THE USE OF VEHICLE VELOCITY AND HEADWAY-CONTROL SYSTEMS FOR TRAFFIC MANAGEMENT

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16. Abstract

This study addresses the problem of finding a method for maintaining smooth, uniform traffic flow under congested conditions. The ultimate goal is to investigate the potential capabilities of a higher-level, traffic management system for vehicles equipped with the types of speed and headway-control systems that will be available soon. In that context, the hypothesis to be tested ultimately is as follows: if a traffic management system were to aid in controlling the velocity and headway of individual vehicles by communicating appropriate speed and headway values for the prevailing traffic conditions, traffic flow would be improved not only with regard to uniformity, but with less chance of rear-end collisions and possibly even greater throughput.

The report presents a modeling approach to the problem and employs the model to illustrate the importance of key parameters and to simulate the time response of vehicle strings.

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TABLE OF CONTENTS

1.0 INTRODUCTION

1.1 Research Problem Statement

This study addresses the problem of finding a method for maintaining smooth, uniform traffic flow under congested conditions. The ultimate goal is to investigate the potential capabilities of a higher-level traffic management system for vehicles equipped with the types of speed and headway-control systems that will be available soon. In that context, the hypothesis to be tested ultimately is as follows: if a traffic management system were to aid in controlling the velocity and headway of individual vehicles by communicating appropriate speeds and headways values for the prevailing traffic conditions, traffic flow would be improved not only with regard to uniformity, but with less chance of rear-end collisions and possibly even greater throughput.

Variations of this idea have been proposed in the past. For example, the PROMETHEUS Program has a study in which a traffic control system would take over the setting of velocity in vehicles equipped with cruise control systems.

The U.S. government has asked for an automated highway demonstration by 1997. Perhaps an automated system for setting velocity and headway, based upon vehicle counts and using smart cruise control systems (*i.e.*, controlling both velocity and headway), could be a feature of a new type of automated highway lane.

The reason for suggesting both velocity and headway control is to centrally control the relationship between headway and speed to yield maximum stable throughput. The crux of the study is to see if intelligent cruise control systems can out-perform unaided drivers. Intelligent cruise control could avoid the delay characteristics of drivers and, through cooperation from the infrastructure, it is hypothesized that vehicles equipped with intelligent cruise control would operate at an appropriate speed and headway for the traffic conditions—something that is very difficult for individual drivers to determine from their location in the traffic stream.

1.2 Research Performed and Proposed

The research is aimed at applying near-term technology to demonstrate the potential for improving traffic flow by controlling the speed and headway of individual vehicles in accordance with an assessment of the local traffic demands.

The technical objectives include developing relationships between velocity and headway, and traffic density and flow; both for situations where drivers are unaided and in situations where the drivers have the aid of velocity and headway levels determined by a traffic management system. The relationships, pertaining to a traffic management system and vehicles equipped with cruise control, are, of course, part of the system in the sense that these relationships have been used to determine the speed and headway based upon traffic flow and density information for the section of roadway including the vehicle. In this regard, a major objective has been to develop control rules based upon the dynamic capabilities of vehicle/cruise-control systems and the uncertainties associated with measuring and identifying traffic characteristics. (The results of this study indicated that individual vehicle rules for controlling velocity and headway can be designed to be more than adequate for use with strings of vehicles interspersed with vehicles traveling at a speed recommended for maintaining a level of traffic flow commensurate with the traffic conditions and demands.)

In order to develop the understanding needed to plan field studies, the research has included reviewing the pertinent literature, developing a simulation of this type of traffic control system, and determining the properties of cruise control systems and traffic measurement systems as needed to represent them in the simulation. The simulation has been used in an analytical first phase in which an initial set of performance goals and methods for evaluating performance are developed. This report presents the findings, conclusions, and recommendations derived from the results of the analytical first phase.

The next phase of the research (if performed) would include (1) developing capabilities for measuring the data needed to evaluate system performance, (2) performing limited scope experiments to test the capabilities of a traffic measurement system, and then (3) developing and demonstrating practical techniques for measuring vehicle performance and traffic characteristics, as needed for system deployment and evaluation. Successful proving-ground tests would be needed before a system could be demonstrated in a field trial.

Given enough knowledge to assemble a basic system, a field trial could be planned for a final phase of the project. This field trial might be based upon usage of Michigan Department Of Transportation's new MTC facilities for the Detroit freeway system. The envisioned trial might involve a temporarily reserved single lane at a time when there is little traffic at a specially selected site. In the reserved lane several vehicles would follow each other at preset speeds and headways. The influences of changing speed and headway according to predetermined relationships would be examined. If several vehicles (perhaps no more than four vehicles) were available, the possibility of unstable oscillations could be assessed, and the need to limit the length of vehicle strings could be investigated. On the other hand, the findings of this study indicate that there will be no spatial stability problems in strings of vehicles equipped with headway-control systems that prevent disturbances from being amplified from vehicle to vehicle. The field trial could provide evidence supporting this finding of stability in strings of vehicles and demonstrate the practical functionality of such a traffic control system.

1.3 Contents of the Report—Milestones Accomplished

The following milestones have been reached since the inception of this study.

- Literature reviewed for relationships between velocity and headway and traffic flow
- System simulation operational
- Descriptive parameters evaluated and available for use in the simulation
- Technical report prepared

The tasks leading to these milestones started in September, 1992 and ran until the milestones were reached.

The next section of this report presents a review of basic relationships between velocity, headway, and traffic flow. Section 3 and Appendix A describe the simulation of a headway-controlled string of vehicles. Findings from the simulation study are presented in Section 3. Section 4 contains a summary of the findings, conclusions, and recommendations concerning performance goals for a prototypic system and concerning methods for evaluating a system operating in a proving-ground environment.

2.0 REVIEW OF RELATIONSHIPS BETWEEN VELOCITY, HEADWAY, AND TRAFFIC FLOW

2.1 Relationships between Velocity and Headway

Theme of this Section. A fundamental difference between driver control and automatic headway control (Intelligent Cruise Control (ICC)) lies in the manner in which headway is used to control speed.

Discussion and Analysis. Currently used microscopic models for analyzing traffic flow are based on velocity versus distance relationships that are characterized by a rapid decrease in velocity occurring as the distance to the preceding vehicle approaches zero. (Papageorgiou [1], May [2]). Apparently, the form of this relationship is inferred from data obtained by observing the distances chosen by drivers in traffic streams flowing at various velocities. A heuristic example, shown in Figure 1, illustrates certain basic features of this relationship.

