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SPEED DISTURBANCE, ABSORPTION AND TRAFFIC STABILITY

By

Ruihua Tao

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ABSTRACT

SPEED DISTURBANCE, ABSORPTION AND TRAFFIC STABILITY

By

Ruihua Tao

Speed disturbance is a natural phenomenon of human-controlled vehicles. When vehicles follow one another the response action of a following vehicle to a speed disturbance from the lead vehicle can vary. The following vehicle may respond to a speed disturbance by reducing its speed immediately if following very close, or may respond to it at a later when the spacing between them is reduced to a certain level, or may not respond to it by its speed reduction but just reduce the spacing between the two vehicles. In the cases when the following vehicle does not respond to a speed disturbance immediately, a speed disturbance can be absorbed (completely or partially) through the reduction of spacing (i.e., distance headway). Limited research has been found on the issue of absorption of a speed disturbance and the effects on traffic stability as a result of speed disturbance absorption.

The work explores driver behavior in a car following mode in response to a speed disturbance from the lead vehicle, and develops a concept of Expected State-Control Action Chains. Afterwards, the study identifies three scenarios of car-following behavior in response to a decrease in the speed of the vehicle immediately downstream. The impact of the responding behavior of the following vehicle on dynamic spacing between the lead-following vehicle pair was analyzed and minimum dynamic spacing for each scenario were obtained. The research conducted as part of this study first

demonstrates the existence of an upper boundary on the magnitude of a speed disturbance that can be absorbed by a single spacing, or by multiple spacings if the speed disturbance is propagated backward through a line of following vehicles. Mathematical models were developed to enable the calculation of the upper limit of speed disturbance absorption. The conditions for local and asymptotic stability were also determined. Results from two simulation experiments confirm the boundary conditions proposed by the mathematical models.

The work presented here sheds some light on the effect that a single speed disturbance of a lead vehicle has on the spacing and speed of the following vehicle in a car-following mode at the microscopic level. This establishes the foundation for further research on multiple speed disturbance absorption and its impact on traffic stability at the macroscopic analysis level.

ACKNOWLEDGEMENTS

It has been a time to express one's feelings when finishing the final page of his/her dissertation. It has been a place to leave his/her words for people to remember. It is a right time and a right place for me to write down something for lasting memories.

Thinking about the years at Michigan State University, I am grateful to all of you, the faculty members of the transportation group, for giving me opportunities to study in its excellent program, which I am always proud of, and to learn from you, whom I always admire to. I am profoundly grateful to Dr. Virginia P. Sisiopiku, my advisor, for her always supports, encouragements and priceless advices; to Dr. William C. Taylor for his guidance, suggestions and assistance whenever I needed; and to Dr. Richard W. Lyles for value of the knowledge he taught and the example he set in his teaching and researching that I am going to follow.

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Looking back the path I walked over, I saw the footprints left behind. Each of them filled with love, supports and efforts of my parents. And each of them costs part spans of their lives.

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Receiving so much loves, supports, understandings, advices, guidance, helps, and knowledge, I have been doing my best to contribute myself to science and engineering in hope to make the world more beautiful through a powerful stream combining each tiny effort from us. As a reward to what I received, I would dedicate this academic work to those whom I love and admire.

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CHAPTER 1 INTRODUCTION

1.1 Background

It has long been recognized that the breakdown of traffic flow is a direct consequence of high traffic volume. In the Highway Capacity Manual (HCM, 2000), capacity is defined as "the maximum sustainable flow rate at which vehicles or persons reasonably can be expected to traverse a point or uniform segment of a lane or roadway during a specified time period under given roadway, geometric, traffic, environmental, and control conditions." The definition of capacity implies that a breakdown occurs immediately after the capacity has been reached. However, numerous field observations confirm that breakdown does not always occur at the highest flow rate observed, nor does a speed drop always correspond to the highest observed flow. Another phenomenon observed in the field is that speed sometimes does not drop, even when flow is at a high rate. These phenomenon supports the hypothesis that breakdown is a probabilistic event (Elefteriadou 1995). If this is accepted, there is a need to determine what random factors can be used to describe the observed traffic behavior.

A study by Hall et al. (*1993*) examined the three types of speed drops suggested in previous studies of Athol, Banks and Koshi (Athol 1965, Banks 1989, Koshi 1983), and concluded that the speed drops seem to be related to the data collection locations or to environmental conditions. The data in Hall's study were collected at different locations in the vicinity of congestion, and support his conclusions. His study provides an explanation of different types of breakdown. However, his study does not explain the phenomenon that speed sometimes does not drop, even when the flow rate is quite high.

Therefore, there must exist some other factors that affect speed drop under such conditions.

Many previous spot speed studies suggested that speed drop is not a continuous process. However, individual vehicular speed change is a continuous process both on the dimensions of time and distance. When a vehicle follows another vehicle closely, the individual vehicular speeds affect each other. A speed drop of a vehicle in a traffic stream can be propagated upstream, if vehicles in a traffic stream are close enough to one another. On the other hand, if traffic is not heavy, the following vehicles do not necessarily respond to temporary speed changes of leading vehicles, and small speed disturbance can simply be absorbed by the traffic stream. Lorenz and Elefteriadou provide the evidence of this phenomenon through their field observations (Lorenz and Elefteriadou 2000). The phenomenon and the evidence lead us to consider speed disturbance as a possible random factor leading to a breakdown. In this respect, two questions are raised: a) Does there exist an upper limit on the magnitude of a speed disturbance that can be absorbed by traffic at a certain flow rate without causing a breakdown, and b) if it does, what is it? This study addresses these issues through exploring driver's behavior in response to a speed disturbance from a vehicle in the front and defines the upper limits on the magnitude of a speed disturbance that a single space (or multiple spaces) can absorb, without causing a breakdown, and the conditions for local or asymptotic stability.

1.2 Literature Review

Car-following theories were first introduced in 1950's and still provide a good way to model speed and space interaction between vehicles. Most engineering-inspired car-following studies model car following behavior first and then analyze the conditions for model's stability. As Boer (2000) comments, those models presumed that driving is equivalent to the continuous application of a single control law in a series manner.

The earlier car-following models discuss speed-spacing relationships from a Newtonian kinetic point of view. For example, the car-following model in the Highway Capacity Manual (FHWA 1950) suggests a minimum spacing between two vehicles as the sum of a vehicle length, the distance that a following vehicle travels during the driver's reaction time and the stop distance of the following vehicle. The car-following models proposed by Pipes (1953) and Forbes (1958) define a minimum headway between two consecutive vehicles as the sum of reaction time plus the time required for the following or lead vehicle to travel a distance equivalent to its length.

A breakthrough in car-following theories took place when human factors were taken into account in stimuli-response car following models first proposed by the General Motor (GM) researchers (Chandler *et al.* 1958, and Herman *et al.* 1959). Chandler considered the car-following law to be

$$\ddot{x}_n(t+\Delta t) = \lambda[\dot{x}_{n+1}(t) - \dot{x}_n(t)] \qquad 1\text{-}1$$

where $\ddot{x}_n(t+\Delta t)$ = the acceleration of the following vehicle at time $t+\Delta t$,

$\dot{x}_{n+1}(t)$, $\dot{x}_n(t)$ = speeds of vehicle n+1, vehicle n, and λ = a constant.

Model 1-1 implied a velocity-headway relation of $v = \lambda(k - k_{jam})$ where k is the concentration and k_{jam} the *jam* concentration. This shows that for $\lambda\Delta t > \frac{1}{2}$ any initial disturbance of an equilibrium state will grow in time as it passes down a line of vehicles and, for a sufficiently long line of vehicles, will create stop-and-go conditions.

However, this stability criterion was "slightly violated" in some cases when traffic should have been stable. Ferrari (1994) showed that when the flow is unstable, instability may take too long to manifest itself and the flow to break down, which partly demonstrates Hall's conclusion (1993) described in the Section 1.1.

Herman *et al.* (1959) continued the investigation of the stability of Chandler's model and concluded that: for $\lambda\Delta t < e^{-1}$, an initial disturbance is non-oscillatory and exponentially damped; for $e^{-1} < \lambda\Delta t < \frac{\pi}{2}$, the initial disturbance is oscillatory with exponential damping; for $\lambda\Delta t = \frac{\pi}{2}$, the initial disturbance is oscillatory with constant amplitude; and for $\lambda\Delta t > \frac{\pi}{2}$, the initial disturbance is oscillatory with increasing amplitude. Figure 1-1 shows the stability of Chandler's model for three values of C $= \lambda\Delta t$

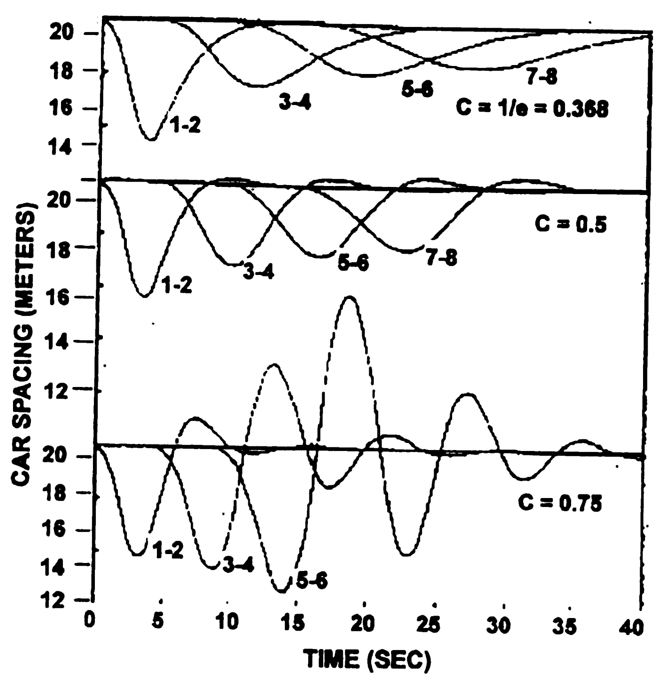

Figure 1-1 Stability of Chandler's Model (Herman *et al.* 1958)

Following the GM pioneers, Gazis *et al.* and Edie explored the sensitivity parameter in the GM models (Gazis *et al.* 1959, Edie 1961, and Gazis *et al.* 1961) and proposed non-linear car-following models. To represent quicker reactions for denser traffic, Gazis *et al.* suggested that

$$\ddot{x}_n(t+\Delta t) = \frac{\lambda}{x_n(t) - x_{n+1}(t)}[\dot{x}_{n+1}(t) - \dot{x}_n(t)] \qquad 1\text{-}2.$$

This equation leads to the velocity-headway relationship $v = \lambda \ln(\frac{k_j}{k})$, which is identical to Greenberg's flow-concentration curve (Greenberg, 1959). Edie found that another amendment should be made to the sensitivity constant, namely, the introduction of the velocity dependent term. This produced a new model of the form

$$\ddot{x}_n(t+\Delta t) = \frac{\lambda \dot{x}_{n+1}(t)}{[x_n(t) - x_{n+1}(t)]^2}[\dot{x}_{n+1}(t) - \dot{x}_n(t)] \qquad 1\text{-}3$$

which can be integrated to give a velocity-headway relationship as $v = v_f \exp(\frac{-k}{k_m})$ where v_f = free flow speed and k_m = density at maximum flow. Further, Gazis *et al.* introduced the general scaling constant *m* and *l* to investigate the sensitivity of their macroscopic relationships to variations in the magnitude of the *v* and the $x_n(t) - x_{n+1}(t)$ terms respectively

$$\ddot{x}_n(t+\Delta t) = \frac{\lambda \dot{x}^m_{n+1}(t)}{[x_n(t) - x_{n+1}(t)]^l}[\dot{x}_{n+1}(t) - \dot{x}_n(t)] \qquad 1\text{-}4.$$

The integration of 1-4 produces a velocity-headway function $v = \left[\frac{\lambda(l-1)b^{1-m}}{1-m} + c\right]^{\frac{1}{l-1}}$ where c = a constant of the solution of the differential equation 1-4. The stability condition of this model is the same as for Chandler's model i.e., for $\lambda'\Delta t < \frac{1}{2}$, the system is stable (Holland, 1998).

Newell (1961) considered consequences of non-linearity and postulated that the velocity of vehicle *n+1* is some nonlinear function of the headway

$$\dot{x}_{n+1}(t+\Delta t) = V\left[1-\exp\left(-\frac{\lambda}{V}(x_n(t)-x_{n+1}(t))-d\right)\right] \qquad 1\text{-}5$$

where V = maximum velocity or free flow speed of vehicle *n+1,* and

d = minimum headway of vehicle *n+1.*

Equation (5) implies a velocity-headway relationship of the form

$$v = V\left[1-\exp[\frac{\lambda}{V}(k-k_{jam})]\right]$$

Newell analyzed the stability of this system and found that for $\lambda\Delta t > \frac{1}{2}$, the system was unstable and the behavior was diffusive under stable conditions.

After Newell's work the engineering-inspired car-following models were less and less investigated until 1995 when Bando *et al.* (1995) suggested a new car-following law

$$\ddot{x}_n(t+\Delta) = a[V(x_{n+1}(t)-x_n(t))-\dot{x}_n(t)] \qquad 1\text{-}6$$

where a = an acceleration constant,

V = a legal velocity which is a function of following distance of the preceding vehicle.

Equation 1-6 leads to a velocity-headway relationship of $v = \tanh(k-2) + \tanh(2)$ and the similar stability condition for the system $a > 2V'(k_0)$, where tanh(k) represents $V(k)$ and k_0 a concentration at steady state flow.

