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UMTRI-95-7

Control of Headway Between Successive Vehicles

FINAL REPORT

Volume I — Technical Report

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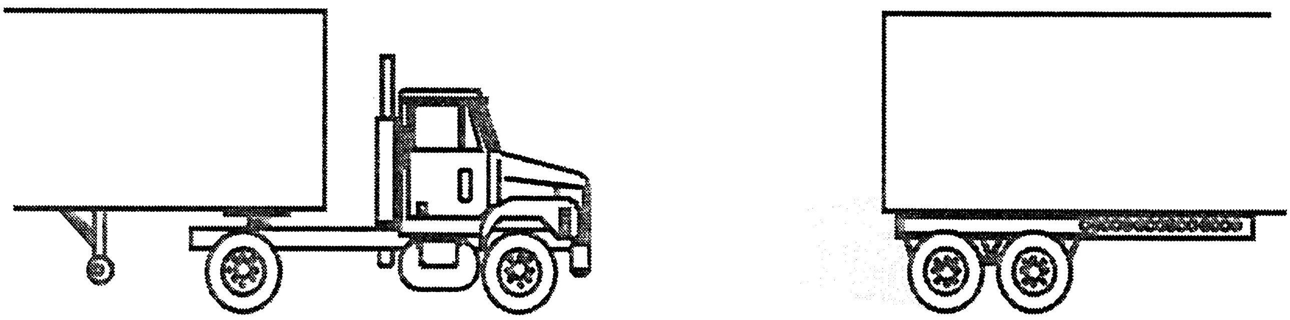

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16. Abstract
This project addresses the general area of robotics and, in particular, TACOM's areas of interest concerning collision avoidance and task automation. The task that is being automated is the control of headway distance or time as is applicable to military convoying operations involving heavy vehicles.
The research contributes to the state-of-the-art and the knowledge and understanding needed to define, develop, and implement an integrated, on-board system that provides control of headway between successive vehicles. The work that was performed included building and experimenting with a prototype testbed. The cooperation of the Eaton Corporation and the Detroit Diesel Corporation has been obtained to augment the simulation, controller design, and the experimental expertise of UMTRI.
A testbed was assembled for use in investigating the impact of a headway-control functionality on the performance of vehicle convoys. The work involved developing and installing a flexible headway control unit, and installing an Eaton/Vorad range and range-rate sensor into an M-915A2 Army vehicle equipped with a Detroit Diesel engine that includes electronic controls. The system was tested on a proving ground and demonstrated to TACOM personnel at their test track.

17. Key Words
Headway control, convoy operation, collision avoidance, task automation, range and range rate sensing, heavy trucks, safety

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NOMENCLATURE

A_m	Maximum acceleration of the following vehicle	(g)
a_p	Acceleration of the preceding vehicle	(g)
a_{warn}	D_{req} (see below) level to issue a warning	(g)
g	Gravity acceleration	(ft/sec^2)
D_m	Maximum coastdown deceleration of the following vehicle	(g)
D_{req}	Required deceleration to avoid a crash	(g)
R	Range from the following to the preceding vehicle	(ft)
R_h	Desirable range at steady-state following	(ft)
R_{min}	Minimum acceptable range between the vehicles	(ft)
Rdot, dR/dt	Range rate (rate of change of R)	(ft/sec)
T_c	Time to crash	(sec)
T_h	Desired headway time	(sec)
T_{hm}	Actual headway time	(sec)
V	Speed of the following vehicle	(ft/sec)
V_p	Speed of the preceding vehicle	(ft/sec)
V_{pf}	Speed of the lead vehicle after a speed-change	(ft/sec)
V_{p0}	Speed of the lead vehicle before a speed-change	(ft/sec)
ΔV_p	Speed-change of the preceding vehicle	(ft/sec)
ø	Time delay for the response of the following truck	(sec)

1.0 INTRODUCTION

This project on the control of headway between successive vehicles addresses the general area of robotics and, in particular, TACOM's areas of interest concerning collision avoidance and task automation. The task that is being automated is the control of headway distance or time as is applicable to military convoying operations involving heavy vehicles. The control of distance and time between vehicles is clearly crucial in avoiding rear end types of collisions.

The research contributes to the state-of-the-art and the knowledge and understanding needed to define, develop, and implement an integrated, on-board system that provides control of headway between successive vehicles. The work that was performed followed from preliminary studies conducted by UMTRI and other researchers. It included extending a simulation of headway-control systems and building and experimenting with a prototype testbed. The cooperation of the Eaton Corporation and the Detroit Diesel Corporation has been obtained to augment the simulation, controller design, and the experimental expertise of UMTRI.

As a result, a testbed was assembled for use in investigating the impact of a headway-control functionality on the performance of vehicle convoys. The work involved installing an instrumentation system specially devised by UMTRI for data gathering, developing, and installing a flexible headway control unit, and installing an Eaton/Vorad range and range-rate sensor into an M-915A2 Army vehicle equipped with a modern diesel engine that includes electronic controls.

The research involved combining the knowledge and experience of the Army in convoying operations with the capabilities of UMTRI, Eaton, and Detroit Diesel, to study the impact of headway-control systems on driver/vehicle system performance, and in reducing the driver's task of controlling headway.

1.1 Type of Project

This project entailed performing a pilot study to examine the integration of software and hardware elements as a provision of headway control between convoyed motor vehicles.

1.2 Objective

The objective of this work is to develop a physical testbed for evaluating the headway-control capabilities of heavy trucks. The ultimate goal is to be able to evaluate the impacts of intelligent cruise control systems on the performance of truck driver/vehicle systems and in reducing the driver's task of controlling headway.

1.3 Hypothesis

The main thrust of this work is to advance the technology of headway-control systems such as may be employed by the Army for efficient convoying of military trucks. The automotive industry is interested in the headway-control function in connection with intelligent cruise control products for both passenger cars and trucks. The analytical and experimental results obtained in this study will be used to evaluate the hypothesis that headway-control systems based upon current technology will aid drivers and improve the performance of vehicles in convoy operations.

The work done was directed at improving the performance of the driver/vehicle system with regard to collision avoidance and automatically providing the capability for following a leading vehicle using a system for controlling headway. The study addresses a partial-control form of robotics, including collision avoidance, task automation, and remote driving. It also has implications with respect to mobility in the sense that the steadiness and level of forward speed, assisted by automatic control of headway, facilitates efficient movement of vehicle convoys.

It was hypothesized that a synergy exists between the Army's interest in automating some vehicular driving functions, under the Advanced Land Combat S & T thrust, and the interest of the industry in developing headway-control systems to assist truck and bus drivers. From the military standpoint, several issues of significance are identified that promote automatic headway control, especially when implemented into a convoy operation:

- Convoys can move faster while maintaining a "tight" formation. Reduced risk of "losing" vehicles;
- Automatic maintenance of headway will minimize the limitations posed on operating convoys in bad weather or under low lighting conditions;
- Headway control can compensate for lack of 3-D perception when driving using night-vision means;
- More attention of the driver can be allocated to other tasks;
- When inadvertent lack of driver's attention occurs, the headway-control system can provide a temporary compensation;
- Critical headway situations can be detected and warnings can be provided;
- The overall safety of convoy operation can be increased.

While the Army seeks primarily to unload driving functions and to enhance the capabilities of vehicle operations, the truck manufacturers seek to enhance the ease of driving while improving safety. Since military and civilian types of systems have many design issues in common, it was hypothesized that dual-use can be made of technology supporting headway control.

2.0 TECHNICAL BACKGROUND[1]

The headway-control problem may be stated as that of developing a system to maintain a desired headway between two successive vehicles by modulating the speed of the following vehicle. As illustrated in Figure 1, the headway range (R) and the range-rate (dR/dt, or Rdot) describe the relative position and relative velocity between the two vehicles. The range-rate is the difference between the velocity of the preceding vehicle (V_p) and the velocity of the trailing vehicle (V), i.e., Rdot = $V_p - V$. This equation indicates that range will remain constant (i.e., Rdot will equal zero) as long as V equals V_p. The objective of the headway-control system is therefore to use measured values of dR/dt and R to maintain a specifically desired value of headway range (R_h) corresponding to the condition $V = V_p$, where V is the velocity of the trailing (or following) vehicle and V_p is the velocity of the preceding (or lead) vehicle.

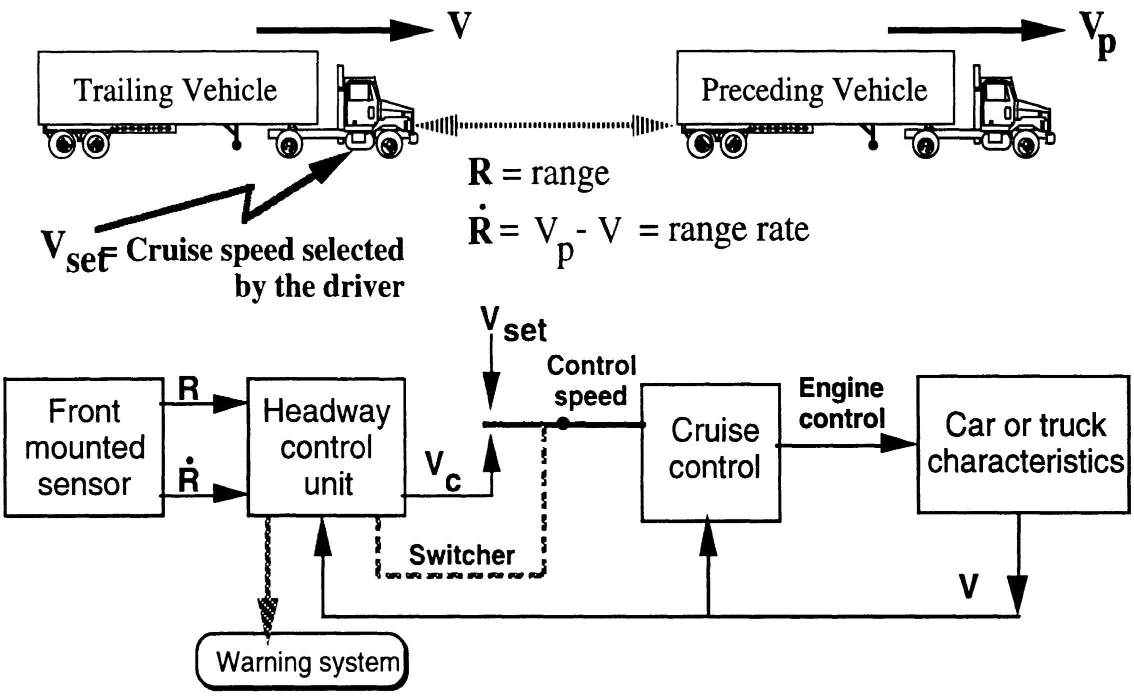

Figure 1. Headway control

In short, the problem is to devise a suitable control algorithm for adjusting speed to establish and maintain $R \approx R_h$, where R_h is the desired range between the lead and the following vehicles.

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1 For further details see: (1) Fancher, P.S. and Bareket, Z., "Evaluating Headway Control Using Range Versus Range-Rate Relationships." *Vehicle System Dynamics, International Journal of Vehicle Mechanics and Mobility,* Vol. 23, No. 8, November 1994, pp. 575-596, and (2) Bareket, Z. and Fancher, P.S. "Controlling Headway Between Successive Vehicles." *Association for Unmanned Vehicle Systems, Proceedings Manual,* Annual Meeting, May 1994, Detroit, MI

2.1 Application of the Rdot-R Diagram to the Development of a Headway-control Algorithm.

The basic nature of the headway-control process may be displayed in a two dimensional space spanned by range (R) and range-rate (Rdot) axes. See Figure 2. The Rdot-R diagram is particularly useful in understanding physical interpretations of sets of range and range-rate signals—either in the form of instantaneous (Rdot, R) points or as an (Rdot, R) trajectory (i.e., a connected set of points) that would take place over a period of time. It should be noted that this discussion regarding the operation of a headway-control system is generic in nature, and does not apply only to the operation of a convoy. Later, in section 4.0, the peculiarities that pertain to headway control in the context of a military convoy are discussed.

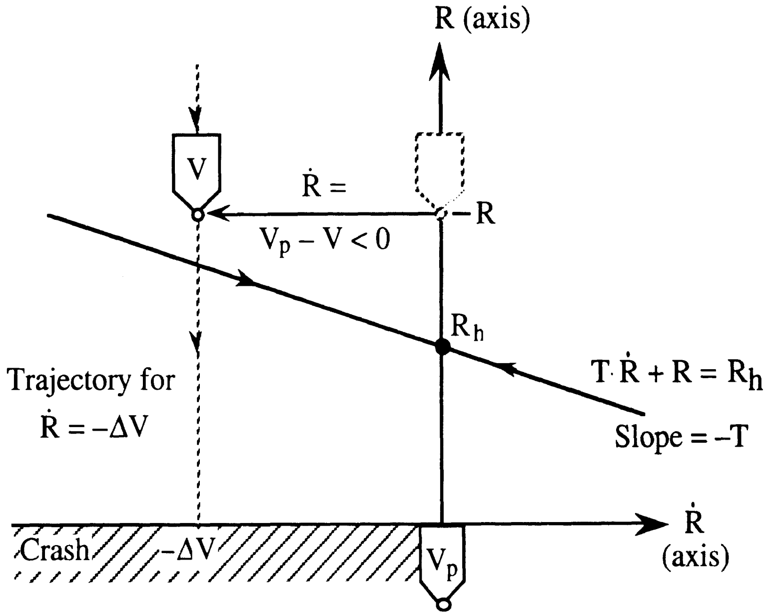


Figure 2. Headway control in the (R, Rdot) space

A fundamental understanding of headway-control systems may be associated with a graphical interpretation of points, lines, and regions in the Rdot-R diagram. For example, the point at (0, R_h) represents the goal of headway-control systems and of headway-control algorithms in general. In addition, trajectories in this diagram have unique properties, which are readily apparent if one properly interprets the implications of Rdot > 0 and Rdot < 0 on the change in R. An example of a straight line trajectory is shown in Figure 2, and parabolic trajectories are shown in Figure 3. The arrow heads associated with these trajectories (lines) all illustrate the implications of Rdot < 0 on the left side of the diagram and Rdot > 0 on the right side of the diagram. There is "upward motion" in the right quadrant and "downward motion" in the left quadrant. To cross the R axis (i.e., where Rdot = 0) in finite time, a trajectory must have zero slope for Rdot = 0. Points on the R axis (Rdot = 0) are convergence points if the slope is negative at Rdot = 0. This means that trajectories will converge towards a point on the R axis if the slope of a trajectory through that point is negative. Conversely, trajectories will diverge from a point on the R axis if their slope is positive at that point.

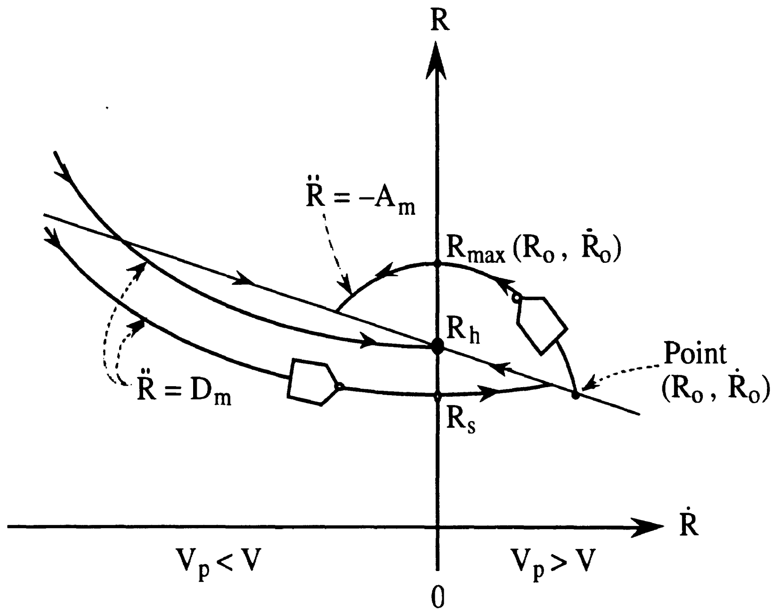


Figure 3. Parabolic trajectories of constant acceleration (see footnote on p.3)

Another facet of the Rdot-R diagram is its relationship to differential equations. In fact, any (Rdot, R) trajectory represents a differential equation, since the equation describing this trajectory is a relationship between R and its derivative, Rdot. For purposes of designing a first order headway controller, consider the following equation:

$$T \cdot Rdot + R = R_h \qquad (1)$$

where (–T) is the slope of the straight line in the Rdot-R diagram (Figure 2.). In terms of differential equations, T is also the time constant appearing in the solution to the above equation. The form shown in that equation and Figure 2 is sufficient to establish the characteristics of a first order headway controller. From a practical standpoint, another important type of trajectory pertains to constant acceleration and deceleration situations. The parabolic trajectories in Figure 3 are examples of these types. These trajectories may be derived from the following equations:

$$dRdot/dt = -D_m \quad \text{for deceleration, and} \qquad (2)$$

$$dRdot/dt = A_m \quad \text{for acceleration.} \qquad (3)$$

These types of trajectories are important because they represent the influences of bounds on the acceleration (A_m) and deceleration (D_m) capabilities to be used by the headway-control system.

Given the ideas presented in Figures 2 and 3, Figure 4 illustrates the basic features of a practical first order headway controller.

To accommodate various speeds of operation of the preceding vehicle, one approach is to let the desired headway range be $R_h = V_p \cdot T_h$, where T_h is called the headway time (this equation can also be used to represent rules such as "one car length for each 10 mph," for example).

If the vehicle has a very responsive cruise control system such that $V \approx V_c$ where V_c is the velocity command to the cruise control, then, except during a short transient period, a speed command based on the equation $V_c = V_p + (R - R_h)/T$ will suffice to provide a system that acts like a first order headway controller.

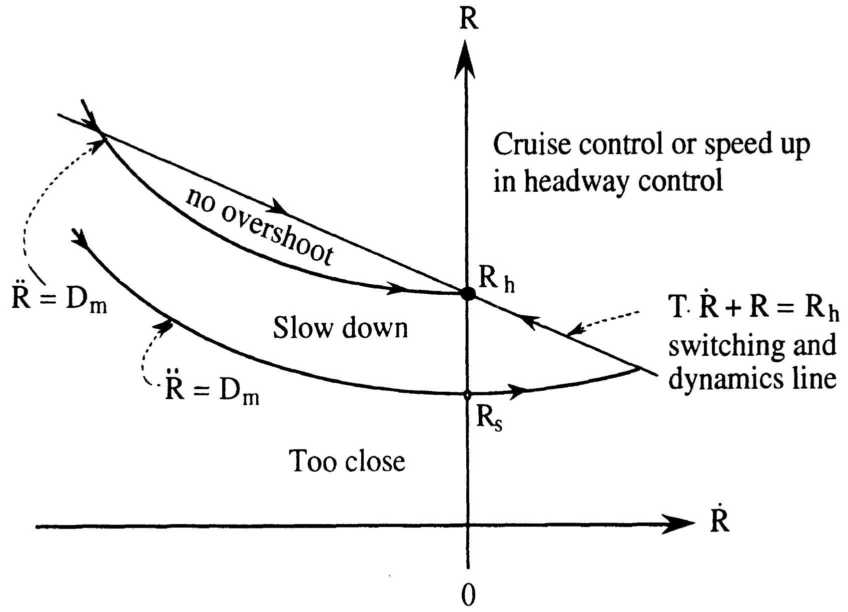
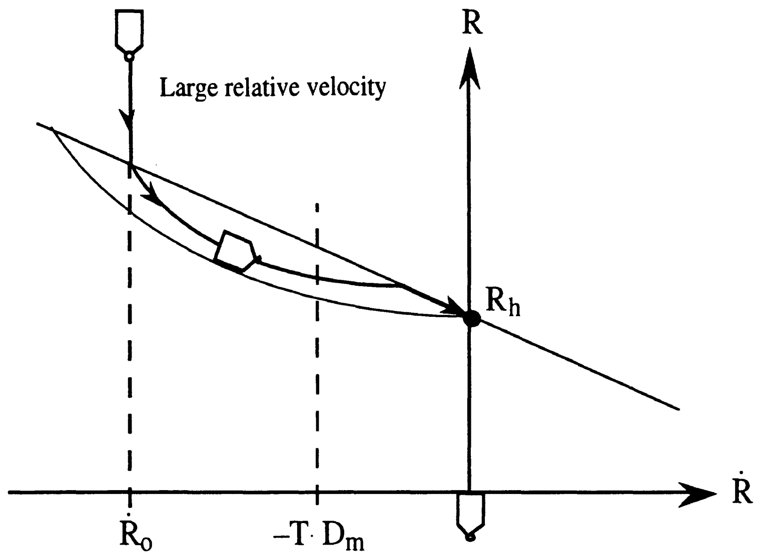


Figure 4. First order headway controller

2.2 Application of the R-Rdot Diagram to Pertinent Driving Situations.

The standard use of headway control for vehicles on the road starts with a following vehicle approaching a preceding vehicle from behind. Under normal circumstances, the sensor on the following vehicle will detect the preceding vehicle at a range that is considerably longer than the range where headway control starts. Once the switching line (described by the equation T·Rdot + R = R_h) is crossed, a headway-control algorithm (based upon the equation for V_c) will then cause this vehicle to adjust its speed accordingly. The extent to which the command speed (V_c) equation is satisfied, depends upon the maximum deceleration and acceleration available to the headway-control system (depending on the inherent dynamics of the vehicle). Figure 5 shows typical trajectories for a headway-controlled vehicle that is approaching a slower moving preceding vehicle. The important aspects of the headway controller with regard to closing-in from a long range are summarized by the design choices for T, D_m, and T_h.



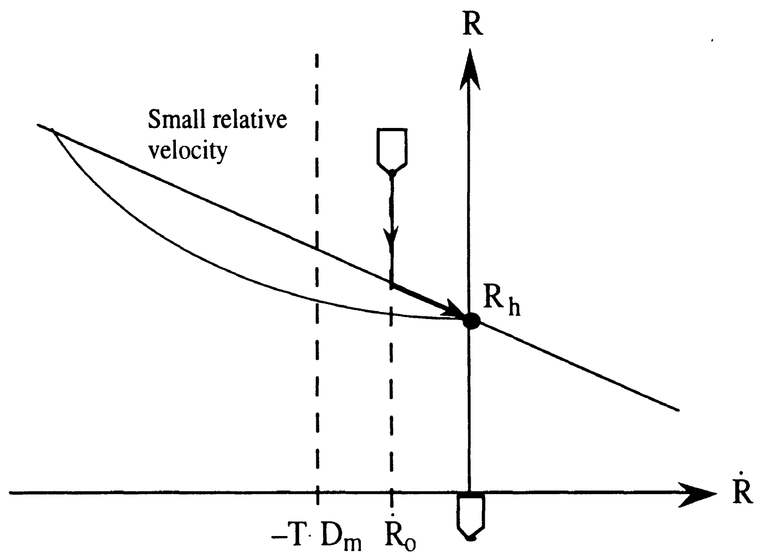


Figure 5. Closing in from a long range

In certain circumstances the sensor may not detect a preceding vehicle until the range is below the "switching line" for the start of headway control. This can happen for narrow-beam sensors if the vehicle is on a curve. Figure 6 shows the form of trajectories that are typical for this driving situation. The quantity R_{min} shown in Figure 6 defines a safety margin in terms of a minimum range that determines if the following vehicle is closer than desired to the preceding vehicle. The values of R_{min} and D_m define a parabola separating the Rdot-R diagram into an acceptable region of operation and a "too close" region. The system may provide a driver warning when the instantaneous value of (Rdot, R) is in the too close region. The important aspects of closing-in from short range are summarized by the choices of R_{min} and D_m as well as A_m and T and T_h.

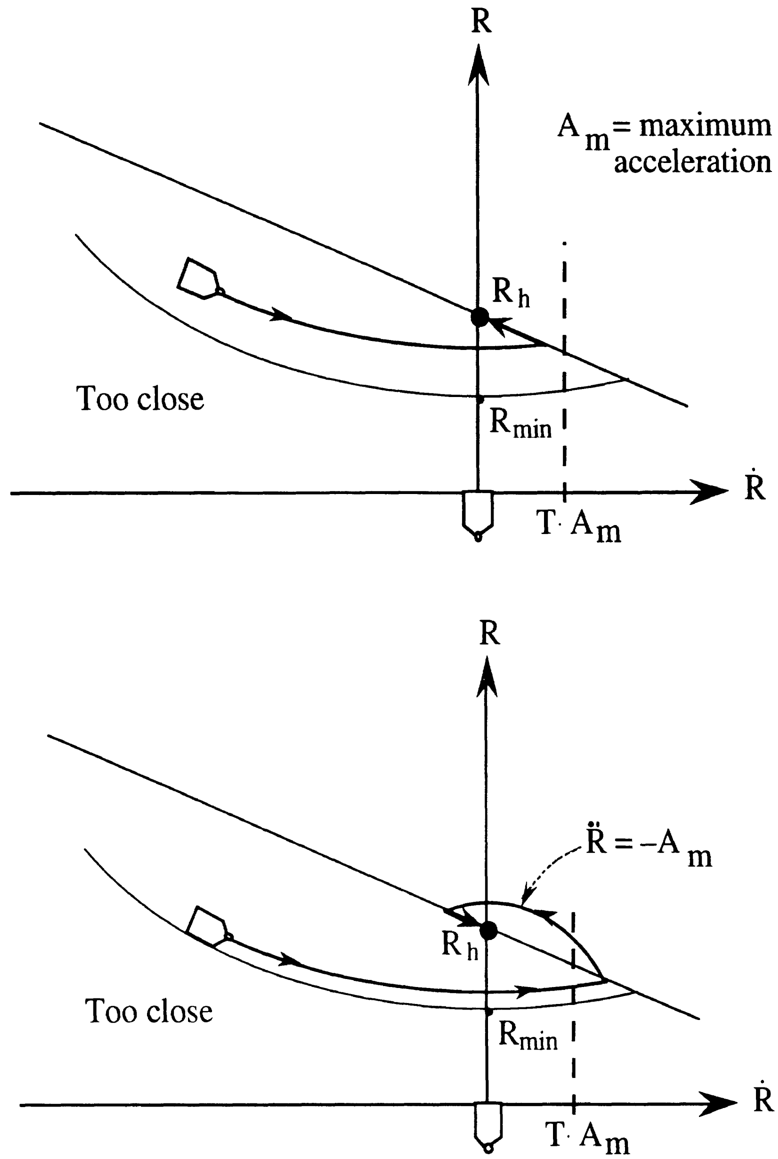


Figure 6. Closing in from a short range

The driving situations presented so far have implicitly assumed that the lead vehicle is travelling at more or less constant velocity. However, the lead vehicle may speed up or slow down as required by the highway situation or as dictated by the military objectives of the convoy. The autonomous control of headway needs to be able to respond to changes in V_p, and hence R_h. Figure 7 has been constructed to illustrate what would happen if the preceding vehicle were to suddenly jump to a new speed. Clearly this hypothetical situation is much more drastic than a real driving situation in which a finite deceleration is used to change the speed of the preceding vehicle. Nevertheless a step function in V_p is a convenient way to illustrate the manner in which a headway-control system will follow the motion of a preceding vehicle. In this case the headway controller benefits from the fact that R_h changes when V_p changes. As can be seen by inspecting Figure 7, it is the magnitude of the jump in V_p that determines whether the following vehicle will come too close to the preceding vehicle. The design choices of T_h, R_{min}, and D_m determine the amount of sudden change in V_p that the headway-control system can handle without coming too close to the preceding vehicle.