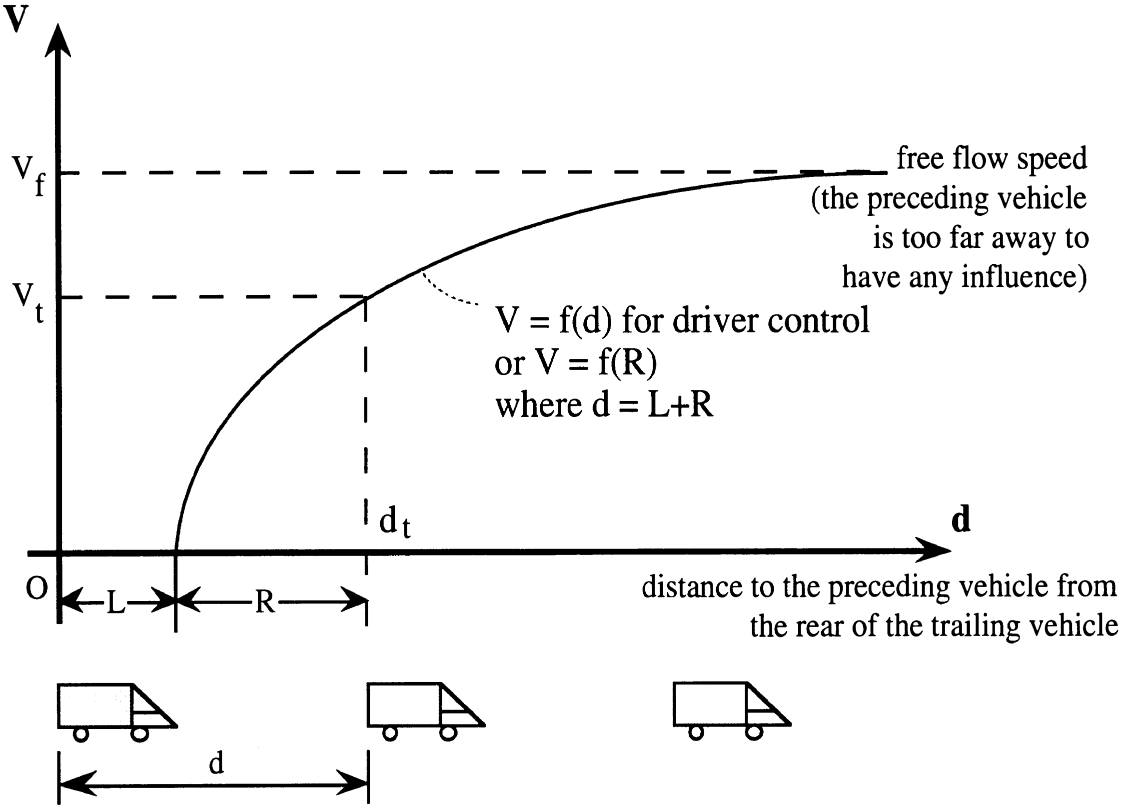

Figure 1. Velocity versus distance relationship for an unaided driver

Figure 1 indicates that the steady velocity of the trailing vehicle is a function of the distance from the rear of the trailing vehicle to the rear of the preceding vehicle. (In the drivers' eyes the velocity of the trailing vehicle is a function of the distance from the front of the trailing vehicle to the rear of the preceding vehicle.) As indicated in Figure 1,

$$d = L + R \tag{1}$$

where:
d is the distance rear-to-rear between vehicles
L is the length of the vehicle
R is the range between vehicles

(In traffic flow analyses, it is conventional to use "d" instead of "R," but "R" is introduced here to aid in making comparisons with intelligent cruise control systems that employ sensors to measure the headway range (R) between vehicles.)

Also as indicated in Figure 1, the slope of the curve, $\partial V/\partial d$ (which equals $\partial V/\partial R$), is monotonically decreasing as distance increases, and the velocity asymptotically approaches the free flow velocity at large headway ranges.

In the version of intelligent cruise control that we have been using in field work (Fancher, et al. [3]). The headway controller changes the trailing vehicle's speed so that the trailing vehicle follows the preceding vehicle at the same speed as the preceding vehicle and at a distance that is proportional to the steady velocity of both the trailing vehicle and the leading vehicle. This steady situation is illustrated in Figure 2.

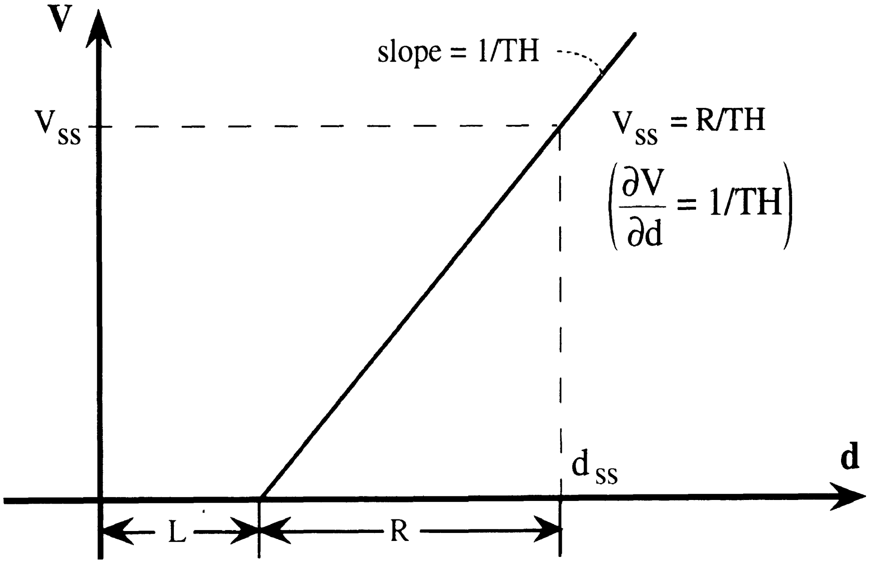

Figure 2. Velocity versus distance relationship used in the reference ICC system (Fancher, Bareket, Johnson [4])

Concluding Summary. The important point to observe here is that the slope of the driver-controlled speed versus distance relationship becomes large as the headway range goes to zero, while, in the ICC system, the slope is determined by a quantity TH, called the "headway time."

For the ICC system, regardless of the speed, the relationship between headway range and speed is

$$R = TH \cdot V \tag{2}$$

where: TH is the headway time.

For drivers, the local approximation for the relationship between velocity and headway range is

$$V = \left(\frac{\partial V}{\partial R}\right)\Bigg|_{R_0} \cdot (R - R_0) + V_0 \tag{3}$$

where: V_0 and R_0 represent the operating point for the local approximation.

The roles of 1/TH in equation (2) and ($\partial V/\partial R$) in equation (3) are critical to determining maximum flow as discussed in the next section.

2.2 Relationships between Traffic Density and Flow

Theme of this Section. The differences between the velocity versus headway relationships given in Figures 1 and 2 lead to fundamentally different considerations for determining the conditions for maximum flow in driver-controlled and headway-controlled situations.

Introductory Discussion. In driver-controlled situations, the maximum flow is called the "capacity." Analysis shows that the capacity for current traffic flows is determined by the slope of the velocity versus distance characteristic and by the delay inherent in the driver. The following section presents analytical results concerning the stability of a string of vehicles in terms of driver delay time and $\partial V/\partial R$, when the distance between vehicles is small such that vehicles are densely packed together.

On the other hand, for an ICC system, if TH is chosen properly, disturbances in a string of vehicles will damp out rather than propagating along the string.

Analytical Results. Starting with equation (3) for one trailing vehicle in a string of driver-controlled vehicles, the local linear approximation to the vehicle control dynamics is given by:

$$V_t \approx \frac{\partial V}{\partial R} \cdot (R - R_0) + V_0 \tag{4}$$

where: $R = x_p - x_t$

x_p is the position of the preceding vehicle

x_t is the position of the trailing vehicle

V_t is the velocity of the trailing vehicle

Given a delay time, TD, for the driver to observe the range to the preceding vehicle, process the information, and perform a speed control action and given the velocity versus headway range of equation (4), the dynamic equation for velocity control is as follows:

$$\frac{d(V_t)}{dt} = \left(\frac{\partial V}{\partial R}\right)\bigg|_{R_o} \cdot \left(V_p(t - T_D) - V_t(t - T_D)\right) \tag{5}$$

(The following analytical results through equation (7) are those of Papageorgiou [1] based on classical microscopic analyses of traffic flow.)