With the exception of the recent work of Bando, all other models imply different velocity-headway relationships, but conclude the same criterion $\lambda\Delta t < \frac{1}{2}$ for traffic stability. The definition of λ in these models vary, but basically it is regarded as a driver-behavior-related parameter, which makes it difficult to envision what the λ exactly represents in car-following theories. As mentioned at the beginning of this literature review, all of the models previously reviewed presupposed that driving is equivalent to the continuous application of a single control law in a series manner. Therefore it is not surprising that there is a single criterion for traffic stability for all models. However, it is commonly acknowledged that drivers use different criteria in different situations when carrying on a single-lane car following task, which inspired researchers to think beyond engineering models.

In 2000, Boer's commentary pointed out that that some important issues that characterize driver behavior are still ignored in engineering car-following models. This position ignited a debate between researchers. The issues raised by Boer include the following: (1) car following is only one of many tasks that drivers perform simultaneously and receives therefore only intermittent attention and control, (2) drivers are satisfied with a range of conditions that extend beyond the boundaries imposed by perceptual and control limitation, and (3) in each driving task drivers use a set of highly informative perceptual variables to guide decision making and control. On the basis of these three issues, Boer proposed a framework that seeks to depart from determinism and presents two approaches to further develop the area, namely satisfying behavior and task scheduling. The problem with this approach, as Brackstone and McDonald pointed out (2000) is obtaining data with which to calibrate the model. Since it is a new concept in modeling car-following behavior, more development is expected as the development of the conjunctive field of traffic psychology progresses.

In the debate, Van Winsum (2000) showed how psychological knowledge about car following behavior by human drivers could be applied in a mathematical model that can be used in traffic engineering. Based on a wide variety of behavior studies, (Van Winsum 1998, Heino 1996, Van der Horst 1999, Fuller 1981, Steven 1957, Schiff and Detwiler 1979, McLeod and Ross 1983, Cavallo *et al.*1986, and Van der Horst 1990), Van Winsum established his human element-based model that describes the relation of psychological factors (time headway, distance headway, and deceleration) used by the driver in car following. Van Winsum's model is established upon three rationales: (1) drivers use time headway as a safety margin; (2) if distance to the lead vehicle is larger than the preferred distance headway that drivers try to maintain (D_p), there is no safety-related reason for the driver to decelerate until the preferred distance headway is reached; and (3) the deceleration initiated by the driver is a function of the Time-to-Collision (TTC) parameter,

$$\ddot{x}_{n+1} = cTTC_{est} + d + \varepsilon \text{, with } d < 0, \qquad \text{1-7}$$

where: $TTC_{est} = 1.04TTC^{0.72}$, the TTC as estimated by the driver,

c and d, constants; and ε, a random error term.

Back in the late 1950's, Helly (1959) used a criterion similar to the second rationale of Van Winsum to develop a model conceptually close to the risk-threshold model of driving behavior. Both models have flaws in their methods to estimate actual distance headways. Helly's model compares the driver's estimation of spacing with the actual spacing, presumably not directly available to the driver. The truthfulness of the assumption of constant time headway proposed in Van Winsum's model, which is the key variable in calculating distance headway, was also questioned. Similar to Boer's model, Van Winsum's model has not been tested with data.

The debate between traffic engineering and psychology researchers finally focused on the question posed in the discussion of Hancock (2000) of whether car following is the real question and if equations are the answer. The answers to both questions by Brackstone (2000) are negative, however it has been acknowledged that the car following concept provided an acceptable tool for the job and equations are the most suitable answers for the task at hand. Brackstone's statements concur with Ranney's (2000) who also suggests that the development of better models of car-following behavior that are applicable to a well-defined situation is probably a more worthwhile approach to follow.

The review of the literature clearly shows that both psychological and Newtonian kinetic principles play important roles in car-following theories. Although, the needs of traffic psychologists and traffic engineers have not yet met in a satisfactory manner, both groups agree that an effort should be made to consider both aspects in developing more understandable car-following models under well-defined situations.

1.3 Objective

The thesis presented here is an attempt to consider both the psychological and engineering aspects in modeling car-following behaviors. This effort explores driver's behavior in response to a speed disturbance from a vehicle in the front and defines the upper limits on the magnitude of a speed disturbance that single space or multiple spaces can absorb, without causing a breakdown, and the conditions for local or asymptotic stability.

1.4 Contributions and Contents

The major contributions of this work are the findings of the upper boundary theory of speed-disturbance absorption and the formulas to calculate this upper boundary. The thesis focuses on the boundary conditions when a speed disturbance occurs. This work is different from previous studies in that it starts from Boer's psychological hierarchical framework to develop a well-defined problem questioned in Section 1.1, and then uses the Newtonian principle in the defined problem to establish equations that lead to the calculation of the boundary conditions of speed disturbance at the levels of either local or asymptotic stability.

The thesis consists of five parts.

Chapter 1 provides an introduction and a discussion of relevant literature.

Chapter 2 discusses salient performance aspects of the human elements in carrying out the car following tasks in the defined problem. By exploring the discrete components of Boer's hierarchically psychological model, including monitoring and controlling processes, perceptual variables and expected state in car following, the chapter discusses the transiting chain of expected states and then obtains three scenarios in car following for further analysis. The chapter focuses on the characteristics of population and propounds a Normative Behavior Hypothesis, and also discusses the error of human beings in the assessment of the perceptual variables and control skills.

Chapter 3 discusses the localized behavior of the following vehicle in response to a change in speed of the vehicle immediately in front and its direct impact on the dynamic spacing between them. Minimum dynamic spacing for each scenario defined in Chapter 2 is obtained, which establishes the fundamental work for the next chapter.

Chapter 4 develops the concepts of speed disturbance absorption, and establishes an upper boundary theory of speed disturbance absorption. It presents the speed disturbance absorbed by a single spacing, and speed disturbance propagation and cumulative absorption by multiple spacing in a traffic stream. Mathematical models are developed that give descriptions on the upper limit of speed disturbance that a single spacing or multiple spacing can absorb. Furthermore the conditions for local and asymptotic stability are determined.

Chapter 5 summarizes results from the use of simulation data to test the validation of the models obtained in Chapter 4.

Chapter 6 briefly states the most important findings from the study and offers recommendations for further research.

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CHAPTER 2 HUMAN BEHAVIOR IN SINGLE-LANE CAR FOLLOWING

Drivers generally engage in multiple tasks on roads, such as lane changing, car following, over-taking, etc. In 1999, Boer attempted to consider elements of human decision-making and action-taking in the development of a hierarchical driver-modeling framework as shown in Figure 2-1.

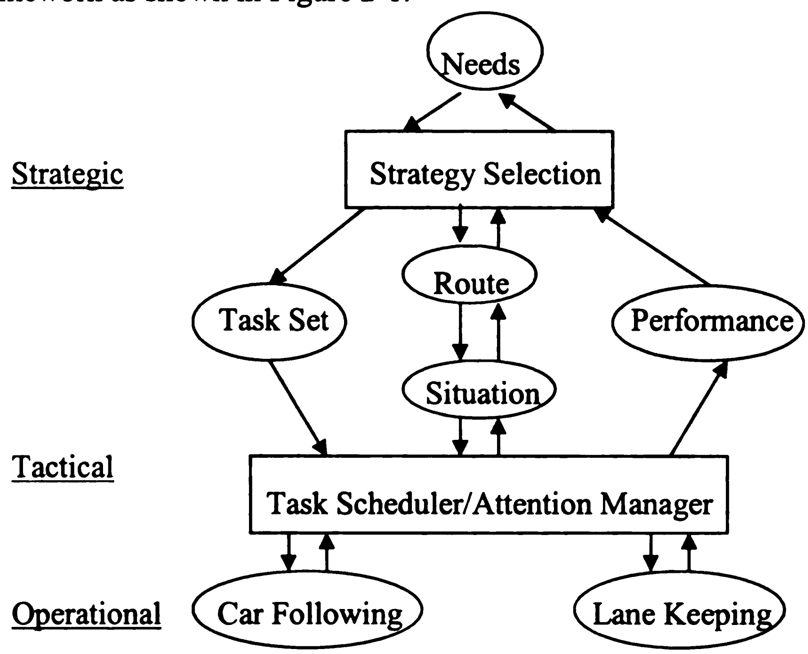


Figure 2-1. Hierarchical Driver Modeling Framework (Boer 1999)

Each vehicle control task consists of two processes, namely monitoring and controlling. The monitoring process once initiated by the attention manager is decomposed into several stages: (1) pay attention to the perceptual variables that characterize a particular task in the form of the present state, (2) use those variables to evaluate current and expected future states, (3) assess whether the present performance will most likely remain acceptable for a certain amount of time, and if so (4) determine when attention should be given to the task again. If the present performance is not satisfactory, then the task scheduler initiates the appropriate control process that employs a suitable skill to bring the vehicle within a limited time into an acceptable state that is expected to remain acceptable for some time (Boer 2000).

Consistently, the conventional control theory describes the car-following task as a process where drivers dynamically and interactively carry out perception and information collection, which is equivalent to the aforementioned stage (1), as well as decision making and execution tasks while following another vehicle in a single lane, which is equivalent to the stages (2) and (3). A detailed generalization of car following from the perspective of a conventional control theory is illustrated in Figure 2-2 (Gartner et al. 2000).

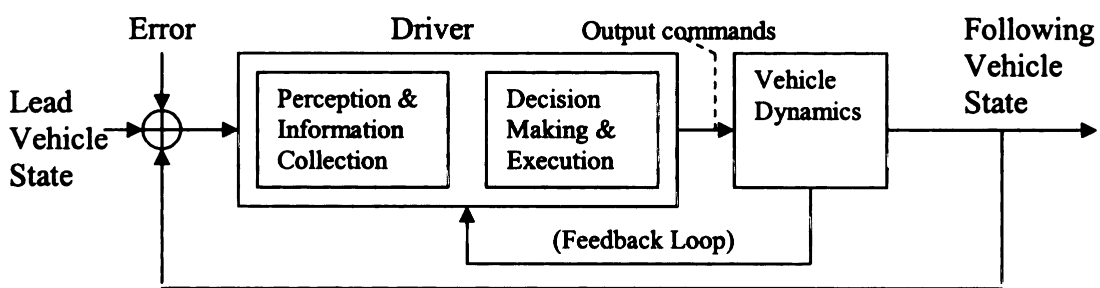


Figure 2-2. Detailed Generalization of Car Following from Conventional Control Theory

2.1 Perceptive Variables and Expected States in Single-Lane Car Following

When carrying on a single-lane car following task, drivers pay attention to two major perceptual variables: spacing and speed. Drivers evaluate their current and expected future states by using these perceptual variables to assess whether they are acceptable. During the assessment process drivers do not always give an equal priority to each of them. If the degree of unacceptability of the spacing perceptual variable is greater than the target risk level, which gives drivers a signal of an oncoming collision, this signal overwhelms speed perceptual variables and triggers the task scheduler to initiate an immediate brake-control action without evaluating speed satisfaction. For example, when following a vehicle in close proximity and observing a brake signal from the vehicle in the front, the driver of the following vehicle responds by applying the brakes immediately without thinking about speed. Sometimes the spacing perceptual variable is unacceptable but not at the target-risk level, and drivers apply comfort deceleration instead of reacting to an emergency. In this case, a new standard of satisfactory speed is adopted. The spacing perceptual variable is improved by trading off the satisfaction of speed. When the spacing perceptual variable is acceptable, drivers adopt a satisfactory speed and keep the current state until a new state emerges. Figure 2-3 illustrates this interactive process.

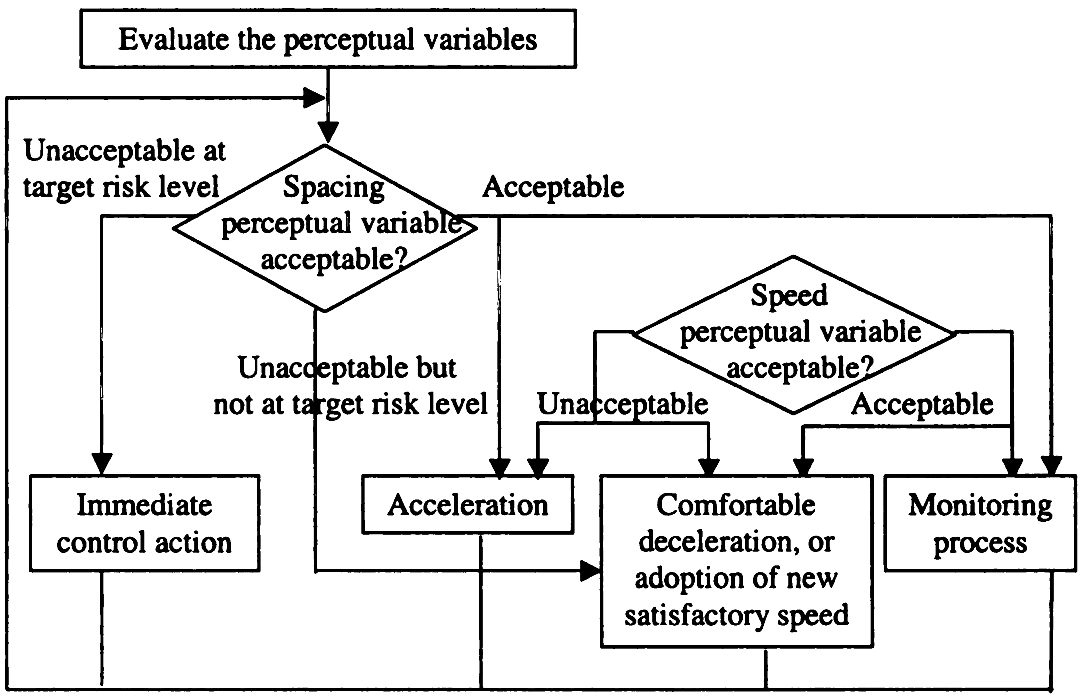


Figure 2-3. Interactive Perception and Reaction Process of Single-Lane Car Following

The assessment of the perceived spacing variable produces three expected states that call for different mental models and control skills. An unacceptable state (at the target risk level) calls for an emergency-response model and skill. An unacceptable state, but not at the target risk level uses a mental model that predicts its new state based on its current state and decides when to take an action to achieve the new state. An acceptable state does not invite any controlling actions, just the monitoring process. The three expected states of the spacing perceptual variable can be represented by the following three spacing limits: a) minimum safety spacing between two consecutive vehicles, S_{safe}, that requires an emergency-response model, b) a spacing that calls for a comfortable control skill, and c) a spacing that invites only the monitoring process.

