Headway Control Systems And The Heavy Commercial Vehicle—A Case Study

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ABSTRACT

The addition of control systems to highway vehicles has received considerable attention in recent years. Much of this work pertains to the development of control systems for passenger cars. However, since the power-to-weight ratios of heavy trucks make them quite different from passenger cars with regard to maintaining speed and headway, heavy trucks merit special attention. This paper focuses on a headway-control system that was designed and installed in a commercial heavy duty tractor-semitrailer combination. The project involved design, simulation, testing, and performance evaluation of the system.

The headway control system described in this paper, utilizes a range and range-rate sensor to determine whether the road is clear. If the road is clear, the system acts as a conventional cruise control. If a slower moving vehicle is detected, the system switches to a headway control mode, whereupon it utilizes information from the sensor to maintain a prescribed headway.

Principles of design are presented, experimental results are presented and analyzed, and a methodology for testing such headway-control systems is suggested. These experimental results are used to highlight and evaluate the engineering measures needed to characterize system performance under various conditions of road geometry, traffic, and maneuvering scenarios. Operational aspects of the use of headway control systems in the environment of heavy-duty trucking are discussed.

This paper will be useful to any parties concerned with developing, evaluating or specifying headway control or other systems in the longitudinal collision avoidance class of functionality.

INTRODUCTION

This paper stems from a research project that was performed by the University of Michigan Transportation Research Institute (UMTRI), for the research center of the US Tank and Automotive Command (TACOM). The objective of this study was to develop a physical testbed for evaluating the headway-control capabilities of heavy military trucks. The ultimate goal was 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. Particular areas of interest concerned collision avoidance and task automation. The task that was being automated is the control of headway distance as is applicable to military convoying operations involving heavy vehicles. The control of distance 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. 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.

The work involved installing an instrumentation system specially devised by UMTRI for data gathering, developing and installing a flexible headway control unit, and also installing an Eaton/Vorad range and range-rate sensor into an M-915A2 Army truck. The research combined the knowledge and experience of the Army in convoying operations, with the capabilities of UMTRI, Eaton, and Detroit Diesel.

DUAL-USE HYPOTHESIS

A synergy exists between the Army's interest in automating vehicular driving functions, 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 were 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;

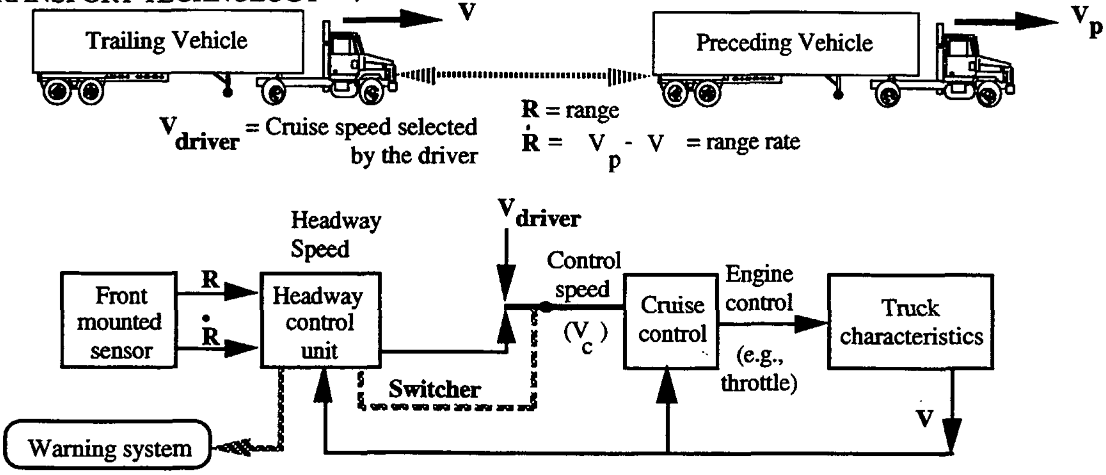

Figure 1. Headway control

- 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;
- The headway-control system can provide a temporary compensation for an inadvertent lack of driver's attention;
- Critical headway situations can be detected and warnings can be provided;
- The overall safety of convoy operation can be increased.

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.

DESIGN PRINCIPLES

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 Rdot and R to maintain a specifically desired value of headway range (R_h) corresponding to the condition $V = V_p$.

In short, the problem is devising 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.

This section describes the theory as applied to the headway-control algorithm, and the setup of the control system in the test truck. It also describes basic principles and considerations that serve as ground rules in the design of the controller. In addition, various control inputs that affect system's performance are discussed.

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 and range-rate 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.

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. 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.