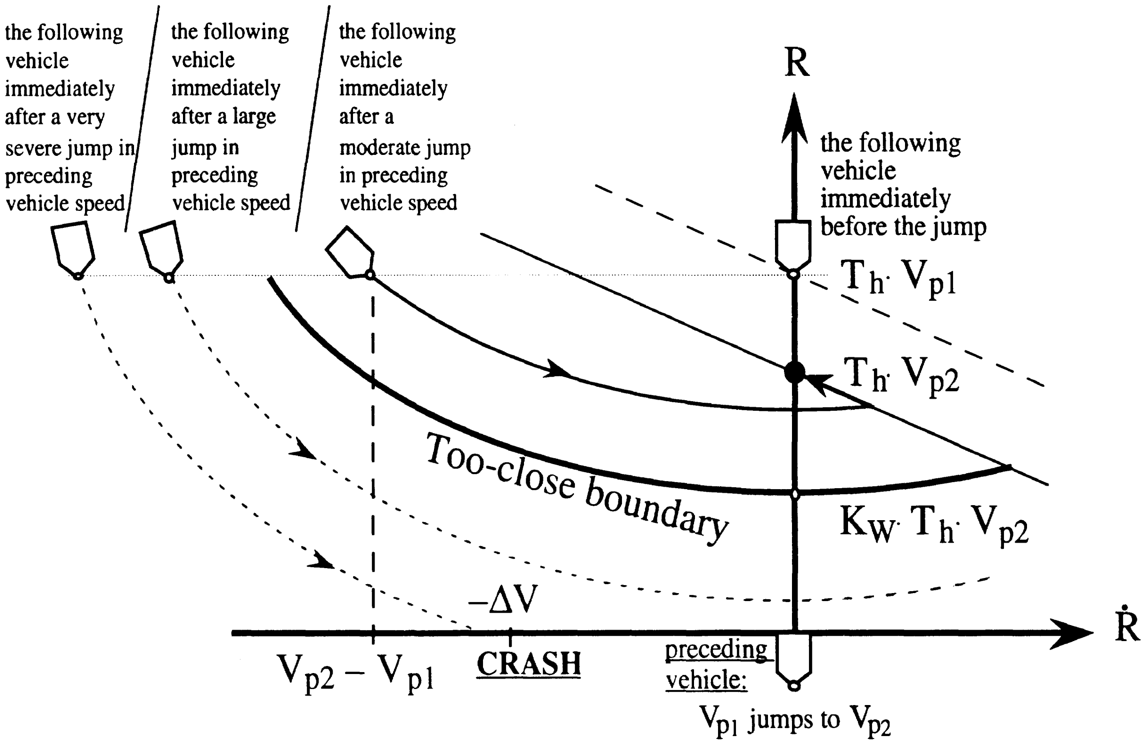


Figure 7. A step change in V_p

From a safety standpoint, a general idea is to have a maximum speed (V_{set}) for the headway-control system so that automatic control does not operate above a maximum speed that is pre-selected by the driver. In this way the automatic system will not cause the following vehicle to accelerate behind a preceding vehicle up to a very high speed. In addition, there probably needs to be a manually operated switch to disconnect the system and return to manual driving whenever desired.

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3.0 PROJECT OVERVIEW

In order to achieve the objectives and goals of this study, the work was broken down to six tasks with six corresponding milestones that were accomplished. In addition, a presentation event was also designated as a milestone. This section describes the tasks and the accomplished milestones.

3.1 Tasks

The work was composed of tasks that were directed at the following activities: (i) Confer with Army personnel and exercise existing simulation model to determine and define performance measurements needed to evaluate headway-control applications in military convoys as well as in typical highway transport; (ii) Design and build the instrumentation and the data-acquisition system, as needed, to gather the performance data required for evaluating the headway-control system; (iii) Outfit a truck as a testbed by installing range and range rate sensor and a headway-control module, as well as the instrumentation and data-acquisition system designed and built in the previous task; (iv) Conduct initial experiments to evaluate the impact of an automatic headway-control system on convoy performance; (v) Analyze the experimental results; and (vi) Prepare a demonstration and a final report covering the work performed.

3.1.1 Task 1 — Formulate a Convoy Performance Evaluation Plan

The purpose of this task was to formulate a plan for evaluating the impacts that an automatic headway-control system might have on convoy performance. The planning activity involved participation of the Army and Eaton along with UMTRI in selecting the vehicle, considering sensor systems, and developing plans for the testbed.

The M915-A2 was determined as the vehicle that would be used as the testbed. The impetus for selecting this truck was based on both tactical and technical considerations. From the tactical standpoint, a significant portion of the missions of the M915-A2 is convoy-related operations. It was reasonable, therefore, to use it to evaluate the impacts of intelligent cruise control systems on convoy operations. In addition, the powertrain of this truck is technically advanced as it is equipped with an electronically-controlled engine. Therefore, also from the technical standpoint, this truck represented a sensible selection as it enabled an easy communication of electronic data to and from the engine.

The issue of the potential impact of an automatic headway control on the convoyed movement of a vehicle string was examined with the aid of UMTRI's computer simulation tools. Various procedures for system evaluation were considered, given a range of baseline convoy densities, average speeds, and vehicle response characteristics. Variables that are present even in the simple case of a single vehicle following another were examined insofar as they offered meaningful measures that can be obtained under controlled proving grounds conditions. These include the absolute headway responses that the system maintains, as a function of various data items collected during testing.

The following steps were taken in the course of performing this task:

- Convoy operation as it pertains to this project was studied together with TACOM, so as to establish a "baseline convoy" (see section 4.0— Operational Concepts). The possibility of using different types of sensors and sensing technologies for various types of vehicle operation (in particular blackout operation) was also considered.
- The nature of the desired results (e.g. establishing headway in terms of speed and distance, limits on operational conditions) was defined and outlined. Measurements and performance measures required to evaluate system performance were also determined (see discussion in section 6.0 — Analysis of the results, and the test plan in Appendix D).
- The array of data that needs to be collected in order to enable a proper analysis of the results was determined and defined (see the data requirement plan in Appendix C).
- Appropriate test procedures were developed to evaluate the various performance measures, using ranges for speeds and headways that were determined given the limitations of the test track environment. A detailed test plan was formulated (see Appendix D).

3.1.2 Task 2 — Design Testbed Instrumentation

Once the planned experiments for the test vehicle were outlined, the instrumentation needed to acquire and record the data was defined. A complete instrument package was designed so as to meet the data-acquisition needs; the components were identified and ordered, and the installation effort was planned. See section 5.0 for a complete description of the instrumented testbed.

The following steps were taken in the course of performing this task:

- The instrumentation required to acquire the data per Task 1 was determined and listed.
- The necessary instrumentation was procured.
- The installation of the instruments, borne in the test truck, was planned.

3.1.3 Task 3 — Outfit the Truck

During this task, the full complement of equipment planned for the test vehicle was obtained and installed. The proper functioning of the system was checked — first in the laboratory and then during actual driving. Specialized calibration fixtures were prepared for establishing the response characteristics of the individual sensors and transducers. Parameters of the headway-control package were determined such that companion simulation of this package could be supported.

Performing this task entailed installing the required equipment per Task 2.

3.1.4 Task 4 — Conduct Experiments

A set of experiments was conducted in this task to evaluate convoy performance in accordance with the test plan (Appendix D). Using the test vehicle, the experiments that were performed covered both proving grounds and on-highway operations. Representative data under various salient operating conditions were collected per the procedures developed in Task 3 and were used to better calibrate simulation work, which addresses the multivehicle convoy.

Performing this task entailed conducting the experiments and collecting data. The tests and the data collection were performed per Task 1.

3.1.5 Task 5 — Analyze Results

During this task, the data collected in the course of the experiments performed in task 4 were analyzed. Performance measures were determined, and the potential impacts of the system on convoy operation were assessed. The overall utility of the evaluation method, as a general tool for considering the wide variety of systems that are expected, was also judged.

The following steps were taken in the course of performing this task:

- The test results were analyzed, and appropriate conclusions were drawn.
- Performance measures were evaluated.
- The impact of a headway-control system on convoys and convoy operations was assessed.
- The overall utility of the evaluation method as a general tool for considering a wide variety of potential headway-control systems was evaluated.

3.1.6 Task 6 — Communicate Results

During this task, which was the final and concluding task of the project, the results and findings of the work that was performed were prepared and presented to TACOM. A presentation of the system development and a live demonstration of the prototypic vehicle were carried out in TACOM's test track. The demonstration was in accordance with the test plan of task 1, and showed the effectiveness of headway control at a range of speeds. This final report documents the work done in this project.

The following steps were taken in the course of performing this task:

- A demonstration of the testbed system was conducted, so as to provide TACOM's personnel with a physical impression of the research work. (The demonstration was held on October 21, 1994.)
- The results, findings, and conclusions of the tests and simulations are documented and are presented in this final report.

3.2 Milestones and Schedule

The objectives and goals of this study were achieved by progressive work that followed a set of prescribed milestones. Seven milestones were accomplished:

- Requirements prepared for instrumentation and data acquisition package.
- Plan ready for evaluative tests of headway-control systems for convoys.
- Instrumentation and data-acquisition package ready for installing in the vehicle.
- Truck outfitted for testing.
- Initial experiments completed.
- Demonstration exercise completed.
- Final report delivered.

The following schedule chart (see Figure 8) illustrates the sequence and the timing of the various activities (tasks and sub-tasks) that were performed during this project in order to achieve the milestones listed above.

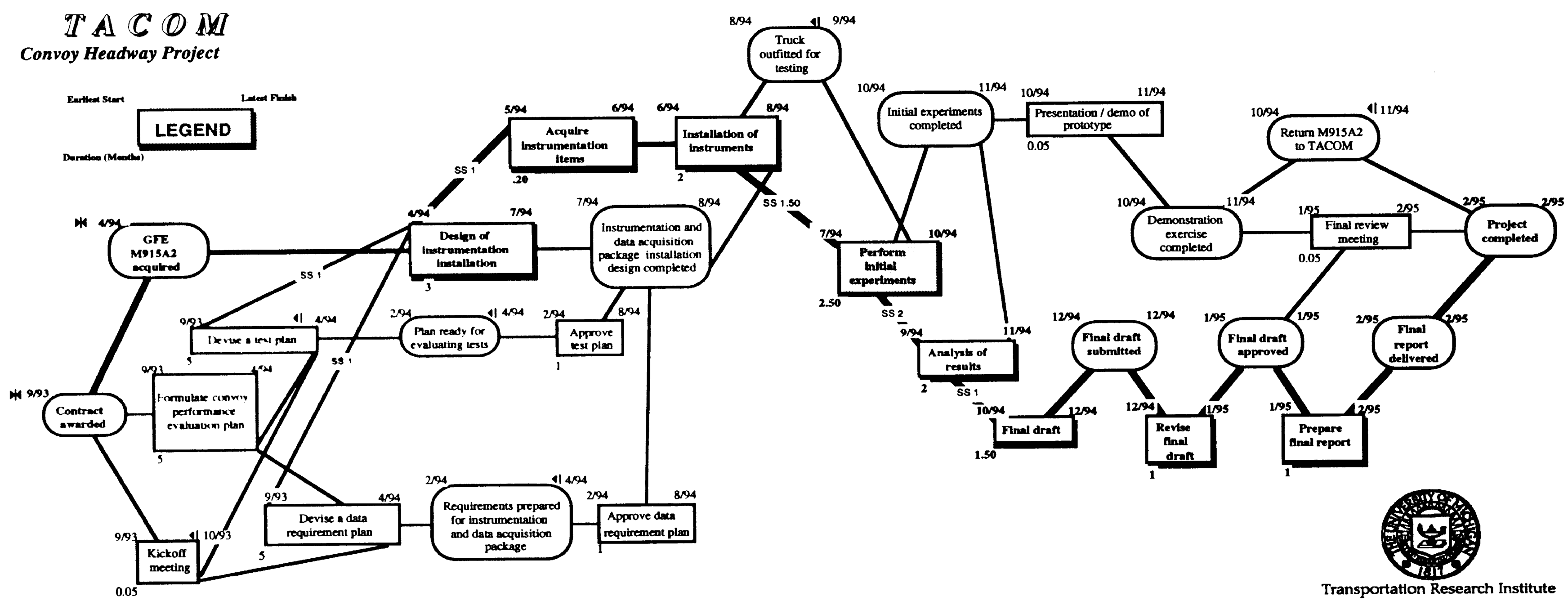

Figure 8. Project schedule chart

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4.0 OPERATIONAL CONCEPTS

This section discusses various concepts and perceptions in regard to convoy operations as they pertain to headway control. In order to design a prototypic headway-control system for military convoys and to devise a plan to evaluate the impacts such a system might have on the way convoys currently operate, a baseline convoy model was established. An automatic headway controller was then designed, and it was exercised together with a simulated model of the convoy to study and confirm its operation prior to employing it in the prototypic truck (M915-A2). This section describes basic principles and considerations that served as ground rules in the design of the controller. In addition, various control inputs that affect its performance are discussed, and possible operational scenarios are outlined.

4.1 Convoy

A convoy is an assembly of several vehicles that are driving along at a coordinated speed. In the context of this work, when a vehicle is said "to convoy" another vehicle, it implies that its speed is being adjusted and maintained to match that of the preceding vehicle. It is assumed that an automatic headway-control system is installed and operating in the following vehicle. However, driver intervention is also considered so that speed adjustments of the follower can be done either in a fully automatic manner by the headway system, or manually by the driver.

Fundamental concepts that describe the operational characteristics of a headway-controlled convoy employed in this work are listed below. It should be noted that these concepts and assumptions are flexible to the extent of: (1) the sensing technology used, (2) the methodology and technical approach employed in controlling the truck's drivetrain, (3) incorporating additional technologies (e.g., communication and navigation), and (4) the authority limits assigned to the system. As it was mentioned before — being a prototype system, some assumptions had to be made.

- A line-of-sight exists between the convoyed vehicles (at least for most of the time).
- Each vehicle has a driver.
- Once engaged manually — the headway-control system controls the headway automatically.
- Some safe, maximum speed value is manually set by the driver.
- The lead vehicle is manually controlled.
- Automatically-controlled gaps between vehicles vary from a few meters up to sensing limits.
- Due to sensing limitations of the prototype, a full tactical flexibility cannot be provided.
- A conceptual design for collision avoidance is included in the system.
- Operation under various environmental conditions is limited by sensing capabilities.

An essential first step that is required before a headway-controlled convoy can operate is its initiation. Two conditions must be satisfied in order to initiate a convoy: (1) the system is turned on, and (2) a leading vehicle is present. Once it was initiated, an automatic convoy operation can commence by having the follower "convoy" the leader. Such operation entails automatic corrections by the system for disturbances (e.g. headway gap variations.) If the system cannot provide an automatic correction for the situation (e.g. headway gap increased beyond sensing range), a manual correction by the driver is required to bring the convoy back to an automatic operation (depressing the accelerator pedal, in this case). Failing to do so will "break" the convoy so that the leader and follower become two independent vehicles.

Figure 9 provides an illustrative depiction of the convoy operative loop as described above. In that figure, the block entitled "initiate convoy" involves turning on the main switch of the system ("convoy switch"), and when a target leading vehicle is acquired by the sensor, the system commences to the block entitled "convoy operation." Throughout the convoy operation mode the convoy switch is on, a target leader is being tracked and no control inputs are provided by the driver through the brake or the accelerator pedals. The disturbances and the ensuing corrective actions are parts of the control loop, and are discussed in the next section.

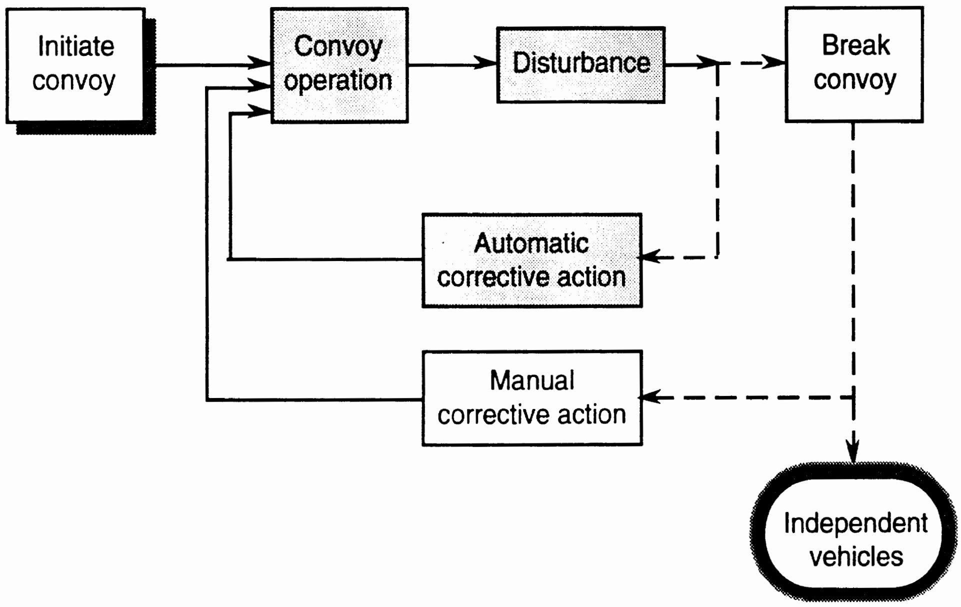

Figure 9. Convoy operative loop

4.2 Controller

Once the convoy, or, for that matter, any pair of leader/follower vehicles, is at a "convoy mode of operation," the controller continuously monitors and automatically adjusts the headway. Such adjustments are called for due to the inevitable introduction of disturbances. The set of rules that defines the system's response to the various disturbances was incorporated into the design of the controller. It is emphasized that manual operator's inputs always override those of the headway controller: the operator remains in complete command and control at all times.

A disturbance can be any form of interruption to a normal system operation. Types of disturbances that were addressed in this work, and the corresponding corrective actions by the system, are described below. The issue of corrective actions will be expanded and discussed at greater length in the next sections.

- Change of leader's speed
  Corrective action: System automatically adjusts vehicle's speed to correct the headway;
- Change of environmental parasitic drag (e.g., road grade)
  Corrective action: System automatically adjusts the engine's power demand;
- Target loss
  Corrective action: System maintains vehicle's commanded speed. Target will either show up again, or manual correction will be required;
- Accelerator pedal depressed
  Corrective action: None. The vehicle accelerates per the driver's input. Possible corrective action will be evaluated when the pedal is released;
- Brake pedal depressed
  Corrective action: None. The vehicle decelerates per the driver's input. Possible corrective action will be evaluated when the pedal is released;
- Convoy switch turned off
  Corrective action: None. Turning on the switch will reinitiate the system.

4.2.1 Control Inputs

There are four logical control inputs to the system that affect its operation. These control inputs (which will be further described in section 5.0) are signals from (1) the accelerator pedal, (2) the brake pedal, (3) the sensing device, or (4) the convoy switch. The response of the system depends on the value of each of those control inputs, both individually and in combination with the others. Figure 10 depicts the logic that determines proper action by the system as a response to various possible combinations of control inputs.

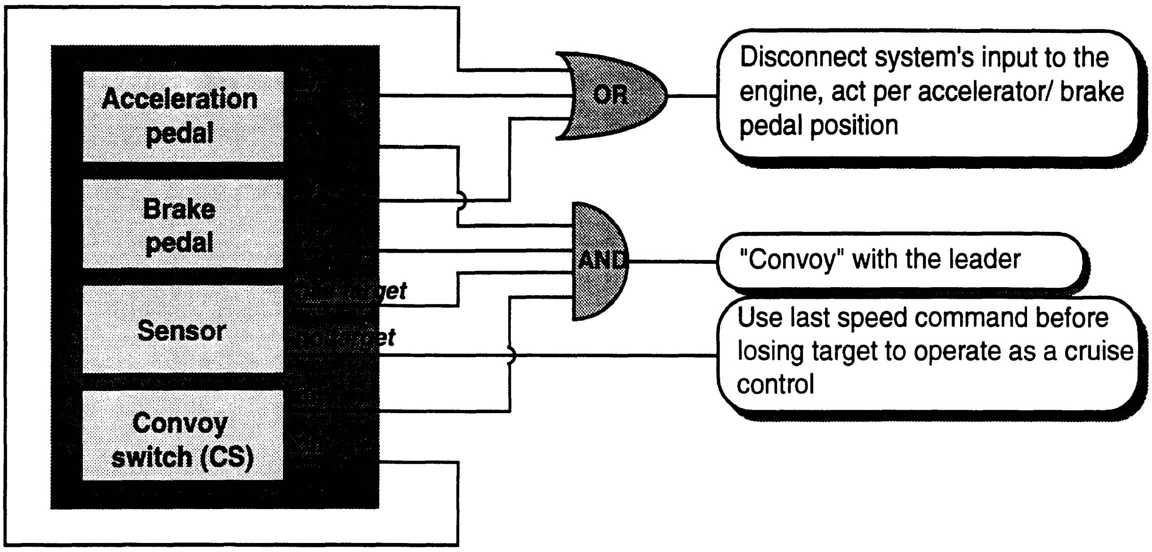

Figure 10. System's logic and control inputs

Two fundamental rules regarding the operation of the system can be observed from Figure 10. First, regardless of the information from the sensor or the position of the convoy switch — input from the driver through the accelerator and/or the brake pedals takes precedence. The truck will accelerate or slow down according to such control inputs regardless of obstacles or headway gap. Second, the convoy switch must be "on" for any form of automatic speed or headway control to take place.

4.2.2 Operational Scenarios

Following is a description of possible scenarios that might take place during the operation of a headway-controlled convoy. Each of the scenarios can involve several possible events, or various combinations of control inputs. The system's response for each case is discussed.

4.2.2.1 Scenario 1 — Startup

Starting up the system (either when launching a convoy or en route). The system is initialized from a complete shut-down status. The command to start up the system is given by switching the convoy switch (CS) to "on." Two possible scenarios can be associated with the event of switching on the CS:

(1) The vehicle has been accelerating or decelerating (acceleration or brake pedal command inputs are being used). The lead vehicle, or any other target, may or may not be present ahead.

(2) The vehicle has been coasting down (e.g. joining the rear of the convoy). No acceleration or brake pedal command inputs are being used.

Based on the logic depicted in Figure 10, the following flow chart (Figure 11) illustrates the system's response for the various possible situations during start up.

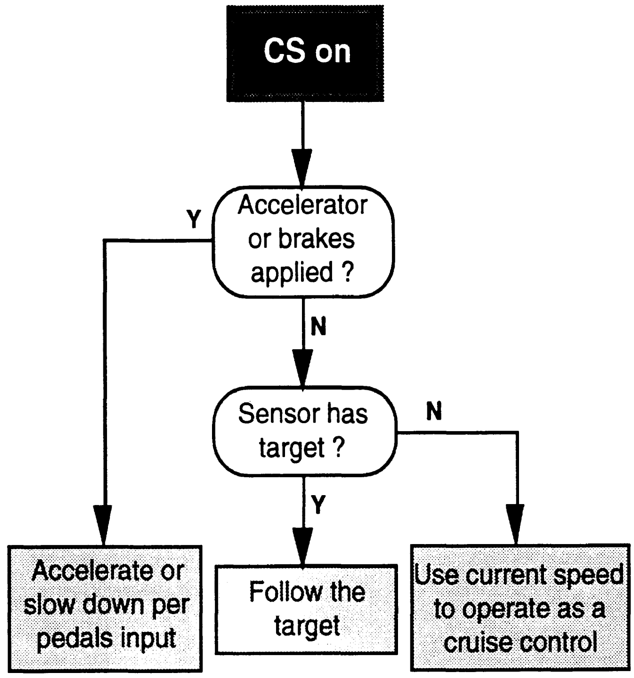

Figure 11. Scenarios associated with starting up the system

4.2.2.2 Scenario 2 — Acceleration override

The driver was manually accelerating the truck, and the accelerator pedal has just been released (CS is on). Three possible scenarios can be associated with the event of releasing the acceleration pedal:

(1) The driver has been accelerating to join a convoy. That can occur either when the convoy is just being initiated, or after contact with the leader was broken and the following truck attempts to catch-up with the leader.

(2) For some reason, the driver has been accelerating to decrease headway even though the truck was "convoying."

(3) The truck has been moving independently, it is not part of a convoy.

Based on the logic depicted in Figure 10, the following flow chart (Figure 12) illustrates the system's response for the various possible situations when the accelerator pedal is released.

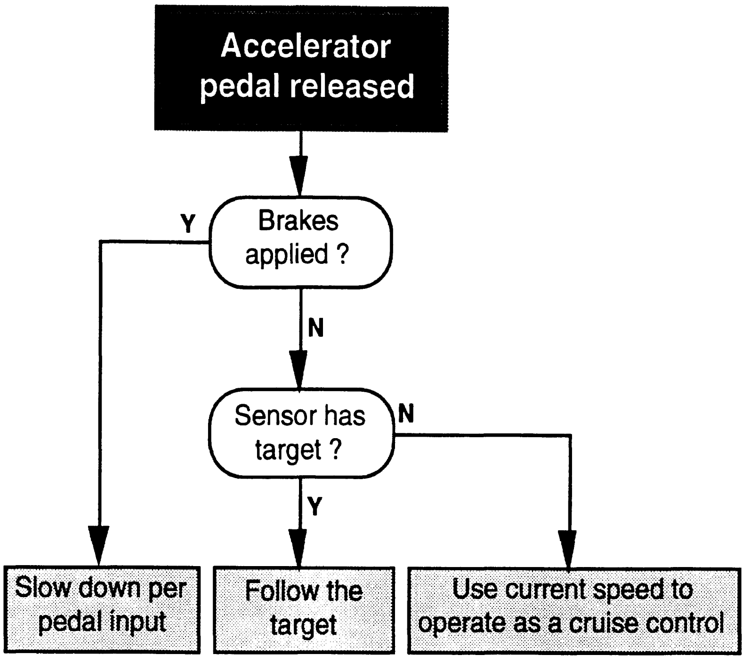

Figure 12. Scenarios associated with releasing accelerator pedal

4.2.2.3 Scenario 3 — Brake override

The truck was slowing down using its brakes, and the pedal has just been released (CS is on). Three possible scenarios can be associated with the event of releasing the brake pedal:

(1) The driver has been slowing down to join a convoy. That can occur either when the convoy is just being initiated, or after contact with the leader was broken.