Equation (5), while stable in the time domain, can lead to an unstable string of vehicles because a small disturbance will be amplified from vehicle to vehicle along the string until some vehicle will reach zero velocity and stop and go conditions will prevail. The condition for asymptotic instability of a string of uniform vehicles and drivers is as follows:

$$\left(\frac{\partial V_t}{\partial R}\right)\bigg|_{R_o} \cdot (T_D) > \frac{1}{2} \tag{6}$$

Relationship (6) means that a range of unstable flow is predicted for speeds and distances (the reciprocal of density) where $\partial V/\partial d$ is too large. A heuristic example of this situation is illustrated in Figure 3.

According to relationship (6), the critical distance, d^*, shown in Figure 3, is where

$$\partial V/\partial d = TD/2 \tag{7}$$

Corresponding to d^*, the critical speed is V^* as shown in Figure 3. The predicted capacity of flow is

$$V^* \text{ (ft/sec)} \cdot \rho^* \text{ (ft/vehicle)} = F_{max} \text{ (vehicles/sec)} \tag{8}$$

where: $\rho^* = 1/d^*$ = the critical density of vehicles and F_{max} is the maximum stable flow.

At speeds above V^*, the ratio V/d will be less than V^*/d^*. At speeds below V^*, the string is unstable and the situation gets worse rapidly as the distance between vehicles gets to be less than R^*.

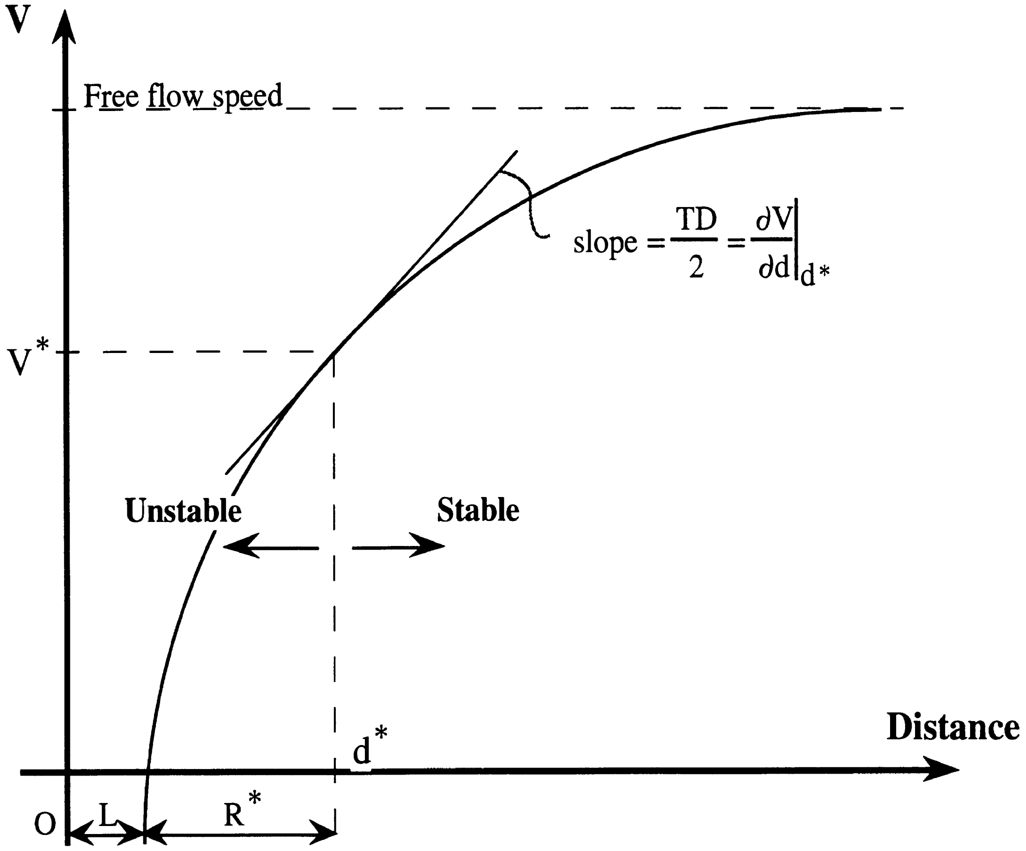

Figure 3. Range of string instability in the velocity versus distance space

In contrast, the situation for a headway-controlled vehicle is different as long as TH is much shorter than the principal time constant of the control system plus any delay in the control system.

In the reference headway-control system (Fancher, Bareket, Johnson [4]), ideas from non-linear control are used to convert a vehicle and its cruise control system into a headway-control system that operates (to a good approximation) in accordance with the following dynamic equations:

$$T\left(dR/dt\right) + R = TH \cdot V_p \tag{9}$$

where: T is the time constant of the headway-control system
TH is the headway time
V_p is the velocity of the preceding vehicle

and,

$$\left(dR/dt\right) = \left(V_p - V_t\right) \tag{10}$$

where: V_t is the velocity of the trailing vehicle.

At this point, it might be desirable to further clarify the differences between TH and T as interpreted from a physical standpoint. TH, the headway time, is the time lapsed between the instant the preceding vehicle has passed some arbitrary landmark and the instant the trailing vehicle passes that point at its current speed. T might be regarded as the "look-ahead time." Once a preceding vehicle has been detected by the system, if the range rate were to remain unchanged it would take T seconds for the trailing vehicle to get closer than the desired headway ($TH \cdot V_p$) to the preceding vehicle. Since the vehicle's coast-down (no-braking) deceleration capability is limited to a rather low level, there is a need to start slowing down soon enough and far enough away to prevent the range to the preceding vehicle from becoming too small. T is an indication of how far forward the headway system needs to "look" and consider traffic. Obviously, the farther ahead the system looks, the smoother its operation will be; however, if the system is designed so that it necessitates a large "look-ahead time," it becomes more prone to disruptions due to target losses and cut-ins by other vehicles.

As long as

$$T / TH > 1/2 \tag{11}$$

a string of identical, headway-controlled vehicles will be stable (because as long as condition (11) is satisfied, the gain of the transfer function of (V_t / V_p) derived from equations (10) and (11) will be less than 1.0 at all frequencies). Clearly, the control system is to be designed with 2T > TH. (This is no problem in practice.)

Given that stability is no issue for a headway-controlled string of vehicles, the maximum flow depends upon constraints set by the choices of TH and maximum speed. Examination of Figure 2 indicates that the density for headway control is given by the following equation:

$$\rho = \frac{1}{L+R} = \frac{1}{L + TH \cdot V} \tag{12}$$

and the flow is

$$F = \rho\ V = \frac{V}{L + TH \cdot V} = \left(\frac{1}{\frac{L}{V} + TH} \right) \tag{13}$$

Examination of equation (13) indicates that the maximum flow approaches 1/TH as V becomes large; i.e.,

$$F_{max} = 1/TH \quad \text{(vehicles/sec)} \tag{14}$$

Concluding Summary. The implication of equation (14), with regard to maximizing flow, is that TH should be as short as safety considerations allow. Table 1 summarizes flow values computed for highway traffic conditions at high speed, so that L/V >> TH.