Unlike the spacing perceptual variable, the speed perceptual variable is assessed by different criteria in different states. A satisfactory speed in one state may not be satisfactory in another, as drivers adopt different satisfactory speeds based on their situation.

2.2 Expected State-Control Action Chains in Single-Lane Car Following Process

For convenience, the discussion in this section starts at the time point t_0. At t_0 the lead vehicle is traveling at a speed $\dot{x}_n(t_0)$ and starts to reduce its speed. This vehicle needs a period of time, denoted as *T*, to recover its speed ($\dot{x}_n(t_0+T)=\dot{x}_n(t_0)$) as shown as in Figure 2-4. During *T*, there exist two phases: the speed disturbance development phase that extends from t_0 to t_1, and the recovery phase, from t_1 to t_0+T.

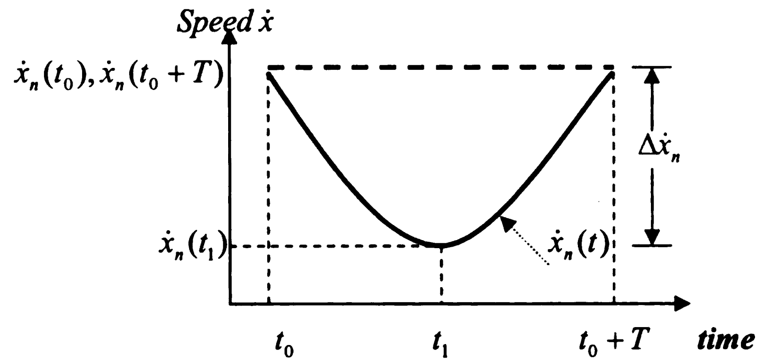


Figure 2-4. Speed Diagram of Lead Vehicle and Its Two Phases of Speed Disturbance

Evidence indicates that speed choice is fairly consistent over time for an individual driver (Haglund and Aberg, 2000). If the original speed that the driver of the lead vehicle adopts is $\dot{x}(t_0)$ in a given situation before a speed disturbance, the desired speed after the speed disturbance is recovered ($\dot{x}_n(t_0+T)$) is most likely to be identical to $\dot{x}_n(t_0)$ in the same situation. Thus to simplify the discussion, we assume that the speed of the vehicle that develops a speed disturbance will be recovered to its original level (Figure 2-4).

At t_0 when the speed disturbance is initiated, the following vehicle could be at any of the three states previously described. The states of the following vehicle could either change or remain unchanged during T as the two consecutive vehicles interact with each other, which forms state-control chains. On one hand, if at t_0 the initial state of the perceptual variables of the following vehicle is acceptable and it remains acceptable during T, then the following vehicle keeps its original speed unchanged, as illustrated in Figure 2-5. On the other hand, it is possible that at t_0 the initial state of the perceptual variables is acceptable and during T the state of the spacing perceptual variable becomes unacceptable due to the speed drop of the lead vehicle (Figure 2-6).

In this case, a control action of deceleration is initiated to bring the unacceptable state of the spacing perceptual variable back to an acceptable level. The perception of acceptable or unacceptable for the spacing perceptual variable varies from driver to driver. The drivers who would like to use controlled deceleration may adopt a larger spacing as an acceptable threshold than the drivers who choose to hit the brake pedals harder. The braking action of the driver of the following vehicle can start as early as when the driver perceives the speed drop of the lead vehicle to as late as when he/she has reached the minimum braking distance to avoid collision. Moreover, the adoption of deceleration rates would differ by drivers. Some may just release the gas pedal to reduce the vehicular speed in response to the speed drop of the lead vehicle when a large enough spacing is available. Other drivers may apply "controlled braking" to control their speed and the spacing between the two vehicles, whereas some drivers may choose to brake at the last minute with "maximum braking force." The reaction of the following vehicle to the speed disturbance from the lead vehicle varies with respect to time from the earliest to the latest possible action time, the region for the speed reduction, from the minimum to maximum, is shown by the dash-dot lines in Figure 2-6. If at t_0 the initial state of the perceptual variables of the following vehicle is unacceptable and at target risk level, an appropriate control action is immediately taken to bring them away from the target risk. In this case the interactive speeds of the two vehicles are shown in Figure 2-7.

Through the above analysis, there are three basic Expected State-Control Action Chains: acceptable-acceptable, acceptable-unacceptable-control action-acceptable, and unacceptable at target risk level-control action-acceptable. Single-lane car following is a process consisting of any combination or repetition of these three basic chains. The basic Expected State-Control Action Chains are summarized in Table 2-1 along with the actions of the following vehicle in response to a speed reduction from the lead vehicle.

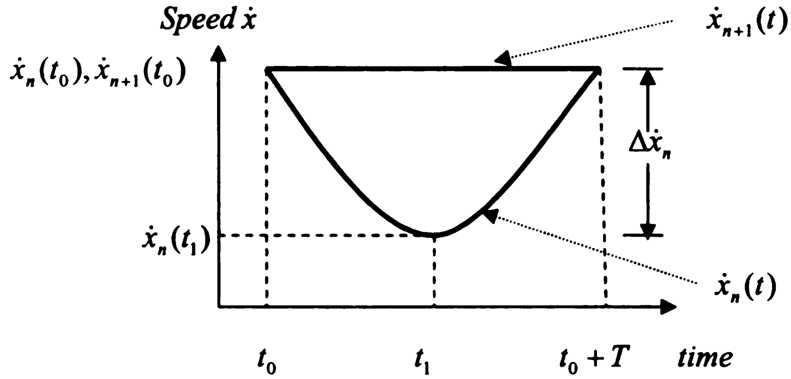


Figure 2-5. Interactive Speeds of Following Vehicle with the State of Perceptual Variables Acceptable from t_0 through T

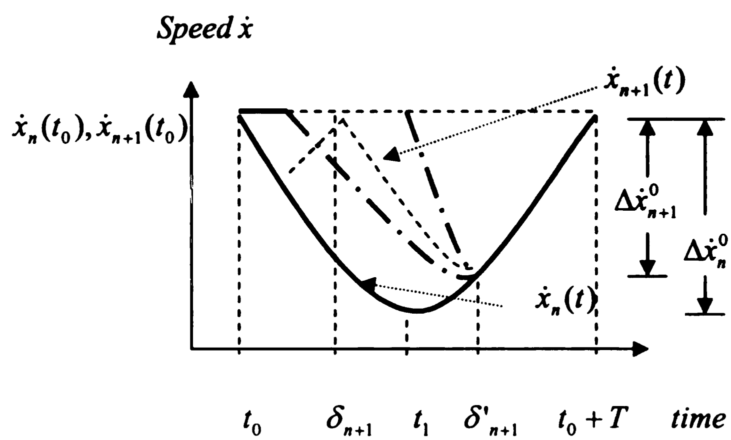
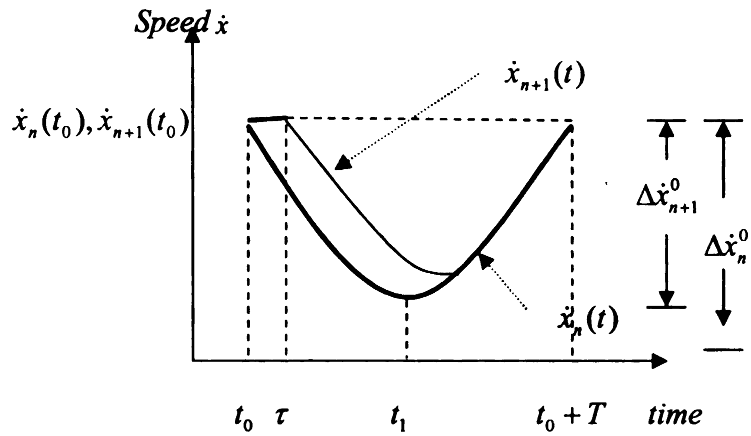


Figure 2-6. Interactive Speeds of Following Vehicle with the States of Perceptual Variables Acceptable at t_0 and Becoming Unacceptable at Sometime between time t_0 and t_0+T



τ : reaction time of the following driver

Figure 2-7. Interactive Speeds of Following Vehicle with the States of Perceptual Variables Unacceptable at t_0

Table 2-1 Basic Expected State-Control Action Chains and Three Scenarios

Basic Expected State-Control Action Chains	Action of the following vehicle	
	Control action	Control action time
Acceptable-Acceptable	No action	N/A
Acceptable-Unacceptable-Control action-Acceptable	Minimum < $\ddot{x}^-_{n+1}$ < maximum	$\tau < \delta <$ latest possible action time
Unacceptable at target-risk level-Control action-Acceptable	$\ddot{x}^-_{n+1} \leq$ maximum	τ

2.3 Normative Behavior Hypothesis

Drivers have the tendency to react to speed disturbance when following another car. The predisposition of reacting behavior is assumed to be determined by individuals' attitudes towards that behavior (Parker et al., 1992; Rothengatter, 1993). The personalities of human beings result in a variety of attitudes towards car following behaviors. Not every driver follows a vehicle in front in accordance to normative behavior nor tends to willingly deviate from that behavior. Although the modern attitude theories assume a causal relation between attitudes and behaviors, only normative behavior is possibly describable for every given situation and every given interaction (Mcknight et al., 1970; Mcknight et al., 1971). In addition, normative behavior represents the behavior of the majority of the drivers. Therefore, it is assumed in this work that the drivers respond to a speed disturbance in single lane car following in a normative manner and have the tendency to react to specific situations predictably (Rothengatter, 1999).

2.4. Deviance of Assessment and Control Skill

The normative behavior hypothesis establishes a ground for the further discussion. However, the hypothesis does not mean that the exact same values are produced in the perceptual variable assessment and control actions. Errors in both the assessment and skills are unavoidable due to the difference of physical and intelligence capabilities of human beings.

Drivers estimate the distance and relative speed from the vehicle ahead through the visual angle change. Human visual angle transition changes from near linear to geometric in magnitude as an object is approaching at a constant velocity. As the rate of change of the visual angle becomes geometric, the perceptual system triggers a warning that an object is going to collide with the observer, or, conversely, that object is pulling away from the observer. This looming phenomenon is a function of distance from the object. If the rate of the change of visual angle is irregular, that provides information to the perceptual system that the object in motion is moving at a changing velocity (Schiff, 1990).

Human visual perception of acceleration of an object in motion is very gross and inaccurate; it is very difficult for a driver to discriminate a speed change from constant velocity unless the object is observed for a relative long period of time – 10 or 15 seconds (Boff and Lincoln, 1988).

The delta speed threshold (i.e., change in relative velocity of the lead vehicle and the following vehicle) for detection of an oncoming collision or pull-away has been studied in collision-avoidance research. Drivers can detect a change in distance between the vehicles they are driving and the one in front when it has varied by approximately 12% (Mortimer, 1988). Mortimer notes that the major cue is rate of change in visual angle. This threshold was estimated in one study as 0.0035 radians/sec (Gartner, 2000). This would suggest that a change of distance of 12 percent in 5.6 seconds or less would trigger a perception of an approach or pulling away. Mortimer concludes that: "… unless the relative velocity between two vehicles becomes quite high, the drivers will respond to changes in their headway, or the change in angular size of the vehicle ahead, and use that as a cue to determine the speed that they should adopt when following another vehicle." This study implies that the perception time τ' of the following drivers during which the driver becomes aware that the distance between his/her vehicle and the vehicle in front is decreasing, depends on the spacing between them and the relative speed of the two vehicles. If we assume that the speed of the following vehicle is kept in a stable state during τ' the relative speed is determined by the speed of the lead vehicle. The speed of the lead vehicle at time point $t \in [t_0, \tau']$ is $\dot{x}_n(t_0) + \int_{t_0}^{t} \ddot{x}_n(t)$.