(2) The truck has been "convoying," but for some reason, the headway gap became too close (e.g. downhill travel). The driver decelerated to increase headway.

(3) The truck has been moving independently without being part of a convoy, for some reason the driver has been slowing down.

Based on the logic depicted in Figure 10, the following flow chart (Figure 13) illustrates the system's response for the various possible situations when the brake pedal is released.

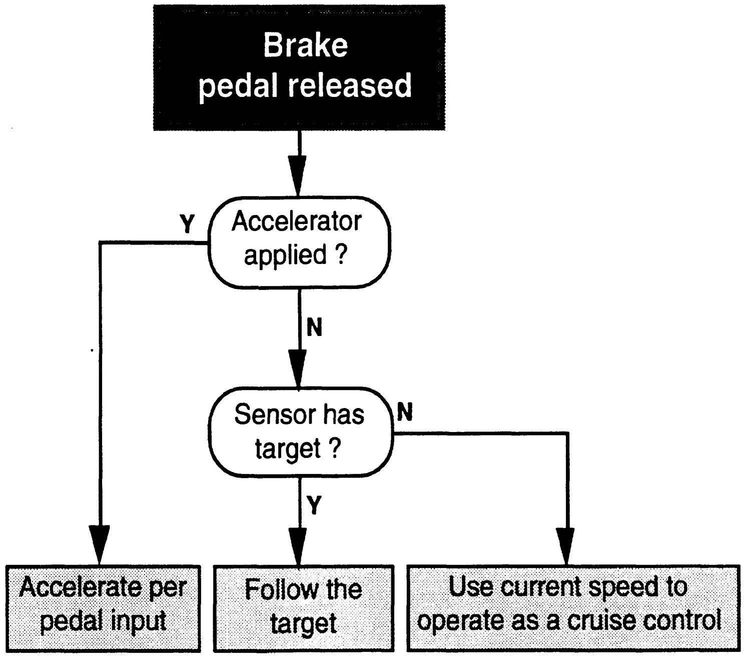

Figure 13. Scenarios associated with releasing brake pedal

4.2.2.4 Scenario 4 — Target loss

The sensor has just lost its target. Three possible scenarios can be associated with the event of losing a target (they all involve a previous speed command stored in the system):

(1) While in a convoy, the driver has been applying the brakes to slow down. Headway gap has increased to the point of losing the leader.

(2) While in a convoy, the driver accelerated and steered away from the leader. The leader is no longer within the sensor's "field of view."

(3) While in a convoy and without any brake/accelerator inputs, the leader disappears from the sensor's "field of view" (e.g. road curvature).

Based on the logic depicted in Figure 10, the system will use the last speed command it had while convoying (just prior to losing the target) to operate as a cruise control.

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5.0 DESCRIPTION OF THE TESTBED

Within the framework of Tasks 2 and 3, a testbed was developed to investigate the impact of an automatic headway-control system on the performance of vehicle convoys. To allow the evaluation of headway-control capabilities of heavy trucks, the testbed that was developed was capable of (1) performing the function of headway control, and (2) acquiring pertinent information, so that a subsequent task of data analysis could commence.

The function of intelligent convoy control is achieved by employing two control loops: (1) speed control, and (2) headway control. Figure 14 depicts these two control loops as distinct loops. Such a system's layout is typical in a case where some sort of a speed-control system (e.g., cruise control) already exists in the vehicle. In the case of the M915A2 testbed, however, such a system did not exist, and the speed control loop, as well as the headway-control loop, had to be specially devised. The speed controller and the headway controller were integrated into a single control unit, and the layout of the system employed in the experiments is illustrated in Figure 15.

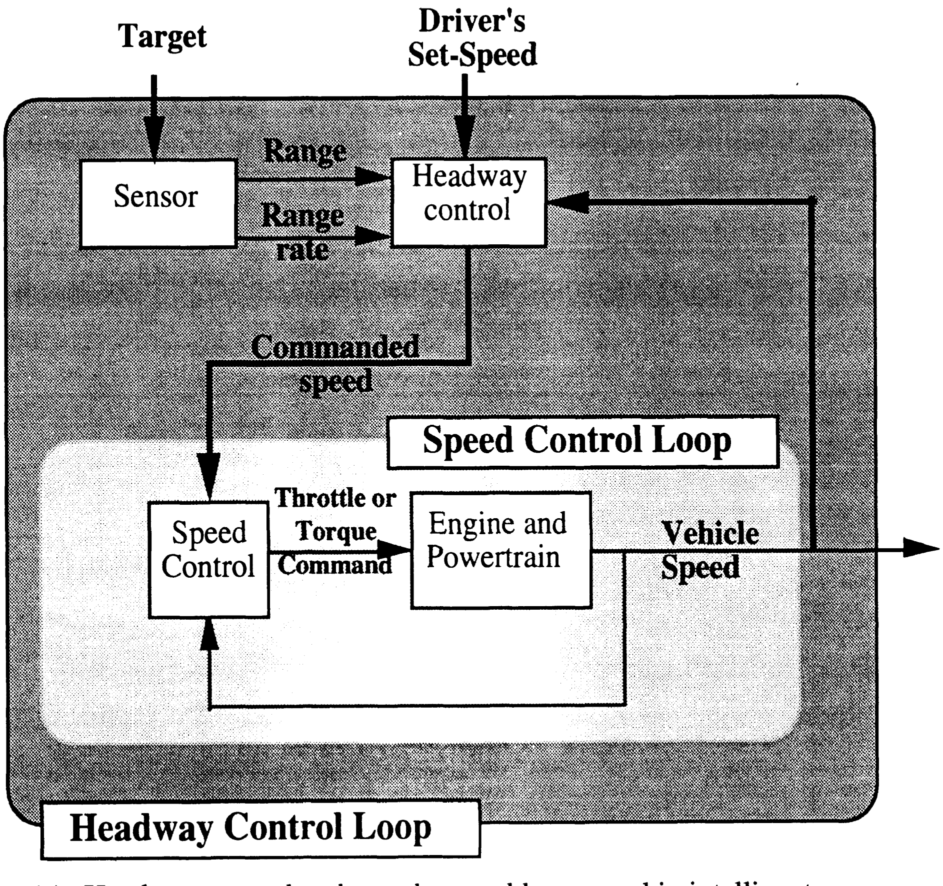

Figure 14. Headway control and speed control loops used in intelligent convoy control

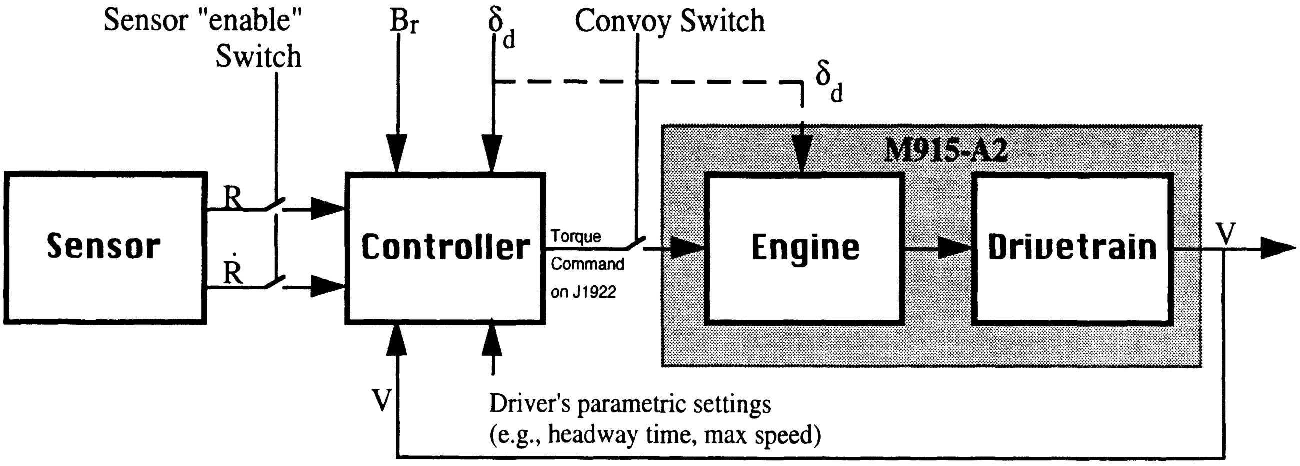

Figure 15. Convoy control as implemented in the testbed

The convoy switch is regarded as the "master switch" of the system: it must be set to its "on" position in order for the system to be operative. When the convoy switch is on, the controller algorithm is in effect, and its commands are transmitted using J-1922 protocol to the engine. If it is off, the engine is controlled strictly by the throttle, and the J-1922 is "silent." Throughout the following discussion, it is assumed that the convoy switch is on.

The status of the sensor "enable" switch determines whether the data from the sensor is being relayed to the controller or not. Its purpose is twofold: (1) some of the experiments required that the preceding vehicle is "invisible" for the system for a prescribed period — which could be achieved by holding the sensor switch at "off" for that period, and (2) based on the operational concepts that were outlined in section 4.0, when the sensor's data do not reach the controller, it assumes that there is no target ahead, and the system keeps a constant speed, much like a conventional cruise control.

Some of the required signals (either for performing control tasks or just for data acquisition) were already available in the truck, and some were not. For example, the accelerator pedal position was readily available on the J-1587 communication buss of the electronically controlled engine, while the activation of the brake pedal had to be detected by connecting a special voltage sensor to the brake-light circuit. Table 1 lists those transducers and sensors that were specially installed in the testbed, as the information provided by them was not available in the original Army M915A2. Table 2 (taken from Appendix C — "Data Requirement Plan") lists all the data signals that were acquired during the tests.

Table 1. Transducers and sensors installed in the testbed

No.	***Name***	***Description***
1	Radar sensor	A microwave sensing device (Eaton-VORAD) mounted on the front bumper to provide range and range rate to the lead vehicle
2	Speed sensor	Pulse generator that converts rotational speed (of the speedometer cable) to electrical signals. (SS-408-UT-8 by Clark Brothers)
3	Accelerometer	An acceleration measuring device (servo type, "Schaevitz LSBC-1) mounted in the driver's cab to measure longitudinal acceleration
4	Yaw-rate sensor	A Yaw-rate measuring device (Solid state, "Watson ARS-C132-1A") mounted in the driver's cab to measure yaw rate
5	Steering pot	A device that converts rotational motion to a measurable longitudinal one. Mounted on the steering wheel column to measure steering angle
6	Voltmeter	Connected to the brake-light circuit, this device provided information regarding the activation of the brakes by the driver.

Table 2. Acquired data items

Data Item	Symbol	Definition	Units	Acquisition Source
Sensor Data				
Range	R	Distance from the sensor to a detected object	ft	VORAD Sensor
Range Rate	Rdot	Rate of change of distance from the sensor to a detected object	fps	VORAD Sensor
Vehicle Data				
Velocity	V	Forward velocity of the headway-controlled truck	fps	Speed transducer
Acceleration	Ax	Forward acceleration of the vehicle	g	Accelerometer
Yaw Rate	Yr	Yaw rate of the vehicle	deg/sec	Yaw-rate transducer
Steering	Csw	Rotational position of the steering wheel	deg	String-pot transducer
Driver Data				
Accelerator	Cac	Accelerator pedal position	%	SAE data communication link
Brake	Lbr	Boolean variable indicating brake pedal status: 0 = brake pedal **<u>is not</u>** depressed 1 = brake pedal **<u>is</u>** depressed	(—)	Brake light circuit
Set speed	Vset	A maximum speed value not to be automatically exceeded; set by the driver	fps	Driver's display dial
Headway time	TH	Desired headway time	sec	Driver's display dial
Controller Data				
Valid target	Ltv	Boolean variable to filter detected objects: 1 = detected object **<u>is</u>** a valid target to consider and to possibly adjust headway to 0 = Otherwise	(—)	Controller algorithm
Command speed	Vc	Velocity command signal from the headway control	fps	Controller algorithm
Torque	Torque	Torque command signal to the engine	%	Controller algorithm
Sensor engaged	Sensor	Boolean variable indicating sensor data status: 0 = sensor data **<u>is not</u>** sent to the controller 1 = sensor data **<u>is</u>** sent to the controller	(—)	Driver's display switch

The driver "communicates" his setting for the system's operation through a driver interface control panel (see Figure 16). That panel also provides the driver with information regarding the operational status of the headway-control system. Table 3 lists the various items on the driver control panel and their functionality.

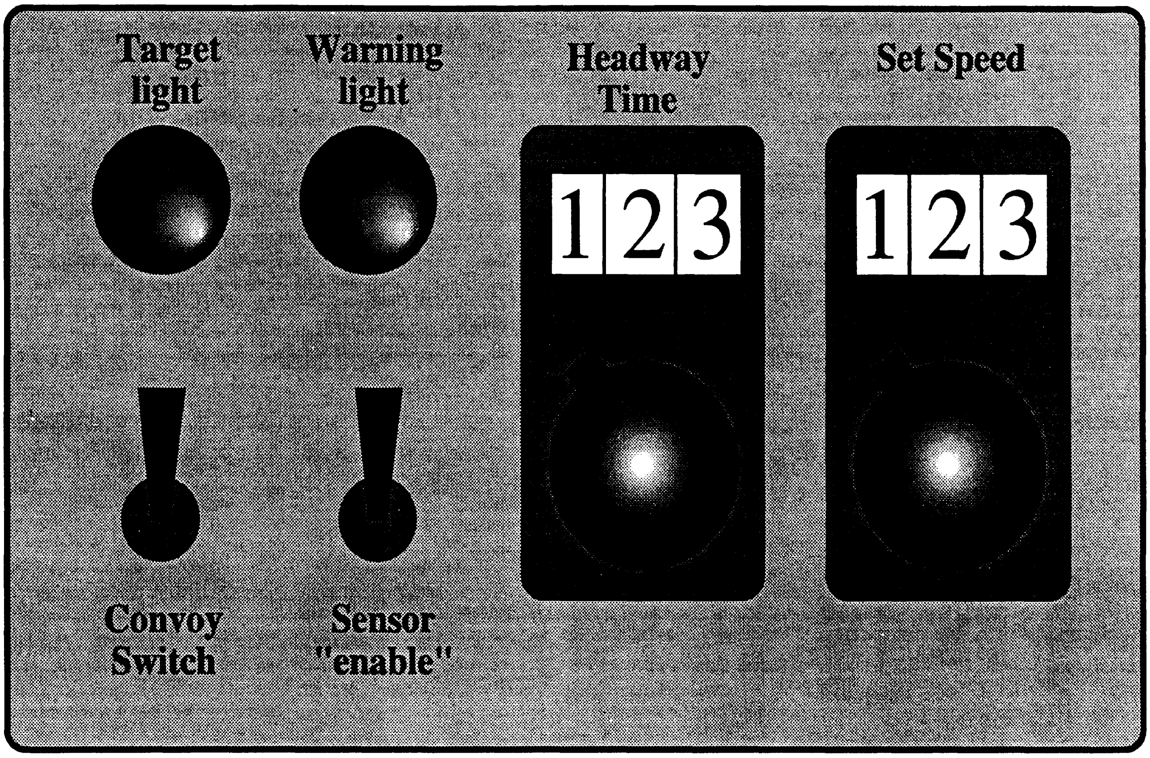

Figure 16. Driver interface control panel

Table 3. Items on driver interface control panel

No.	*Name*	*Description*
1	Convoy switch	Main switch to engage the headway system
2	Sensor "enable"	Determines whether the sensor data is communicated to the controller
3	Target light	Lit when a target that is "valid-to-follow" is detected
4	Warning light	Lit when driver's intervention is called for to avoid a crash
5	Headway time	An adjustable dial for the driver to set his desired following headway time
6	Set speed	An adjustable dial set by the driver — a speed value that the system should never exceed automatically (the driver can always override it manually with the accelerator pedal)

The data from the sensors, as well as the other signals listed in Table 1 of Appendix C, were collected by a Macintosh PowerBook 180 computer using its serial port. Figure 17 shows the layout of the testbed and the instruments.

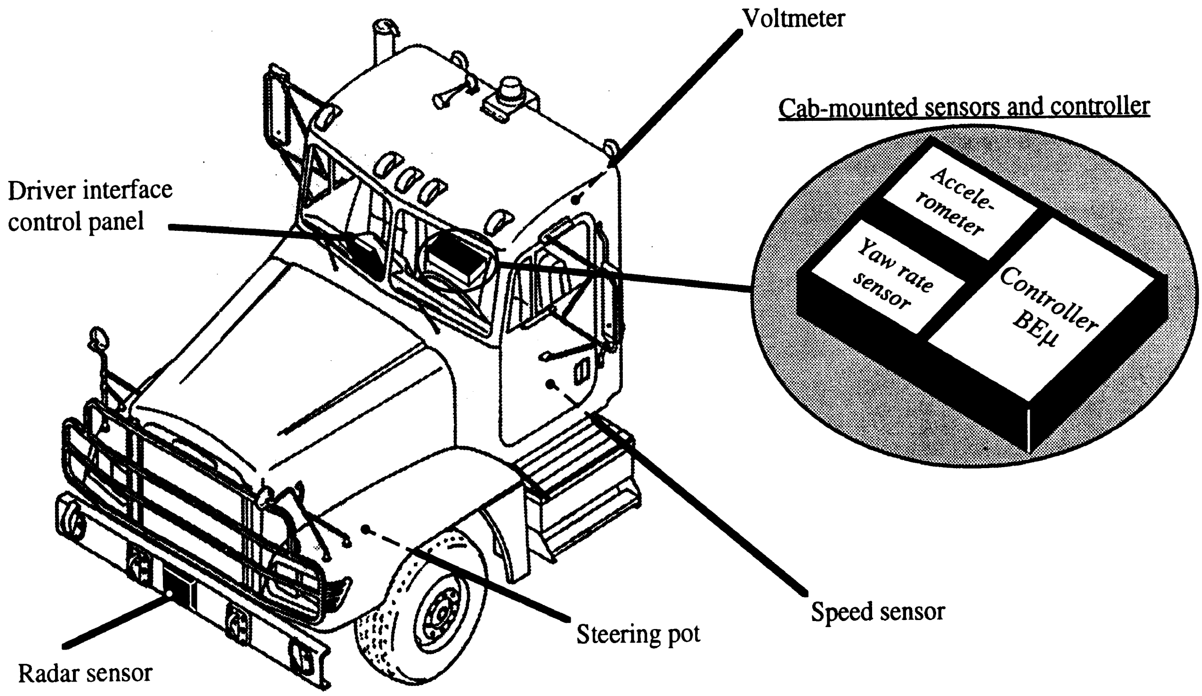

Figure 17. Testbed instrumentation layout

Figure 18 is a schematic depiction of the various items that the headway-control system and data acquisition are composed of, and how they are linked between themselves and the testbed truck.

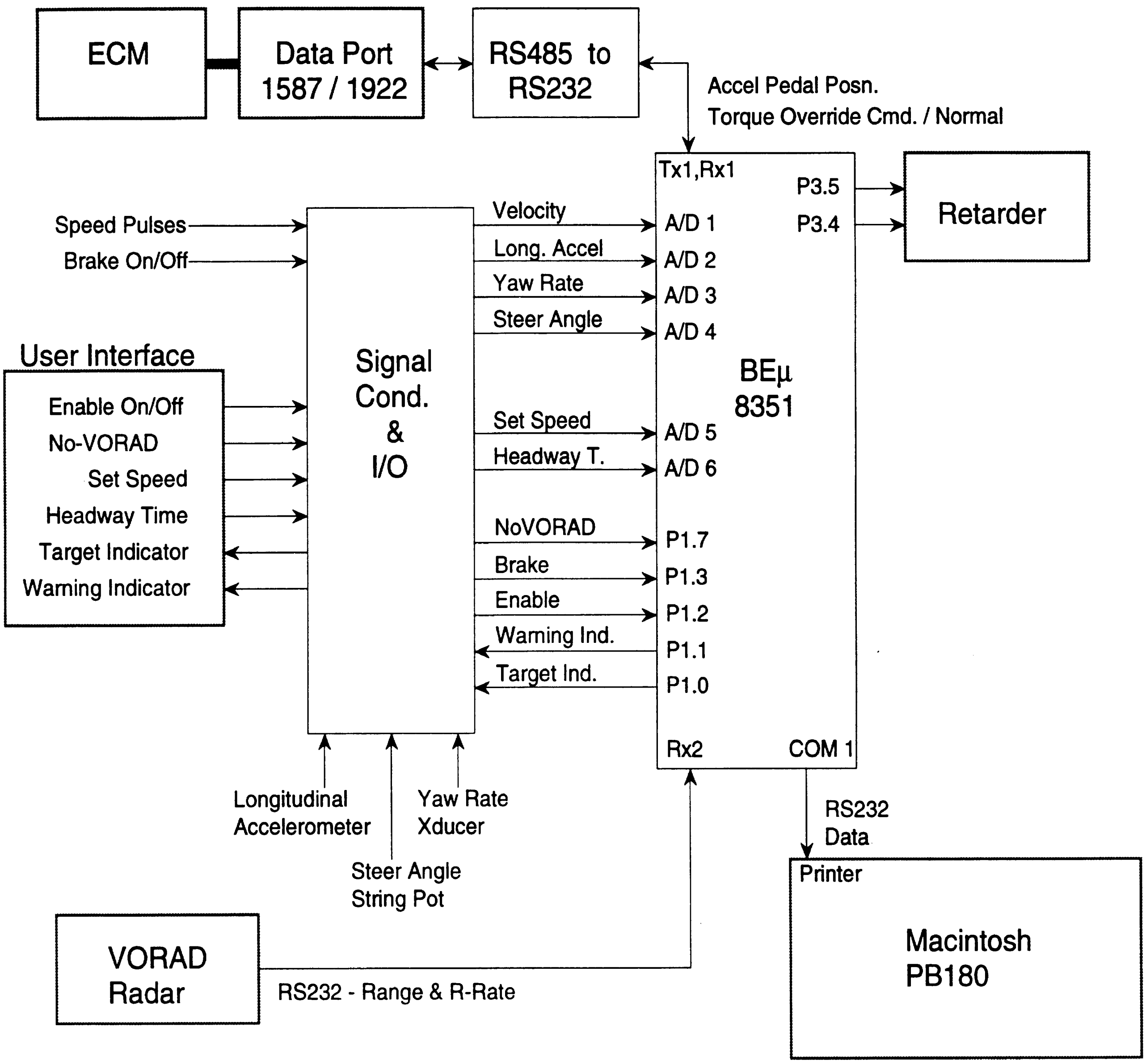

Figure 18. Testbed instrumentation and control

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6.0 ANALYSIS OF THE RESULTS

By properly processing data that were collected during testing, one can identify the system's capabilities and limitations. Table 2 (see section 5.0) summarizes all the data items that were collected. These data are used to address the following questions and system properties (the items in italics are properties of the system that the question pertains to):

1. When joining a convoy — how far ahead can the system "see" and identify a target to follow? (*sensor capability*) Once a target has been identified — how long does it take for the headway-controlled truck to close 63 percent of the gap (between the initial range and the desired range)? (*truck's longitudinal dynamics*) And, once the target is identified, what is the range between the vehicles after 30 seconds (one time constant)? (*truck's longitudinal dynamics*)
2. When convoying — what is the average range rate during a following mode (maintaining constant headway at a constant speed)? (*controller's performance*) How close are we to the desired range? (*controller's performance*) During speed changes by the lead vehicle — what are the limits up to which the system can accommodate the situation and autonomously perform the necessary adjustments, and beyond these limits the driver had to "take over?" (*truck's longitudinal dynamics*)
3. During a conventional cruise-control operation — how closely does the system maintain the desired speed? (*controller's performance*)
4. When a target shows suddenly — what are the limits up to which the system can accommodate the situation and autonomously perform the necessary adjustments? (*truck's longitudinal dynamics*)
5. When a target is lost momentarily — Does the driver need to intervene? (*controller's performance*)
6. Identify driver/system boundaries — under what conditions does the driver take control from the system and initiate braking? (*driver interface*) (When is a cue required to inform the driver that the system cannot handle the situation?)
7. When the alarm is turned on — how often is it due to a false target (false alarm)? (*controller's performance and sensor capability*)

6.1 Joining a Convoy

This test is described in detail in section 2.2.1 of the test plan (see appendix D). The plan contains a total of nine situations, four of which are with a headway time of 1.5 seconds, and five with a headway time of 2.0 seconds. Table 4 lists the tests performed.

Table 4. Joining a convoy — tests performed

No.	Test ID	Test Description	Test Plan Ref.
1	7	from 50 mph (73.3 fps) to 40 mph (58.7 fps), T_h=2.0 sec.	§ 2.2.1 (# 5)
2	9	from 50 mph (73.3 fps) to 35 mph (51.3 fps), T_h=2.0 sec.	§ 2.2.1 (# 6)
3	10	from 40 mph (58.7 fps) to 35 mph (51.3 fps), T_h=2.0 sec.	§ 2.2.1 (# 7)
4	16	from 40 mph (58.7 fps) to 30 mph (44.0 fps), T_h=2.0 sec.	§ 2.2.1 (# 8)
5	17	from 40 mph (58.7 fps) to 25 mph (36.7 fps), T_h=2.0 sec.	§ 2.2.1 (# 9)
6	18	from 50 mph (73.3 fps) to 40 mph (58.7 fps), T_h=1.5 sec.	§ 2.2.1 (# 9)
7	20	from 50 mph (73.3 fps) to 35 mph (51.3 fps), T_h=1.5 sec.	§ 2.2.1 (# 2)
8	21	from 40 mph (58.7 fps) to 30 mph (44.0 fps), T_h=1.5 sec.	§ 2.2.1 (# 3)
9	22	from 40 mph (58.7 fps) to 25 mph (36.7 fps), T_h=1.5 sec.	§ 2.2.1 (# 4)
10	23	from 40 mph (58.7 fps) to 25 mph (36.7 fps), T_h=1.5 sec.	§ 2.2.1 (# 4)

These tests assess the ability of a following vehicle to pick up a preceding vehicle and then to move into position in a convoy at a desired range. Figure 19 illustrates the type of (Rdot, R) trajectory that is produced as a vehicle joins a convoy from above the dynamics line.