Table 1. Flow values for highway traffic conditions

Data used:	L = 20 ft., V = 100 ft/sec. (L/V = 0.2 sec.)	
Headway Time (TH)	**Flow (F)**	
0 sec.*	5.0000 veh/sec	(18000 veh/hr)
1 sec.	0.8333 veh/sec	(3000 veh/hr)
1.24 sec.	0.6944 veh/sec	(2500 veh/hr)
2 sec.	0.4545 veh/sec	(1640 veh/hr)

* bumper to bumper

A flow of 2500 vehicles per hour per lane is fairly high for a current freeway filled with unaided drivers, yet, such flow has been observed. If one could effectively and safely use TH = 1 sec., the lane flow would increase to 3000 vehicles per hour.

Clearly, the possibility of improving freeway flow depends upon either going faster or increasing the density (decreasing the distance between vehicles) or both. The ability of drivers to drive closer and faster seems to have reached a satiated level on crowded freeways today. The potential for using headway control to increase flow depends upon the reliability with which close headways can be used without incidents.

2.3 Headway Allowances to Improve Safety

Theme of this Section. Designs of headway-control systems often feature allowances for the deceleration characteristics of the preceding and trailing vehicles.

Introductory Ideas and Analytical Expressions. A basic relationship for constant deceleration situations is

$$S = \frac{V_i^2 - V_f^2}{2A} \tag{15}$$

where: S is distance

A is deceleration

V_i is the initial velocity

V_f is the final velocity

The deceleration distance for a driver is

$$SD = TD\ V_i + S \tag{16}$$

where: SD is the distance covered in reaching V_f

TD is the driver's response time (time to perceive, process, and perform)

Equations (15) and (16) form a possible basis for use in selecting headway distances in headway-control algorithms.

The range between vehicles is critical in determining whether a crash will occur. For a trailing vehicle to stop without crashing into a lead vehicle depends upon the driver's reaction time, the initial velocity, the range between vehicles, the deceleration rate of the preceding vehicle, and the deceleration capability of the trailing vehicle. The following relationship between these quantities expresses a possible means for determining a desired range for use in a headway-control system:

$$R_D = TD\ V + \frac{V^2}{2\ a_t} - \frac{V^2}{2\ a_p} \tag{17}$$

where: R_D is the desired range

TD is the driver's response

V is the velocity

a_p is the deceleration of the preceding vehicle

a_t is the deceleration of the trailing vehicle

Many times safety-conscious researchers conservatively chose $a_p > a_t$ such that $R_D > TD\ V$ in their control systems. However, if it is presumed that both vehicles have nearly the same deceleration capabilities (i.e., $a_t \approx a_p$), then R_D would be approximately equal to TD V. In many driving situations, drivers' response times are found to average around 1 second with 2 seconds being unusually long, but not unheard of.

Recently produced headway warning systems have used a "time to crash," TC, defined as follows:

$$TC = R \Big/ \left(dR/dt \right) \tag{18}$$

Experimental evidence has been obtained indicating that TC evaluated when drivers apply the brakes to stop or slow down is in the neighborhood of four seconds.

In limited experience with an autonomous cruise control system, we have been operating comfortably with a headway time, TH = 1.4 to 1.0 seconds, and a control time constant T = 12 to 14 seconds. (In this case, the reference system is characterized by the following equation, $12\left(dR/dt\right) + R = 1.4V_p$.) The reason for T=12 seconds is that this headway-control system depends on natural retardation from rolling resistance and aerodynamic drag (plus engine and transmission drag) to decelerate. The foundation brakes are not used for headway control. The choice of 12 seconds is compatible with a maximum deceleration capability comparable to that achieved through engine drag and natural retardation (about 0.04g for a passenger car).

Our experience as drivers of an ICC-equipped vehicle has shown that, even though the system has a large time constant, we are comfortable with the operation of the headway-control system and rarely need to intervene with the brakes. The point is that a headway time of less than 2 seconds may be practical. It seems that drivers on current freeways with capacities over 2000 vehicles per hour are operating with headway times under 2.0 seconds.

Concluding Summary. Although safety advocates will call for greater headway ranges and headway times, the desire for greater traffic flow may lead to the use of shorter headway times and distances than those currently observed. Vehicles equipped with headway-control systems appear to have stability characteristics that will make shorter headway times feasible. The crux of the matter may lie in developing crash avoidance aids telling the driver to intervene, and, if the driver does not intervene, automatic systems for applying the brakes might be employed.

3.0 SIMULATION OF A HEADWAY-CONTROLLED STRING OF VEHICLES

Theme of this Section. Simulation models representing a leading/trailing vehicle pair have been duplicated to calculate results for strings of vehicles that are operating under headway control.

Introductory Description. In previous work rather complete engine and vehicle models were developed (Fancher, Bareket, and Johnson [4]). Although the original models represented heavy trucks, they are fairly easily adjusted to represent passenger cars. One of the simulation models now available consists of three of these individual vehicle models coupled together to represent a string of four vehicles including a leading vehicle and three trailing vehicles. This is a detailed nonlinear simulation. (Nevertheless, it operates on a personal computer.)

Operation of this simulation model (and previous work in (Fancher, Bareket, and Johnson [4])) indicates that the headway-control system effectively cancels most of the nonlinearities, with the exception of the saturation of the braking deceleration, at a level equal to the coast down properties of the vehicle. The time constant, T, chosen for the headway-control system is made large enough to compensate for this limit on braking deceleration.

Experience with the detailed model has verified that similar results can be obtained from simpler models based upon the premise that the headway-control system performs as designed. This premise has been further justified by constructing simplified models and in fact obtaining results similar to those produced by the more detailed model.

The simplified models have been implemented in a MATLAB™ environment using SIMULINK™ [1]. This allows duplicating vehicle models so that it is easy to build models of long strings of vehicles. Currently, we have been using strings consisting of a leading vehicle and 30 trailing vehicles.

Simulation Findings. Appendix A contains time histories for ranges between vehicles and for individual vehicle velocities throughout the string. (Usually time histories are recorded for the first four or five vehicles in the string, and then, for the thirtieth trailing vehicle.) These time histories were generated by starting the string in equilibrium at an initial speed and then abruptly changing the speed of the leading vehicle to a lower speed. If there is any spatial instability along the string, the amplitude of the response from vehicle to vehicle grows until the velocity of one of the trailing vehicles reaches zero. The simulation results verify the analytical relationships for spatial

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[1] MATLAB and SIMULINK are trademarks of The MathWorks, Inc.

instability of the string, as given in Section 2. In addition, for operation at values of T and TH far removed from instability, the results show that if the first trailing vehicle performs well, the rest of the string will have no difficulties.

The simulations are most useful in studying the effects of constraints on performance due to the level of braking deceleration available. We do not know for sure the levels of deceleration that drivers will find uncomfortable, but we believe that they are on the order of 0.15 g (5 ft/sec^2). Depending upon the reliability of vehicle performance in the string, decelerations exceeding 0.1g should be almost unheard of. If this is the case, only very moderate braking would be needed.

Summary of Observations. The simulation results show very stable operation of a headway-controlled string of vehicles. The rules for choosing T and TH are clearly known now. A level of deceleration capability of 0.1g is adequate for first trials of normal operation of a headway-controlled string. A deceleration capability of 0.2g would be adequate for handling extraordinarily large decelerations of the leading vehicle, on the order of 0.25g for sufficient time to slow from 50 mph to 30 mph, for example.

For proving-ground experiments, a string of three vehicles would be enough to see if the reference headway-control system would perform adequately and in a stable manner. The reason for this is that if the amplitude of the range and velocity changes (due to a change in lead vehicle) speed are growing from vehicle to vehicle, a longer string would eventually oscillate enough so that some vehicles would reach stop and go conditions.

