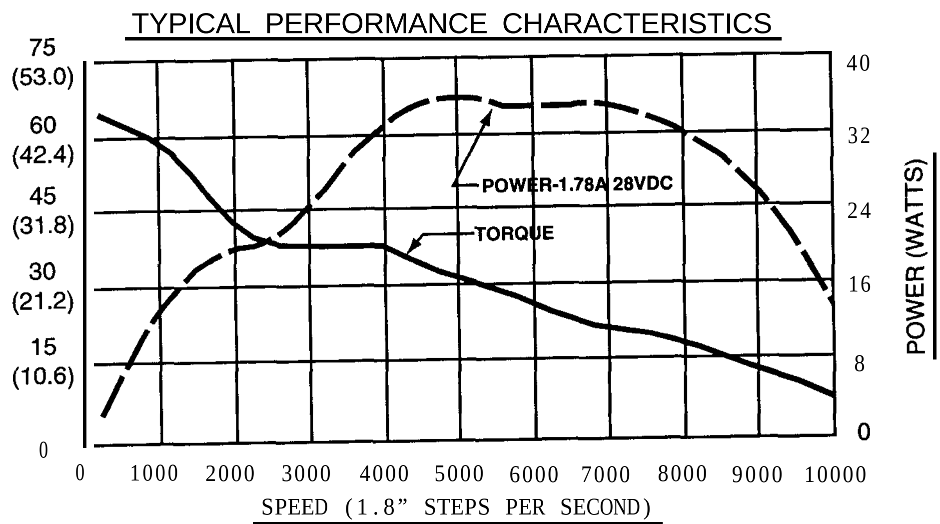


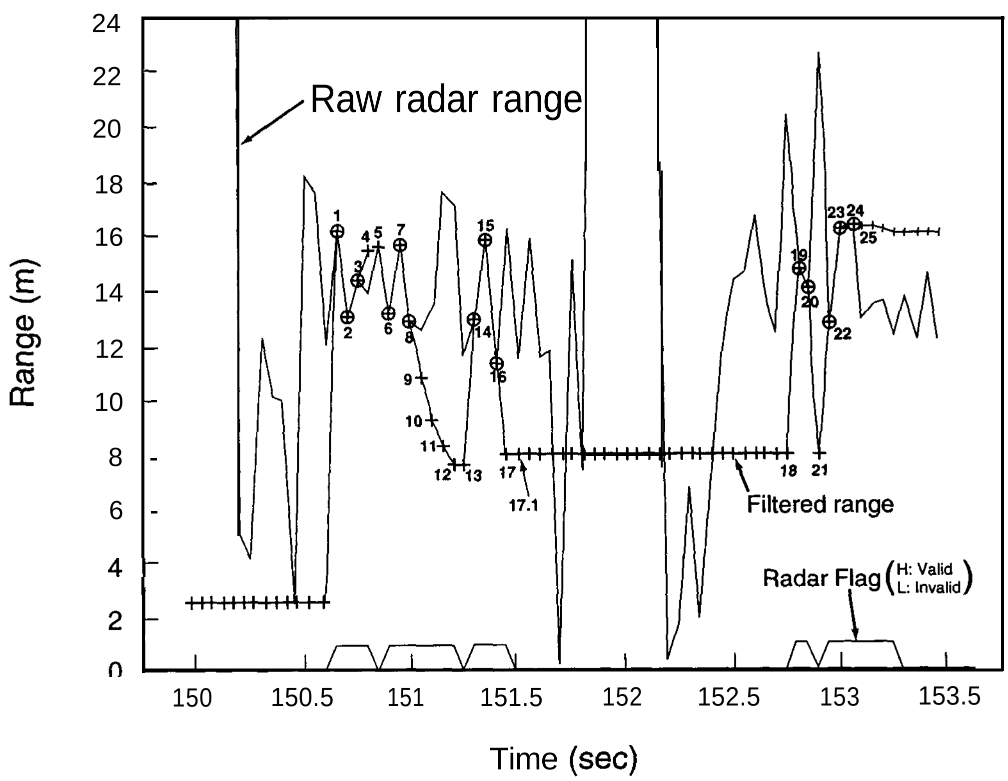
Fig. A.42 Example Radar Test for Comparison Between Raw Range Data and Estimate (Gray LTC, 7/21/92)

Fig A.43 Throttle Actuator Characteristics



PARALLEL CONNECTION
MO63-CE09 AND MO63-LE09 MOTORS

Fig. A44 Example Illustrating How to Filter Raw Radar Range Measurements



Data Points

1,2,3	First three data samples for the new filtering at the start of the valid period
4	Filtered data
5	Data during invalid period which is holding the previous value (#4)
6,7,8	First three data samples for the new filtering at the start of the valid period
9,10,11,12	Filtered data
13	Data during invalid period which is holding the previous value (#12)
14,15,16	First three data samples for the new filtering at the start of the valid period
17	Filtered data
17.1 - 18	Data during invalid period which is holding the previous value (#17)
19,20	Two of the first three data samples for the new filtering
21	Data during invalid period which is holding the previous value (#18)
22,23,24	First three data samples for the new filtering at the start of the valid period
25,...........	Filtered data

Fig. A.45 Example of Filtered and Estimated Radar Range Measurements