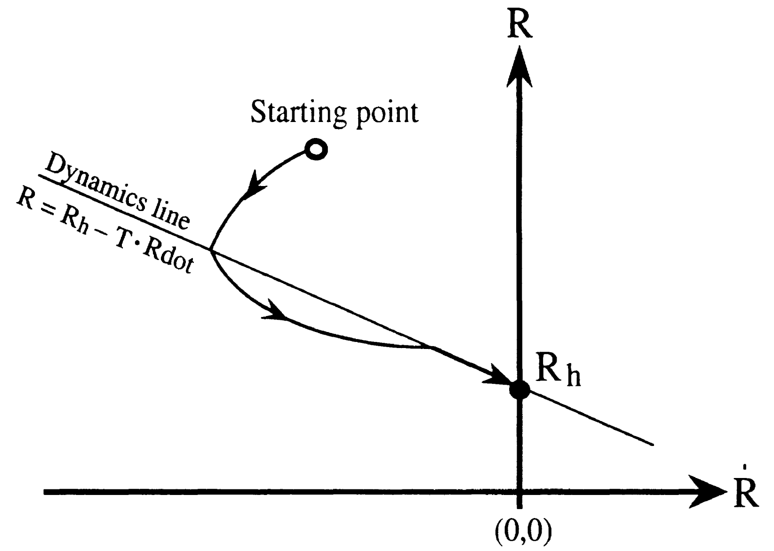

Figure 19. Joining a convoy

It is desirable for the driver to pick a starting point (for turning on the headway control) that is close to the point (0, R_h). The reason for this is twofold. First, the sensor signals for Rdot and R will drop in and out more frequently at long range. And, second, the convoy controller will cause the truck to accelerate initially to get to the dynamics line, if the vehicle is at an (Rdot, R) point that is above the dynamics line (this is the usual situation for joining a convoy). If the vehicle's (Rdot, R) coordinates are far removed from the dynamics line, accelerating to get to the dynamics line may cause Rdot to become too high. Under these circumstances, the required deceleration (D_m, see Figure 4 in section 2.1) might be such that the truck could not decelerate (by coastdown only) without getting too close to the preceding vehicle.

In the course of the testing, it was observed that once the sensor picks up a target, it does not necessarily maintain it for an extended period of time. The test data for joining a convoy have been examined to establish bounds for a consistent sensing of range and range-rate information over periods of time from one to ten seconds. Figure 20 displays the results showing the average range for which a consistent sensing existed throughout the prescribed period of time.

According to the test results, one can expect consistent sensor information — uninterrupted data for at least 7 seconds — if the range to the preceding vehicle is under 200 ft. This means that the convoy control system will operate reliably if it uses sensor data of up to approximately 200 ft.

Hence, with regard to joining a convoy the driver should try to position his vehicle at a range that is less than 200 ft behind a preceding vehicle, before turning on the convoy switch.

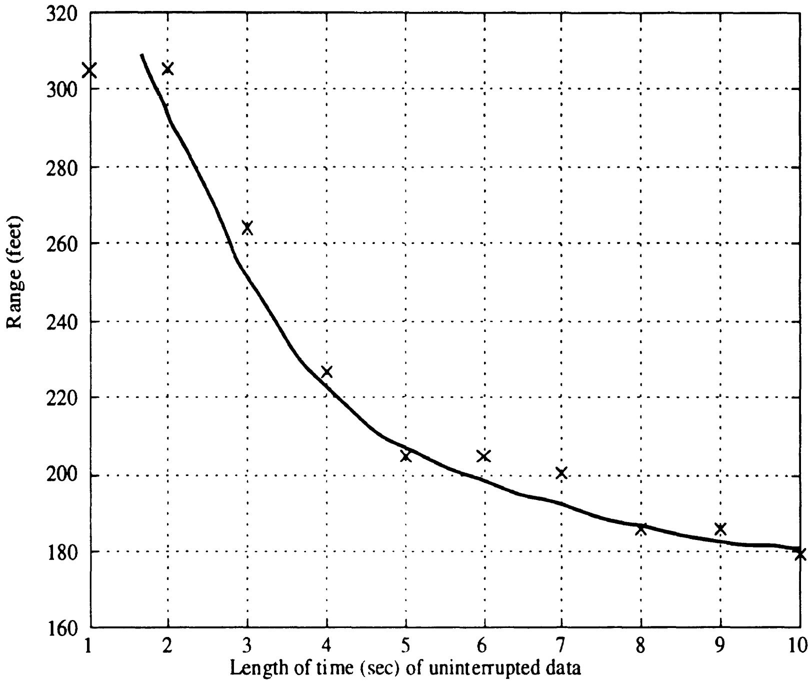

Figure 20. Range of first "established" reading

Once a target has been identified, the control algorithm commences to adjust the truck's speed so that it follows the preceding vehicle. This process of speed adjustment is a transition state of the system: from an independent-speed control mode, to a following mode of operation. The performance measure, devised to help evaluate the quality of the speed transition, is the range between the vehicles 30 seconds after the target is acquired.

Ideally, after a target is acquired, the transition to a following (or headway) mode is done by modulating the throttle (see technical discussion in section 2.0). A time history plot of how the range between the vehicles changes during such an ideal transition and the pertinent mathematical expression are portrayed in Figure 21. In the equation shown, "T" is the time constant of the vehicle, or "preview" time (see section 2.0). The algorithm employed in the controller was designed with T=30 seconds to reflect the truck's limited acceleration capability. Accordingly, the test results presented in Table 5 use the range, existing 30 seconds after target acquisition, as a measure of performance in joining a convoy.

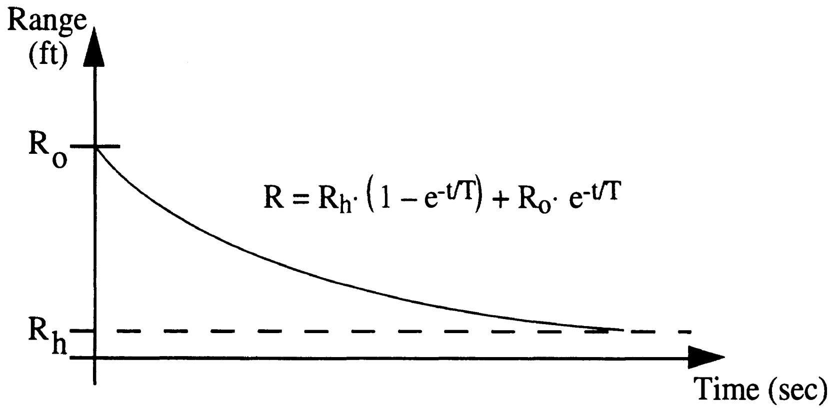

Figure 21. Typical time history of range when closing on a lead vehicle

Table 5. Joining a convoy; the range at 30 seconds after target detection

Test ID	Range after 30 seconds	Desired range (R_h)	Error (percent)
7	124	118.8	4.4
9	98	103.7	- 5.5
10	112	103.0	8.8
16	48	85.7	- 44.0
17	78	72.5	7.6
18	110	87.4	26.0
20	46	74.3	- 38.1
21	88	64.3	36.9
22	(—)	52.8	(—)
23	(—)	52.0	(—)

These data show that a velocity difference of 10 to 15 mph (i.e., Rdot < –15) can result in the following vehicle coming much closer than desired to the preceding vehicle. Based on these results, drivers should approach a preceding vehicle traveling no more than 5 or 6 mph faster than the preceding vehicle. That is, Rdot should not exceed approximately –9 ft/sec when joining a convoy. In any event, the driver should be prepared to apply braking if he/she starts to join a convoy with a relative speed that is faster than 5 or 6 mph.

6.2 Convoying

This test is described in detail in section 2.2.2 of the test plan (see appendix D). It entails a total of twenty-five cases, sixteen of which are with a headway time of 1.5 seconds, and nine with a headway time of 2.0 seconds. Table 6 lists the tests performed. ("Low decel" or "Low accel" means that the lead vehicle changes speed slowly, and "High decel" or "High accel" means that the lead vehicle changes speed rapidly.)

The primary objectives of this experiment are: (1) to examine the controller's performance in maintaining speed and range while following a vehicle, and (2) to establish bounds for the system's performance (the truck and the controller) as far as its ability to accommodate various speed changes introduced by the lead vehicle.

During convoy operation each following vehicle is to follow its preceding vehicle with only small deviations from the desired range. These deviation should be correctable using small amounts of longitudinal acceleration or deceleration. A region of the Rdot–R diagram corresponding to correctable amounts of deviation from the point (0, R_h) is illustrated in Figure 22. Inspection of the figure shows that this region is bounded by acceleration and deceleration parabolas. If acceptable deviations from the desired range are within ±10% of R_h, then the acceleration and deceleration parabolas in Figure 22 correspond to the curves:

$$R = 0.9 \cdot R_h + \frac{Rdot^2}{2 \cdot D_m}$$

and

$$R = 1.1 \cdot R_h - \frac{Rdot^2}{2 \cdot A_m}$$

where:

A_m is the maximum acceleration authority available to the convoy control system

D_m is the maximum deceleration authority available to the convoy control system

Table 6. Convoying — tests performed and data collected

No.	Test ID	Test Description	Test Plan Ref.
1	24	from 50 mph (73.3 fps) to 40 mph (58.7 fps), T_h=1.5 sec., high Decel.....	§ 2.2.2 (# 1)
2	25	from 50 mph (73.3 fps) to 40 mph (58.7 fps), T_h=1.5 sec., high Decel.....	§ 2.2.2 (# 1)
3	26	from 50 mph (73.3 fps) to 40 mph (58.7 fps), T_h=1.5 sec., high Decel.....	§ 2.2.2 (# 1)
4	27	from 50 mph (73.3 fps) to 40 mph (58.7 fps), T_h=1.5 sec., low Decel......	§ 2.2.2 (# 2)
5	28	from 50 mph (73.3 fps) to 40 mph (58.7 fps), T_h=1.5 sec., low Decel......	§ 2.2.2 (# 2)
6	29	from 50 mph (73.3 fps) to 40 mph (58.7 fps), T_h=1.5 sec., low Decel......	§ 2.2.2 (# 2)
7	30	from 50 mph (73.3 fps) to 40 mph (58.7 fps), T_h=1.5 sec., low Decel......	§ 2.2.2 (# 2)
8	31	from 50 mph (73.3 fps) to 40 mph (58.7 fps), T_h=1.5 sec., low Decel......	§ 2.2.2 (# 2)
9	32	from 50 mph (73.3 fps) to 35 mph (51.3 fps), T_h=1.5 sec., high Decel.....	§ 2.2.2 (# 3)
10	33	from 50 mph (73.3 fps) to 35 mph (51.3 fps), T_h=1.5 sec., low Decel......	§ 2.2.2 (# 4)
11	34	from 50 mph (73.3 fps) to 35 mph (51.3 fps), T_h=1.5 sec., low Decel......	§ 2.2.2 (# 4)
12	35	from 50 mph (73.3 fps) to 35 mph (51.3 fps), T_h=1.5 sec., low Decel......	§ 2.2.2 (# 4)
13	36	from 50 mph (73.3 fps) to 35 mph (51.3 fps), T_h=1.5 sec., low Decel......	§ 2.2.2 (# 4)
14	37	from 50 mph (73.3 fps) to 35 mph (51.3 fps), T_h=1.5 sec., low Decel......	§ 2.2.2 (# 4)
15	38	from 40 mph (58.7 fps) to 50 mph (73.3 fps), T_h=1.5 sec., high Accel.....	§ 2.2.2 (# 5)
16	39	from 40 mph (58.7 fps) to 50 mph (73.3 fps), T_h=1.5 sec., low Accel......	§ 2.2.2 (# 6)
17	40	from 40 mph (58.7 fps) to 50 mph (73.3 fps), T_h=1.5 sec., low Accel......	§ 2.2.2 (# 6)
18	41	from 40 mph (58.7 fps) to 30 mph (44.0 fps), T_h=1.5 sec., high Decel.....	§ 2.2.2 (# 7)
19	42	from 40 mph (58.7 fps) to 30 mph (44.0 fps), T_h=1.5 sec., low Decel......	§ 2.2.2 (# 8)
20	43	from 30 mph (44.0 fps) to 50 mph (73.3 fps), T_h=1.5 sec., high Accel.....	§ 2.2.2 (# 9)
21	44	from 30 mph (44.0 fps) to 50 mph (73.3 fps), T_h=1.5 sec., high Accel.....	§ 2.2.2 (# 9)
22	45	from 30 mph (44.0 fps) to 50 mph (73.3 fps), T_h=1.5 sec., low Accel......	§ 2.2.2 (# 10)
23	46	from 30 mph (44.0 fps) to 40 mph (58.7 fps), T_h=1.5 sec., low Accel......	§ 2.2.2 (# 11)
24	47	from 30 mph (44.0 fps) to 25 mph (36.7 fps), T_h=1.5 sec., low Decel......	§ 2.2.2 (# 13)
25	48	from 30 mph (44.0 fps) to 25 mph (36.7 fps), T_h=1.5 sec., low Decel......	§ 2.2.2 (# 13)
26	49	from 25 mph (36.7 fps) to 50 mph (73.3 fps), T_h=1.5 sec., low Accel......	§ 2.2.2 (# 14)
27	50	from 25 mph (36.7 fps) to 40 mph (58.7 fps), T_h=1.5 sec., low Accel......	§ 2.2.2 (# 15)
28	51	from 50 mph (73.3 fps) to 40 mph (58.7 fps), T_h=2.0 sec., high Decel.....	§ 2.2.2 (# 17)
29	52	from 50 mph (73.3 fps) to 40 mph (58.7 fps), T_h=2.0 sec., high Decel.....	§ 2.2.2 (# 17)
30	53	from 50 mph (73.3 fps) to 35 mph (51.3 fps), T_h=2.0 sec., high Decel.....	§ 2.2.2 (# 18)
31	54	from 40 mph (58.7 fps) to 30 mph (44.0 fps), T_h=2.0 sec., high Decel.....	§ 2.2.2 (# 19)
32	55	from 40 mph (58.7 fps) to 30 mph (44.0 fps), T_h=2.0 sec., low Decel......	§ 2.2.2 (# 20)
33	56	from 30 mph (44.0 fps) to 40 mph (58.7 fps), T_h=2.0 sec., low Accel......	§ 2.2.2 (# 21)
34	57	from 30 mph (44.0 fps) to 40 mph (58.7 fps), T_h=2.0 sec., low Accel......	§ 2.2.2 (# 21)
35	58	from 30 mph (44.0 fps) to 25 mph (36.7 fps), T_h=2.0 sec., high Decel.....	§ 2.2.2 (# 22)
36	59	from 30 mph (44.0 fps) to 25 mph (36.7 fps), T_h=2.0 sec., low Decel......	§ 2.2.2 (# 23)
37	60	from 25 mph (36.7 fps) to 40 mph (58.7 fps), T_h=2.0 sec., low Accel......	§ 2.2.2 (# 24)
38	62	from 25 mph (36.7 fps) to 40 mph (58.7 fps), T_h=2.0 sec., low Accel......	§ 2.2.2 (# 24)
39	63	from 25 mph (36.7 fps) to 40 mph (58.7 fps), T_h=2.0 sec., low Accel......	§ 2.2.2 (# 24)
40	64	from 25 mph (36.7 fps) to 30 mph (44.0 fps), T_h=2.0 sec., low Accel......	§ 2.2.2 (# 25)

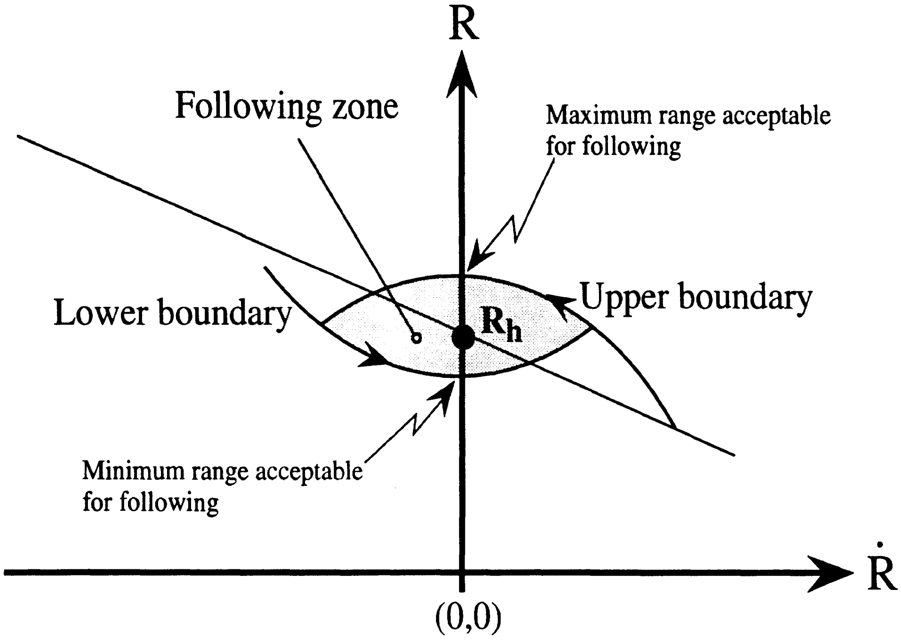

Figure 22. Desired region of operation during convoying

"Good" following is characterized by an average of zero for range rate, with a low standard deviation value, and by an average of zero for the range error (the deviation of the actual range from the desired headway range), also with a low standard deviation value. Ideally, we should have two following sessions for each of the tests performed: one before, and one after the speed change. However, some of the speed changes introduce disturbances that cannot easily be handled by the acceleration or deceleration authority available to the control system. These speed changes challenge the system's capabilities and will be discussed later. Each test has a region of "good following," followed by a sudden change in speed by the preceding vehicle. Figure 23 depicts the fraction of the time that the range-rate is between ±1ft/sec for the first following session (before changing speed).

Figure 23 shows that the range rate is not always zero during steady following. The question that naturally arises is "what is the significance of that deviation?" Or alternatively, "how close to the absolute zero should the range rate be, in order to be practically zero?" Inasmuch as experimental data is at issue — one might expect some deviation.

The inertia of the truck, and its low power-to-weight ratio, caused it to be sluggish in its longitudinal response to the point that it oscillated slowly about the desired values of speed and range to the preceding vehicle. In addition, these oscillations were not symmetrical.

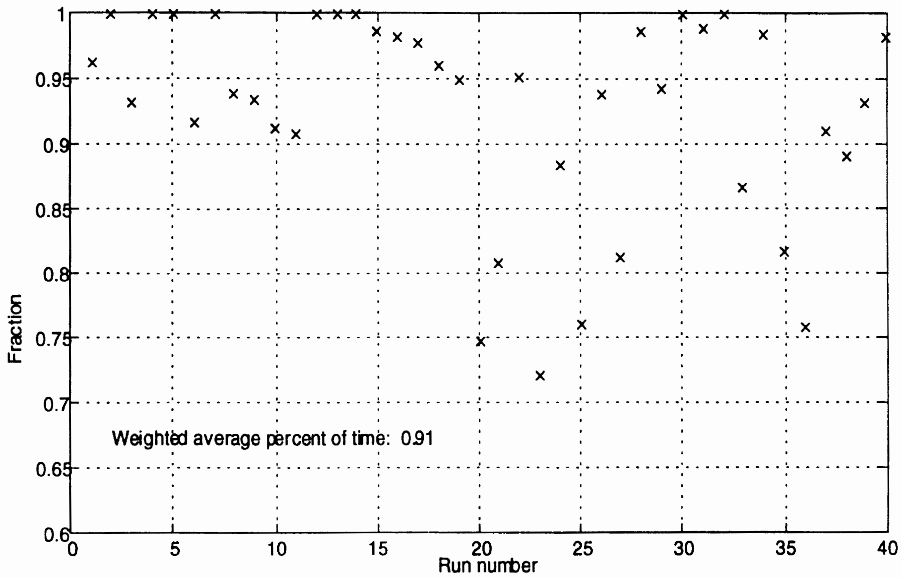

Figure 23. Fraction of time range rate was ±1fps during following

Similar to the range rate, which should be zero during following, the deviation of the actual range from the desired range should also be zero during following. Figure 24 shows the range error (the deviation of the actual range from the desired headway range, average and standard deviation) for following sessions. Figure 25 depicts the same data in a format of a histogram. The fact that the deviation in range is positive (smaller than the desired gap) may be due to the time delays and lags associated with the operation of the retarder.

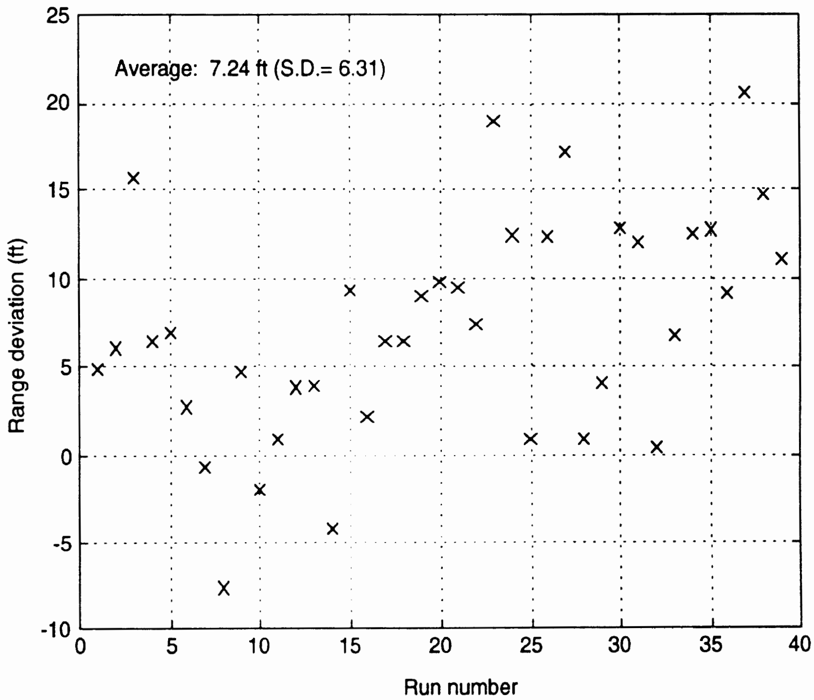

Figure 24. Average deviation of range (R_h–R) during following

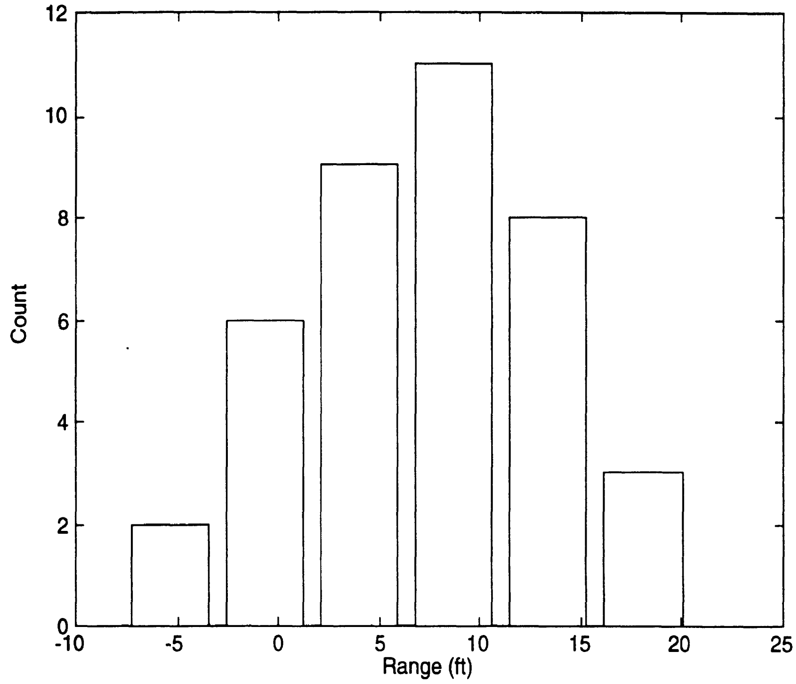

Figure 25. Histogram of average deviation of range (R_h–R) during following

The results given in Figures 23 through 25 show that the controller is capable of controlling speed and headway with only small deviations from the (0, R_h) point in the Rdot–R diagram. Drivers can expect their vehicles to follow reliably as long as the preceding vehicle proceeds at approximately constant speed.

So far in this discussion, the data pertain to a following situation in which the speed, the range, and the range rate are maintained at a constant value. Next, we consider evaluating the performance of the system during a speed change.

Only some of the speed-changing maneuvers are expected to be within the capacity of the system. For those, the system will be able to adjust the truck's speed autonomously without need for driver intervention. Speed-changing maneuvers that are beyond the capacity of the system will result in an intervention by the driver who will brake to avoid a crash — or to avoid getting too close to the preceding vehicle according to the driver's judgment of an acceptable safety margin. As mentioned earlier, this experiment was done using two headway-time values: 1.5 and 2.0 seconds. Figure 26 is a raw portrayal of the results. It should be noted that only those tests that involved deceleration of the preceding vehicle are presented. Speed changes where the lead vehicle accelerated are not shown, as they do not serve as potential scenarios for driver intervention by braking.

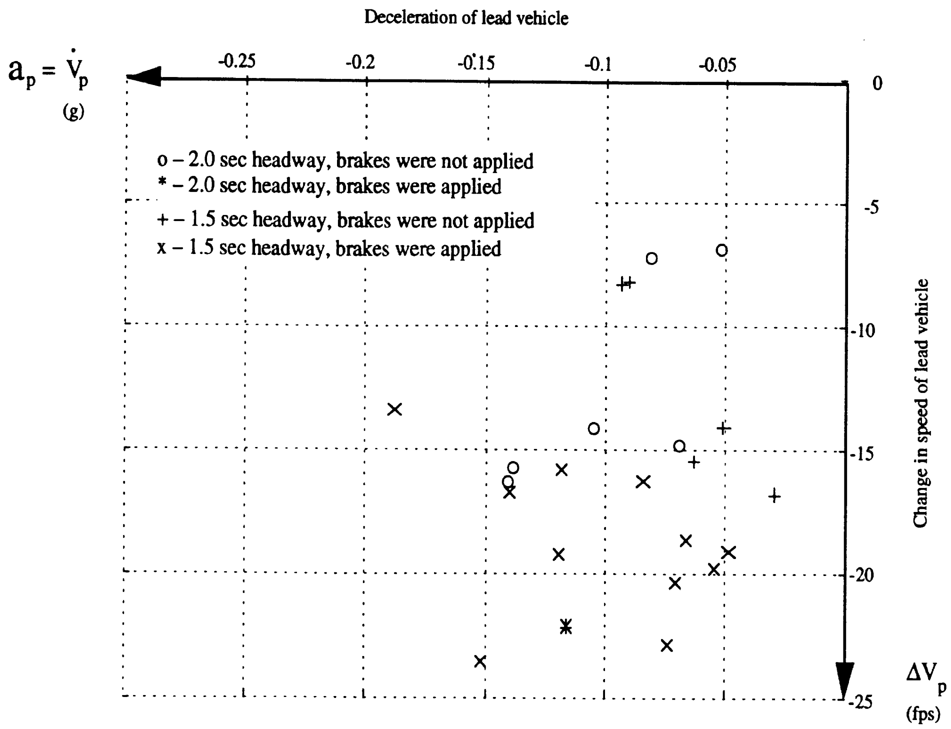

Figure 26. Braking results for speed changes by the lead vehicle

It was hypothesized that in the $\Delta V_p - a_p$ plane there should be a boundary between braking and no braking. Such a boundary will separate between those speed changes and deceleration levels that will necessitate braking by the driver and those that the system will be capable of handling. The nature of that boundary is illustrated in Figure 27.