On the other hand, if the motion of the second trailing vehicle is much less than that of the first trailing vehicle in the string, the string will be very stable. This means that disturbances originating at a preceding vehicle are reduced at the next trailing vehicle.

Even if the leading vehicle decelerates at a level such that the first trailing vehicle reaches its saturation level of deceleration, the next trailing vehicle will not need to follow a speed change that takes place at greater than the common level of deceleration saturation. A critical problem is ensuring that preceding vehicles do not decelerate at levels exceeding the deceleration limit. If preceding vehicles decelerate too rapidly, drivers will have to brake their vehicles accordingly, and the string will revert to a driver-controlled string rather than remaining as a headway-controlled string.

4.0 SUMMARY OF FINDINGS, CONCLUSIONS, AND RECOMMENDATIONS

Findings Regarding a Vehicle by Vehicle System to Aid in Eliminating Stop and Go Driving. The analytical and simulation results presented in this report indicate that headway-control systems can be arranged to smooth traffic flow. This improvement in traffic flow is achieved by designing headway controllers that have reduced time delays and improved headway-speed relationships compared to those inherent in driver-controlled traffic flow.

Conclusions Regarding Experimental Evaluation of a Headway-Controlled String of Vehicles. A key issue in the performance of a headway-controlled string of vehicles is whether disturbances amplify spatial oscillations along the string going from preceding to trailing vehicles in the string. A condition for spatial stability is that the response of any trailing vehicle to the deceleration of its preceding vehicle does not come closer to the leading vehicle than the desired headway for the new speed of the preceding vehicle. Furthermore, even if (due to limited deceleration) the first trailing vehicle does come closer than desired to the vehicle ahead, the vehicle after the first trailing vehicle will not come too close to the first trailing vehicle (because the vehicle ahead decelerated only at the limit deceleration for which the headway control was designed). In this way, spatial oscillations along the string can be damped out even though there may be some operation at headway ranges that are less than desired. The point is that, given this understanding of the nature of the spatial instability from vehicle to vehicle, an evaluation of the performance of as few as three or four vehicles will be sufficient to infer the smoothness of the performance of a long string of vehicles.

Recommendations concerning Proving-Grounds Tests and Field Trials and Demonstrations. Proving grounds tests with three or four vehicles can be used to extrapolate to a long string of headway-controlled vehicles. In these tests the leading vehicle would be used to enter disturbances to the trailing vehicles. The damping of range and velocity from vehicle to vehicle would be observed. Values of the headway-control parameters (i.e., T, the prediction or system time constant; TH, the time to impact or headway time; and D max, the limit on deceleration used for headway control) would be investigated to find values for acceptably stable and smooth operation.

Given that acceptable values of the headway-control parameters are identified experimentally and that these values are compatible with our understanding as illustrated by our simulation models, further tests using naive subjects are in order. If these tests show that drivers perform reliably in a headway-controlled environment, field trials on a secured, but real, road are warranted. At each stage of this process the performance of the system would be evaluated and risky situations that might arise would be resolved as the experiments approach real world situations. Once satisfactory performance is obtained on a real road, albeit one with special traffic controls, a demonstration can be planned and performed. At some advanced point, appropriate speeds can be communicated to the drivers in a simulated, dense headway situation and the system operation and capability can be demonstrated.

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APPENDIX A

In the course of this work, the operation of strings of vehicles under headway control was investigated using several simulation tools. First, a rather complete set of engine and vehicle models that was developed in a previous work (Fancher, Bareket, and Johnson [4]) was used to assemble and simulate a string of consecutive vehicles. Then, by applying some simplifying assumptions that reduced computational complexity, simplified sets of driver-vehicle models were derived and used to evaluate long strings (30+) of vehicles. This appendix presents the results of both the complex and some of the simplified models.

Initially, the complex simulation model was developed to examine longitudinal control of heavy duty trucks. However, by modifying the pertinent dynamic parameters, the model can easily be adjusted to represent passenger cars and to study the longitudinal control of such vehicles. This model is a detailed, nonlinear simulation of the vehicle. Though it is elaborately described in [4], the following paragraph briefly summarizes its main features.

The engine is modeled as a delayed power plant. The delay is in a form of a torque-growth time lag that represents the combustion process and the turbo pressure build-up (if applicable). Peak torque and horsepower values and the corresponding engine speeds are used to compute a mathematical approximation to the power curve. Local linearization is applied to determine the available net engine torque based on throttle setting. In addition to volumetric efficiency, torque losses in the engine are primarily due to friction. Torque loss computation due to friction is based on a model that incorporates compression ratio, engine speed, engine volume, and mean speed of the piston. With the net available traction torque computed, the longitudinal motion of the vehicle is determined by accounting for inertial properties of the engine and the drivetrain, gear ratios, tire slip, aerodynamics, rolling resistance (based also on tire type), and the appropriate grade forces.

A traffic flow simulation that incorporates such a nonlinear vehicle model was derived, and it operates on a personal computer. In addition to the leading vehicle, which is represented by a time-varied speed profile, the simulated string of vehicles can consist of up to nine trailing vehicles. A PI (Proportional + Integral control) method is used for the cruise control, and a headway-control algorithm couples the string of vehicles.

Results from the detailed model simulation are presented here for a four-vehicle string (a leader with three following vehicles). Figure A-1 illustrates the speed changes of the individual trailing vehicles in the string as a response to two typical events for such an operation: (1) when the four vehicles are converging into a headway-controlled group, and (2) when the lead vehicle changes its speed after the string of vehicles has reached steady state at a desired speed. The deceleration rate of the lead vehicle in this example was approximately 0.09 g (from 40 mph to 34 mph in 3 seconds). The changes in headway distance (range) between the vehicles are depicted in figure A-2. According to the headway-control algorithm that was used in the simulation, the desired headway time was 2 seconds.

During the process of converging, the last vehicle had to go through the most radical speed change (from 55 to 40 mph). Given its initial range and its no-brakes deceleration capabilities (approx. 0.06 g), that vehicle "overshot" the target speed of 40 mph and the desired range of 117 feet (2 sec at 40 mph). Since they were traveling at a lower initial speed, the other vehicles were able to adapt their speed more gradually.

When the lead vehicle slowed to 34 mph, the first of the trailing vehicles, which was also capable of only 0.06 g, was not able to keep up, and overshot both the desired speed and the desired headway. As it had more headway cushion, the second vehicle in the string slightly missed the speed, but was able to maintain headway. The third vehicle was able to properly adjust both its speed and the range to the preceding vehicle.