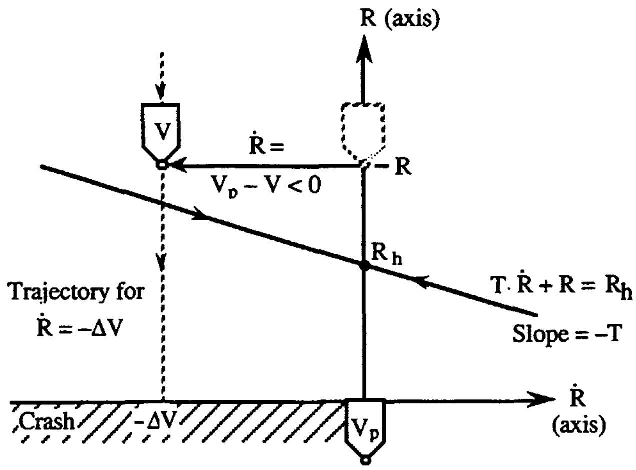

Figure 2. Headway control in the (Rdot, R) space

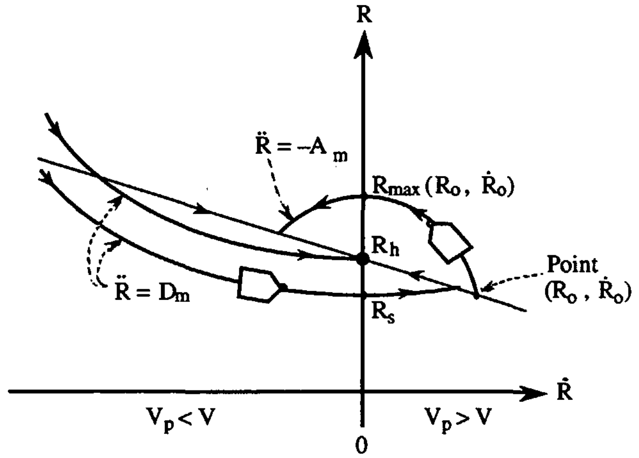

Figure 3. Parabolic trajectories of constant acceleration

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:

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

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,

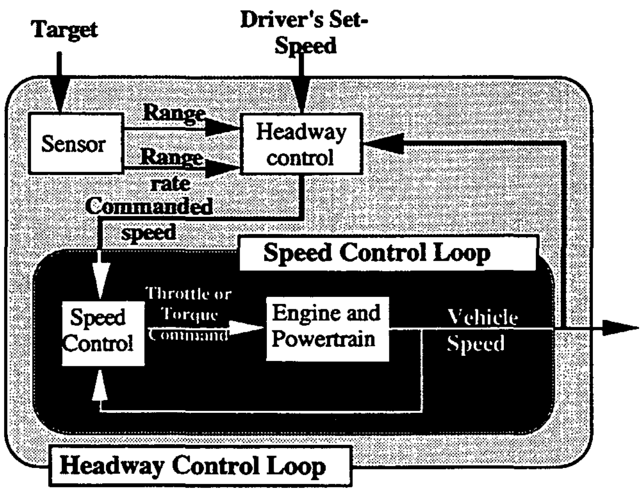

Figure 4. Headway control and speed control loops used in intelligent cruise control

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:

$dRdot/dt = -D_m$ for deceleration, and (2)

$dRdot/dt = A_m$ for acceleration. (3)

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

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. The section entitled "testing methodology for headway-control systems" described some peculiar locations and trajectories in the Rdot-R space that are of interest to highway operations of trucks.

CONTROL SETUP OF THE TESTBED

The function of intelligent cruise control is achieved by employing two control loops: (1) speed control, and (2) headway control. Figure 4 depicts these two control loops as distinct loops. Such a system 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 5.

The ICC 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 ICC 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 (δ_d).

The status of the sensor "enable" switch determines whether the data from the sensor is being relayed to the controller or not. This switch was installed for experimental and practical purposes: (1) some of the experiments required that the preceding vehicle is "invisible" for the system (see the section "testing methodology for headway-control systems"), and (2) 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, so it can operate like a conventional cruise control.

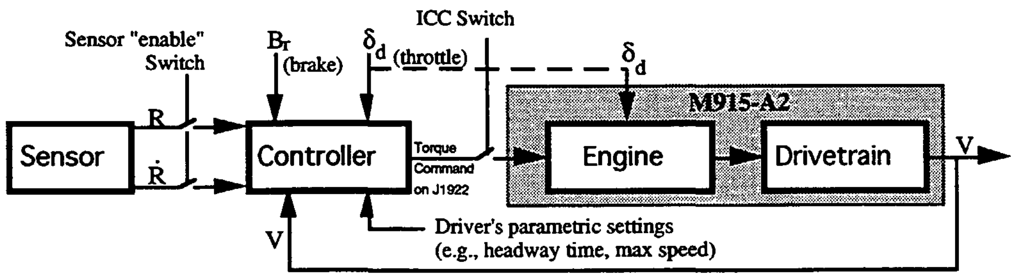

Figure 5. Control setup as implemented in the testbed

CONTROLLER DESIGN

In order to design such a prototypic headway-control system and to devise a plan to evaluate the impacts such a system might have on the way truck-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 M915-A2 truck.