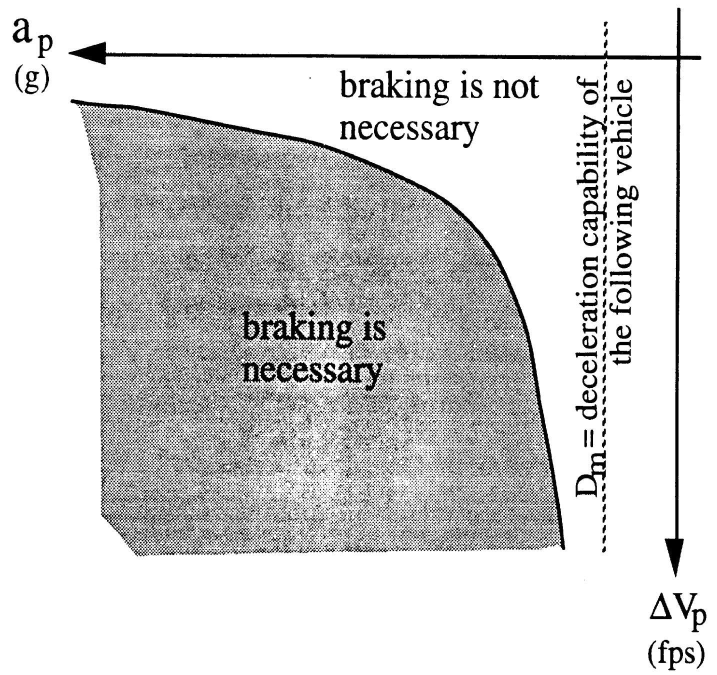

Figure 27. Braking / no-braking boundary when the lead vehicle changes speed

When the lead vehicle changes its speed, it takes some time for the headway-control system in the following vehicle to respond. Once that time delay has lapsed, the following vehicle starts to slow down. The deceleration level that is employed is limited by the maximum coast-down deceleration (D_m) of the truck (including the retarder, but no brakes). At a certain point, the throttle of the following truck is modulated, so as to bring the two vehicles to a coordinated speed at the desired range. It is assumed that the speed adjustment is carried out successfully, without a crash. Figure 28 illustrates the process that was described above. If the driver of the truck feels that the speed adjustment cannot be executed without hitting the lead vehicle, or without crossing the driver's prescribed safety margin, the driver intervenes by employing the brakes.

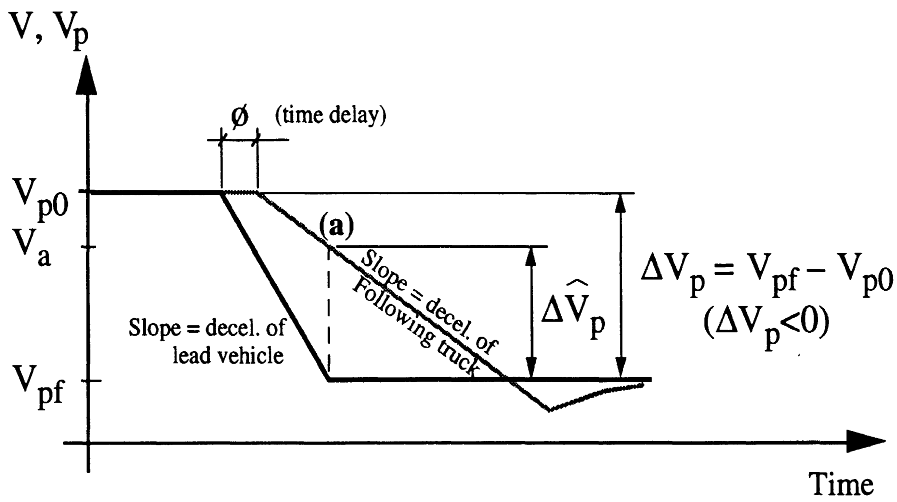

Figure 28. Speed adjustment of the following vehicle

Using time-distance-speed-deceleration relationships written to represent the speed adjustment process depicted in Figure 28, an expression for ΔV_p can be derived. After performing the algebra, ΔV_p can be written as:

$$\Delta V_p = D_m \cdot \phi \cdot g \pm \sqrt{(D_m \cdot \phi \cdot g)^2 - \frac{2 \cdot D_m \cdot a_p \cdot g \cdot \left(\frac{D_m \cdot \phi^2 \cdot g}{2} - V_{p0} \cdot T_h + R_{min}\right)}{a_p - D_m}} \quad (4)$$

where:

D_m	is the maximum coast-down deceleration of the following truck (fraction, 0 to 1g)
ϕ	is the time delay for the response of the following truck (sec.)
g	is gravity (32.2 ft/sec/sec)
a_p	is the deceleration by which the lead vehicle changed its speed (fraction, 0 to 1)
V_{p0}	is the initial speed of the lead vehicle (before the speed change) (ft/sec)
T_h	is the desired headway time of the following truck (sec.)
R_{min}	is the minimum range acceptable to the truck driver (ft)

Based on measurements that were performed on the testbed truck, and using parametric values that represent the driving conditions during the testing, the following values were used in solving for ΔV_p:

(1) the following truck's maximum deceleration (D_m) is 0.05g

(2) there is a 0.08 sec. delay (ø) between the instant when the need to decelerate is introduced, and the instant when the truck develops its maximum deceleration (retarder activation)

(3) the minimum range that the driver of the truck is willing to tolerate in the process of the speed adjustment is 50 ft. (R_{min}) (if the range gets shorter, or if the driver perceives that the range will get shorter than 50 ft, the driver applies the brakes) (note: this value pertains to the particular driver used in this testing session; it might vary with drivers)

(4) the headway time (T_h) used was alternately 1.5 seconds and 2.0 seconds.

The results of these calculations are represented by the "lines of constant V_p0" drawn in Figures 29 and 30. These lines depict brake / no-brake boundaries for various values of V_p0 according to equation (4).

Raw data from the tests (see Figure 26) have been overlaid on Figures 29 and 30 to compare with the lines of constant V_p0 generated from equation (4). Comparisons indicate that equation (4) is a reasonable predictor for the need to brake, except in a few cases with a headway time of 1.5 seconds.

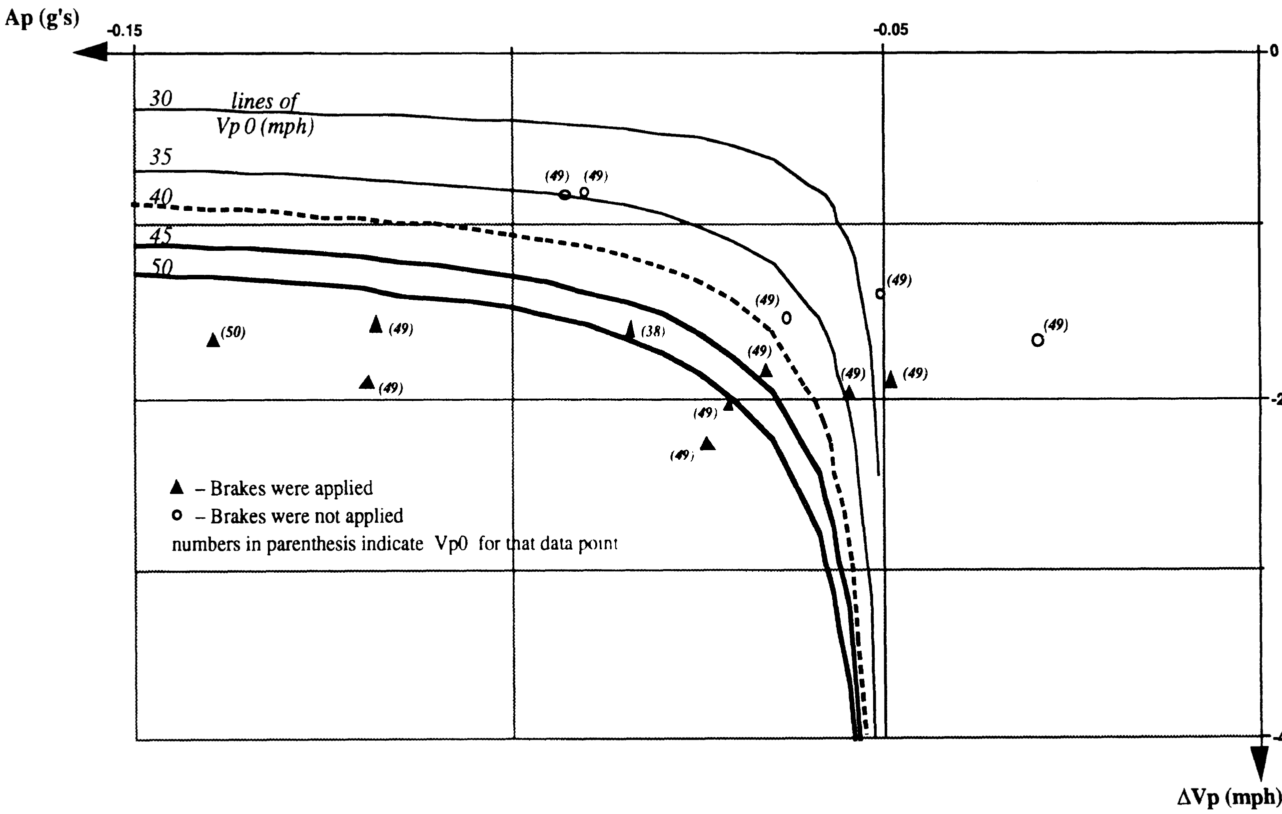

Figure 29. Braking / no-braking boundary for 1.5 seconds headway time

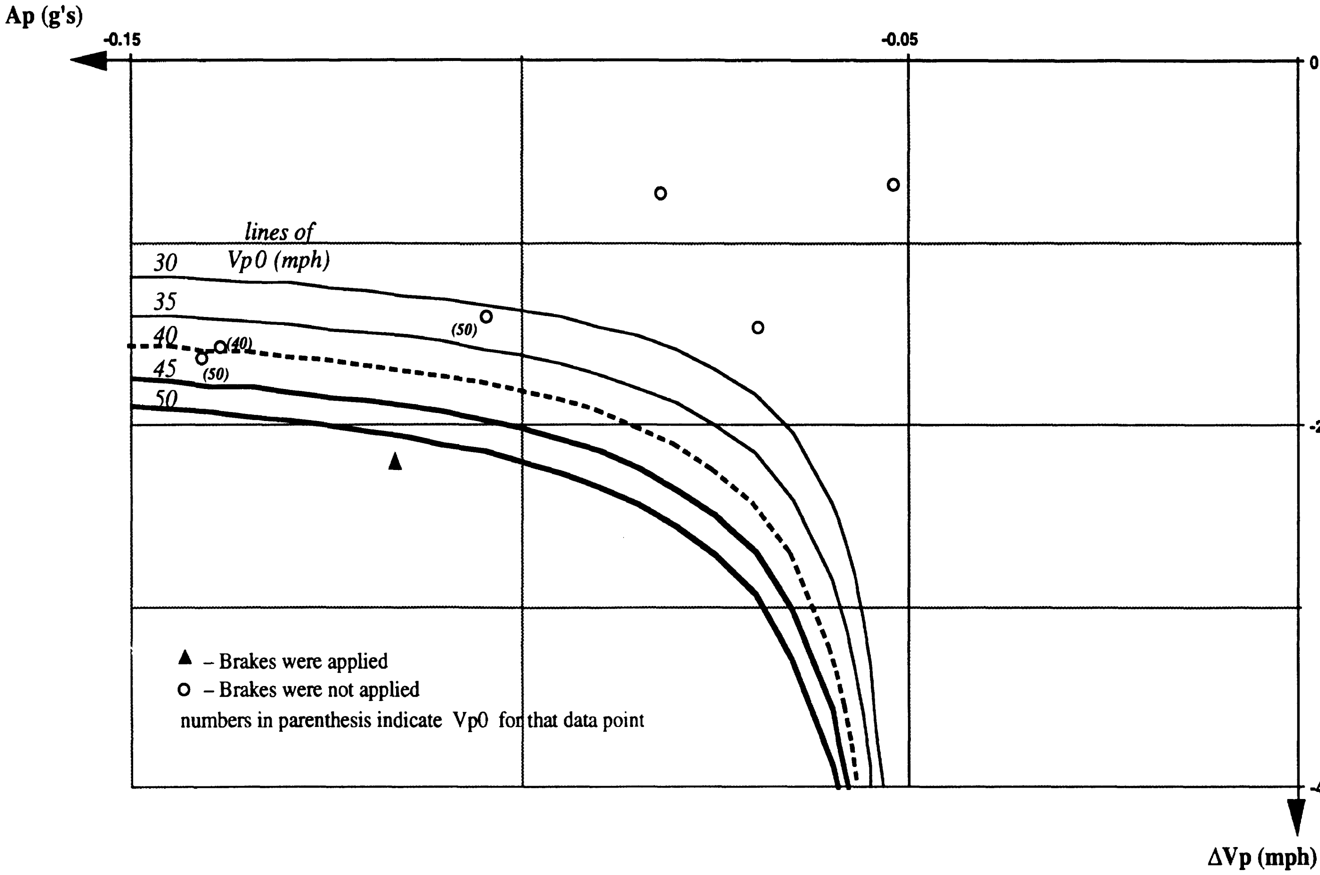

Figure 30. Braking / no-braking boundary for 2.0 seconds headway time

For those "unjustified" braking points in Figure 29 (points of brake application above the boundary curve), a close examination of the data files reveals that the time delay was significantly larger than 0.08 sec. (up to approximately 1.4 sec.).

The results for speed changes have three implications concerning headway operations using this system. First, speed changes should be relatively small (e.g., $\Delta V_p < 10$ mph) and should be carried out relatively slowly (e.g., $a_p < 0.1g$). Large changes in speed are best achieved by coasting. Second, a headway time (T_h) of 2.0 seconds is preferable to 1.5 seconds. And third, the driver's option to use the brakes or the accelerator without losing convoy control should be useful in situations where a preceding vehicle needs to make small but quick speed changes. (The idea in this case is that the driver may brake without ceasing convoy operation altogether. As soon as an acceptable convoy situation is attained, the driver may release the brake and following will proceed using the convoy control system. Incidentally, the same feature applies to accelerator use also, so that the driver can speed up to trim the vehicle's position as desired.)

6.3 Independent Speed Control

This test is described in section 2.2.3 of the test plan. It entails a total of five trials, each involves maintaining a different speed: 20, 30, 40, 50, and 55 mph. The primary objective of this experiment was to examine the controller's performance in maintaining a constant speed (cruise control operation).

The results — average deviation from the desired speed and the standard deviation of that average — are depicted in Table 7. On an average, the truck is 0.027 fps slower than the desired speed — which is practically zero. It appears that the speed control of the truck (see section 5.0) performs in a satisfactory manner to maintain a constant speed.

Table 7. Independent speed control — deviation from a constant speed

Nominal constant speed (mph)	**Average speed deviation (fps)**	**Standard deviation (fps)**
20	0.008	0.29
30	-0.010	0.24
40	0.074	0.30
50	0.074	0.31
55	0.013	0.28

6.4 Sudden Target Acquisition

This test is described in section 2.2.4 of the test plan. It simulates a "cut-in" situation, or a target that appears too close for the execution of an orderly speed adjustment (as in joining a convoy). A total of sixteen trials was planned: eight cut-in speeds, and two headway times. However, in the course of the testing it was evident that not only would the system be incapable of handling one of the prescribed cut-in situations, but that attempting to perform that test could jeopardize the safety of the participants (specifically, when the lead vehicle changes its speed from 50 mph to 30 mph, and the truck attempts to follow this maneuver while maintaining a 1.5 seconds headway time). The number of trials actually performed, and for which data were actually collected was fifteen (see Table 8).

Table 8. Sudden target acquisition — tests performed and data collected

No.	Test ID	Test Description	Test Plan Ref.
1	1	target at 140 ft, 30 mph (44.0 fps), we're 50 mph (73.3 fps), T_h=2.0 sec..	§ 2.2.4 (# 1B)
2	2	target at 130 ft, 35 mph (51.3 fps), we're 50 mph (73.3 fps), T_h=2.0 sec..	§ 2.2.4 (# 2B)
3	3	target at 190 ft, 35 mph (51.3 fps), we're 50 mph (73.3 fps), T_h=2.0 sec..	§ 2.2.4 (# 3B)
4	4	target at 170 ft, 40 mph (58.7 fps), we're 50 mph (73.3 fps), T_h=2.0 sec..	§ 2.2.4 (# 4B)
5	6	target at 100 ft, 40 mph (58.7 fps), we're 50 mph (73.3 fps), T_h=2.0 sec..	§ 2.2.4 (# 5B)
6	8	target at 100 ft, 45 mph (66.0 fps), we're 50 mph (73.3 fps), T_h=2.0 sec..	§ 2.2.4 (# 6B)
7	10	target at 100 ft, 51 mph (74.8 fps), we're 50 mph (73.3 fps), T_h=2.0 sec..	§ 2.2.4 (# 7B)
8	11	target at 70 ft, 55 mph (80.7 fps), we're 50 mph (73.3 fps), T_h=2.0 sec....	§ 2.2.4 (# 8B)
9	12	target at 75 ft, 35 mph (51.3 fps), we're 50 mph (73.3 fps), T_h=1.5 sec....	§ 2.2.4 (# 2A)
10	13	target at 175 ft, 35 mph (51.3 fps), we're 50 mph (73.3 fps), T_h=1.5 sec..	§ 2.2.4 (# 3A)
11	15	target at 90 ft, 40 mph (58.7 fps), we're 50 mph (73.3 fps), T_h=1.5 sec....	§ 2.2.4 (# 4A)
12	17	target at 145 ft, 40 mph (58.7 fps), we're 50 mph (73.3 fps), T_h=1.5 sec..	§ 2.2.4 (# 5A)
13	20	target at 85 ft, 45 mph (66.0 fps), we're 50 mph (73.3 fps), T_h=1.5 sec....	§ 2.2.4 (# 6A)
14	21	target at 90 ft, 51 mph (74.8 fps), we're 50 mph (73.3 fps), T_h=1.5 sec....	§ 2.2.4 (# 7A)
15	22	target at 45 ft, 55 mph (80.7 fps), we're 50 mph (73.3 fps), T_h=1.5 sec.	§ 2.2.4 (# 8A)

The primary objective of this experiment was to verify the controller's performance envelope in the sense that it will handle or fail to handle certain cut-in situations. The results of the tests are depicted in Figures 31 and 32.

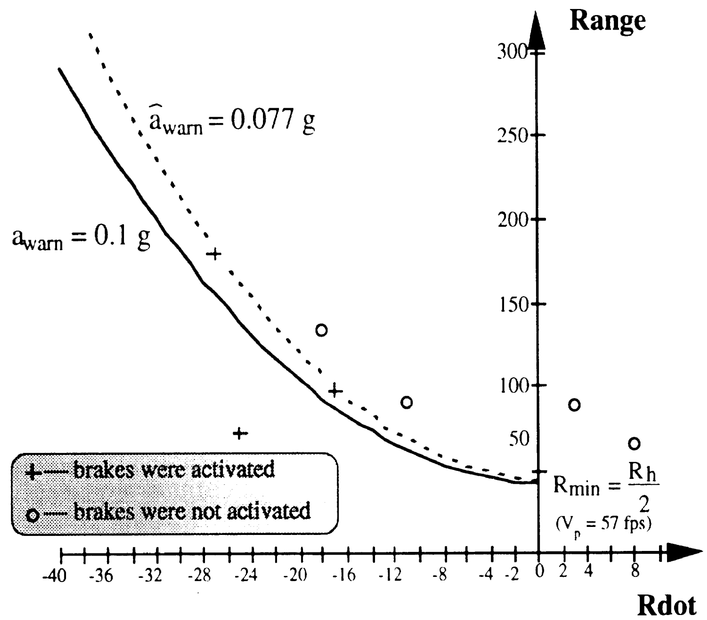

Figure 31. Deceleration boundary that calls for driver's intervention, T_h=1.5 sec.

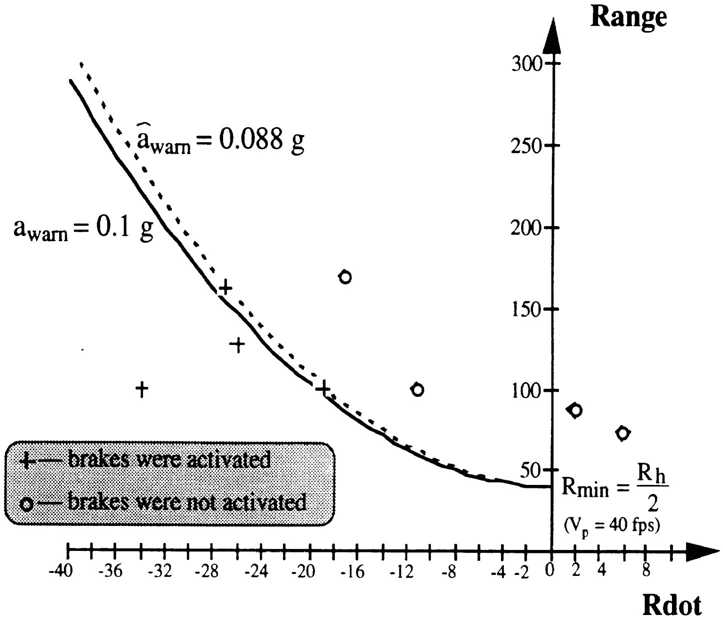

Figure 32. Deceleration boundary that calls for driver's intervention, T_h=2.0 sec.

The parabolic lines, which serve as deceleration boundaries in these figures, are written in terms of the deceleration that is associated with them:

$$R = \frac{Rdot^2}{2 \cdot a_{warn}} + R_{min} \qquad (5)$$

Observing these figures, it is evident that whenever the designed warning line (the parabola that corresponds to a required deceleration of 0.1g, which also determines when the warning light should be turned on) was crossed — it always resulted in a necessity of the driver to intervene. There were no false alarms. However, the results further show that there were some situations when the driver intervened before the warning light came on (when the (Rdot, R) coordinates were above the warning parabola). This is a situation that is opposite to a false alarm — a belated alarm. It means that the driver should be warned when the required deceleration to avoid a crash is less acute than 0.1g. Such amended warning lines are: 0.077g (for 1.5 sec. headway time), and 0.088g (for 2.0 sec. headway time). However, since the driving conditions during the tests were aimed at experiencing the system at its boundaries, a more conservative warning line might be recommended for normal operation. It might indeed trigger some false alarms (unnecessary warnings), but it will minimize belated alarms (missing necessary warnings). It appears that 0.05g (for all headway times) will appropriately serve this purpose.

6.5 Momentary Target Loss

This test is described in section 2.2.5 of the test plan, and it simulates situations when the sensor loses the target momentarily (e.g., driving around a curve). A total of twenty-one trials was planned and executed (see Table 9). The primary objective of this experiment was to verify the controller's ability to handle questionable no-target situations.

The design of the control system is such, that in a case of a target loss (momentary or permanent), the last speed command is maintained. Therefore, due to this inherent safety feature that was built into the system's design, it was assumed that unless some erroneous speed command was issued just before the target is lost, the system will successfully manage questionable no-target situations.

The above assumption was proven correct, as driver's intervention was not called for throughout these experiments. All the test cases were successfully handled by the system in an autonomous manner.

Table 9. Momentary target loss — tests performed and data collected

No.	Test ID	Test Description	Test Plan Ref.
1	23	target loss for 3 sec. at 20 mph (29.3 fps), T_h=1.5 sec.	§ 2.2.5 (# 1)
2	24	target loss for 6 sec. at 20 mph (29.3 fps), T_h=1.5 sec.	§ 2.2.5 (# 2)
3	25	target loss for 9 sec. at 20 mph (29.3 fps), T_h=1.5 sec.	§ 2.2.5 (# 3)
4	26	target loss for 3 sec. at 30 mph (44.0 fps), T_h=1.5 sec.	§ 2.2.5 (# 4)
5	27	target loss for 6 sec. at 30 mph (44.0 fps), T_h=1.5 sec.	§ 2.2.5 (# 5)
6	28	target loss for 9 sec. at 30 mph (44.0 fps), T_h=1.5 sec.	§ 2.2.5 (# 6)
7	29	target loss for 3 sec. at 40 mph (58.7 fps), T_h=1.5 sec.	§ 2.2.5 (# 7)
8	30	target loss for 6 sec. at 40 mph (58.7 fps), T_h=1.5 sec.	§ 2.2.5 (# 8)
9	31	target loss for 9 sec. at 40 mph (58.7 fps), T_h=1.5 sec.	§ 2.2.5 (# 9)
10	32	target loss for 3 sec. at 20 mph (29.3 fps), T_h=2.0 sec.	§ 2.2.5 (# 10)
11	33	target loss for 6 sec. at 20 mph (29.3 fps), T_h=2.0 sec.	§ 2.2.5 (# 11)
12	34	target loss for 9 sec. at 20 mph (29.3 fps), T_h=2.0 sec.	§ 2.2.5 (# 12)
13	35	target loss for 3 sec. at 30 mph (44.0 fps), T_h=2.0 sec.	§ 2.2.5 (# 13)
14	36	target loss for 6 sec. at 30 mph (44.0 fps), T_h=2.0 sec.	§ 2.2.5 (# 14)
15	37	target loss for 9 sec. at 30 mph (44.0 fps), T_h=2.0 sec.	§ 2.2.5 (# 15)
16	38	target loss for 3 sec. at 40 mph (58.7 fps), T_h=2.0 sec.	§ 2.2.5 (# 16)
17	39	target loss for 6 sec. at 40 mph (58.7 fps), T_h=2.0 sec.	§ 2.2.5 (# 17)
18	40	target loss for 9 sec. at 40 mph (58.7 fps), T_h=2.0 sec.	§ 2.2.5 (# 18)
19	41	target loss for 3 sec. at 50 mph (73.3 fps), T_h=2.0 sec.	§ 2.2.5 (# 19)
20	42	target loss for 6 sec. at 50 mph (73.3 fps), T_h=2.0 sec.	§ 2.2.5 (# 20)
21	43	target loss for 9 sec. at 50 mph (73.3 fps), T_h=2.0 sec.	§ 2.2.5 (# 21)

6.6 Driver / System Boundaries

Rather than relating to a single set of prescribed tests, this element of the data analysis addresses all of the testing. The goal is to identify those sets of conditions under which the driver takes control from the system and initiates braking.