Rothery (1968) revisited the speed curves obtained by Ohio State University in their steady-state car following study (Todosiev, 1963) and concluded that the acceleration/deceleration rate can be considered roughly to be constant (Gartner, 2000). Therefore, the integration equation above can be rewritten as

$\dot{x}_n(t_0) + \int_{t_0}^{t} \ddot{x}_n(t) = \dot{x}_n(t_0) + \ddot{x}_n \Delta t$, $\Delta t = t - t_0$. The dynamic distance $S(t)$ between two consecutive vehicles is as follows:

$$S(t) = S(t_0) + \dot{x}_n(t_0)\Delta t + \frac{1}{2}\ddot{x}_n \Delta^2 t - \dot{x}_{n+1}(t_0)\Delta t.$$

The relative spacing change

$$\frac{S(t_0) - S(t)}{S(t_0)} = \frac{1}{S(t_0)}[-\dot{x}_n(t_0)\Delta t - \frac{1}{2}\ddot{x}_n(t_0)\Delta^2 t + \dot{x}_{n+1}(t_0)\Delta t] \qquad 2\text{-}1.$$

Based on Mortimer's results, drivers can detect a change in distance between their own vehicle- and the one in front when it has varied by approximately 12%. Based on this observation we set Equation 2-1 equal to 0.12. The time that allows the driver of the following vehicle to become aware the speed change of the lead vehicle can be obtained as follows

$$\tau' = \frac{(\dot{x}_n(t_0) - \dot{x}_{n+1}(t_0)) \pm \sqrt{(\dot{x}_n(t_0) - \dot{x}_{n+1}(t_0))^2 - 2 \times 0.12 \ddot{x}_n S(t_0)}}{\ddot{x}_n(t_0)} \qquad 2\text{-}2.$$

If we assume that at t_0, $\dot{x}_n(t_0) = \dot{x}_{n+1}(t_0)$,

$$\tau' = \frac{\sqrt{-2 \times 0.12 \ddot{x}_n S(t_0)}}{\ddot{x}_n} = 0.4899\sqrt{\frac{S(t_0)}{-\ddot{x}_n}} \qquad 2\text{-}3.$$

Driver's input to a planned braking situation approximates a "ramp" function with the slope determined by the distance to the desired stop location or steady-state speed in the case of a platoon being overtaken (Gartner, 2000). The driver applies pedal pressure to the brakes until a desired deceleration is obtained. The maximum "comfortable" braking deceleration is generally accepted to be in the neighborhood of - 0.30 g, or around 3 m/sec^2 (ITE, 1992). Wortman and Matthias observed a range of - 0.22 to - 0.43 g with a mean level of - 0.36 g (Wortman and Matthias, 1985). Hence, "comfortable" braking performance that yields a g force of about - 0.2 would be a reasonable lower level, i.e. almost any driver could be expected to change the velocity of a passenger car by at least that amount, while a "typical" level would be around - 0.35 g. If a driver responds to the speed disturbance by removing his or her foot from the accelerator pedal, dragging and rolling resistance produce deceleration at about the same level as "unhurried" acceleration, approximately 1 m/sec^2. Drivers use controlled braking skills to respond to an unexpected braking situation or an anticipated one when they are unsure of when it would happen. The empirical data collected on drivers in their own vehicles show a wide variation ranging from –0.46 g to –0.7 g with a mean level of –0.55 g for "unexpected" situations and –0.45 g for "anticipated but unsure when" situations (Fambro, 1994). In general, the deceleration rates can be from 1 m/sec^2 to 3.6 m/sec^2 with a reasonable low rate of 2.2 m/sec^2 for a "planned" situation, from 4.6 m/sec^2 to 7.0 m/sec^2 with a mean rate of 5.5 m/sec^2 for an "unexpected" situation, and from 2.4 m/sec^2 to 6.6 m/sec^2 with a mean rate of 4.5 m/sec^2 for "anticipated but unsure when" situation. Therefore the deceleration rates of a following vehicle could be from the minimum of 1.0 m/sec^2 to the maximum of 7.0 m/sec^2. The driver's braking behaviors under the three situations discussed above are summarized in Table 2-2.

Table 2-2. Driver's Braking Behaviors under Three Situations

Situations	"Planned situation"	"Anticipated but unsure when"	"Unexpected"
Deceleration Rate Range	1– 3.6 m/sec^2 (3– 12 ft/sec^2)	2.4 - 6.6 m/sec^2 (8 - 22 ft/sec^2)	4.6 – 7.0 m/sec^2 (15.3– 23.3 ft/sec^2)
Mean of Deceleration Rate	2.3 m/sec^2 (8 ft/sec^2)	4.5 m/sec^2 (15 ft/sec^2)	5.5 m/sec^2 (18 ft/sec^2)

The amount of time required to make the braking input movement (*MT*) was also investigated in three studies that proposed mean times ranging from 0.20 – 0.26 sec. Research indicates that the relationship between perception-reaction time and *MT* is weak to nonexistent. That is, a long perception time does not necessarily predict a long *MT* (Berman, 1994). Thus, the earliest possible time at which the speed of the following vehicle is expected to be reduced is the sum of the perception time, τ' plus the braking-input time as follows

$$\tau = \tau' + MT = 0.4899\sqrt{\frac{S(t_0)}{-\ddot{x}_n}} + MT \qquad 2\text{-}4.$$

The values of τ as a function of ($S(t_0), \ddot{x}_n$) for the spacing from 100 m to 10 m and deceleration rate from 1.0 m/sec^2 to 7.0 m/sec^2 with $MT = 0.2$ seconds are calculated in Table 2-3.

Table 2-3. Earliest Perception-Reaction Time as a Function of Spacing and Deceleration Rates

Spacing (m)		τ						
Original spacing	Reduced spacing	$\ddot{x} = 1.0$ m/sec^2	$\ddot{x} = 2.0$ m/sec^2	$\ddot{x} = 3.0$ m/sec^2	$\ddot{x} = 4.0$ m/sec^2	$\ddot{x} = 5.0$ m/sec^2	$\ddot{x} = 6.0$ m/sec^2	$\ddot{x} = 7.0$ m/sec^2
100.0	88.0	5.10	3.66	3.03	2.65	2.39	2.20	2.05
90.0	79.2	4.85	3.49	2.88	2.52	2.28	2.10	1.96
80.0	70.4	4.58	3.30	2.73	2.39	2.16	1.99	1.86
70.0	61.6	4.30	3.10	2.57	2.25	2.03	1.87	1.75
60.0	52.8	3.99	2.88	2.39	2.10	1.90	1.75	1.63
50.0	44.0	3.66	2.65	2.20	1.93	1.75	1.61	1.51
40.0	35.2	3.30	2.39	1.99	1.75	1.59	1.46	1.37
30.0	26.4	2.88	2.10	1.75	1.54	1.40	1.30	1.21
20.0	17.6	2.39	1.75	1.46	1.30	1.18	1.09	1.03
10	8.8	1.75	1.30	1.09	0.97	0.89	0.83	0.79

When following very closely, the driver of the following vehicle is alerted, because their assessment of the perceptual variable has been near the threshold of the target risk level. Therefore, a braking signal of the lead vehicle could trigger the driver's reaction to the signal almost immediately. There is no specific study of the response lag to a braking signal. However, studies at signalized intersections suggested that the average driver's response lag to a signal change (time of change to onset of break lamps) is 1.3 seconds and is somewhat inelastic with respect to distance from the signal at which the signal state changed (Chang, 1985 and Wortman, 1983). If we assume a value of brake response lag to a braking signal of the lead vehicle similar to the response lag to achange in signal indication at intersections, then the earliest time that the following vehicle starts to reduce its speed after receiving a brake signal would be 1.3 seconds. It is worth noticing that the times shaded in Table 2.1 are times needed by a driver to recognize a spacing change under certain circumstances. Some of these times are shorter than 1.3 seconds, the time lag for a driver to respond to a signal change. In those cases, the drivers could use their brake at anytime when they recognize the distance change, which could be less or more than 1.3 seconds.

Drivers control their vehicular speeds by the skills of speed keeping, accelerating and decelerating. Under steady-state car following conditions, the range of speed-control error was estimated to be no more than +/- 1.5 m/sec (Evans and Rothery, 1973). The acceleration rates, particularly in a traffic stream as opposed to a standing start, are typically much lower than the performance capabilities of the vehicle. Drivers under "unhurried" circumstances use approximately 65% of the maximum acceleration for the vehicle, or approximately 1 m/sec^2 (ITE, 1992). AASHTO places the nominal range for "comfortable" acceleration at speeds of 48 km/h and above to 0.6 to 0.7 m/sec^2 (AASHTO, 1990). In steady-state car following circumstance, the arcs of relative speed versus spacing are approximately parabolic implying that acceleration/deceleration can be considered roughly to be constant (Barbosa, 1961). Overall, the acceleration/deceleration rates for an individual vehicle could be constant, for the vehicles in a traffic stream however, the rate could range from a maximum of 1.5 m/sec^2 to 0.6 m/sec^2.

2.5 Summary

Through exploring the hierarchical driver modeling framework proposed by Boer, this chapter developed the concepts of Expected State-Control Action Chains and further obtained the three scenarios of the car-following process when a lead vehicle has a speed disturbance. On the basis of previous studies on driver's behavior in perceiving and reacting to a speed change of the lead vehicle, we proposed the possible control-action time and control strategies that could be used by the driver of the following vehicle to respond to a speed disturbance from the lead vehicle. They are summarized in Tables 2-2 and 2-3 and will be used in Chapter 5.

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CHAPTER 3 SINGLE SPEED DISTURBANCE AND DYNAMIC SPACING

Error and deviation of speed in manual controlled vehicles is common. The speed of a human-controlled car usually fluctuates around desired value that the driver adopts. Therefore, speed disturbance is a natural phenomenon of traffic flow. The speed disturbance could be large or small in value, long or short in duration, could occur under various traffic conditions and has various degrees of impact on traffic stability. The response of the following vehicle to a speed disturbance of a lead vehicle can be very different depending on the characteristics of the disturbance.

This chapter discusses the localized behavior of a following vehicle in response to a fluctuation in the motion of the vehicle directly in front and the dynamic spacing between the two vehicles. Formulas to calculate minimum dynamic spacing for each of the scenarios of speed disturbance defined in Chapter 2 are obtained in this chapter.

For the readers convenience, the notations used in the following discussion are defined as:

n: lead vehicle

$n+1$: the first following vehicle

t_0: beginning time point of the scenario,

t: time variable ,

t_1: time point at which vehicle n starts to accelerate,

Δt: time interval variable,

δ: time point before which vehicle n+1 travels at its original speed,

δ': time point at which vehicle n+1 completes its speed reduction,

T: time period during which vehicle n completes its speed recovery,

$\dot{x}_n(t)$: speed of vehicle n (lead vehicle) at time t,

$\dot{x}_{n+1}(t)$:speed of vehicle n+1 (following vehicle) at time t,

$\ddot{x}_n^+$: acceleration rate of vehicle n, roughly to be constant (Rothery 2000),

$\ddot{x}_n^-$: the deceleration rate of vehicle n, roughly to be constant (Rothery 2000),

$\ddot{x}_{n+1}^-$: the deceleration rate of vehicle n+1, roughly to be constant (Rothery 2000),

S_{safe}: minimum safe distance headway for following vehicle, and

$S(t)$: distance headway between vehicles n, and n+1 at time t.

As assumed in Section 2.3, vehicles n and n+1 are in an acceptable car-following mode which is considered to be the beginning state of the system, and the original speeds of the two vehicles are roughly the same. At t_0, vehicle n develops a speed disturbance and starts to recover it at t_1. At $t_0 + T$ the vehicle n completes its speed recovery. During the development and recovery of a speed disturbance the following vehicle may not reduce its speed to respond to it or may respond to it with different rates of deceleration depending on the assessment of perceptual variables and the Expected State of the following vehicle as seen in Figure 2-5, 2-6 and 2-7. In the period of $[t_0, t_0 + T]$ the dynamic spacing between the two vehicles can vary greatly but will follow the law

$$S(t) = S(t_0) + \int_{t_0}^{t} \dot{x}_n(t)dt - \int_{t_0}^{t} \dot{x}_{n+1}(t)dt \qquad 3\text{-}1.$$

3.1 Dynamic Spacing with Acceptable-Acceptable Expected States

As illustrated in Figure 2.5, during the lead vehicle speed disturbance the following vehicle does not need to take any control action to respond to the speed disturbance, therefore, $\ddot{x}_{n+1}(t)=0$ for $t \in [t_0, t_0+T]$.