It should be noted that the set of operative rules used here for the design of the controller, is strictly for the operation of military convoys. The controller can be programmed to accept any set of rules desired by the commercial user. Clearly, as it will be discussed later, commercial operation of heavy-duty trucks will entail a different set of "control-rules" than those outlined here.

Once the ICC-equipped truck (the "follower"), is positioned behind another vehicle (the "leader"), 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 study, and the corresponding corrective actions by the system, are described below.

- 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 re-initiate the system.

CONTROL INPUTS

There are four logical control inputs to the system that affect its operation. These control inputs are signals from (1) the accelerator pedal, (2) the brake pedal, (3) the sensing device, or (4) the ICC 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 6 depicts the logic that determines proper action by the system as a response to various possible combinations of control inputs.

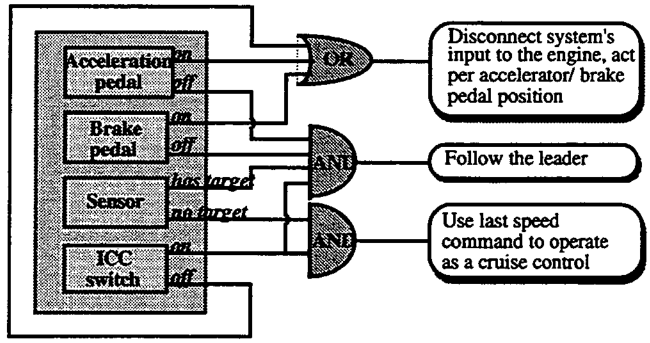

Figure 6. System's logic and control inputs

TESTING METHODOLOGY FOR HEADWAY-CONTROL SYSTEMS

The purpose of the testing is twofold: (1) to assess the utility and the functionality of the headway-control system, and (2) to evaluate the influence of the system on pertinent operational characteristics of the truck's performance. Therefore, the test addresses both the control system and the operation of a heavy-duty truck. Different control conditions are evaluated in conjunction with pertinent driving operation.

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

- approaching a "leader"
- following a "leader"
- independent speed control (conventional cruise control)
- sudden target acquisition ("cut-in")
- momentary target loss

Each operating situation is investigated using a specially devised test procedure. This section provides details concerning the individual experiments that comprise a proving-ground test for a headway-control system. Most of the tests involve using another vehicle as the lead vehicle. It is recommended that this vehicle is equipped with cruise control, and that radio communication exists between the vehicles.

APPROACHING A "LEADER" TEST

Using its cruise control, the lead vehicle is driven at a prescribed constant speed. The test truck approaches from behind, driven at a faster prescribed constant speed. In planning the test, a table should be prepared with several prescribed speed pairs: leader's speed, and the speed of the converging truck. If the test track is oval, effort should be made to ensure that the speed adaptation will be done on the straightway. Rules to determine when an experiment is completed are established in advance.

Approaching a leader, as expressed in terms of a typical trajectory in the Rdot-R space, is depicted in Figure 7. The important aspects of the headway controller with regard to approaching a leader are summarized by the design choices for T, D_m, and T_h.

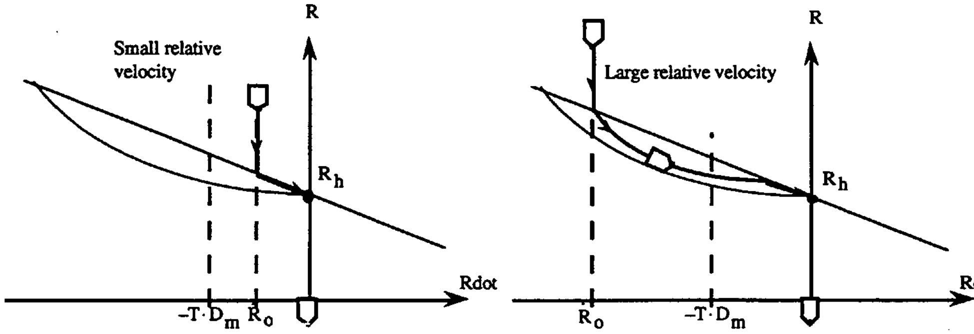

Figure 7. Approaching a "leader"

FOLLOWING A "LEADER" TEST

The experiment starts with the two vehicles moving at a coordinated speed, using automatic headway control. The lead vehicle then changes its speed at a prescribed rate of deceleration, and resets its cruise control to a prescribed new speed. In planning the test, a table should be prepared with several prescribed initial speeds, final speeds, and leader's deceleration rates.