Using the Rdot–R diagram, Figure 33 depicts the first instants of brake application. A curve fit that was made indicates that 0.1g is approximately the warning boundary for the driver. That value agrees with the deceleration level that was selected in the controller design. However, "fine tuning" per the discussion in section 6.4 leads to a deceleration limit of 0.05g. The limiting curves that are associated with these two deceleration values are shown in Figure 33.

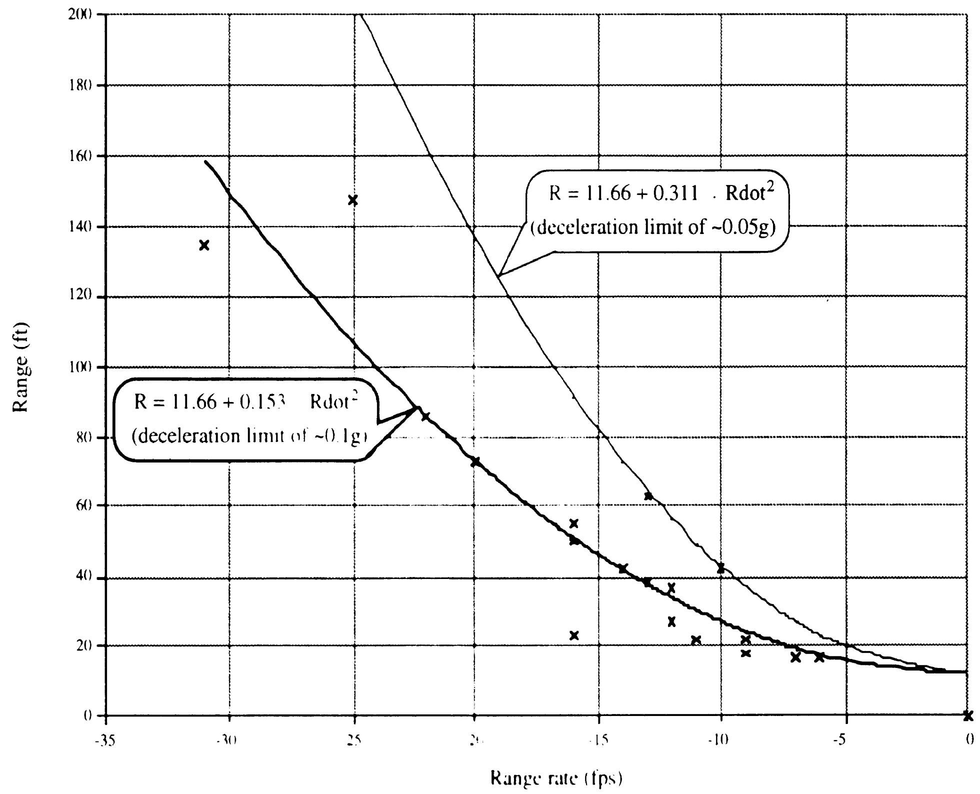

Figure 33. Brake activation points

Figure 34 depicts D_{req} (required deceleration to avoid a crash, see Table 2 in appendix C) for the first instance of brake application. Since only 72 percent of the data points are within the average value ± one standard deviation, D_{req} cannot be considered as the most consistent indicator for the necessity of a warning or for a more drastic crash-prevention control action.

The time to crash (or time to collision, see Table 2 in appendix C), T_c, is depicted in Figure 35. The values shown pertain to the first instant the brakes were applied. For this parameter, 91 percent of the data points are included within the range of average ± one standard deviation. Therefore, it appears that using the average value of T_C (3.92 sec.) as a bounding value for warning activation or for a drastic control action, might be compatible with the driver's own perception.

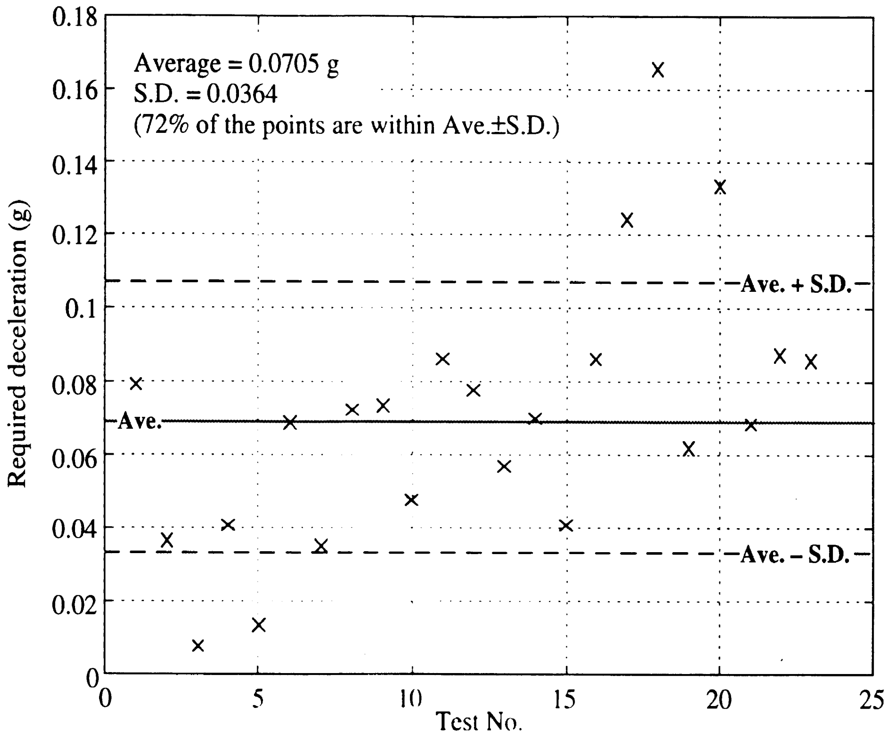

Figure 34. D_{req} at brake activation points

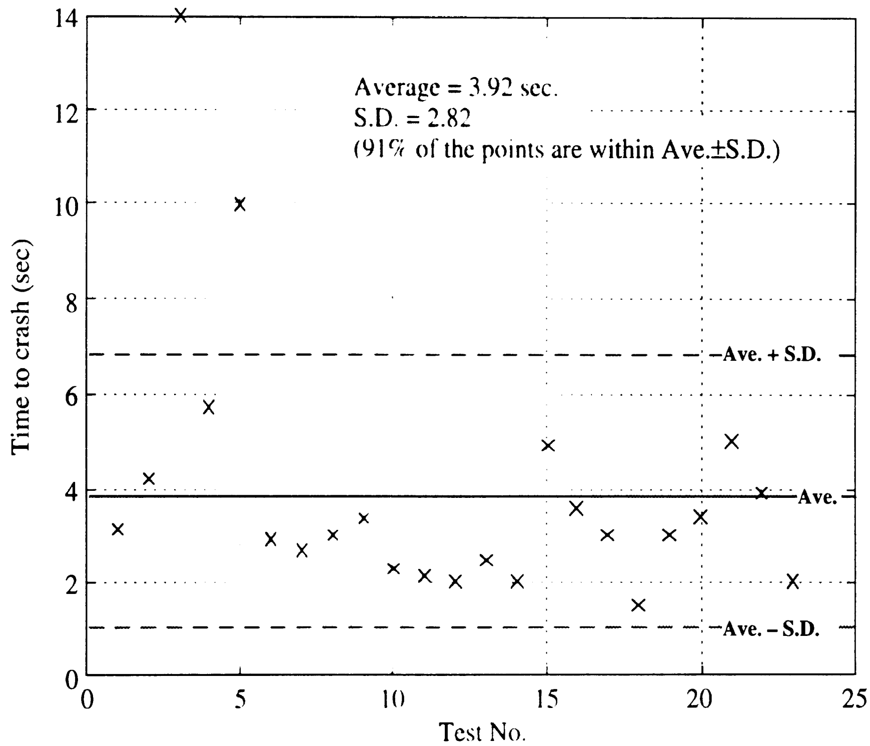

Figure 35. T_C at brake activation points

Figure 36 depicts T_a (available reaction time, see Table 2 in appendix C) at the instant the brakes were applied. Only 52 percent of the data points are included within the range of average ± one standard deviation. Being so inconsistent, this parameter appears to be a rather poor indication for warning. It might be so far off the driver's apprehension of the situation, that it can end up being ignored. Similarly, T_{hm} (actual headway time, see Table 2 in appendix C) is rather inconsistent (see Figure 37), and probably cannot be used as a reliable indication for a needed warning.

The results for D_{req}, T_c, T_a, and T_{hm} show that no one of them alone appears to be satisfactory for setting driver / system boundaries in general. However, a boundary based on the results given in Figure 33, provides an indication of range and range-rate conditions when the driver needs to, and wants to brake. In general, the system is capable of acting autonomously without driver intervention above the 0.05g line in Figure 33.

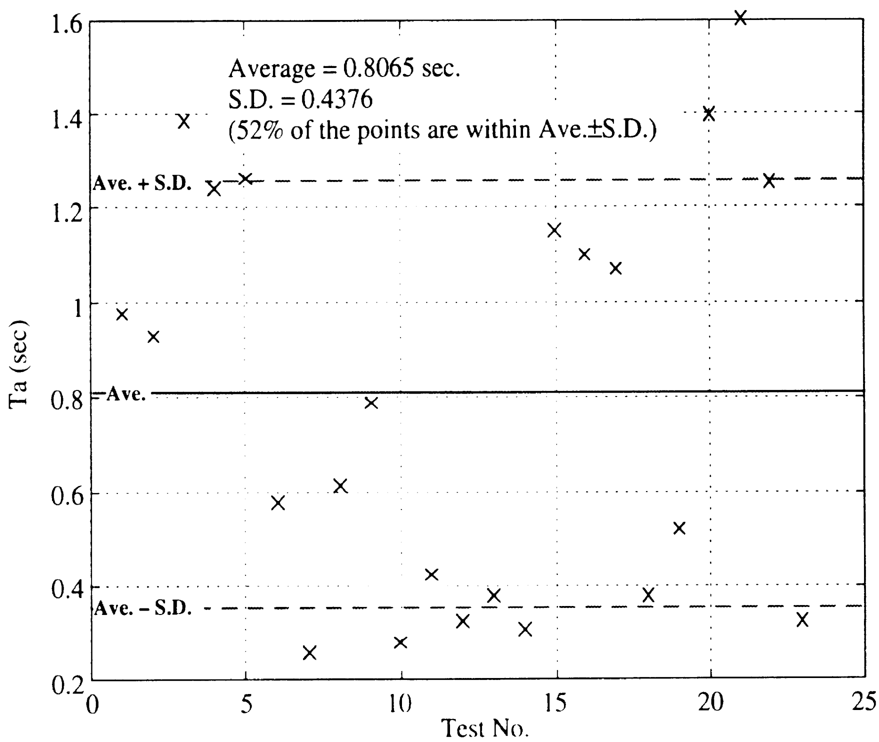

Figure 36. T_a at brake activation points

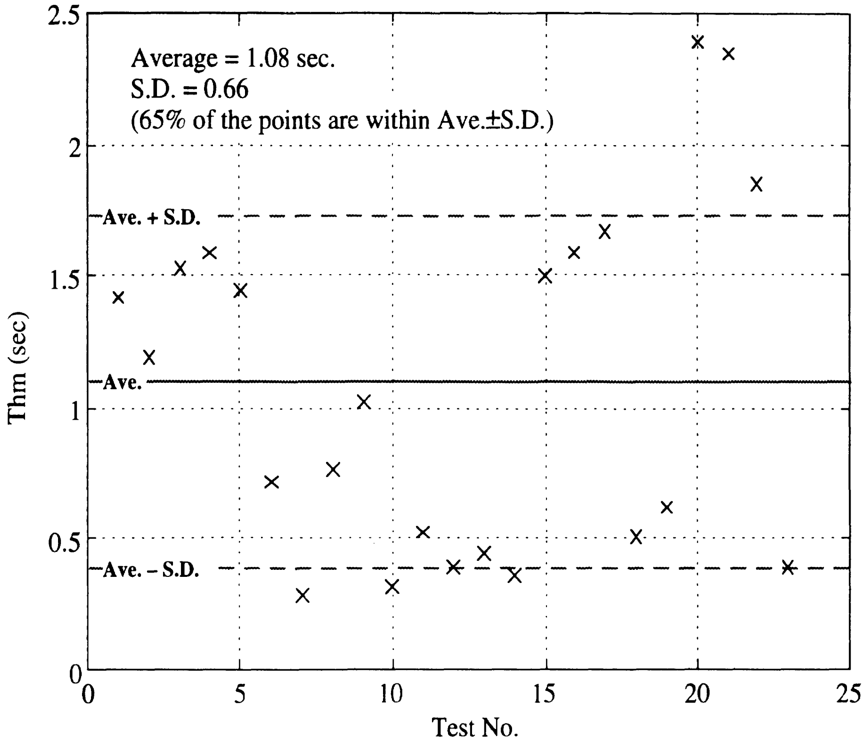

Figure 37. Thm at brake activation points

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7.0 CONCLUSIONS AND RECOMMENDATIONS

The primary objective of this project is to develop a physical headway-controlled testbed. This objective has been successfully accomplished. The prototype system performed well during both the pilot test program and at the demonstration at TACOM. A meaningful advancement was made toward acquiring the ability to comprehensively evaluate the impact of headway-control systems on convoy and driver performance.

7.1 Conclusions

7.1.1 Conclusion 1

A working prototype of an automatic headway-control system for convoys was developed, installed in a military M915-A2 truck, and successfully tested.

7.1.2 Conclusion 2

The performance capabilities of the prototype system have been evaluated. Based on the findings from the experiments, the performance boundaries are as follows:

- When joining a convoy, the truck should not approach a preceding vehicle at a relative speed that is faster than 5 mph, and the system should not be turned on at a distance beyond 200 ft.
- During convoying, the lead vehicle should not change its speed more than 10 mph at a time, and these speed changes should be carried out at a rate of no more than 0.1g. Tests involving following in a convoy show that the system successfully maintains speed and range while following a vehicle that drives at a constant speed. Maneuvers that involve changing the speed of the preceding vehicle can be successfully accommodated by the control system, when speed changes are relatively small (i.e., $\Delta V_p < 10$ mph) and they are carried out relatively slowly (i.e., the acceleration of the preceding vehicle is less than 0.1g).
- If for any reason the truck needs to decelerate at a rate of more than 0.05 g's, the driver should intervene by applying the brakes.
- Performance capabilities with regard to constant speed control or after losing the target were found to be good without any obvious operational limitations.
- Tests involving sudden target acquisition indicate that the predicted performance of the headway controller agrees with the actual test results. If a target shows up so the truck needs to decelerate at a rate of 0.077 to 0.088 g's (predicted value was 0.1 g), the driver

intervened and applied the brakes. It seems, however, that a more conservative value of 0.05 g for a warning threshold would be safer.

- Tests involving independent speed control show that the speed control of the truck performs in a satisfactory manner to maintain a constant speed. (The average accuracy of the system is 0.027 fps.)
- The sensor provides reliable range and range-rate readings at ranges up to 200 ft.

7.1.3 Conclusion 3

The convoy control system is designed to be easy to use and to be safe at the same time. It maintains convoy integrity when operated autonomously, or when needed, it accommodates driver intervention in braking or accelerating. From the functionality standpoint, its operational algorithm, which was described in detail in section 4.0, is comprised of three fundamental rules: (1) when a preceding vehicle is present, the system will automatically attempt to achieve and maintain a prescribed headway, (2) whatever the driver does takes precedence over any system commands, and (3) when a preceding vehicle is not present, and the driver does not provide any control input, the system will maintain the last speed input. During the experiments, the above "operational philosophy" was found to function well. The following features were consistently observed in the data:

- Whenever the driver pushes either the brake pedal or the accelerator pedal, the driver is given authority over the control system. There is never a conflict between these means of driver input and the convoy control system.
- Whenever the driver releases either the brake pedal or the accelerator pedal so that authority is returned to the control system, the commanded speed from the system is either the speed of the truck at the time the pedal was released (if a preceding vehicle is not present), or an appropriate speed to achieve the desired headway (if a preceding vehicle is present).

7.1.4 Conclusion 4

The software and hardware, developed for the prototype system, constitute a robust system for headway control. A detailed description of the hardware is presented in section 5.0, and the software is described in detail (actual code) in appendix A.

7.2 Recommendations

The recommendations are aimed at (1) further enhancing the state of knowledge concerning headway control for convoys and (2) exploring new concepts that emerged from findings of the pilot testing.

7.2.1 Recommendation 1

A prototype model that incorporates braking should be developed. During the experiments it was evident that the coastdown deceleration capability (even with the retarder) of the truck severely limited the performance of the system. Added deceleration is needed to ensure that the performance boundaries of the prototype will conform to military convoy requirements. Furthermore, an algorithm, similar to that used for crash warning, can be used to apply braking as well as issuing warning.

7.2.2 Recommendation 2

The prototype headway-control system should be developed and tested using different types of sensors for range and range-rate information. Sensors to consider include:

- vision: such that its functionality is based on image processing (both visible images and those that require infrared capabilities). From a military standpoint, these sensors hold the advantage of being passive sensing devices as they do not emit energy.
- time-of-flight: using either light, radio, or other electromagnetic waves. The sensor's reading is based on the time it takes for the "beam" to reach the target and to be echoed back from it.
- GPS (Global Positioning System): use satellite navigation information for the vehicles' locations. Such sensors are likely to be less accurate than any of those mentioned above. However, unlike the other sensors they can operate with no line of sight to maintain practically unlimited headway gaps.

Further developing the prototype system with different sensors as described above can have a meaningful bearing on the operation of military convoys. The utility of the system could be evaluated under military-specific condition such as blackout, large headway gaps, out-of-sight convoy operation, etc. Given the limited performance capabilities of the prototype system as they were discussed before, the advantages of such extended sensing capacity are obvious. Experimenting with a variety of sensing devices could determine which type of sensor maximizes the utility of the system in terms of reliability and robustness for each operational condition. Considering this approach of a maximized utility, the prospect of operating the system with a "quick-change" sensor should also be evaluated. Clearly, no single sensor has a complete and total advantage over the rest. If sensors could quickly be swapped, the application of the best sensor for the upcoming task can always be provided.

7.2.3 Recommendation 3

The stability of a string of vehicles should be investigated experimentally. During this study tests were performed with just one following vehicle. Longer convoys were studied by simulation only. Using at least four or five vehicles in a convoy will allow a real-life evaluation of the impact that the string stability phenomenon might have on convoy operation. It is also desirable to study a string of nonidentical vehicles.

7.2.4 Recommendation 4

The prototype headway-control system installed in the M915-A2 should receive further operational testing and development. The performance boundaries of the prototype testbed, as derived from the test results and findings (listed in the previous section), are likely not to conform with military convoy requirements. Convoy performance capabilities should probably be extended to allow the following:

- handling of larger headway gaps (perhaps even out of sight)
- a higher relative speed when converging to a convoy
- a higher deceleration for crash avoidance
- handling of more severe speed-change maneuvers by the lead vehicle
- maintaining a more accurate headway gap while convoying

7.2.5 Recommendation 5

Provision for simultaneously changing speed throughout a convoy should be investigated. Using some form of communication between the vehicles, a cooperative convoy operation can be obtained. This approach might eliminate the need for high deceleration under certain conditions, and it also has the potential of increasing the longitudinal stability of a multivehicle convoy.

7.2.6 Recommendation 6

The relationships between system's capability to handle various scenarios and the vehicle's acceleration capability should be investigated. Tests and analyses should be performed to determine the convoying speed as a function of vehicle mass and engine horsepower.

7.2.7 Recommendation 7

Human factors studies should be performed to further develop user-friendliness of the convoy control system and its associated displays.

APPENDICES C-E

APPENDIX C

DATA REQUIREMENTS PLAN

1.0 GENERAL

A data requirements plan has been devised for the project entitled "Control of Headway Between Successive Vehicles". Convoy operation has been studied, and pertinent measures that are required to evaluate convoy performance impacts have been defined. Using an M-915 A2 vehicle, tests will later be conducted at Dana test track. A detailed plan for those experiments is currently being devised. The data provided by those experiments will be gathered in accordance with this data requirement plan.

1.1 Purpose

The purpose of this plan is to describe the data requirements for evaluating the influence of a headway-control system on the performance of convoy operations. The plan also defines convoy operations and performance.

1.2 Scope

Following the definition of convoy operations and performance, the plan starts with a list of the basic quantities to be measured. The plan then lists quantities to be computed, and expands from there to briefly reflect on how we plan to process the data.

1.3 Definition of Convoy Performance and Automatic Convoy Operation

A convoy is made up of several vehicles that are driving along together at a coordinated speed. The headway distances between vehicles in the convoy may be chosen to fit a variety of desired spacing patterns.

Automatic convoy operation is achieved by using a control system consisting of a sensor, a processor for computing control commands, and actuation hardware for implementing the desired control actions. The control system for automatic convoy operation interacts with driver control of the vehicle. The driver may intervene at any time to aid in resolving problems that may interrupt the automatic control of convoy operations. Insofar as driver interventions are seldom needed, the automatic convoy control system largely handles the longitudinal control of the vehicle with the advantages that (1) the convoying operation is performed with greater diligence and precision than what drivers are likely to achieve and (2) the driver/soldier is more capable of performing other tasks associated with the mission of the convoy.

In order to provide the overall flexibility needed to address any problems that may arise, the driver is able to override the action of the control system or any automatic measures included in the system. The driver's observational capabilities are the backup for the sensor in situations where the sensor misses a target, loses a target, or indicates a false target. (In the convoy application, the sensor's target is the preceding vehicle.) Temporary losses of target may be resolved by automatically holding speed constant until the target reappears to the sensor. If this automatic countermeasure does not quickly resolve the problem, the driver will need to intervene in order to re-establish automatic convoy operation. However, correcting for temporary losses of target could burden the driver to the extent that the system would be of limited value. The goal is to keep driver interventions to a minimum number of easily recognized cases involving easily performed corrective actions.

The relationship between automatic convoy operation and actions aimed at establishing or re-establishing automatic convoy operation are illustrated and summarized in Figure 1. Two conditions must be satisfied in order to initiate automatic convoy operation: (1) the system used for performing the convoying function is turned on and (2) a leading vehicle presents a suitable target to the sensor. To join a convoy, the driver brings his/her vehicle into sensor range of the preceding vehicle. When the convoying system recognizes the target, automatic convoy operation begins. During automatic convoy operation, the control system corrects for errors in headway gap and/or vehicle speed. If the control system cannot provide an automatic correction for the situation (e.g., headway gap increased beyond sensing range), a manual correction by the driver is required to bring the convoy back into automatic operation. Failing to do so will break the convoy. When this happens, the original follower will become the leader of a shortened convoy, and the originally preceding vehicle will become the last vehicle in a shortened version of the original convoy.

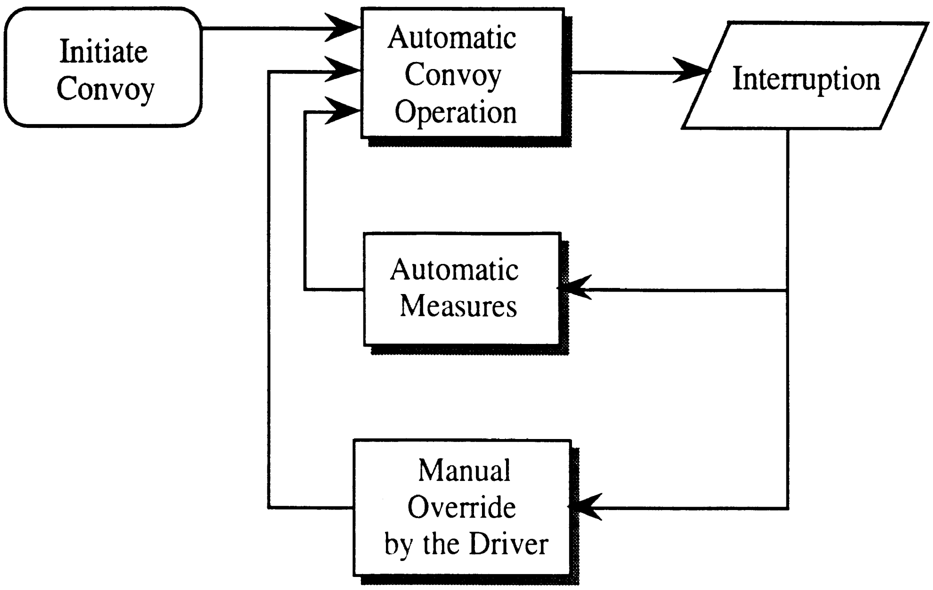

Figure 1 Establishing and re-establishing automatic convoy operation

For the purpose of this project, certain operative driving states deserve particular attention when considered in the context of convoy operation. These states may be thought of as "control regimes", and they are listed below:

(I) driving at a set speed with no preceding vehicle close enough to influence velocity

(II) closing on a preceding vehicle under automatic tracking

(III) following (tracking) a preceding vehicle at a desired headway range

(IV) operating at closer than the desired headway range behind the preceding vehicle (e.g., due to a sudden target acquisition)

(V) operating strictly under driver control (including passing other vehicles)

The operation of the headway-control system within these five control regimes will be used to assess its impacts on convoy performance. Later in this document, when data processing is discussed, basic questions pertaining to these driving regimes will be presented.