In the time interval $[t_0, t_1]$ vehicle n reduces its speed and a speed disturbance is developed. According to Rothery's conclusion (Gartner *et al.* 2000) in reexamining the data obtained in the studies by Todosiev (1963) and Rothery (1968), the deceleration rate of an individual vehicle can be assumed as almost constant. Thus Equation 3.1 becomes:

$$S(t) = S(t_0) + \frac{1}{2}\ddot{x}_n^- \times (t-t_0)^2 \qquad \text{where } \ddot{x}_n^- < 0, t \in [t_0, t_1] \qquad 3\text{-}2.$$

Since $\frac{dS(t)}{dt} = \ddot{x}_n^-(t-t_0) < 0$, the *S(t)* in the equation 3-2 monotonically decreases and has its minimum value as shown in Equation 3-3 below:

$$\textit{Minimum} \quad S(t) = S(t_1) = S(t_0) + \frac{1}{2}\ddot{x}_n^- \times (t_1-t_0)^2, \qquad \text{at } t = t_1 \qquad 3\text{-}3.$$

In the time interval $(t_1, t_0+T]$ vehicle n increases its speed and the speed disturbance is being recovered. The dynamic spacing between the two vehicles becomes:

$$S(t) = S(t_1) + \int_{t_1}^{t} \dot{x}_n(t)dt - \int_{t_1}^{t} \dot{x}_{n+1}(t)dt \qquad t \in [t_1, t_1+T) \qquad 3\text{-}4$$

where $S(t_1) = S(t_0) + \frac{1}{2}\ddot{x}_n^- \times (t_1 - t_0)^2$,

$\dot{x}_n(t_1) = \dot{x}_n(t_0) + \ddot{x}_n^- \times (t_1 - t_0)$,

$\dot{x}_{n+1}(t) = \dot{x}_{n+1}(t_0)$, and

$$\dot{x}_n(t) = \dot{x}_n(t_1) + \int_{t_1}^{t} \ddot{x}_n(t)dt = \dot{x}_n(t_0) + \ddot{x}_n^- \times (t_1 - t_0) + \int_{t_1}^{t} \ddot{x}_n^+(t)dt$$

$$= \dot{x}_n(t_0) + \ddot{x}_n^- \times (t_1 - t_0) + \ddot{x}_n^+ \times (t - t_1)$$

Equation 3-4 can be reorganized and simplified as follows:

$$S(t) = S(t_0) + \frac{1}{2}\ddot{x}_n^- \times (t_1 - t_0)^2 + \ddot{x}_n^- \times (t_1 - t_0) \times (t - t_1) + \frac{1}{2}\ddot{x}_n^+ \times (t - t_1)^2 \quad 3\text{-}5.$$

Since $\frac{dS(t)}{dt} = \ddot{x}_n^- \times (t_1 - t_0) + \ddot{x}_n^+(t - t_1)$ and $\frac{d^2S(t)}{dt^2} = \ddot{x}_n^+ > 0$, the $S(t)$ has a minimum value in $(t_1, t_0 + T]$. Let $\frac{dS(t)}{dt} = 0$, we solve

$$t - t_1 = -\frac{\ddot{x}_n^-}{\ddot{x}_n^+}(t_1 - t_0) = \frac{\dot{x}_n(t_0) - \dot{x}_n(t_1)}{\ddot{x}_n^+} = (t_0 + T) - t_1 \quad 3\text{-}6.$$

The $S(t)$ has a minimum value:

$$Minimum \quad S(t) = S(t_0 + T) = S(t_0) + \frac{1}{2}\ddot{x}_n^- \times (t_1 - t_0)^2 \times [1 - \frac{\ddot{x}_n^-}{\ddot{x}_n^+}], \text{ at } t = t_0 + T \quad 3\text{-}7.$$

Comparison of Equations 3-3 and 3-7 shows that, since $[1 - \frac{\ddot{x}_n^-}{\ddot{x}_n^+}] > 1$ and $\ddot{x}_n^-(t) <$ 0, $S(t_0 + T) < S(t_1)$. Thus in this scenario during the entire period of $[t_0, t_0 + T]$ *S(t)* has a minimum value of

$$Minimum \quad S(t) = S(t_0 + T) = S(t_0) + \frac{1}{2}\ddot{x}_n^- \times (t_1 - t_0)^2 \times [1 - \frac{\ddot{x}_n^-}{\ddot{x}_n^+}] \quad 3\text{-}8.$$

3.2 Dynamic Spacing with Acceptable-Unacceptable-Acceptable Expected States

In this scenario, as illustrated in Figure 2-6, during the lead vehicle speed disturbance the expected states of the following vehicle changes from acceptable to unacceptable, and it would take a speed control action from the following vehicle to keep a safe spacing. A control action can be taken as early as at time t_0 + *Perception-Reaction Time* to the time at which the driver of the following vehicle is required to reduce its speed to avoid a collision. The deceleration rate as analyzed in Chapter 2 can be as small as 1 m/sec to a 7 m/sec. If δ represents the beginning time of a control action and δ' its ending time, there exist three cases to be discussed: Case 1) $\delta < t_1$ and $\delta' > t_1$, Case 2) $\delta < t_1$ and $\delta' < t_1$, and Case 3) $\delta > t_1$ and $\delta' > t_1$. They are illustrated in Figure 3-1.

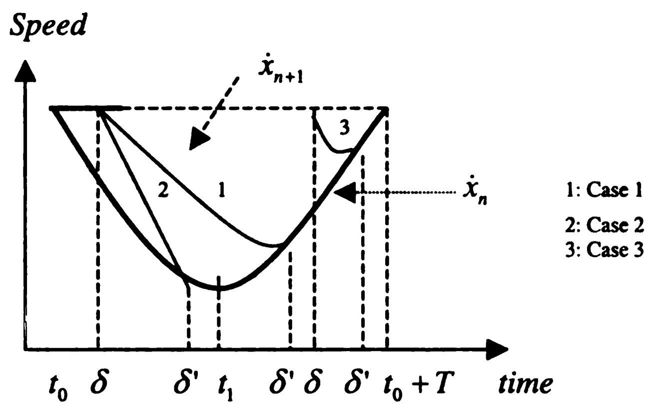


Figure 3-1. Possible Control-Action Strategies that Following Vehicle Can Take with Expected States of Acceptable-Unacceptable-Acceptable

Case 1. $\delta < t_1$ and $\delta' > t_1$

In $[t_0, \delta]$, the following vehicle keeps its original speed and the dynamic spacing between it and the vehicle in front follows the same way as described in 3-2, and

$$Minimum\ S(t) = S(\delta) = S(t_0) + \frac{1}{2}\ddot{x}_n^- \times (\delta - t_0)^2 \qquad 3\text{-}9.$$

In $(\delta, t_1]$, the following vehicle reduces its speed to keep a safe distance from the vehicle in front. The dynamic spacing between them is:

$$S(t) = S(\delta) + \int_{\delta}^{t} \dot{x}_n(t)dt - \int_{\delta}^{t} \dot{x}_{n+1}(t)dt \tag{3-10.}$$

where $S(\delta) = S(t_0) + \frac{1}{2}\ddot{x}_n^- \times (\delta - t_0)^2$,

$\dot{x}_{n+1}(t) = \dot{x}_{n+1}(\delta) + \int_{\delta}^{t} \ddot{x}_{n+1}(t)dt = \dot{x}_{n+1}(t_0) + \ddot{x}_{n+1}^{--} \times (t - \delta)$, and

$\dot{x}_n(t) = \dot{x}_n(\delta) + \int_{\delta}^{t} \ddot{x}_n(t)dt = \dot{x}_n(t_0) + \ddot{x}_n^- \times (\delta - t_0) + \int_{\delta}^{t} \ddot{x}_n^- dt = \dot{x}_n(t_0) + \ddot{x}_n^- \times (t - t_0)$,

Equation 3-10 can be rewritten and simplified as:

$$S(t) = S(t_0) + \frac{1}{2}\ddot{x}_n^- \times (t - t_0)^2 - \frac{1}{2}\ddot{x}_{n+1}^{--} \times (t - \delta)^2 \tag{3-11.}$$

$\frac{dS(t)}{dt} = \ddot{x}_n^- \times (t - t_0) - \ddot{x}_{n+1}^{--} \times (t - \delta) < 0$, which means that 3-11 monotonically

decreases and has its minimum value at $t = t_1$ as:

$$Minimum\, S(t) = S(t_1) = S(t_0) + \frac{1}{2}\ddot{x}_n^- (t_1 - t_0)^2 - \frac{1}{2}\ddot{x}_{n+1}^{--}(t_1 - \delta)^2 \tag{3-12.}$$

In $(t_1, \delta']$, the following vehicle n+1 keeps reducing its speed and the lead vehicle n recovers its speed. The dynamic spacing between them is:

$$S(t) = S(t_1) + \int_{t_1}^{t} \dot{x}_n(t)dt - \int_{t_1}^{t} \dot{x}_{n+1}(t)dt \tag{3-13.}$$

If substitute $S(t_1)$, $\dot{x}_n(t) = \dot{x}_n(t_0) + \ddot{x}_n^- \times (t_1 - t_0) + \ddot{x}_n^+(t - t_1)$, and

$\dot{x}_{n+1}(t) = \dot{x}_{n+1}(t_0) + \ddot{x}_{n+1}^{--} \times (t_1 - \delta) + \ddot{x}_{n+1}^{--}(t - t_1)$ into Equation 3-13, it becomes:

$$S(t) = S(t_0) + \frac{1}{2}\ddot{x}_n^- \times (t_1 - t_0)^2 + \ddot{x}_n^- \times (t_1 - t_0) \times (t - t_1) + \frac{1}{2}\ddot{x}_n^+ \times (t - t_1)^2$$

$$- \frac{1}{2}\ddot{x}_{n+1}^{--} \times (t_1 - \delta)^2 - \ddot{x}_{n+1}^{--} \times (t_1 - \delta) \times (t - t_1) - \frac{1}{2}\ddot{x}_{n+1}^{--} \times (t - t_1)^2 \tag{3-14.}$$

Since in the time interval of $t \in (t_1, \delta']$ the differentials of Equation 3-14 are:

$$\frac{dS(t)}{dt} = \ddot{x}_n^- \times (t_1 - t_0) + \ddot{x}_n^+ \times (t - t_1) - \ddot{x}_{n+1}^- \times (t_1 - \delta) - \ddot{x}_{n+1}^- \times (t - t_1) = \dot{x}_n(t) - \dot{x}_{n+1}(t) \le 0,$$

$\frac{dS^2(t)}{dt^2} = \ddot{x}_n^+ - \ddot{x}_{n+1}^- > 0$, and $S(t)$ is continuous on t, Equation 3-14 has its minimum value at $t = \delta'$ as:

$$S(\delta') = S(t_0) + \frac{1}{2}\ddot{x}_n^- \times (t_1 - t_0)^2 + \ddot{x}_n^- \times (t_1 - t_0) \times (\delta' - t_1) + \frac{1}{2}\ddot{x}_n^+ \times (\delta' - t_1)^2 - \frac{1}{2}\ddot{x}_{n+1}^- \times (\delta' - \delta)^2$$

$$= S(t_0) + \frac{1}{2}\ddot{x}_n^- \times (t_1 - t_0)(\delta' - t_0) - \frac{1}{2}\ddot{x}_{n+1}^- \times (\delta' - \delta)(t_1 - \delta) \qquad \text{3-15.}$$

At $t = \delta'$, the speed of the vehicle n+1 is reduced to roughly the same speed as that of the vehicle n and in the period $(\delta', t_0 + T]$ this vehicle keeps following the lead one at roughly the same speed. Therefore the spacing in this time interval can be roughly regarded as constant.

If subtract Equation 3-9 from 3-12, we have:

$$S(t_1) - S(\delta) = \ddot{x}_n^- \times (t_1 - \delta) \times (\delta - t_0) + \frac{1}{2}\ddot{x}_n^- \times (t_1 - \delta)^2 - \frac{1}{2}\ddot{x}_{n+1}^- \times (t_1 - \delta)^2$$

$$= \frac{(t_1 - \delta)}{2}[\dot{x}_n(t_1) - \dot{x}_{n+1}(t_1) + \ddot{x}_n^- \times (\delta - t_0)] < 0,$$

which means that in the time interval of $(t_0, t_1]$ *Minimum* $S(t) = S(t_1)$.

Again, if subtract Equation 3-12 from 3-15, we have:

$$S(\delta') - S(t_1) = (\delta' - t_1)[\ddot{x}_n^- \times (t_1 - t_0) + \frac{1}{2}\ddot{x}_n^+ \times (\delta' - t_1) - \ddot{x}_{n+1}^- \times (t_1 - \delta)(\delta' - t_1) - \frac{1}{2}\ddot{x}_{n+1}^- \times (\delta' - t_1)]$$

. Since $\dot{x}_n(\delta') = \dot{x}_{n+1}(\delta')$ as assumed in the definition of this scenario, i.e.,

$\dot{x}_n(t_0) + \ddot{x}_n^- \times (t_1 - t_0) + \ddot{x}_n^+ \times (\delta' - t_1) = \dot{x}_{n+1}(t_0) + \ddot{x}_{n+1}^- \times (t_1 - \delta) + \ddot{x}_{n+1}^- \times (\delta' - t_1)$, and

$\dot{x}_n(t_0) = \dot{x}_{n+1}(t_0)$, $S(\delta') - S(t_1)$ can be rewritten and simplified as:

$$S(\delta') - S(t_1) = \frac{1}{2}(\delta' - t_1)[\dot{x}_n(t_1) - \dot{x}_{n+1}(t_1)] < 0,$$

which means that in the time interval of $(t_0, \delta']$ *Minimum S(t)* = $S(\delta')$. Thus in this scenario

$$Minimum\ S(t) = S(\delta') \qquad 3\text{-}16.$$

Case 2. $\delta < t_1$ and $\delta' < t_1$

In $[t_0, \delta]$, the following vehicle keeps its original speed and the dynamic spacing between it and the vehicle in front follows the same way as described in 3-2. In this time interval

$$Minimum\ S(t) = S(\delta) = S(t_0) + \frac{1}{2}\ddot{x}_n^- \times (\delta - t_0)^2 \qquad 3\text{-}17.$$

In $(\delta, \delta']$, the speed disturbance is continuously developed and vehicle n+1 reduces its speed starting at $t = \delta$ to keep a safe distance space in front until $t = \delta'$ at which time its speed is reduced to about the same as that of vehicle n. The dynamic spacing between them is:

$$S(t) = S(\delta) + \int_{\delta}^{t} \dot{x}_n(t)dt - \int_{\delta}^{t} \dot{x}_{n+1}(t)dt \qquad 3\text{-}18$$

where $S(\delta) = S(t_0) + \frac{1}{2}\ddot{x}_n^- \times (\delta - t_0)^2$,

$\dot{x}_{n+1}(t) = \dot{x}_{n+1}(\delta) + \int_{\delta}^{t} \ddot{x}_{n+1}(t)dt = \dot{x}_{n+1}(t_0) + \ddot{x}_{n+1}^- \times (t - \delta)$, and

$\dot{x}_n(t) = \dot{x}_n(\delta) + \int_{\delta}^{t} \ddot{x}_n(t)dt = = \dot{x}_n(t_0) + \ddot{x}_n^- \times (\delta - t_0) + \ddot{x}_n^- \times (t - \delta)$.