The desired region of operation in the Rdot-R space during following, is shown in Figure 8. The important aspects of the headway controller with regard to following a leader are the boundaries that define the "eye" around R_h in Figure 8.

During the speed-change phase, various combinations of headway range and rate of deceleration of the leader, will result in various Rdot-R trajectories. Some of these combinations could be handled by the headway-control system, and some will necessitate driver's intervention by applying the brakes. Figure 9 illustrates the various possible situations.

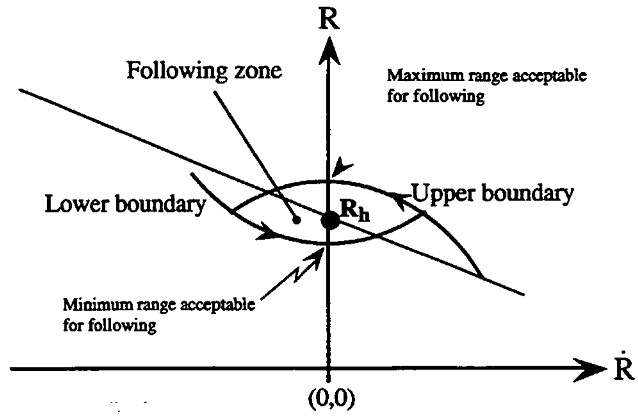

Figure 8. Desired region of operation during following

INDEPENDENT SPEED CONTROL TEST

In this experiment, the test truck is driven steadily at a prescribed speed (no leader). The speed control should be engaged to automatically control the speed. The system should be exercised in this experiment using several prescribed speed values.

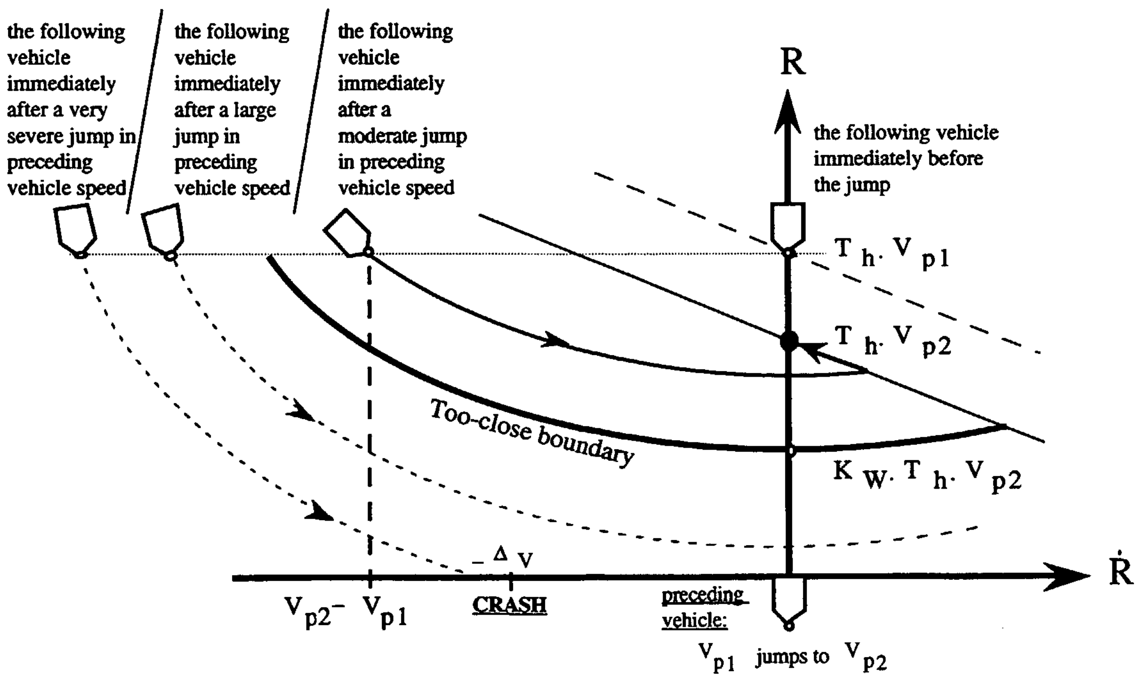

Figure 9. A step change in Vp

SUDDEN TARGET ACQUISITION TEST

The experiment starts with the lead vehicle and the test truck moving one behind the other at certain stabilized speeds (using cruise control, not the headway control). During this stage of the experiment, the sensor "enable" switch is set to "off". By doing so, the sensor ignores the lead vehicle, and no control action is taken by the headway-control system. When the range between the vehicles is at a prescribed "cut-in" value, the experimenter switches the sensor "enable" switch to "on", thus obtaining the effect of a suddenly acquired target. In planning the test, a table should be prepared with several prescribed initial speeds, "cut-in" values, and headway times.