1.3.1 The Driver's Perspective of Automatic Convoy Operation

The ensuing discussion provides a summary of convoy operation from the perspective of the driver. The driver is part of an overall system consisting of three major parts: an outside world, hardware (and software) constituting the intelligent vehicle, and (of course) the driver. See Figure 2. The driver observes both the outside world and the intelligent vehicle. The driver sends commands to the intelligent vehicle to control whether and how

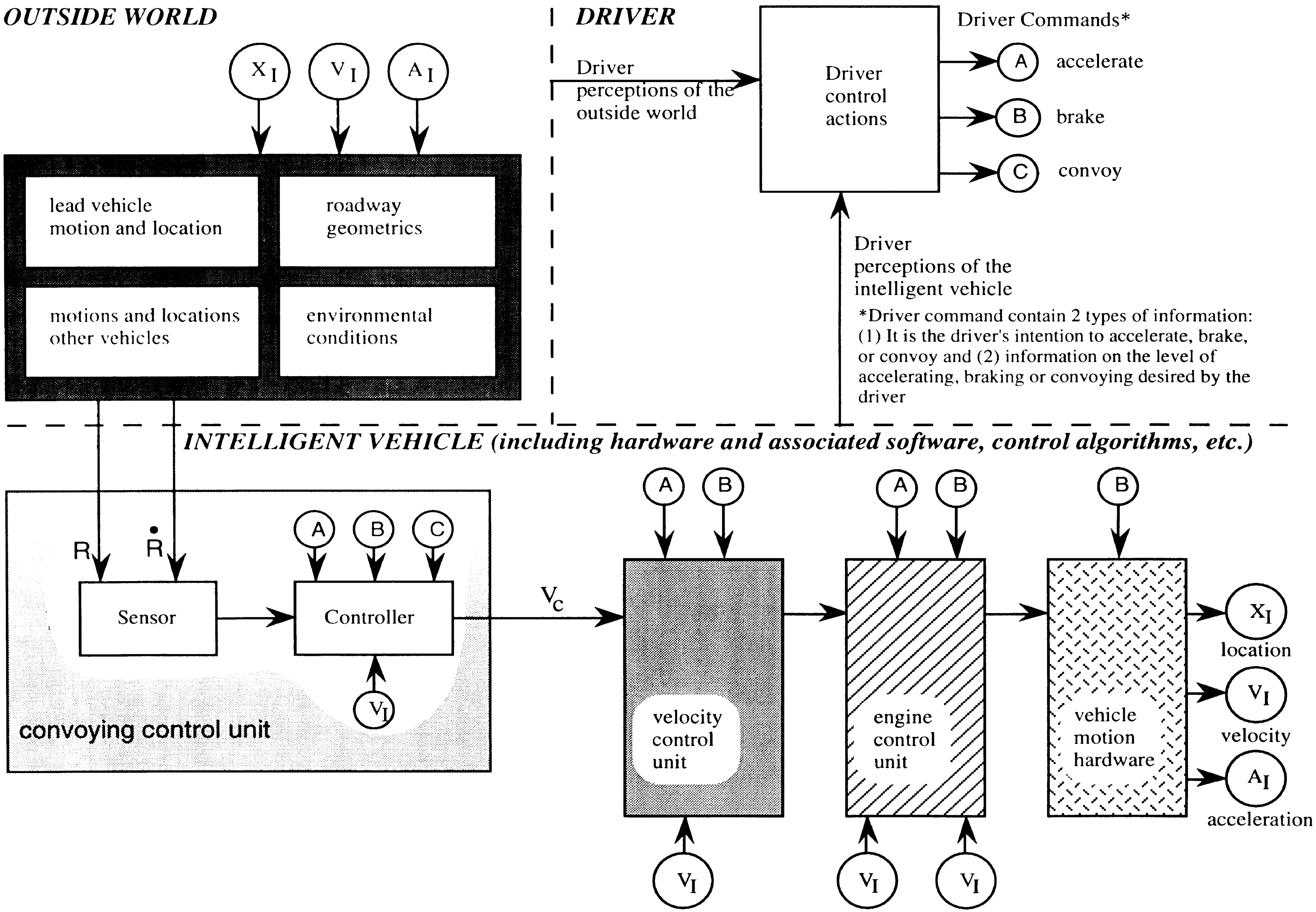

Figure 2. An overall system consisting of the outside world, a driver and an intelligent vehicle

the vehicle is accelerating or braking. Even in the convoy mode of operation, the driver can override the convoy control functionality by braking or accelerating.

In order to be in convoy operation, the driver turns on a convoy switch. The desired level of headway range is adjusted by the driver. The convoying control unit uses the desired range information to adjust vehicle speed as needed to acquire and maintain the desired range as well as it can. The input from the driver to the controller, labeled (C) in the convoying control unit in the overall system diagram (Figure 2), contains information indicating (1) that the driver intends to operate in a convoy fashion and (2) the level of desired headway range to the preceding vehicle in the convoy. The driver may change the headway range as instructed or as needed at any convenient time.

The primary difference to the driver between convoying and normal driving is that when the driver does not actuate the brake or the accelerator and the convoy switch is on, the vehicle does not coast as it would normally. Without the brake or accelerator activated, the convoying control unit performs its convoying function according to its own algorithm. The vehicle will speed up, slow down, or maintain speed as determined by the convoying rules built into the intelligent vehicle.

Clearly, Figure 2 can be viewed from many perspectives besides the driver's. This discussion emphasizes the driver's perspective because that seems to be closely associated with the military's role in evaluating the system. Nevertheless, Figure 2 provides an indication of other aspects of what the system will be like, particularly with respect to the intelligent vehicle. These aspects are generally more technical and more deterministic than those aspects of the system that are driver-related. Although the data requirement plan addresses matters that will influence driver opinions, the data gathering and processing activities proposed are primarily based upon deterministic measurements of system variables and logical signals defining system modes. These data provide the information needed to assess the functional capabilities of the system as provided by the properties of sensor, the control algorithm, and the vehicle itself.

2.0 DATA REQUIREMENTS

This section describes the data required for evaluating the performance of the headway-control system. The capabilities of the instrumentation required to acquire the data is discussed. Based on experience with data acquired while using a working headway-control system, it has been concluded that additional data items (that will be computed from the acquired data) are desired.

These computed data, which may be referred to as auxiliary variables, will provide additional information to be used in evaluating the performance of the convoy control system.

2.1 Description of Data

Basic data pertaining to: (1) the sensor, (2) the vehicle, (3) the driver, and (4) the controller will be used to evaluate convoy operations. The data pertain to each of these sources is discussed below.

Sensor Data

The sensor measures range (R) and range-rate (dR/dt) data pertaining to objects it detects. That information is fundamental to evaluating and controlling headway. The span of range values to be measured is from 50 to 300 feet (15 to 90 m), and range-rates from -20 ft/s to + 20 ft/s (± 14 mph, or ± 6 m/s). The desired accuracy for range data is ± 2 m, and ± 0.15 m/s for range-rate data. In this case, the precision of these measurements will depend upon the accuracy of the Eaton/VORAD sensor.

Vehicle Data

In the longitudinal direction, the essential vehicle data are velocity and acceleration. We plan to measure forward velocity over a range from 22 ft/s (15 mph, 7 m/s) to 110 ft/s (75 mph, 33 m/s). The desired accuracy is one percent. We may need to use a fifth wheel for this measurement if a good source of velocity is not available within the communication-buss system of the vehicle or at the speedometer.

The vehicle will be instrumented with an accelerometer for direct measurement of acceleration and deceleration. Available sensors are in the 1 to 2 g range with resolution down to 0.01 g. We will also use velocity and/or range-rate changes over measured periods of time to calculate decelerations especially when a resolution of better than 0.01 g is desired.

To identify when the vehicle is in a turn, yaw rate and steering wheel angle will be measured. This information is useful in identifying whether a target is in the sensor's field of view. The yaw rate is to be measured over a range of from – 20 deg/s to + 20 deg/s with a resolution of one percent. The steering wheel angle will be measured over the range of – 150° to + 150° with a resolution of two degrees.

Driver Data

"Driver data" refers to the actions taken by the driver to control forward velocity. The measured quantities include accelerator pedal position and brake actuation (yes or no). The brake actuation signal will be acquired from the brake light circuit. The accelerator pedal position is available from the electronic circuit for engine control. (If there is a problem with this, the foot pedal or linkage can be instrumented to produce a "yes / no" actuation indication.)

In addition, the desired cruise speed (or any other value of fixed-speed) set by the driver, and the driver's desired headway time setting will be recorded. This "system-setting" information will be used later to assess the quality of the controller's operation. These data items will be made available at the communication link between the driver's controls and the controller unit.

Controller Data

The controller pre-processes the range and range-rate data from the sensor to discriminate between targets that should be ignored (e.g., road signs), and valid targets for which speed adjustment should be considered. This boolean signal (valid or not valid) will be collected from a data serial port on the controller.

The controller's output commands to the vehicle's systems, available at the controller's communication link, will also be recorded. These signals include the commanded speed to the cruise control (with data range and accuracy similar to those of the forward velocity), the requested engine torque, and the required level of supplementary powertrain retardation. Engine torque data will span over the range of 0 to 1300 lb. ft., with a desired accuracy of 10 lb. ft. The required level of supplementary retardation will be obtained by monitoring the state of the retarder. The collected data will be of a Boolean nature: 0 for no retarder activity, and 1 for the retarder being applied (perhaps different levels depending upon the number of cylinders used).

2.2 Acquired Data

The array of data that needs to be collected to enable a proper analysis of the results is listed in Table 1 below. For each data item listed in the table, its description, units, and a possible acquisition source are provided. Data items that are written in **bold** are safety-related control parameters to be closely monitored during the tests.

2.3 Computed Data

In addition to the data collected during the tests, there are auxiliary variables that we wish to compute and evaluate. These auxiliary variables will be derived from the acquired data listed in Table 1, and will be appended to the original data files. The purpose of these variables is to enhance data processing by providing additional information concerning operating within, and transitioning between various control regimes such as those discussed earlier in section 1.3. A better understanding of driver's operating patterns can also be achieved. Table 2 lists the auxiliary variables that we plan to compute and store for later use.

Table 1. Acquired data items

Data Item	Symbol	Definition	Units	Acquisition Source
Sensor Data				
Range	R	Distance from the sensor to a detected object	ft	VORAD Sensor
Range Rate	Rdot	Rate of change of distance from the sensor to a detected object	fps	VORAD Sensor
Vehicle Data				
Velocity	V	Forward velocity of the headway-controlled truck	fps	Speed transducer
Acceleration	Ax	Forward acceleration of the vehicle	g	Accelerometer
Yaw Rate	Yr	Yaw rate of the vehicle	deg/sec	Yaw-rate transducer
Steering	Csw	Rotational position of the steering wheel	deg	String-pot transducer
Driver Data				
Accelerator	Cac	Accelerator pedal position	%	SAE data communication link
Brake	Lbr	Boolean variable indicating brake pedal status: 0 = brake pedal **is not** depressed 1 = brake pedal **is** depressed	(—)	Brake light circuit
Set speed	Vset	A maximum speed value not to be automatically exceeded; set by the driver	fps	Driver's display dial
Headway time	TH	Desired headway time	sec	Driver's display dial
Controller Data				
Valid target	Ltv	Boolean variable to filter detected objects: 1 = detected object **is** a valid target to consider and to possibly adjust headway to 0 = Otherwise	(—)	Controller algorithm
Command speed	Vc	Velocity command signal from the headway control	fps	Controller algorithm
Torque	Torque	Torque command signal to the engine	%	Controller algorithm
Sensor engaged	Sensor	Boolean variable indicating sensor data status: 0 = sensor data **is not** sent to the controller 1 = sensor data **is** sent to the controller	(—)	Driver's display switch

Table 2. Computed data items

Description of variable	***Expression***	***Units***
Available reaction time (for Rdot < 0)	$T_a = \frac{R}{V}$	sec
Measured headway time	$T_{hm} = \frac{R}{V_p}$	sec
Time to collision (for Rdot < 0)	$T_c = \frac{R}{-\text{Rdot}}$	sec
Target headway range	$R_h = T_h \cdot V_p$	ft
Velocity of the preceding vehicle	$V_p = \text{Rdot} + V$	fps
Minimum Required Deceleration to avoid a crash (for Rdot < 0)	$D_{req} = \frac{\text{Rdot}^2}{2 \cdot R}$	ft/sec/sec
Measured command velocity	$V_{cm} = Vp + \frac{R - R_h}{T}$	fps

APPENDIX D

REVISED TEST PLAN

1.0 GENERAL

This test plan has been devised for the project entitled "Control of Headway Between Successive Vehicles". Convoy operational scenarios have been studied, and pertinent experiments that are required to evaluate convoy performance impacts have been defined. Using an M-915 A2 vehicle, tests will be conducted at the Dana test track per this plan, and data will be collected in accordance with the data requirement plan that is presented in a separate document.

1.1 Purpose

The purpose of this plan is to describe various experiments that will be performed to evaluate the influence of a headway-control system on the performance of convoy operations.

1.2 Scope

Following a description of the test track and the constraints it imposes, the plan describes the intended tests. The plan provides a detailed description of the individual experiments that comprise the complete proving-ground testing of the system.

1.3 Test track

All the experiments that comprise this test plan will be conducted at Dana's test track, in Ottawa Lake, Michigan. Other experiments that are not part of the prescribed test plan, will cover highway operations, and will provide a qualitative assessment of the impacts that a headway-control system might have on convoy performance. This section describes the test track, and discusses constraints imposed by its geometry.

1.3.1 Description

The geometry of Dana's test track is portrayed in figure 1, together with its pertinent data. The curves are superelevated to support lateral acceleration, and the spiral sections are designed to provide a smooth transition between the straightways and the curves.

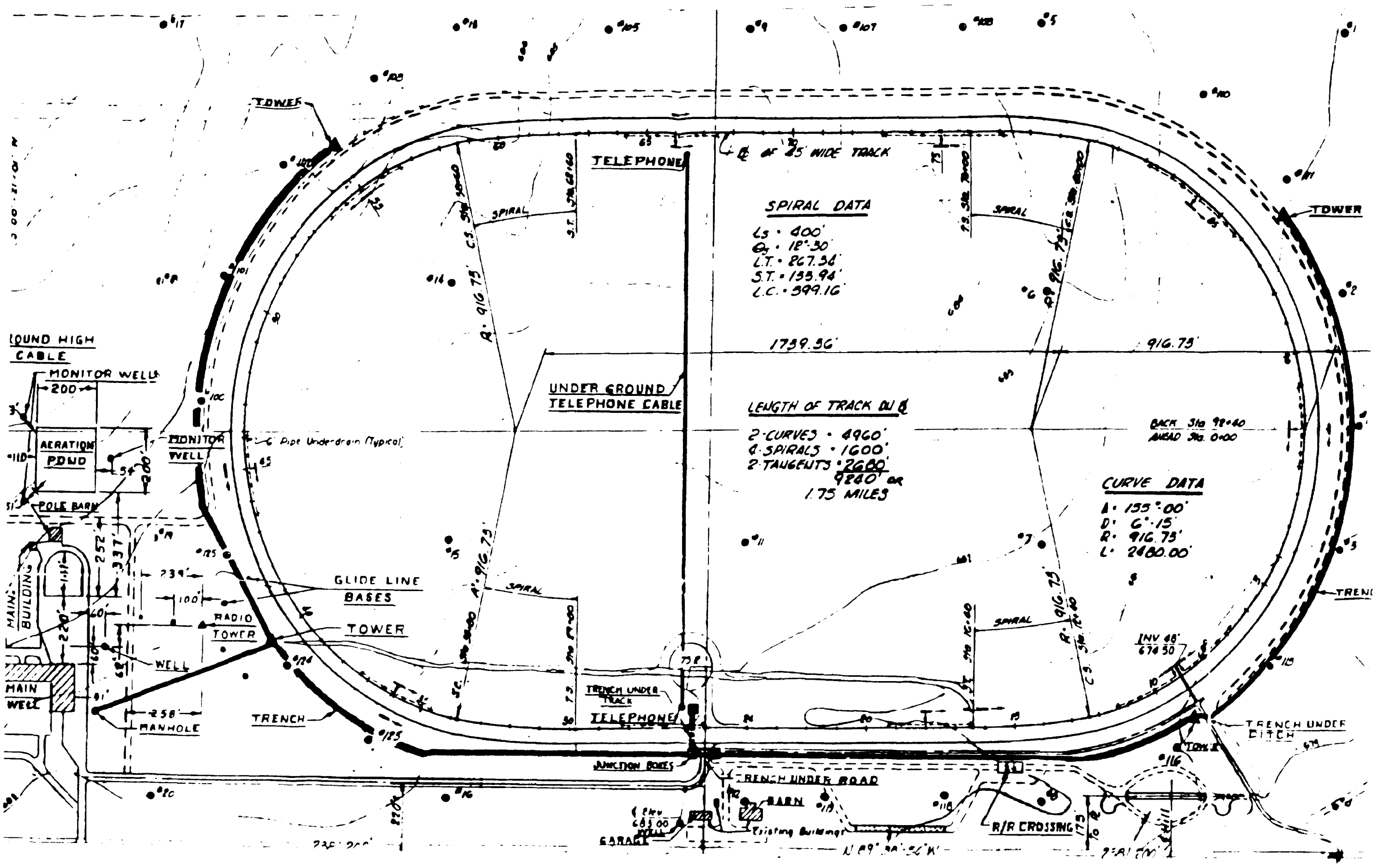

Figure 1. Dana's test track

1.3.2 Constraints

The sensor has a limited field of view that is only ±2 degrees sideways from its centerline, and ±3 degrees vertically. To test the headway-control system, it is imperative that the sensor is able to "see" the target. Under test conditions, no involuntary (as opposed to planned) loss of target should occur. Therefore, the experiments that are required to evaluate convoy performance impacts, would ideally involve a long, straight roadway. The test track however, as shown in Figure 1, has an oval shape with relatively sharp curves and rather short straightways. The constraints imposed by the geometry of the test track have been carefully accounted for in the process of preparing the test plan.

The primary problem involves the sensor loosing the lead vehicle, with both vehicles on the curve. From geometry, and by using the most favorable positioning (lead vehicle on the outermost lane and the test truck on the inside lane), the maximum range at which the lead vehicle is still "visible" to the sensor under such conditions, is close to 300 ft. Obviously, that range is sufficient when steady-state convoying is in process (at 50 mph and 2 seconds headway time, the required headway is 147 ft). However, situations other than steady-state convoying require significantly higher ranges, and some compensation by the driver of the leading vehicle is required to ensure that the lead vehicle is in the field of view of the sensor. This issue will be resolved through planning and hardware. Experiments that require large distances between the vehicles are planned to start at the beginning of the straightway, so that by the time the vehicles reach the curved section of the track they are close to each other. A sighting aid will be installed on the hood of the test truck to help the driver in maintaining the lead vehicle in the field of view of the sensor.

It is expected that after a few practice runs on the track, the drivers of both the lead vehicle and the test truck will learn to optimally position the vehicles. Radio communication for enhanced coordination and perhaps some visual markings on the track, will also be used to resolve conflicts and overcome the constraints.

2.0 TEST PLAN

2.1 Description of Test

As described before, the purpose of the test is to evaluate the influence of a headway-control system on convoy performance. Therefore, the test should address both the control system and the operation of a convoy. Different control conditions will be evaluated in conjunction with the pertinent convoy operation.

The tests involve various scenarios that are likely to occur during convoy operation. These scenarios cover the following operational situations:

- joining a convoy
- following a leading vehicle ("convoying")
- independent speed control (conventional cruise control)
- sudden target acquisition
- momentary target loss

The control regimes encountered in these operating situations are: (1) free travel with "no target in range", (2) target in range but no desire to control headway, and (3) control of headway to a preceding vehicle.

Each operating situation will be investigated using a specially devised test procedure for evaluating convoy performance in a carefully defined scenario.

2.2 Test Procedure

This section provides details concerning the individual experiments that comprise the complete proving-ground test of the system.

2.2.1 Joining a convoy

Scenario 1: A truck that was moving at an arbitrary speed, is joining the tail of a convoy. That truck could represent either an individual entity, or the "leader" of another string of vehicles. This situation entails closure on a preceding vehicle, and properly executing speed adaptation..

Hardware requirements: An instrumented M915-A2, a lead vehicle with cruise control, radio communication between the vehicles.

Procedure: Using its cruise control, the lead vehicle will be driven at a constant speed per table 1 below. The test truck will approach from behind, driven at the appropriate constant speed (see table 1). Effort should be made prior to the actual test to determine the relative initial position of the vehicles along the track, so that the speed adaptation will be mostly done on the straightway. The drivers should familiarize themselves with the optimal path on the curved portion of the track.

Duration: The experiment should be performed successfully once for each combination of speeds. A successful termination will be determined by the experimenter using the following guidelines: (1) executing speed adaptation with no exceptional events, (2) reaching and maintaining the final speed within approximately ±2 mph, (3) reaching and maintaining the target range within approximately 5% , (4) maintaining the steady state range and range rate for approximately 1 minute.

Table 1. Test matrix for joining a convoy

Trial No.	Speed (mph) Truck	Speed (mph) Lead vehicle	Headway time T_H (sec)	Target final range (ft)
1	50	40	1.5	88
2	50	35		77
3	40	30		66
4	40	25		55
5	50	40	2.0	117
6	50	35		103
7	40	35		103
8	40	30		88
9	40	25		73

Special instructions: At least 3 of the trials should be performed while driving in an opposite direction along the track.

2.2.2 Convoying

Scenario 2: Two vehicles are moving at a coordinated speed. In the course of this experiment the lead vehicle changes its speed to evaluate the fidelity with which the following test truck can adjust speed and maintain proper range. This situation represents a typical convoy operation.

Hardware requirements: An instrumented M915-A2, a lead vehicle with cruise control, radio communication between the vehicles.

Procedure: The experiment starts with the two vehicles moving at a coordinated speed, using automatic headway control. Once a steady state is established, it should be maintained for approximately 2 minutes. The lead vehicle should then change its speed and reset its cruise control to the new speed. An effort should be made to perform speed changes over the prescribed duration (see table 2). Each speed change may commence only after the required period of the initial steady-state following is completed. Once a new steady state at the final speed is obtained, it should be maintained for approximately 2 minutes. Table 2 below lists initial speeds, speed changes, time duration of maintaining steady-state, and approximated rates for speed changes.

Table 2. Test matrix for convoying

	Initial steady state		Final steady state		Speed change		
Trial No.	Speed (mph)	Desired range (ft)	Speed (mph)	Desired range (ft)	Acceleration (g)	Duration (sec)	Headway time (sec)
1	50	110	40	88	-0.10	3	
2	50	110	40	88	-0.05	6	
3	50	110	35	77	-0.10	5	
4	50	110	35	77	-0.05	9	
5	40	88	50	110	0.10	3	
6	40	88	50	110	0.02	16	
7	40	88	30	66	-0.10	3	
8	40	88	30	66	-0.05	6	1.5
9	30	66	50	110	0.10	6	
10	30	66	50	110	0.02	31	
11	30	66	40	88	0.02	16	
~~12~~	~~30~~	~~66~~	~~25~~	~~55~~	~~-0.10~~	~~2~~	
13	30	66	25	55	-0.05	3	
14	25	55	50	110	0.02	39	
15	25	55	40	88	0.02	23	
~~16~~	~~25~~	~~55~~	~~30~~	~~66~~	~~0.02~~	~~8~~	
17	50	147	40	117	-0.10	3	
18	50	147	35	103	-0.10	5	
19	40	117	30	88	-0.10	3	
20	40	117	30	88	-0.05	6	
21	30	88	40	117	0.02	16	2
22	30	88	25	73	-0.10	2	
23	30	88	25	73	-0.05	3	
24	25	73	40	117	0.02	23	
25	25	73	30	88	0.02	8	

Duration: The experiment should be perform successfully once for each speed (once for each row in table 2). A successful termination will be determined by the experimenter using the following guidelines: (1) executing speed changes with no exceptional events, (2) executing speed changes over the required periods, (3) reaching and maintaining speeds within approximately ±2 mph, (4) reaching and maintaining target ranges within approximately 5% , (5) fulfilling the approximately two-minutes requirement for maintaining steady state conditions.

Special instructions: Use an experimenter in the leading vehicle to aid in timing speed changes. At least 8 of the trials should be performed while driving in an opposite direction along the track. Those trials that involve deceleration rate of 0.1g and some of those with 0.05g, should activate the driver's warning signal. If the signal is not activated, the 0.1g trials should be repeated with increased deceleration (shorter duration) until the alarm is invoked. The experimenter should take note of such incidents.

2.2.3 Independent speed control

Scenario 3: The test truck is independently driven at an arbitrarily set speed. No lead vehicle or any other traffic is involved. That truck could represent either an individual entity, or the "leader" of another string of vehicles. This situation entails operation similar to a conventional cruise control.

Hardware requirements: An instrumented M915-A2.

Procedure: The experiment begins with the test truck steadily driven at a prescribed speed. At that time the speed control should be engaged to automatically control the speed. The system will be exercised in this experiment using four speed values: 20, 30, 40, 50 and 55 mph. For each speed, once a steady state is established it should be maintained for approximately 2 minutes.

Duration: The experiment should be perform successfully once for each speed. A successful termination will be determined by the experimenter using the following guidelines: (1) reaching and maintaining the prescribed speeds within approximately ±1 mph, (2) fulfilling the approximately two-minutes requirement for maintaining a steady state speed.

Special instructions: none

2.2.4 Sudden target

Scenario 4: A truck that is moving under either speed or headway control needs to respond to a target (a preceding vehicle) that appears suddenly. In the context of headway control and automatic convoying, "suddenly" means that the target appears too close to perform an orderly speed adaptation. This situation necessitates a more abrupt response than that for in 2.2.1. Distinction is also made between sudden targets that are slower than the test vehicle, and those that are faster.

Hardware requirements: An instrumented M915-A2, a lead vehicle with cruise control, radio communication between the vehicles.

Procedure: The experiment starts at the beginning of the straightway section of the track, with the lead vehicle and the test truck moving one behind the other at stabilized speeds per table 3 (using cruise control). During this stage of the experiment, the headway system is in an "ignore" mode. The "ignore" mode is a unique testing mode: even though a target might be detected by the system, no control action is taken. When the range between the vehicles is at the "cut-in" value, the experimenter switches the headway system from "ignore" to normal mode, thus obtaining the effect of a suddenly acquired target. Required accuracies for parameters in table 3: cut-in range at the point of cut in is approximately ±5 ft, speed of vehicles is approximately ±1 mph.

Duration: The experiment should be performed successfully 16 times: eight cut-in speeds, and two headway time settings. A successful termination of a step will be determined by the experimenter using the following guidelines: (1) execution within the speed and range tolerances prescribed above, and (2) having the test truck properly respond to the cut-in target (adjust its speed or ignore), and maintaining a steady state for approximately two-minutes.