If substitute them into Equation 3-18, we have:

$$S(t) = S(\delta) + \ddot{x}_n^- \times (\delta - t_0) \times (t - \delta) + \frac{1}{2}\ddot{x}_n^- \times (t - \delta)^2 - \frac{1}{2}\ddot{x}_{n+1}^- \times (t - \delta)^2 \qquad 3\text{-}19.$$

Since in the time interval of $t \in (\delta, \delta']$ the differentials of Equation 3-19 are:

$$\frac{dS(t)}{dt} = \ddot{x}_n^- \times (\delta - t_0) + \ddot{x}_n^- \times (t - \delta) - \ddot{x}_{n+1}^- \times (t - \delta) = \dot{x}_n(t) - \dot{x}_{n+1}(t) \leq 0,$$

$\frac{dS^2(t)}{dt^2} = \ddot{x}_n^- - \ddot{x}_{n+1}^- > 0$, and $S(t)$ is continuous over *t*, Equation 3-19 has its minimum value in the time interval of $(\delta, \delta']$ as:

$$Minimum\ S(t) = S(\delta') = S(t_0) + \frac{1}{2}\ddot{x}_n^- \times (\delta' - t_0)^2 - \frac{1}{2}\ddot{x}_{n+1}^- \times (\delta' - \delta)^2, \text{ at } t = \delta' \qquad 3\text{-}20.$$

In $(\delta', t_0 + T]$, the following vehicle keeps roughly the same speed profile as that of the vehicle directly in front. The dynamic spacing between them can be regarded as constant. Therefore, the minimum value of dynamic spacing in this scenario is:

$Minimum\ S(t) = S(\delta')$.

Case 3. $\delta > t_1$ and $\delta' > t_1$

In $[t_0, t_1]$, the following vehicle keeps its original speed and the dynamic spacing between it and the vehicle in front follows the same way as described in 3-2 and reaches its minimum value at $t = t_1$, i.e.,

$$Minimum\ S(t) = S(t_1) = S(t_0) + \frac{1}{2}\ddot{x}_n^- \times (t_1 - t_0)^2 \qquad 3\text{-}21.$$

In $[t_1, \delta]$, vehicle n recovers its speed. The Expected States of vehicle n+1 have been kept acceptable and the following vehicle travels at its original speed until $t = \delta$. The dynamic spacing between the two vehicles is:

$$S(t) = S(t_1) + \int_{t_1}^{t} \dot{x}_n(t)dt - \int_{t_1}^{t} \dot{x}_{n+1}(t)dt \qquad 3\text{-}22.$$

As we did above, substitute $\dot{x}_n(t) = \dot{x}_n(t_0) + \ddot{x}_n^-(t - t_0)$ and $\dot{x}_{n+1}(t) = \dot{x}_{n+1}(t_0) + \ddot{x}_{n+1}^-(t - t_0)$ into Equation 3-22, we have:

$$S(t) = S(t_0) + \frac{1}{2}\ddot{x}_n^- \times (t_1 - t_0)^2 + \ddot{x}_n^- \times (t_1 - t_0)(t - t_1) + \frac{1}{2}\ddot{x}_n^+ \times (t - t_1)^2 \qquad \text{3-23.}$$

Since $\frac{dS(t)}{dt} = \ddot{x}_n^- \times (t_1 - t_0) + \ddot{x}_n^+ \times (t - t_1) < 0$ the *S(t)* in this time interval monotonically decreases and has its minimum value at $t = \delta$ as :

$$\textit{Minimum } S(t) = S(t_0) + \frac{1}{2}\ddot{x}_n^- \times (t_1 - t_0)^2 + \ddot{x}_n^- \times (t_1 - t_0)(\delta - t_1) + \frac{1}{2}\ddot{x}_n^+ \times (\delta - t_1)^2 \qquad \text{3-24.}$$

In $(\delta, \delta']$, vehicle n continuously recovers its speed and vehicle n+1 reduces its speed to keep a safe distance headway from the vehicle in front. The dynamic spacing is:

$$S(t) = S(\delta) + \int_\delta^t \dot{x}_n(t)dt - \int_\delta^t \dot{x}_{n+1}(t)dt \qquad \text{3-25.}$$

Since $\dot{x}_n(t) = \dot{x}_n(\delta) + \ddot{x}_n^+ \times (t - \delta) = \dot{x}_n(t_0) + \ddot{x}_n^- \times (t_1 - t_0) + \ddot{x}_n^+ \times (t - t_1)$, and $\dot{x}_{n+1}(t) = \dot{x}_{n+1}(t_0) + \ddot{x}_{n+1}^- \times (t - \delta)$, the above equation can be rewritten and simplified as:

$$S(t) = S(t_0) + \frac{1}{2}\ddot{x}_n^+ \times (t - t_1)^2 + \frac{1}{2}\ddot{x}_n^- \times (t_1 - t_0)^2 + \ddot{x}_n^- \times (t_1 - t_0)(t - t_1) - \frac{1}{2}\ddot{x}_{n+1}^- \times (t - \delta)^2 \qquad \text{3-26}$$

It is:

$$\frac{dS(t)}{dt} = \ddot{x}_n^+ \times (t - t_1) + \ddot{x}_n^- \times (t_1 - t_0) - \ddot{x}_{n+1}^- \times (t - \delta) = \ddot{x}_n^+ \times (t - \delta') - \ddot{x}_{n+1}^- \times (t - \delta')$$

$$= (\delta' - t)(\ddot{x}_{n+1}^- - \ddot{x}_n^+) < 0.$$

The *S(t)* monotonically decreases and reaches its minimum value at $t = \delta'$ as:

Minimum S(t) $= S(\delta') =$

$$= S(t_0) + \frac{1}{2}\ddot{x}_n^+ \times (\delta' - t_1)^2 + \frac{1}{2}\ddot{x}_n^- \times (t_1 - t_0)^2 + \ddot{x}_n^- \times (t_1 - t_0)(\delta' - t_1) - \frac{1}{2}\ddot{x}_{n+1}^- \times (\delta' - \delta)^2 \quad \text{3-27.}$$

In $(\delta', t_0 + T]$, the two vehicles keep the same speed profile and the spacing between them is roughly constant.

If subtract Equation 3-21 from 3-24, we have:

$$S(\delta) - S(t_1) = (\delta - t_1)[\ddot{x}_n^- \times (t_1 - t_0) + \frac{1}{2}\ddot{x}_n^+ \times (\delta - t_1)$$

$$< (\delta - t_1)[\ddot{x}_n^- \times (t_1 - t_0) + \ddot{x}_n^+ \times (\delta - t_1) < 0, \text{ i.e., } S(\delta) < S(t_1).$$

Subtract Equation 3-24 from 3-26, then we have:

$$S(\delta) - S(\delta')$$

$$= (\delta - t_1)[\ddot{x}_n^- \times (t_1 - t_0) + \frac{1}{2}\ddot{x}_n^+ \times (\delta - t_1)] + (\delta' - t_1)[\ddot{x}_{n+1}^- \times (\delta' - \delta)] - \frac{1}{2}\ddot{x}_n^+ \times (\delta' - t_1)$$

$$< (\delta - t_1)[\ddot{x}_n^- \times (t_1 - t_0) + \ddot{x}_n^+ \times (\delta - t_1)] + (\delta' - t_1)[\ddot{x}_{n+1}^- \times (\delta' - \delta)] - \frac{1}{2}\ddot{x}_n^+ \times (\delta' - t_1)$$

$$< 0, \text{ i.e., } S(\delta') < S(\delta) \quad \text{3-28.}$$

Thus in this scenario, *Minimum* $S(t) = S(\delta')$.

3.3 Dynamic Spacing with Unacceptable Expected State at Target-Risk Level

Under this scenario, as described in Figure 2-7, the driver of the following vehicle is alert at all times and would take control action when receiving any stimulus, such as brake signals from the vehicle in front. In this case the control action occurs as soon as $t = t_0 + \tau$. There are two cases in this scenario: $\delta' > t_1$ and $\delta' < t_1$, shown in Figure 3-2.

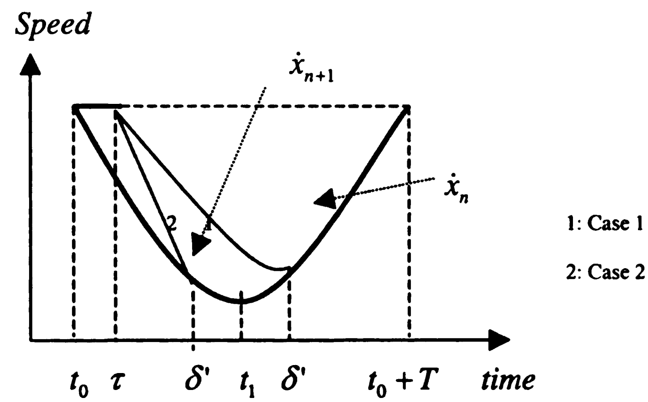


Figure 3-2. Possible Control-Action Strategies that Following Vehicle Can Take with Expected States of Unacceptable at Target-Risk Level

Case 1. $\delta' > t_1$

This case is similar to**Case 1** in **Section 3.2** except for the beginning time of a control action of the following vehicle. In this case the beginning time of a control action is$t = \tau$, while in the **Case 1** of **Section 3.2** the beginning time of a control action is $t = \delta$. If δ is replaced by τ, the equations in the **Case 1** of **Section 3.2** are applicable in this case. Therefore the minimum spacing in this case becomes:

$$Minimum\, S(t) = S(\delta') = S(t_0) + \frac{1}{2}\ddot{x}_n^- \times (t_1 - t_0)^2 + \ddot{x}_n^- \times (t_1 - t_0) \times (\delta' - t_1) + \frac{1}{2}\ddot{x}_n^+ \times (\delta' - t_1)^2$$

$$-\frac{1}{2}\ddot{x}_{n+1}^- \times (\delta' - \tau)^2 \qquad 3\text{-}29.$$

Case 2. $\delta' < t_1$

This case is similar to the **Case 2** in **Section 3.2**. As pointed out in the above case that the beginning time of a control action of the following vehicle in this case is $t = \tau$, in stead of $t = \delta$. If δ is replaced by τ, the equations derived for the **Case 2** in **Section 3.2** are applicable in this case. Therefore the minimum spacing in this case becomes:

$$\textit{Minimum}\ S(t) = S(\delta') = S(t_0) + \frac{1}{2}\ddot{x}_n^- \times (\delta' - t_0)^2 - \frac{1}{2}\ddot{x}_{n+1}^- \times (\delta' - \tau)^2 \text{ at } t = \delta' \qquad 3\text{-}28.$$

3.4 Summary

Localized behavior of the following vehicle, in response to a speed disturbance of the vehicle directly in front, changes the spacing in a continuous and dynamic manner. Minimum values of the dynamic spacing for each case analyzed in **Sections 3.1, 3.2** and **3.3** have been derived and are summarized in Table 3-1. These values are of interest in the discussion of upper boundary conditions for stabilities. This discussion is presented in detail in Chapter 4.

References

Gartner, N. Traffic Flow Theory. Chapter 4 of R.W. Rothery, Car Following Models. Transportation Research Board Special Report 165, Transportation Research Board, 2000, pp.

Todosiev, E.P. The Action Point Model of the Driver Vehicle System. Report No. 202A-3. Ohio State University, Engineering Experiment Station, Columbus, Ohio, 1963.

Table 3-1. Formulas to Calculate Minimum Spacing for the Scenarios Defined in Chapter 2

Expected States/Cases		Time at which dynamic spacing is minimum	Formula to calculate minimum spacing, Minimum $S(t)$
Acceptable-Acceptable		$t = t_0 + T$	$S(t_0) + \frac{1}{2}\ddot{x}_n^- \times (t_1 - t_0)^2 \times [1 - \frac{\ddot{x}_n^-}{\ddot{x}_n^+}]$
Acceptable-Unacceptable-Acceptable	$\delta < t_1$ and $\delta' > t_1$	$t = \delta'$	$S(t_0) + \frac{1}{2}\ddot{x}_n^- \times (t_1 - t_0) \times (\delta' - t_0) - \frac{1}{2}\ddot{x}_{n+1}^- \times (\delta' - \delta) \times (t_1 - \delta)$
	$\delta < t_1$ and $\delta' < t_1$	$t = \delta'$	$S(t_0) + \frac{1}{2}\ddot{x}_n^- \times (\delta' - t_0)^2 - \frac{1}{2}\ddot{x}_{n+1}^- \times (\delta' - \delta)^2$
	$\delta > t_1$ and $\delta' > t_1$	$t = \delta'$	$S(t_0) + \frac{1}{2}\ddot{x}_n^+ \times (\delta' - t_1)^2 + \frac{1}{2}\ddot{x}_n^- \times (t_1 - t_0)^2 + \ddot{x}_n^- \times (t_1 - t_0) \times (\delta' - t_1) - \frac{1}{2}\ddot{x}_{n+1}^- \times (\delta' - \delta)^2$
Unacceptable at Target-Risk Level	$\delta' > t_1$	$t = \delta'$	$S(t_0) + \frac{1}{2}\ddot{x}_n^- \times (t_1 - t_0)^2 + \ddot{x}_n^- \times (t_1 - t_0) \times (\delta' - t_1) + \frac{1}{2}\ddot{x}_n^+ \times (\delta' - t_1)^2 - \frac{1}{2}\ddot{x}_{n+1}^- \times (\delta' - \tau)^2$
	$\delta' < t_1$	$t = \delta'$	$S(t_0) + \frac{1}{2}\ddot{x}_n^- \times (\delta' - t_0)^2 - \frac{1}{2}\ddot{x}_{n+1}^- \times (\delta' - \tau)^2$

CHAPTER 4 SPEED DISTURBANCE AND STABILITY

During the interaction of the following vehicle in response to a speed disturbance the minimum dynamic spacing is a key restrictive parameter to safely carry out a single-lane car-following task. Therefore it becomes of interest to discuss the upper boundary conditions for speed-disturbance absorption and stability. On the basis of the Chapter 3, the existence of an upper boundary will be demonstrated and the magnitude of a speed disturbance that a single spacing can absorb will be quantified. Moreover, the conditions for local and asymptotic stability will be discussed.