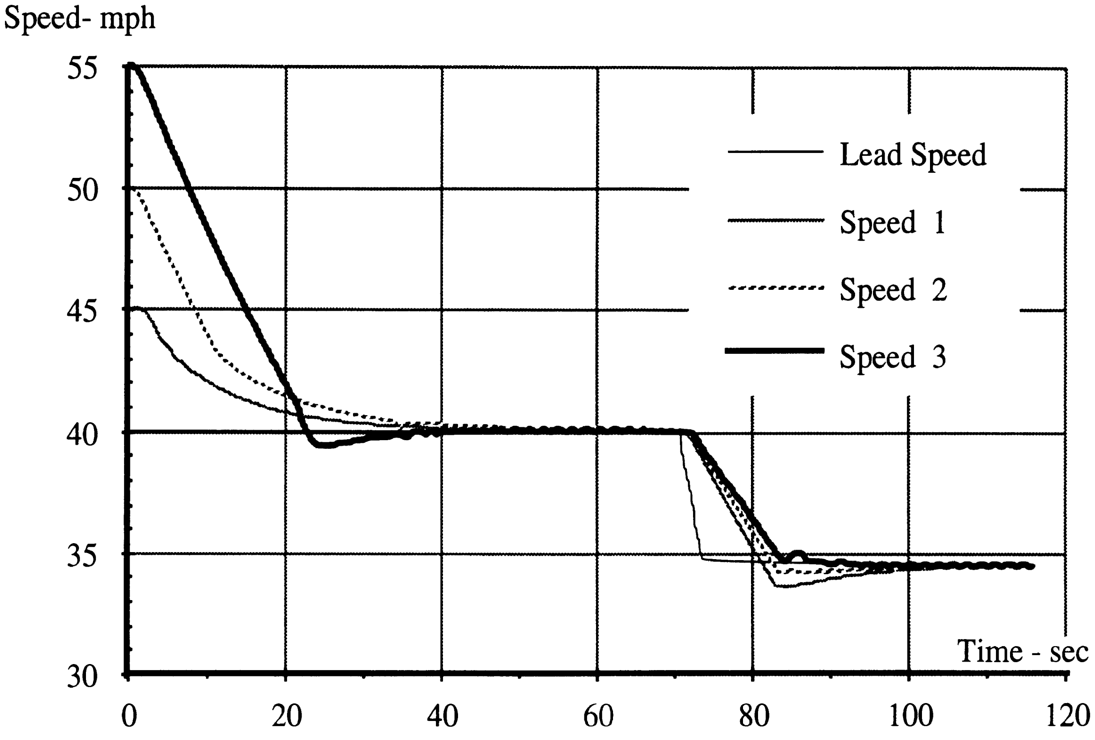

Figure A-1.

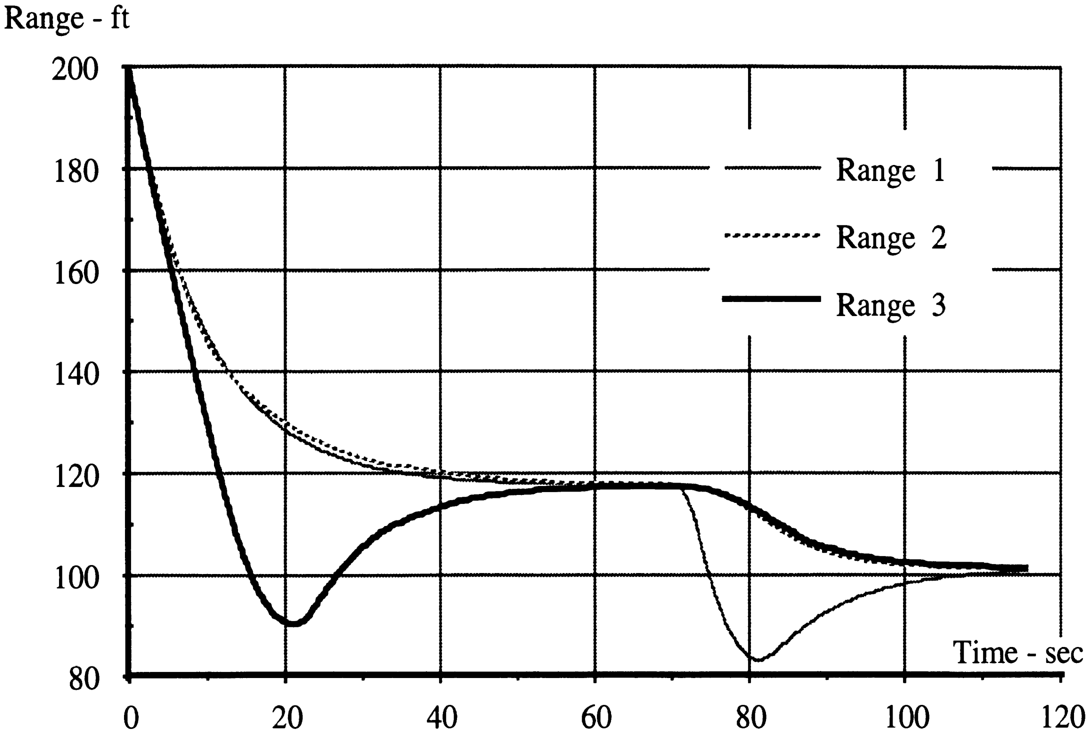

Figure A-2.

Next, an attempt was made to study the response of long strings of vehicles (more than 20) to speed disturbances. In order to maintain computing-power requirements to those of desktop computers, some simplifications to the model were necessary.

Exercising the detailed simulation model indicated that when operating at a headway-control mode, the system effectively cancels most of the nonlinearities. However, saturation of the deceleration capability at a level equal to the coast-down properties of the vehicle still remains an inherent nonlinear characteristic. By using a properly chosen time constant for the headway-control system and introducing a limiter function, it was possible to compensate for this limitation.

Experience with both the detailed model and the simplified models that were derived has verified that qualitatively, similar results can be obtained. The simplified models in fact produced results similar to those obtained by the more detailed model. These models have been implemented in a MATLAB™ environment using SIMULINK™.

Simulation results using the SIMULINK™ models are brought here for a thirty-vehicle string (a leader with twenty-nine following vehicles). Three combinations of characteristic properties for the trailing vehicles are shown: (1) headway time of 1 second with a deceleration limit of 0.18 g, (2) headway time of 1 second with a deceleration limit of 0.09 g, and (3) headway time of 2 seconds with a deceleration limit of 0.18 g. In all three cases the trailing vehicles had a time constant of 12 seconds, and the speed disturbance introduced by the lead vehicle was a 0.22 g deceleration (from 50 mph to 30 mph in 4 seconds). The converging scenario was not simulated since the initial conditions for the model pertain to a steady-state situation where the vehicles are already in the headway-control mode of operation.

Figure A-3 illustrates the speed response of the first string to the 0.22 g deceleration of the leader. Time history plots depict the lead vehicle, the first four individual trailing vehicles, and the last trailing vehicle in the string. Similarly, the changes in headway distance (range) between the vehicles are depicted in figure A-4.

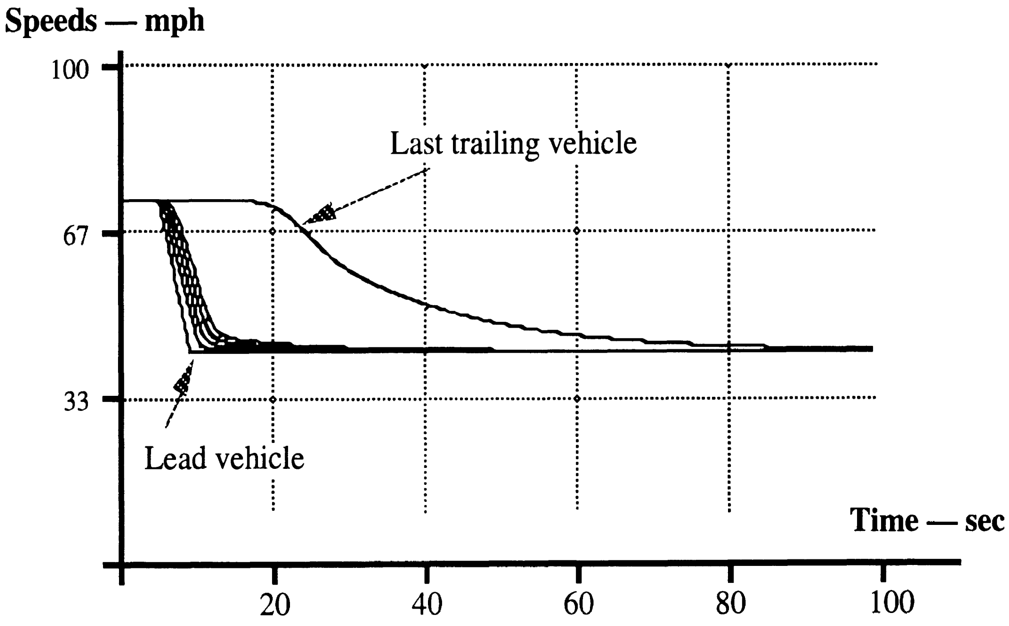

Figure A-3.