Table 3. Test matrix for sudden target

			Cut-in range (ft)	
Trial No.	Speed of test truck (mph)	Speed of lead vehicle (mph)	$T_H = 1.5$ **A**	$T_H = 2.0$ **B**
1		30		140
2		35	75	130
3		35	175	190
4	50	40	90	170
5		40	145	100
6		45	85	100
7		51	90	100
8		55	45	70

Special instructions: Use an experimenter in the test truck to aid in timing cut-in point. At least 2 of the trials should be performed while driving in an opposite direction along the track. Trials 1, 2, 4, and 6 involve deceleration rates that should activate the driver's warning signal. If the signal is not activated, these trials should be repeated with increased deceleration (lower speeds of lead vehicle) until the alarm is invoked. The experimenter should take note of such incidents.

2.2.5 Momentary target loss

Scenario 5: A truck that was moving under headway control in a convoy, needs to respond to a momentary target loss. In the context of headway control and automatic convoying, "momentary target loss" means that a target that has been steadily followed, disappears for a brief period, and is soon detected again. During that period, change in speed is either minor and does not reach a steady state, or does not take place at all. Momentary target loss can occur when the convoy goes through a relatively sharp curve, or if due to some environmental conditions the preceding vehicle becomes temporarily invisible to the sensor, or perhaps the shape and materials of that vehicle might have some "stealth" properties that encumber its detection by the sensor. This experiment addresses the ability of the system to sustain a smooth operation during questionable situations.

Hardware requirements: An instrumented M915-A2, a lead vehicle with cruise control, radio communication between the vehicles.

Procedure: The experimental starting point is at the beginning of the straightway section of the track, with the two vehicles moving as a convoy at a coordinated speed. The speed of the convoy will be determined by the cruise control of the lead vehicle. However, the cruise control "set speed" of the headway-controlled test truck will be set to 50 mph. At the starting point, the experimenter switches the headway system from normal to "ignore" mode as if the target was momentary lost, and then after the prescribed period, the system is switched back to normal as if the target were re-acquired. Three convoy speeds will be experimented with: 40, 30, and 20 mph. For each speed, three "target loss periods" will be examined: 3 seconds, 6 seconds, and 9 seconds. The complete procedure should be performed twice: once for a convoy operated at 1.5 seconds headway, and once for 2 seconds (see table 4).

Table 4. Test matrix for momentary target loss

Headway Time (sec)	Convoy Speed (mph)	Period of Target Loss (sec)
1.5	20	3
		6
		9
	30	3
		6
		9
	40	3
		6
		9
2.0	20	3
		6
		9
	30	3
		6
		9
	40	3
		6
		9
	50	3
		6
		9

Duration: The experiment should be perform successfully 18 times: three speeds, three target loss periods for each speed, and two headway time settings. A successful termination of a step will be determined by the experimenter after the test truck has automatically adjusted its speed to that of the cut-in target, and a steady state was maintained for approximately two-minutes.

Special instructions: Use an experimenter in the test truck to time target re-acquisition point.

APPENDIX E

A SAMPLE DATA SET

Within the framework of this project an extensive set of tests was performed on DANA's test track. These tests were constructed in such a way, so as to represent typical scenarios that might be anticipated during a convoy operation. This appendix presents a sample data output from such a test.

The example shown here (Figure E-1 through 8) represents a convoy that goes through a speed change from 40 to 30 mph. At first, the convoy is driven at a constant speed of 40 mph (58 fps). That is during the time period of 0-35 sec. On the figures, that period is inscribed by **A**. The range is about constant at 120 ft, and the range rate is zero (no relative speed between the leading and the trailing vehicles). Torque command to the engine is changing around 30% due to variations in elevation along the testing course. The course is elliptical, as shown by the steering and yaw data. When the lead vehicle slows to 30 mph (44 fps), the truck also slows down and adjusts its speed (**B** on the plots). The range rate drops to a negative value as the truck closes on the lead vehicle, and the range drops to a minimum of approx. 25 ft. At that time the torque command to the engine is zero as we need to decelerate. As the speed of the truck is adjusted, the range rate becomes positive, and slowly returns to zero as it should for good speed tracking. The range also gets to the desired range value of 88 ft.

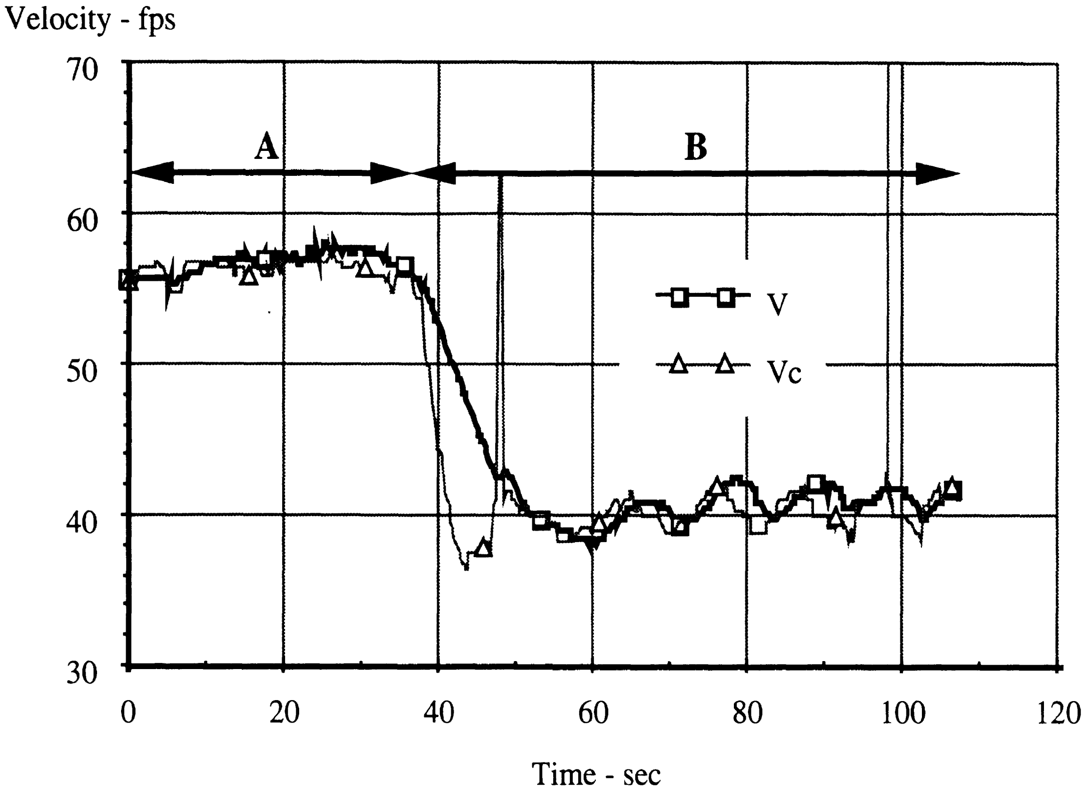

Figure E-1. Actual speed and commanded speed when a convoy slows down

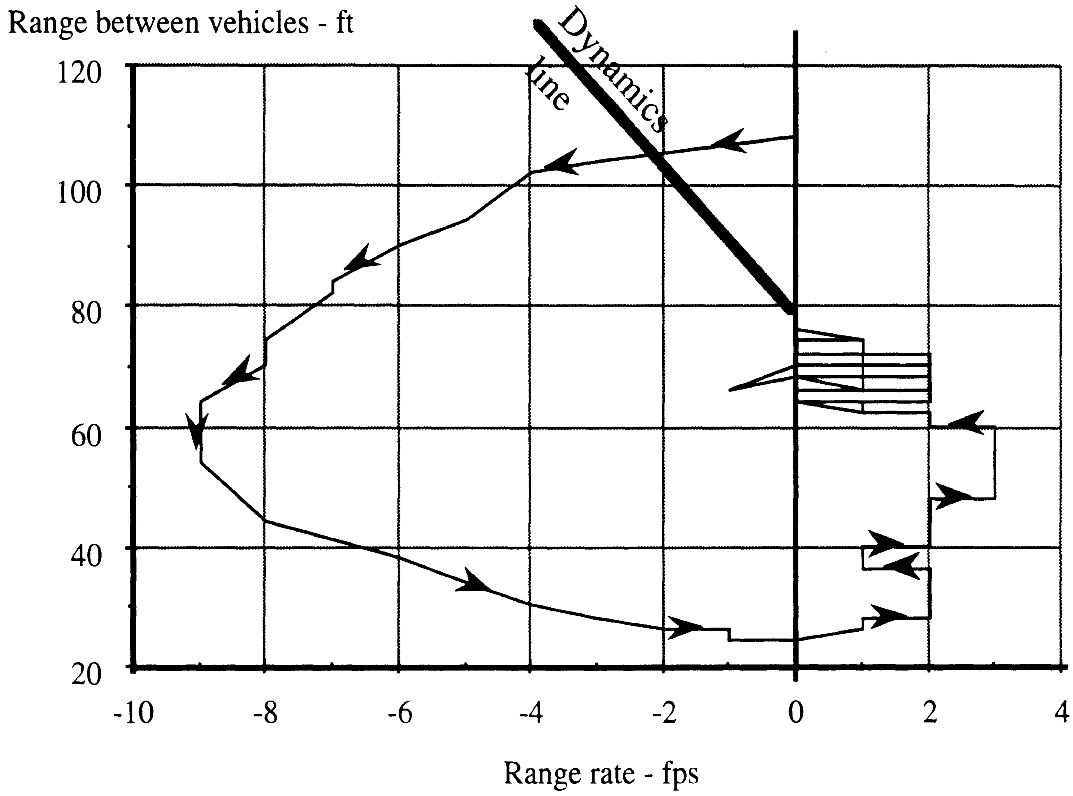

Figure E-2. Range versus range rate when a convoy slows down

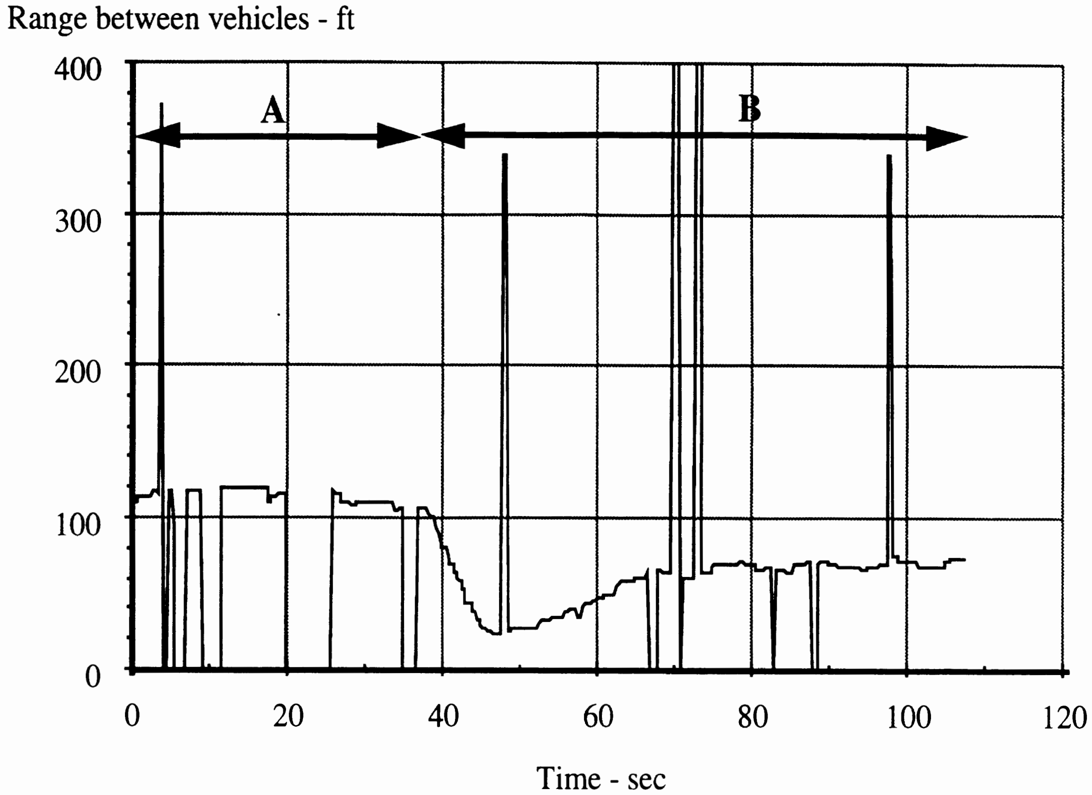

Figure E-3. Range versus time when a convoy slows down

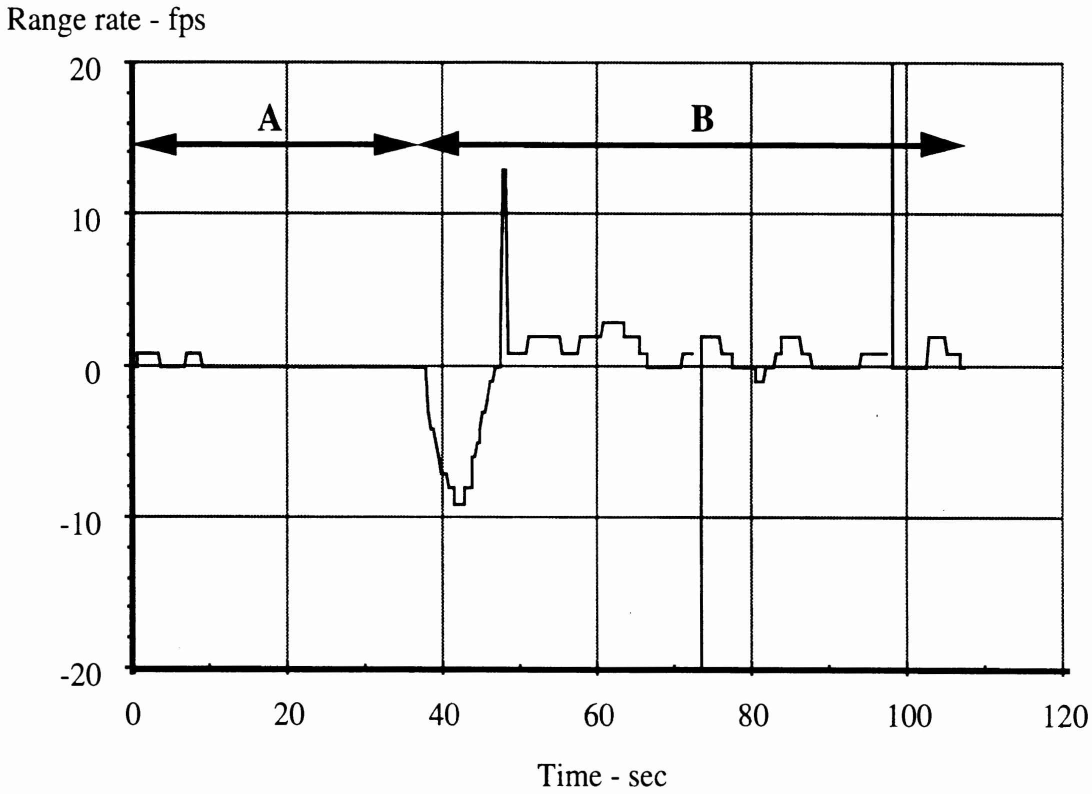

Figure E-4. Range rate versus time when a convoy slows down

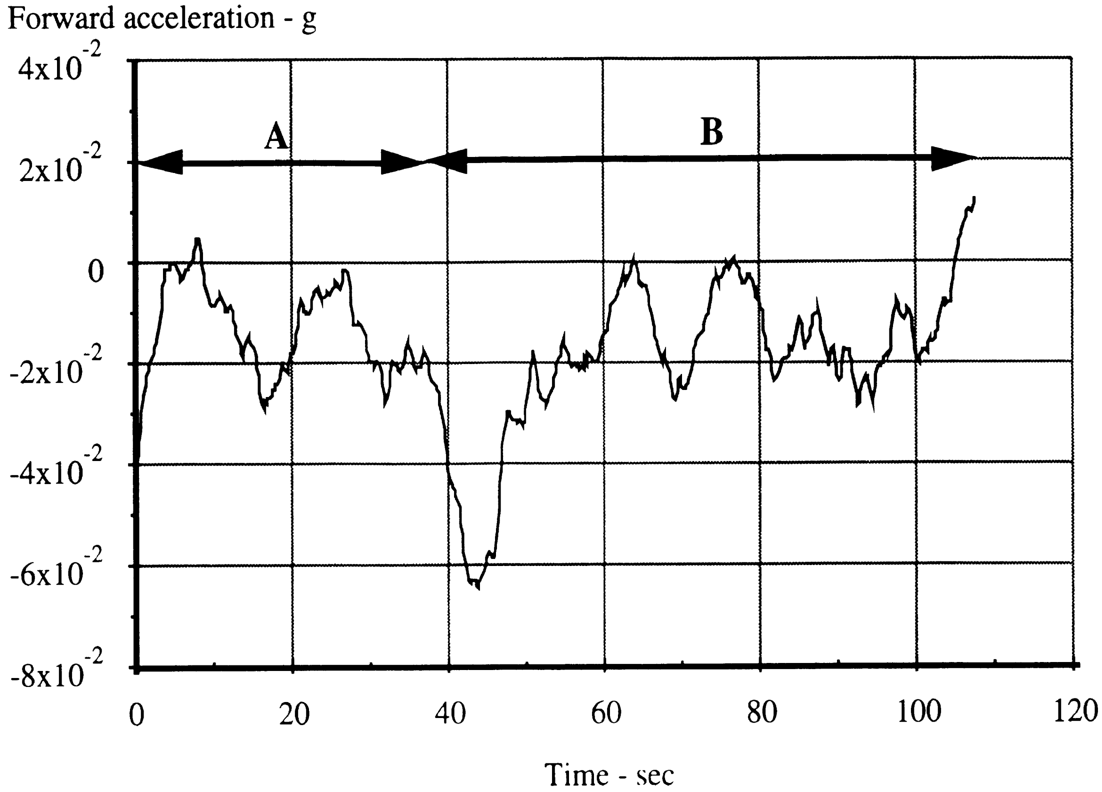

Figure E-5. Longitudinal acceleration when a convoy slows down

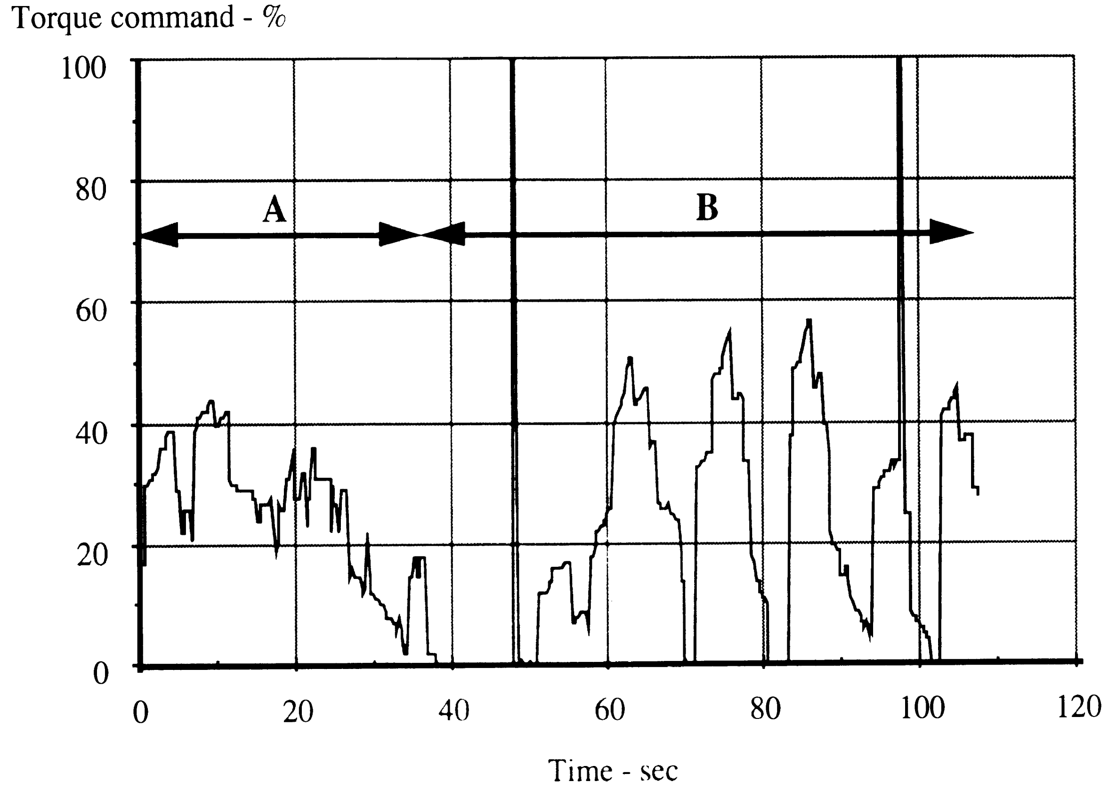

Figure E-6. Torque command to the engine when a convoy slows down

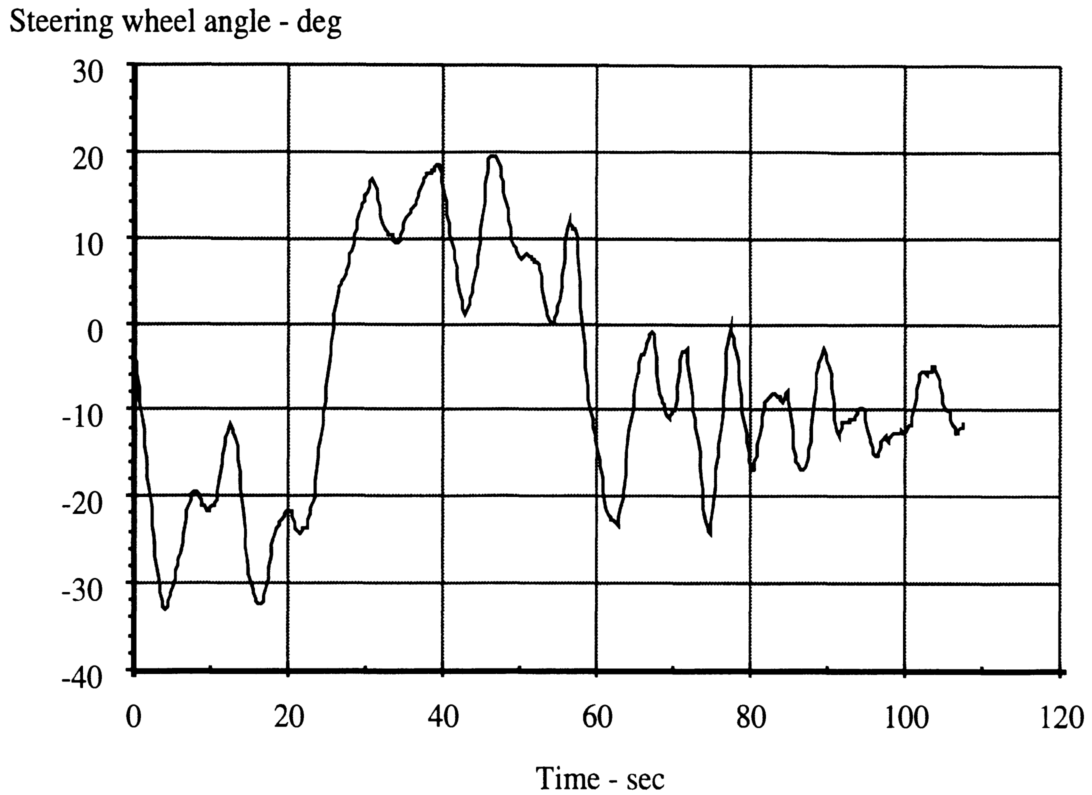

Figure E-7. Steering angle versus time when a convoy slows down

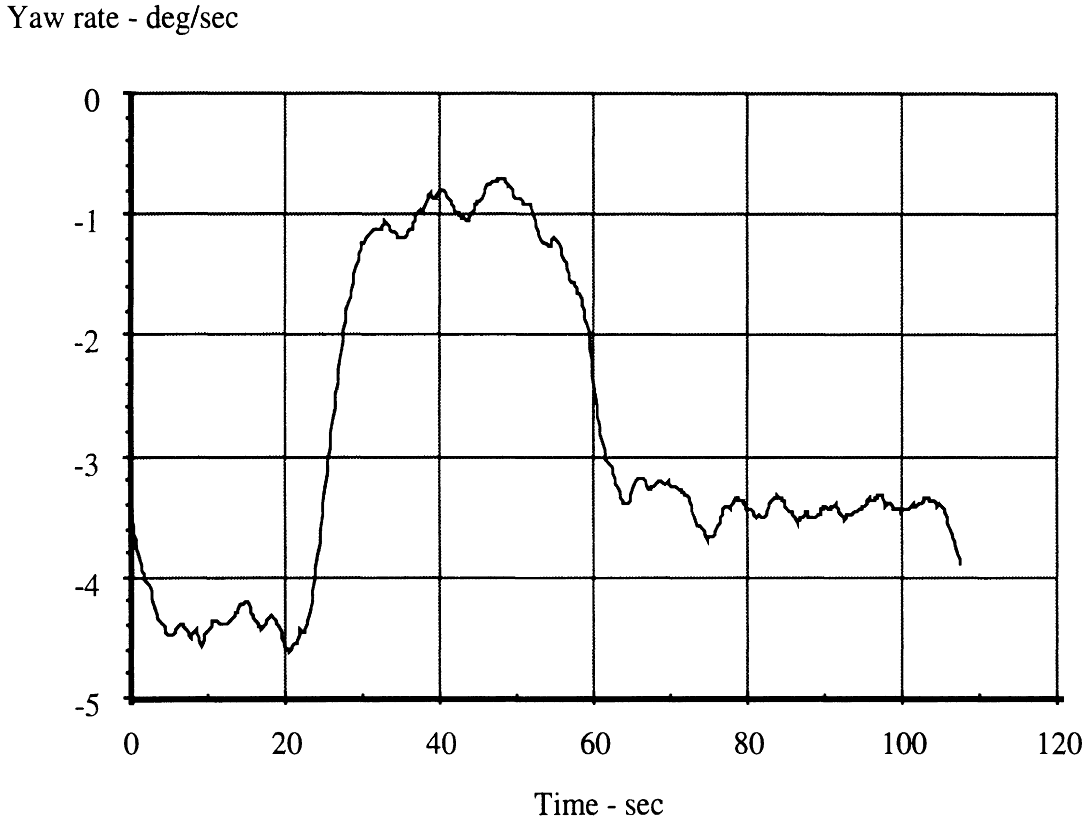

Figure E-8. Yaw rate versus time when a convoy slows down