The following definitions will be found useful for the discussion that follows.

Definition 4-1: The value of a speed disturbance is expressed as

$$\Delta\dot{x}_n = \dot{x}_n(t_0) - \dot{x}_n(t_1) = \left|\ddot{x}_n^-\right| \times (t_1 - t_0).$$

Definition 4-2: A generated speed disturbance is defined as the speed reduction of the following vehicle in response to the speed disturbance of the vehicle direct in front. It can be quantified by

$$\Delta\dot{x}_{n+1} = \left|\ddot{x}_{n+1}^-\right| \times (\delta' - \delta).$$

Definition 4-3: The amount of a speed disturbance absorbed by the spacing between the lead vehicle n and the following vehicle n+1 is defined as

$$\Delta\dot{x}_n - \Delta\dot{x}_{n+1} = \left|\dot{x}_n^-\right| \times (t_1 - t_0) - \left|\dot{x}_{n+1}^-\right| \times (\delta' - \delta).$$

Obviously, $\Delta\dot{x}_n - \Delta\dot{x}_{n+1}$ is a function of the speed change of the two vehicles, and the control-action time of the following vehicle.

Definition 4-4: The upper boundary on the magnitude of a speed disturbance that a single spacing can absorb is defined as

$$\Delta\dot{x}_n^0 = Maximum(\Delta\dot{x}_n - \Delta\dot{x}_{n+1}) = Maximum\{|\ddot{x}_n^-| \times (t_1 - t_0) - |\ddot{x}_{n+1}^-| \times (\delta' - \delta)\}.$$

4.1 Value of Upper Limit of A Speed Disturbance that a Single Spacing Can Completely Absorb

As illustrated in Figure 2-5, when a speed disturbance from a lead vehicle occurs. the following vehicle may not need to reduce its speed in response to it during the period of the speed disturbance development and recovery. In this case, the speed disturbance does not have any impact on the speed of the following vehicles, but reduces the spacing between them. In other words, the speed disturbance is completely absorbed by the single spacing. The minimum dynamic spacing in this scenario is at $t = t_0 + T$ as

$$Minimum \qquad S(t) = S(t_0 + T) = S(t_0) + \frac{1}{2}\ddot{x}_n^- \times (t_1 - t_0)^2 \times [1 - \frac{\ddot{x}_n^-}{\ddot{x}_n^+}].$$

The above equation has to be equal to or greater than a minimum safe distance, S_{safe}, for safety reason, i.e.,

$$S(t_0) + \frac{1}{2}\ddot{x}_n^- \times (t_1 - t_0)^2 \times [1 - \frac{\ddot{x}_n^-}{\ddot{x}_n^+}] \geq S_{safe} \qquad 4\text{-}1.$$

Equation 4-1 can be rewritten as

$$S(t_0) - S_{safe} \geq -\frac{1}{2}\ddot{x}_n^- \times (t_1 - t_0)^2 \times [1 - \frac{\ddot{x}_n^-}{\ddot{x}_n^+}]$$

$$= \frac{1}{2}\Delta\dot{x}_n \times (t_1 - t_0) \times [1 - \frac{\ddot{x}_n^-}{\ddot{x}_n^+}].$$

$$S(t_0) - S_{safe} = \frac{1}{2}\Delta\dot{x}_n \times (t_1 - t_0) \times [1 - \frac{\ddot{x}_n^-}{\ddot{x}_n^+}].$$

Solving the above equation, we get

$$\Delta\dot{x}_n \le \frac{2[S(t_0) - S_{safe}]}{(t_1 - t_0)[1 - \frac{\ddot{x}_n^-}{\ddot{x}_n^+}]} \qquad 4\text{-}2.$$

Since $t_1 - t_0 = \frac{\Delta\dot{x}_n}{\ddot{x}_n^-}$, we can substitute into 4-2 Equation and obtain

$$\Delta\dot{x}_n \le \sqrt{\frac{-2\ddot{x}_n^-[S(t_0) - S_{safe}]}{[1 - \frac{\ddot{x}_n^-}{\ddot{x}_n^+}]}} \le \sqrt{\frac{2[S(t_0) - S_{safe}]}{-\frac{1}{\ddot{x}_n^-} + \frac{1}{\ddot{x}_n^+}}} \qquad 4\text{-}3.$$

One can easily find that the upper boundary on the magnitude of a speed disturbance that a single spacing can completely absorb, denoted as $\Delta\dot{x}_n^0$, can be obtained when

$$\Delta\dot{x}_n^0 = \sqrt{\frac{2[S(t_0) - S_{safe}]}{-\frac{1}{\ddot{x}_n^-} + \frac{1}{\ddot{x}_n^+}}} \qquad 4\text{-}4.$$

Equation 4-4 gives the upper boundary on the magnitude of a speed disturbance that a single spacing can completely absorb. It confirms that when the acceleration and deceleration rates are chosen, a larger spacing absorbs greater speed disturbance.

4.2 Value of Upper Limit of A Speed Disturbance that A Single Spacing Can Partially Absorb

When a speed disturbance is larger than $\Delta\dot{x}_n^0$ in Equation 4-3, the spacing between the two vehicles cannot completely absorb the speed disturbance. The following vehicle reduces its speed at sometime $t = \delta$ to maintain an acceptable spacing in front. When taking a control action, the driver will decide when and how to do this, i.e., will decide on δ and $\ddot{x}_{n+1}^-$. If a control-action strategy is denoted by Ω it can be described by $\Omega(\ddot{x}_{n+1}^-, \delta)$.

Definition 4-5: A control-action strategy $\Omega(\ddot{x}_{n+1}^-, \delta)$ is feasible if its corresponding dynamic spacing defined in **Section 3.2** is equal to or greater than S_{safe}.

Theory 4-1: For any control-action strategy $\Omega(\ddot{x}_{n+1}^-, \delta)$ there exists an equivalent control-action strategy $\overline{\Omega}(\overline{\ddot{x}}_{n+1}^-, \overline{\delta})$ where $\overline{\ddot{x}}_{n+1}^- = \ddot{x}_n^-$ such that the $\Delta\dot{x}_{n+1} = \Delta\dot{x}_n$.

Proof: By definition, $\Delta\dot{x}_{n+1} =|\ddot{x}_{n+1}^-| \times (\delta_1' - \delta_1)$. When $\Omega(\ddot{x}_{n+1}^-, \delta)$ is given, $\Delta\dot{x}_{n+1} =|\ddot{x}_{n+1}^-| \times (\delta_1' - \delta_1)$ is determined. For a given $\Delta\dot{x}_{n+1}$ due to the contiguity of $\Delta\dot{x}_{n+1}$ on both t and the deceleration rate $\ddot{x}_{n+1}^-$, one can always find a $\overline{\Omega}(\ddot{x}_n^-, \overline{\delta})$ such that $|\ddot{x}_{n+1}^-| \times (\delta' - \delta) = |\ddot{x}_n^-| \times (\overline{\delta}' - \overline{\delta})$.

Now we come to prove the feasibility of $\overline{\Omega}(\ddot{x}_n^-, \overline{\delta})$, i.e., its *Minimum S(t)* $\geq S_{safe}$.

Case 1 in Section 3.2

a. First we consider the case when $\bar{\ddot{x}}_{n+1}^{-} = |\ddot{x}_n^{-}| > |\ddot{x}_{n+1}^{-}|$.

The minimum dynamic spacing for the control strategy $\bar{\Omega}(\ddot{x}_n^{-}, \bar{\delta})$ can be determined by Equation 3-15 as

$$Minimum\ S(t) = S(t_0) + \frac{1}{2}\ddot{x}_n^{-} \times (t_1 - t_0)(\delta' - t_0) - \frac{1}{2}\ddot{x}_{n+1}^{-} \times (\delta' - \delta)(t_1 - \delta)$$

$$= S(t_0) + \frac{1}{2}\ddot{x}_n^{-} \times (t_1 - t_0)(\bar{\delta}' - t_0) - \frac{1}{2}\ddot{x}_{n+1}^{-} \times (\bar{\delta}' - \bar{\delta})(t_1 - \bar{\delta})$$

$$= S(t_0) - \frac{1}{2}\Delta\dot{x}_n \times (\bar{\delta}' - t_0) + \frac{1}{2}\Delta\dot{x}_{n+1} \times (t_1 - \bar{\delta}) \qquad 4\text{-}5.$$

Likewise, the minimum dynamic spacing for the control strategy $\Omega(\ddot{x}_{n+1}^{-}, \delta)$ is

$$Minimum\ S(t) = S(t_0) + \frac{1}{2}\ddot{x}_n^{-} \times (t_1 - t_0)(\delta' - t_0) - \frac{1}{2}\ddot{x}_{n+1}^{-} \times (\delta' - \delta)(t_1 - \delta)$$

$$= S(t_0) + \frac{1}{2}\ddot{x}_n^{-} \times (t_1 - t_0)(\delta' - t_0) - \frac{1}{2}\ddot{x}_{n+1}^{-} \times (\delta' - \delta)(t_1 - \delta)$$

$$= S(t_0) - \frac{1}{2}\Delta\dot{x}_n \times (\delta' - t_0) + \frac{1}{2}\Delta\dot{x}_{n+1} \times (t_1 - \delta) \qquad 4\text{-}6.$$

If the control-action time of $\bar{\Omega}(\ddot{x}_n^{-}, \bar{\delta})$ starts at $\bar{\delta} = \delta$ its ending time will be $\bar{\delta}' < \delta'$. Then Equation 4-5 can be rewritten as

$$Minimum\ S(t) = S(t_0) - \frac{1}{2}\Delta\dot{x}_n \times (\bar{\delta}' - t_0) + \frac{1}{2}\Delta\dot{x}_{n+1} \times (t_1 - \delta)$$

$$> S(t_0) - \frac{1}{2}\Delta\dot{x}_n \times (\delta' - t_0) + \frac{1}{2}\Delta\dot{x}_{n+1} \times (t_1 - \delta) \qquad 4\text{-}7.$$

Since the control-action strategy $\Omega(\ddot{x}_{n+1}^{-}, \delta)$ is feasible Equation 4-6 $\geq S_{safe}$. Thus, Equation 4-5 $\geq$ Equation 4-5 $\geq S_{safe}$.

b. Secondly consider the case when $\bar{\ddot{x}}_{n+1}^- = |\ddot{x}_n^-| < |\ddot{x}_{n+1}^-|$.

If we let the control-action $\overline{\Omega}(\ddot{x}_n^-, \bar{\delta})$ end at δ', the starting time $\bar{\delta} < \delta$. The minimum dynamic spacing for $\overline{\Omega}(\ddot{x}_n^-, \bar{\delta})$ is

$$\textit{Minimum } S(t) = S(t_0) - \frac{1}{2}\Delta\dot{x}_n \times (\bar{\delta}' - t_0) + \frac{1}{2}\Delta\dot{x}_{n+1} \times (t_1 - \bar{\delta})$$

$$= S(t_0) - \frac{1}{2}\Delta\dot{x}_n \times (\delta' - t_0) + \frac{1}{2}\Delta\dot{x}_{n+1} \times (t_1 - \bar{\delta}) \qquad \text{4-8.}$$

Since $\bar{\delta} < \delta$, $(t_1 - \bar{\delta}) > (t_1 - \delta)$. Equation 4-8 $\geq$ Equation 4-7 $\geq S_{safe}$, i.e.,

$$\textit{Minimum } S(t) = S(t_0) - \frac{1}{2}\Delta\dot{x}_n \times (\delta' - t_0) + \frac{1}{2}\Delta\dot{x}_{n+1} \times (t_1 - \bar{\delta}) \geq S_{safe}.$$

Thus, the existence of $\overline{\Omega}(\ddot{x}_n^-, \bar{\delta})$ is true for the situation of **Case 1** in **Section 3.2.**

Case 3 in **Section 3.2**

If we replace the δ in Equation 4-6 by τ, the Proof that **Theory 4-1** is true for the **Case 3** is similar to that for **Case 1.**

Case 2 in **Section 3.2**

In **Case 2,** all of the control-action strategies start and end before t_1. If $\Omega(\ddot{x}_{n+1}^-, \delta)$ is a control-action strategy defined in **Case 2** and $\ddot{x}_{n+1}^- > \ddot{x}_n^-$, its minimum dynamic spacing can be determined by Equation 3-20 as shown below

$$\textit{Minimum } S(t) = S(\delta') = S(t_0) + \frac{1}{2}\ddot{x}_n^- \times (\delta' - t_0)^2 - \frac{1}{2}\ddot{x}_{n+1}^- \times (\delta' - \delta)^2, \text{ at } t = \delta' \qquad \text{4-9.}$$

Equation 4-9 must be greater than S_{safe}, otherwise, the speed reduction of the following vehicle, $\Delta\dot{x}_{n+1}$ should equal the speed reduction of the lead vehicle, $\Delta\dot{x}_n$, which is not a case defined in this scenario.