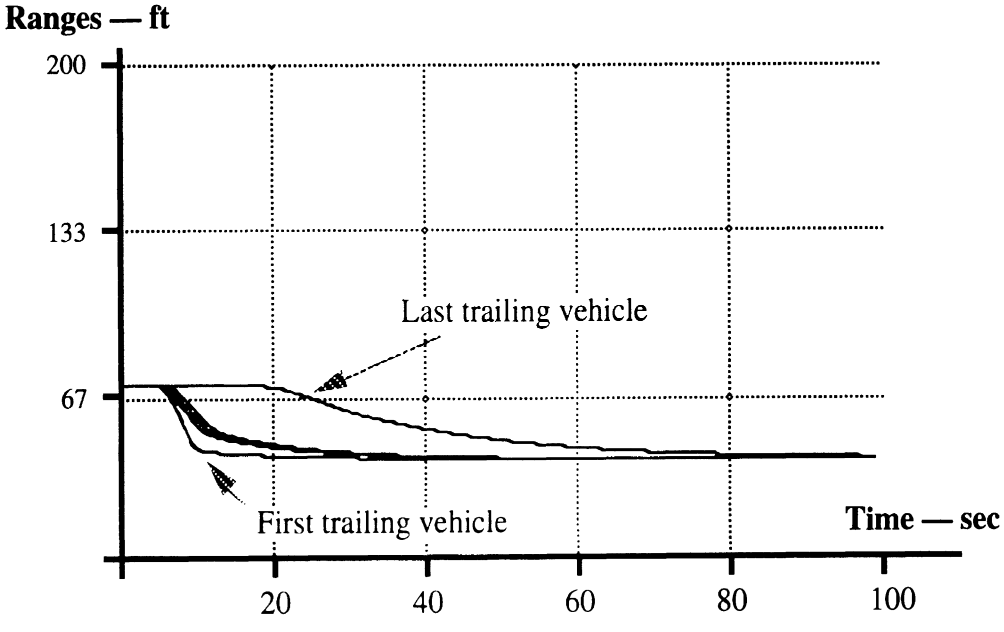

Figure A-4.

One might recall that the detailed simulation incorporated vehicles that were capable of only 0.06 g deceleration. In this example, the deceleration capability of the trailing vehicles is significantly higher — 0.18 g. Such a high level of deceleration enables the gradual adaptation of both speed and range to the disturbance introduced by the lead vehicle, in spite of the fact that the simulated string of vehicles is moving rather densely (only 1 second headway distance). It takes a total of approximately 100 seconds for the transient response to diminish, and for the whole group of thirty vehicles to reach a new steady-state flow with the new values of speed and range.

The next example that was studied using this model simulated similar traffic flow conditions — same speed and the same headway of 1 second. However, this string consisted of vehicles with substantially lower deceleration characteristics. In contrast to the vehicles in the previous example, which were capable of 0.18 g deceleration, this example incorporates vehicles with a deceleration limit of only 0.09 g. Figures A-5 and A-6 depict the speed response and changes of headway distance (range), respectively, of the vehicles in the string to a 0.22 g deceleration of the leader.

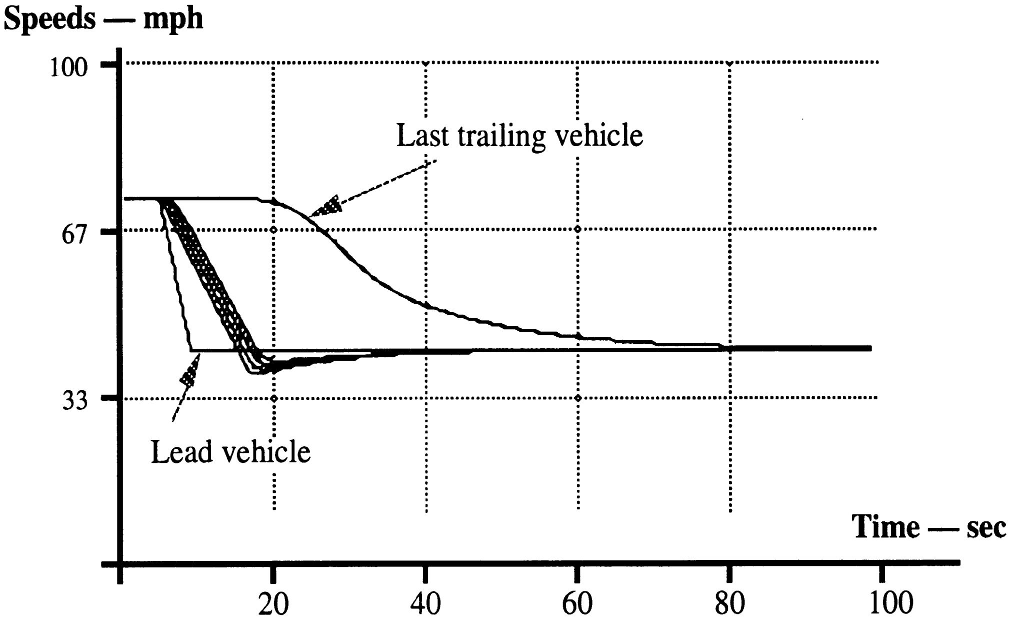

Figure A-5.

Observing figures A-5 and A-6, it is evident that the combination of a short headway distance with a very limited deceleration rate is detrimental for such traffic flow conditions. The 0.22 g deceleration of the lead vehicle is way beyond the capability of the trailing vehicles. The vehicle that immediately follows the leader quickly saturates its deceleration capacity, and since it travels closely behind, there is not enough headway distance to "cushion" and absorb the speed differences. In figure A-6 at the time point of approximately 10 seconds, the range between the first trailing vehicle and the leader crosses the zero value, which indicates a rear-end collision. However, since all the trailing vehicles have a common limit of deceleration, they successfully follow the first vehicle in the trailing group without "rear-ending" it.

Considering the range values portrayed in figure A-6, it is conceivable that by removing the first trailing vehicle such a string of vehicles could be made to handle even a 0.22 g deceleration maneuver. In other words, if a group of vehicles with a very limited deceleration capability follows a vehicle with ample braking power, only the first headway gap needs to be increased. The total length of the group, or the total traffic flow rate, will hardly be affected.

As in the preceding example, it takes approximately 100 seconds for the transient response to diminish, and for the whole group of vehicles to reach a new steady state flow with the new values of speed and range. That is, of course, based on the premise that the rear-end collision of the first trailing vehicle does not occur.