Figure 10 shows the form of trajectories that are typical for this driving situation. The quantity R_{min} shown in Figure 10 defines a safety margin in terms of a minimum range. 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 such a sudden target are summarized by the choices of R_{min} and D_m as well as A_m and T and T_h.

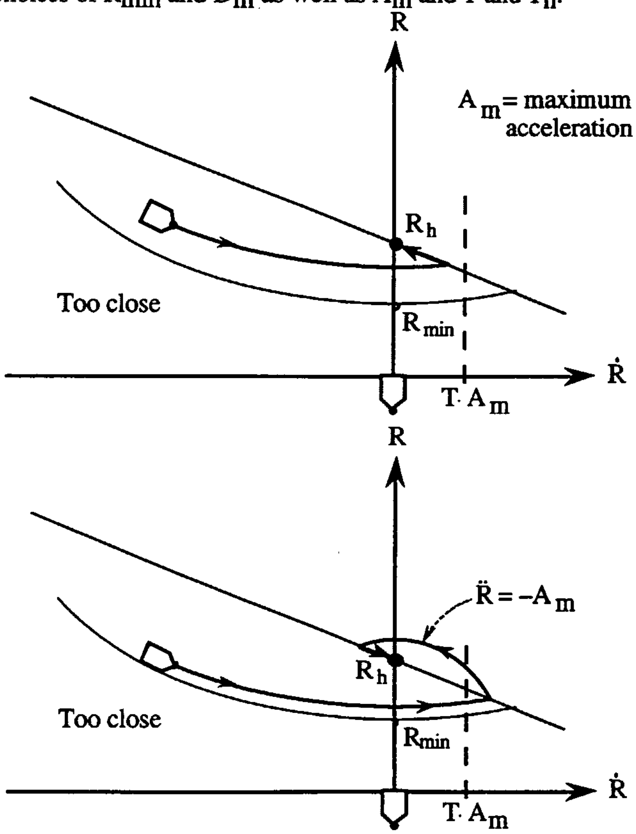

Figure 10. Sudden target acquisition

MOMENTARY TARGET LOSS TEST

The starting point is with the two vehicles moving as a pair at a coordinated speed using headway control. The speed is determined by the cruise control of the lead vehicle. However, the cruise control "set speed" of the headway-controlled test truck should be set to some higher prescribed value. The experimenter then switches the sensor "enable" switch to "off" as if the target was momentary lost, and then after a prescribed period, the sensor "enable" switch is switched back to "on", as if the target were re-acquired. In planning the test, a table should be prepared with several prescribed following speeds, "target loss periods", and headway times.

EXPERIMENTAL RESULTS AND FINDINGS (R&F)

By properly processing data that are collected during testing, one can identify the system's capabilities and limitations. Table 1 summarizes the data items 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 approaching a "leader" — how far ahead can the system "see" and identify a target to follow? (*sensor capability*)
2. When following a "leader" — what is the variation in range rate during a following mode (maintaining constant headway at a constant speed)? (*controller performance*) How close are we to the desired range? (*controller 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 (beyond these limits the driver "takes-over")? (*truck longitudinal dynamics*)
3. During a conventional cruise-control operation — how closely does the system maintain the desired speed? (*controller performance*)
4. When a target shows suddenly ("cut-in") — what are the limits up to which the system can accommodate the situation and autonomously perform the necessary adjustments? (*truck longitudinal dynamics*)
5. When a target is lost momentarily (e.g., around a curve) — Does the driver need to intervene? (*controller 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 performance and sensor capability*)

Table 1. Data items collected

Headway-test data	
Range	Yaw rate
Range rate	Steering
Velocity	Brake pedal
Longitudinal acceleration	Set speed
Throttle (engine)	Desired headway time
Accelerator (pedal)	Headway commanded speed

APPROACHING A "LEADER" (R&F)

The test plan contained a total of nine situations, four of which were with a headway time of 1.5 seconds, and five with a headway time of 2.0 seconds.

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. Data "drop-outs" might occur more frequently if the target (the lead vehicle) is at a range higher than 200ft. Given this initial detection range, and given the dynamics of a heavy-duty truck and its deceleration capacity (without using brakes), it became evident that the speed differential at the time of detection should not exceed 15–20 mph. If the initial closure rate exceeds that value, it is likely that the driver will have to use the brakes.

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.