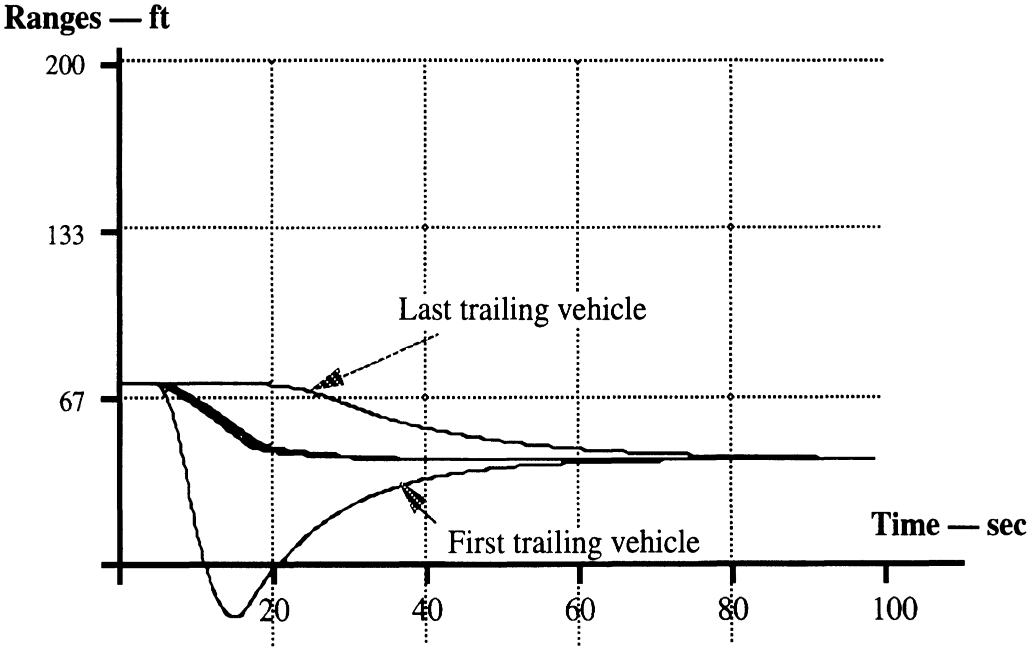

Figure A-6.

The last example considered here combined light traffic conditions with limited deceleration. Headway distance was set to 2 seconds, and the braking level capacity of the trailing vehicles was limited to 0.09 g. The speed response and changes of headway distance in the string to a 0.22 g deceleration by the leader are presented in figures A-7 and A-8, respectively.

The impact of the low deceleration rate is demonstrated in the range plot of the first trailing vehicle in figure A-8. Its braking capability is saturated and it overshoots the desired range. In contrast to the previous example, however, the headway distance was large enough to cushion the overshoot without resulting in a rear-end collision. The other trailing vehicles follow closely without saturating their deceleration capability. Nevertheless, when compared to the previous example, the performance level of the string of vehicles simulated here is inferior from the traffic flow standpoint. After 100 seconds, when the strings at the earlier examples already reached steady state — here it still has a long way to go. That is because there is an under-used headway space between each of the trailing vehicles, except for the first one.

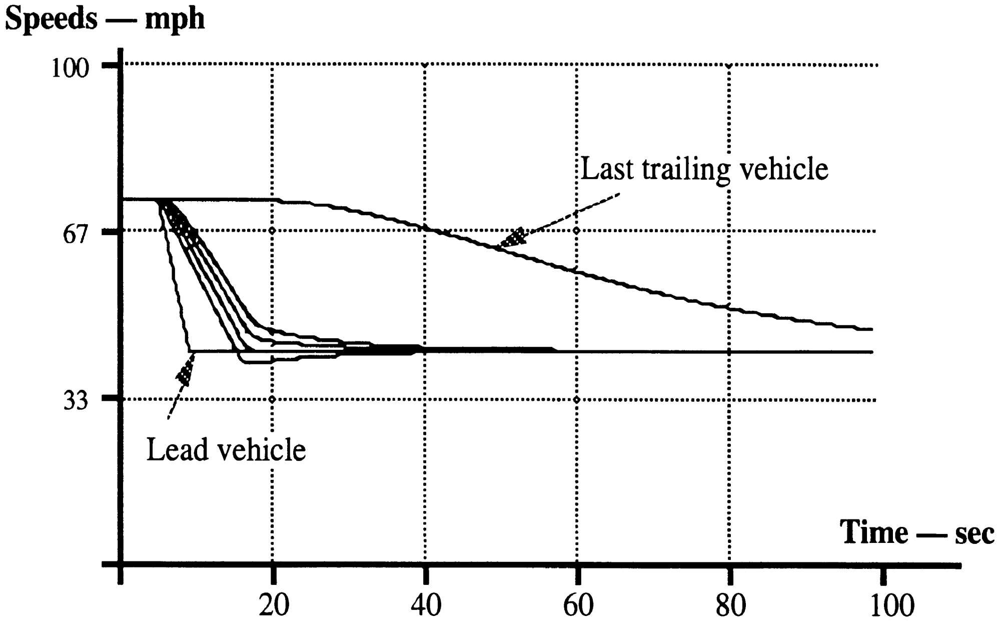

Figure A-7.

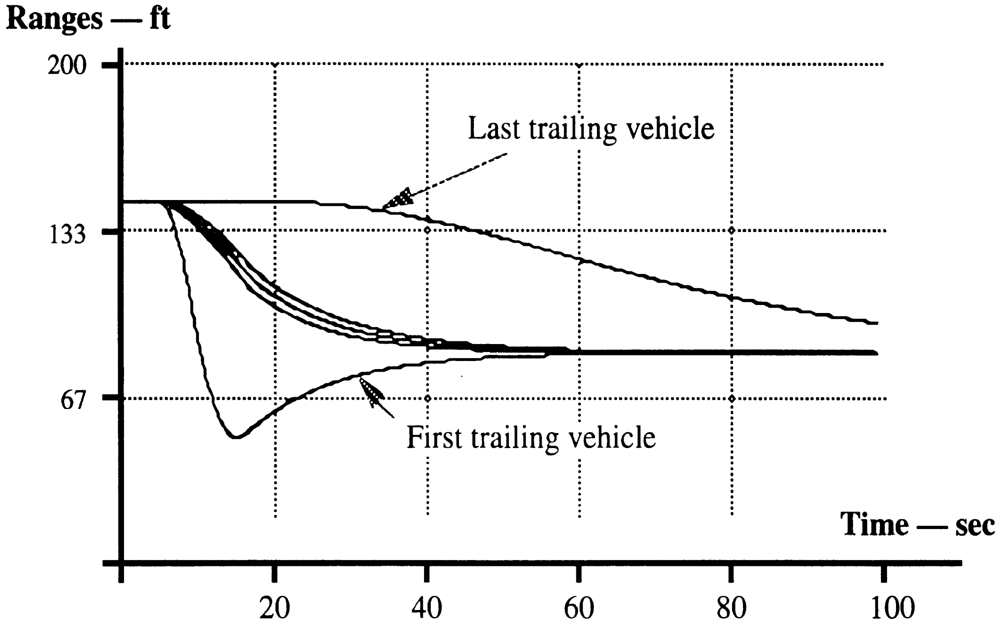

Figure A-8.

It is readily apparent that to achieve high levels of traffic flow rate, the headway time should be minimized. That requirement, however, seems to be at odds with highway safety concepts. Nevertheless, that conflict might be resolved if weakness points (e.g. a low deceleration vehicle traveling behind a more agile one) along the string are identified, and only local increases of headway are applied.