FOLLOWING A "LEADER" (R&F)

This experiment entailed 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. Also, two levels of deceleration rates by the lead vehicle were exercised. The results of this test could be viewed in two parts: (1) following, and (2) speed change.

During the "following" part of the experiment, the range-rate values were mostly bounded by ±1fps (see Figure 11). Given the inertia of the truck and its low power-to-weight ratio which caused it to be somewhat sluggish in its longitudinal response, this performance level can be considered satisfactory.

Similarly, the average range error (deviation of the actual range from the desired range) during this part of the experiment, was found to be small enough. The results given in Figure 12 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.

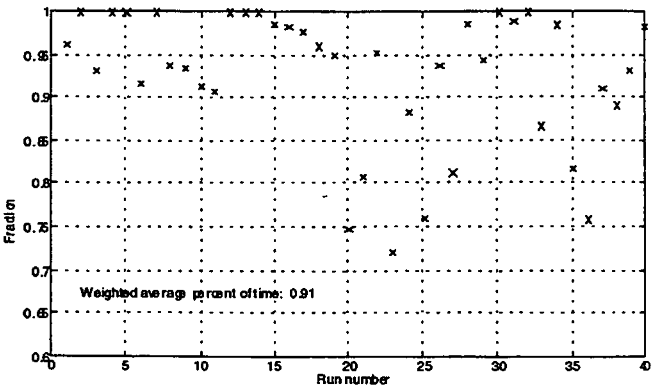

Figure 11. Fraction of time range rate was ±1fps during following

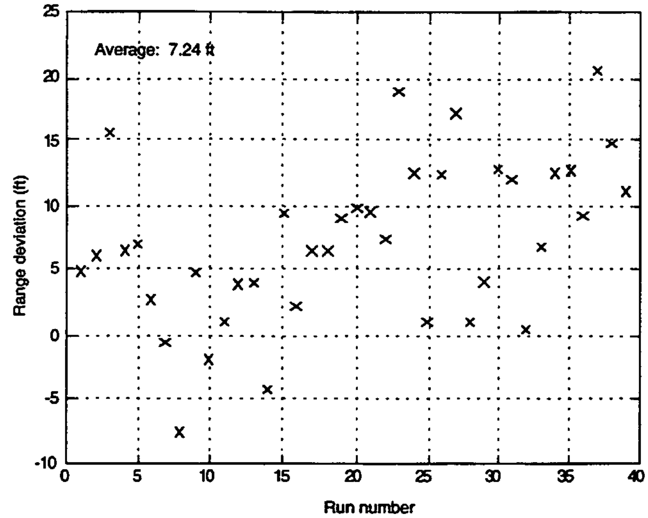

Figure 12. Average deviation of range (R_h–R) during following

Since the test plan was designed to examine not only the system's performance, but also its boundaries, not all speed-changing maneuvers were expected to be within the capacity of the system. 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. Figure 13 depicts the results of this part of the test. Each individual point represents a speed change by the lead vehicle and the deceleration rate. The headway time is also denoted, and those speed changes that necessitated braking by the driver of the following vehicle, are also shown.

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 (a) those speed changes and deceleration levels that will necessitate braking by the driver and (b) those that the system will be capable of handling autonomously.

When the lead vehicle changes its speed, it takes some time for the following vehicle to respond. The deceleration level that is employed is limited by the maximum coast-down deceleration (D_m) of the truck (including the retarder,

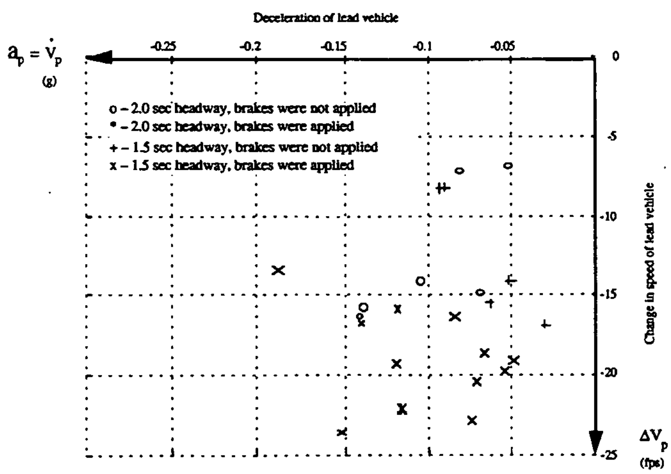

Figure 13. Braking results for speed changes by the lead vehicle

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. If the driver of the truck feels that the speed adjustment cannot be executed without a crash, or without crossing the driver's prescribed safety margin, the driver intervenes by employing the brakes.

Using time-distance-speed-deceleration relationships written to represent the speed adjustment process, an expression for ΔV_p can be derived; viz.,

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

where:

- D_m is the maximum coast-down deceleration of the following truck (fraction, 0 to 1g)
- ø 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)

Equation (4) was applied to the data in Figure 13. The results are represented by "lines of constant V_{p0}", and they are drawn in Figure 14 (for a 1.5 sec. headway time). The pertinent test data are also shown. Comparisons indicate that equation (4) is a reasonable predictor for the need to brake.

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., $a_p < 0.1g$). 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 headway 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 disconnecting headway operation altogether. Incidentally, the same feature applies to accelerator use also, so that the driver can speed up to trim the vehicle's position as desired.)

INDEPENDENT SPEED CONTROL (R&F)

This test entailed a total of five trials, each involves maintaining a different speed. The results showed that on an average, the truck was within 0.027 fps of the desired speed — which is practically zero. It appears that the speed control of the truck performs in a satisfactory manner to maintain a constant speed.

SUDDEN TARGET ACQUISITION (R&F)

This test simulates a "cut-in" situation, or a target that appears too close for the execution of an orderly speed adjustment (as in approaching a leader). A total of sixteen trials was executed: eight cut-in speeds, and two headway times.

The primary objective of this experiment was to explore the controller's performance envelope in the sense that it will handle or fail to handle certain cut-in situations, and to establish a boundary beyond which driver's intervention is called for. The results of the tests are depicted in Figures 15 and 16.

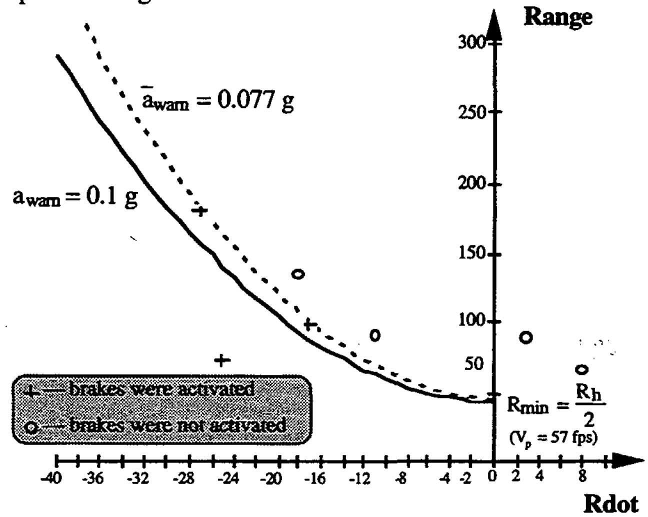

Figure 15. Deceleration boundary that calls for driver's intervention, T_h=1.5 sec.

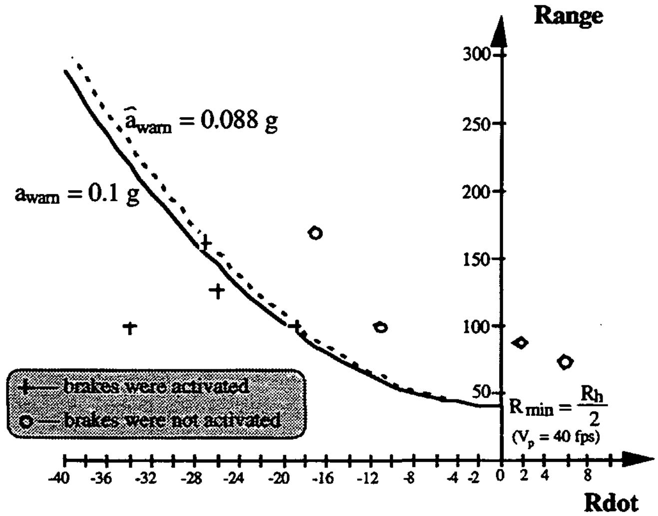

Figure 16. Deceleration boundary that calls for driver's intervention, T_h=2.0 sec.

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

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

Observing Figures 15 and 16, 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, for highway operations, a more conservative warning line might be recommended. It might indeed trigger some false alarms (unnecessary warnings), but it will minimize belated alarms. It appears that 0.05g (for all headway times) will appropriately serve this purpose.

MOMENTARY TARGET LOSS (R&F)

This test simulates situations when the sensor loses the target momentarily (e.g., driving around a curve). A total of twenty-one trials were executed. The primary objective of this experiment was to verify the controller's ability to handle questionable no-target situations.

The design of this particular control system was such, that in a case of a target loss (momentary or permanent), the last speed command was maintained. Therefore, due to this inherent safety feature that was built into the system's design, it was assumed that the system will safely 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. However, it should be noted, that in a commercial application of such headway-control system, the logic is likely to be different. If that logic is designed so that in a case of "no target" the system resumes to the driver's set speed — which will probably be higher that the last speed command — a momentary target loss might have a more detrimental effect on the system's performance.

DRIVER / SYSTEM BOUNDARIES (R&F)

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

Using the Rdot–R diagram, Figure 17 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, per the discussion in "sudden target acquisition", a deceleration limit of 0.05g is more desirable. The limiting curves that are associated with these two deceleration values are shown in Figure 17.

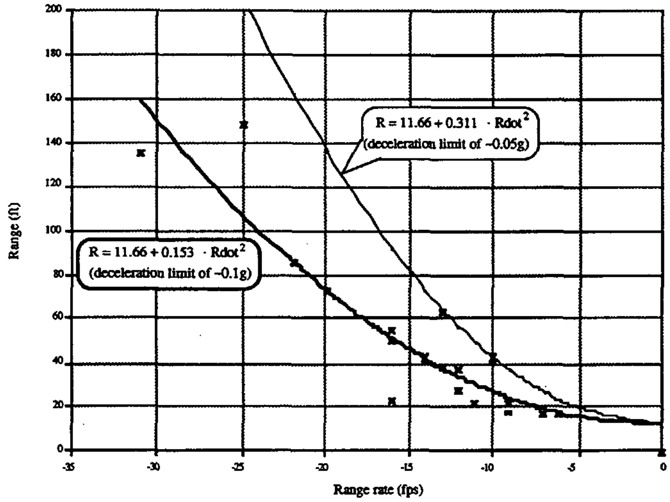

Figure 17. Brake activation points

The time to crash, $T_C = R/R_{dot}$, is depicted in Figure 18. The values shown pertain to the first instant the brakes were applied. Ninety-one percent of the data points are included within the range of average ± one standard deviation. 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.

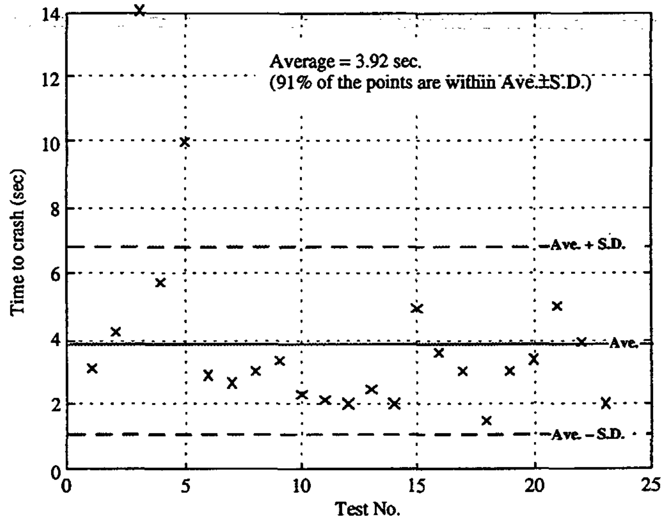

Figure 18. T_C at brake activation points

OPERATIONAL ASPECTS OF HEADWAY CONTROL SYSTEMS IN HEAVY-DUTY TRUCKING — CONCLUSIONS

The primary objective of this project was to develop a physical headway-controlled testbed. This objective has been successfully accomplished, and the prototype system performed well during the test program. A meaningful advancement was made toward acquiring the ability to comprehensively evaluate the impact of headway-control systems on heavy-duty trucks operations and driver performance. Based on the findings from the experiments, the performance boundaries are as follows:

- When approaching a leader, the truck should not approach a preceding vehicle at a relative speed that is faster than 15–20 mph.

- 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 if speed changes are relatively small (i.e., $\Delta V_p < 10$ mph) and they are carried out relatively slowly (i.e., $a_p < 0.1g$).
- If for any reason the truck needs to decelerate at a rate of more than 0.05g'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 if a target shows up so the truck needs to decelerate at a rate of 0.077 to 0.088 g's, 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.
- The useful operational range of the sensor is up to 200 ft.

The headway-control system was found to be safe and easy to use at the same time. It maintained follower–leader integrity when operated autonomously, or when needed, it accommodated driver intervention in braking or accelerating.

Aimed at (1) further enhancing the state of knowledge concerning headway control for trucks, and (2) exploring new concepts that emerged from findings of the pilot testing, the following is recommended:

- A prototype model that incorporates braking should be developed. An algorithm, similar to that used for crash warning, can be used to apply braking as well as issuing warning.
- The prototype headway-control system should be developed and tested using different types of sensors.
- The stability of a string of vehicles should be investigated experimentally.
- Human factors studies should be performed to further develop user-friendliness of the headway-control system and its associated displays.

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