Now let us keep $\ddot{x}^-_{n+1}$ unchanged but increase δ. As δ increases, the δ' and the (δ' - δ) increase, but Equation 4-9 is monotonically decreases if $\delta' < t_1$. During the increase of δ Equation 4-7 cannot become equal to S_{safe} before δ' becomes greater than t_1 since it is not a case defined in this scenario. Therefore, the increment of δ until δ' becomes greater than t_1 results in either **Case 1** or **Case 3**. For both of these cases it has just been proven that there exists an equivalent control-action strategy $\overline{\Omega}\,(\ddot{x}^-_n, \overline{\delta})$ such that $|\ddot{x}^-_{n+1}| \times (\delta' - \delta) = |\ddot{x}^-_n| \times (\overline{\delta}' - \overline{\delta})$.

Thus, **Theory 4-1** is true for the all of cases in this scenario.

Definition 4-6: For any given $\ddot{x}^-_{n+1}$, a control-action strategy $\Omega\,(\ddot{x}^-_{n+1}, \delta_i)$ is superior than another control-action strategy $\Omega_j\,(\ddot{x}^-_{n+1}, \delta_j)$ if $\Delta_i \dot{x}^0_{n+1} < \Delta_j \dot{x}_{n+1}$, and subject to *Minimum S(t)* $\geq S_{safe}$

Lemma 4-1: For any given $\ddot{x}^-_{n+1}$ there exists a control-action strategy $\Omega_0(\ddot{x}^-_{n+1}, \delta_0)$ such that

$$\Delta\dot{x}^0_{n+1} \leq \{\, \Delta\dot{x}_{n+1} \mid \Omega_i\,(\ddot{x}^-_{n+1}, \delta_i),\ i = 1,2,3,\ldots\ldots,\ \textit{Minimum } S(t) \geq S_{safe} \,\}.$$

Proof:

Case 1 and **Case 3** in **Section 3.2**

As illustrated in Figure 4-1, for the given $\ddot{x}^-_{n+1}$, the speed reduction of the following vehicle is $\Delta_i \dot{x}_{n+1} = |\ddot{x}^-_{n+1}| \times (\delta_i' - \delta_i) = \ddot{x}^+_n \times (t_0 + T - \delta_i')$, where i = *1, 2, 3,.......*

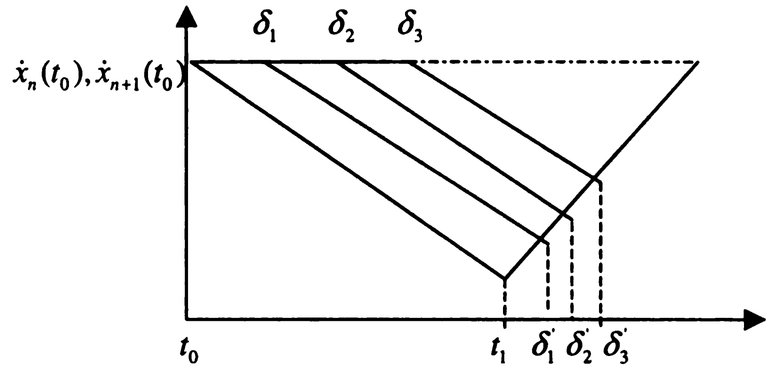


Figure 4-1 Absorption of speed disturbance with a certain $\ddot{x}_{n+1}^-$ but different δ

Since the $\ddot{x}_{n+1}^-$ and $\ddot{x}_n^+$ can be regarded as constants (Rothery 2000) and as δ_i' increases, the $(\delta_i' - \delta_i)$ decreases, and $\Delta_i \dot{x}_{n+1} = |\ddot{x}_{n+1}^-| \times (\delta_i' - \delta_i)$ monotonically decreases. The minimum dynamic spacing for the any control-action strategies in **Case 1** and **Case 3** discussed in **Section 3.2** is continuous on δ and decreases as δ increases and $(\delta_i' - \delta_i)$ decreases. Thus there must exist a δ_0 such that

Minimum S(t) $= S_{safe}$, and

$\Delta\dot{x}_{n+1}^0 =$ *Minimum* $\{ \Delta\dot{x}_{n+1} \mid \Omega(\ddot{x}_{n+1}^-, \delta_i), i = 1,2,3,\ldots\ldots,$ *Minimum S(t)* $= S_{safe} \}$.

Similar to the analysis in **Theory 4-1** for **Case 2**, any control-action strategies in **Case 2** can be either transferred to an equivalent one in either **Case 1** or **Case 3**. Therefore **Lemma 4-1** is true for all of the cases in this scenario.

Definition 4-7: A control-action strategy is optimal if its

$\Delta\dot{x}_{n+1} =$ *Minimum* $\{ \Delta\dot{x}_{n+1} \}$.

According to **Lemma 4-1,** for any given $\ddot{x}_{n+1}^-$ there will be a $\Omega(\ddot{x}_{n+1}^-, \delta_0)$ such that $\Delta\dot{x}_{n+1}^0 =$ *Minimum* $\{ \Delta\dot{x}_{n+1} \mid \Omega(\ddot{x}_{n+1}^-, \delta_i), i = 1,2,3,\ldots\ldots,$ *Minimum S(t)* $= S_{safe} \}$. Thus, an optimal control-action strategy must be one among the control-action strategies of $\Omega(\ddot{x}_{n+1}^-, \delta_0)$, and the $\Delta\dot{x}_{n+1}^0$ of which is minimal of the all $\Delta\dot{x}_{n+1}^0$. If we denote an optimal control-action strategy as $\Omega_0(\ddot{x}_{n+1}^-, \delta_0)$ and its speed reduction in response to a speed disturbance from the lead vehicle as $\Delta_0\dot{x}_{n+1}^0$ respectively, then

$$\Delta_0\dot{x}_{n+1}^0 = \mathit{Minimum}\ \{\ \Delta\dot{x}_{n+1}^0\ \}.$$

Theory 4-2: If $\Omega_0(\ddot{x}_{n+1}^-, \delta_0)$ is optimal, its equivalent control-action strategy $\overline{\Omega}(\ddot{x}_n^-, \overline{\delta})$ is also optimal and $|\ \ddot{x}_{n+1}^-\ |\times(\delta'-\delta) = |\ \ddot{x}_n^-\ |\times(\overline{\delta}'-\overline{\delta}) = \Delta_0\dot{x}_{n+1}^0$.

Proof: We use the method of reduction to absurdity. We assume that the equivalent control-action strategy $\overline{\Omega}(\ddot{x}_n^-, \overline{\delta})$ is not optimal.

If the $\overline{\Omega}(\ddot{x}_n^-, \overline{\delta})$ is not optimal, the $\overline{\Omega}(\ddot{x}_n^-, \overline{\delta})$ is not a control-action strategy of $\Omega(\ddot{x}_n^-, \delta_0)$ that belongs to $\{\Omega(\ddot{x}_{n+1}^-, \delta_0)|$ for any given $\ddot{x}_{n+1}^-\}$. Otherwise, the assumption at the beginning of the proof is not correct, and the **Theory 4-2** is true.

If the $\overline{\Omega}(\ddot{x}_n^-, \overline{\delta})$ is not a control-action strategy of $\Omega(\ddot{x}_n^-, \delta_0)$ that belongs to $\{\Omega(\ddot{x}_{n+1}^-, \delta_0)|$ for any given $\ddot{x}_{n+1}^-\}$, according to the **Lemma 4-1** there exists an $\overline{\Omega}(\ddot{x}_n^-, \overline{\delta}_0)$ such that

$\Delta\dot{x}_{n+1}^0 = |\ \ddot{x}_n^-\ |\times(\overline{\delta}_0'-\overline{\delta}_0) = \mathit{Minimum}\ \{\ \Delta\dot{x}_{n+1}\ |$ for all $\Omega(\ddot{x}_n^-, \delta)$ and subject to *Minimum* $S(t) \geq S_{safe}\ \}$. Thus there exists a $\overline{\Omega}(\ddot{x}_n^-, \overline{\delta}_0)$ such that $|\ \ddot{x}_n^-\ |\times(\overline{\delta}_0'-\overline{\delta}_0) < |\ \ddot{x}_n^-\ |\times(\overline{\delta}'-\overline{\delta}) = |\ \ddot{x}_{n+1}^-\ |\times(\delta'-\delta)$, which is contradictory to the assumption at the beginning that the equivalent control-action strategy $\overline{\Omega}(\ddot{x}_n^-, \overline{\delta})$ is not optimal. Thus, the equivalent control-action strategy $\overline{\Omega}(\ddot{x}_n^-, \overline{\delta})$ is also optimal and the **Theory 4-2** is true.

According to **Definition 4-4,**

$\Delta\dot{x}_n^0 = Maximum(\Delta\dot{x}_n - \Delta\dot{x}_{n+1})$

$= \Delta\dot{x}_n$ - $Minimum$ { $\Delta\dot{x}_{n+1}$ }.

Theory 4-1, Lemma 4-1 and **Theory 4-2** demonstrate not only the existence of an upper limit on the magnitude of a speed disturbance that can be absorbed but also indicate that this upper boundary condition can be obtained by discovering an optimal control-action strategy of $\Omega(\ddot{x}_n^-, \delta_0)$. Therefore the discussion regarding the finding of an upper boundary on the magnitude of a single speed disturbance that spacing can absorb is simplified to the condition when $\ddot{x}_n^- = \ddot{x}_{n+1}^-$.

Case 1 in **Section 3.2**

If $\ddot{x}_n^- = \ddot{x}_{n+1}^-$, the minimum dynamic spacing given in Equation 3-15 can be simplified as

$$Minimum\ S(t) = S(t_0) + \frac{1}{2}\ddot{x}_n^- \times (t_1 - t_0)(\delta' - t_0) - \frac{1}{2}\ddot{x}_{n+1}^- \times (\delta' - \delta)(t_1 - \delta)$$

$$= S(t_0) - \frac{\delta - t_0}{2} \times (\Delta\dot{x}_{n+1} + \Delta\dot{x}_n) \qquad \text{4-10.}$$

As shown in Figure 4-2, Line cd is parallel to the Line hg and Line bd is parallel to Line eg. Thus, the length of Line bd is equal to the length of Line eg which is equal to $\Delta\dot{x}_n - \Delta\dot{x}_{n+1}$. Since $\ddot{x}_n^- = \ddot{x}_{n+1}^-$, it is easy to calculate that the length of Line c-b = $\frac{\Delta\dot{x}_n - \Delta\dot{x}_{n+1}}{\ddot{x}_n^+}$ and the length of Line b-a $= \frac{\Delta\dot{x}_n - \Delta\dot{x}_{n+1}}{\ddot{x}_n^-}$. Therefore we get

$$\delta - t_0 = (b - a) + (c - b) = (\frac{1}{\ddot{x}_n^+} - \frac{1}{\ddot{x}_n^-}) \times (\Delta\dot{x}_n - \Delta\dot{x}_{n+1}) \qquad \text{4-11.}$$

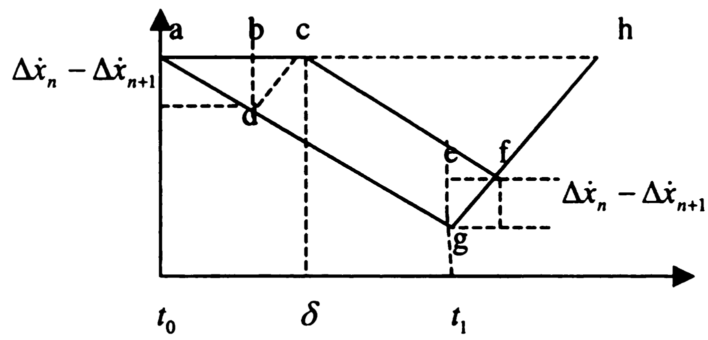


Figure –4-2 control-action strategy of the following vehicle with $\ddot{x}_n^- = \ddot{x}_{n+1}^-$

If we substitute Equation 4-11 into 4-10, we get

$$\textit{Minimum } S(t) = S(t_0) - \frac{\delta - t_0}{2} \times (\Delta\dot{x}_{n+1} + \Delta\dot{x}_n)$$

$$= S(t_0) - \frac{1}{2} \times \left(\frac{1}{\ddot{x}_n^+} - \frac{1}{\ddot{x}_n^-}\right) \times [(\Delta\dot{x}_n)^2 - (\Delta\dot{x}_{n+1})^2] = S_{safe} \qquad \text{4-12.}$$

By solving Equation 4-12, we obtain

$$(\Delta\dot{x}_n)^2 = \frac{2[S(t_0) - S_{safe}]}{\frac{1}{\ddot{x}_n^+} - \frac{1}{\ddot{x}_n^-}} + (\Delta\dot{x}_{n+1})^2 \qquad \text{4-13.}$$

Equation 4-13 suggests that square of the single speed disturbance produced by the lead vehicle n is composed of two parts, one of which is absorbed by the single spacing and another that is transmitted backward through the speed reduction of vehicle n+1. If we let the $\Delta\dot{x}_{n+1} = 0$, the speed disturbance that the single spacing absorbs is

$$\Delta\dot{x}_n^0 = \sqrt{\frac{2[S(t_0) - S_{safe}]}{\frac{1}{\ddot{x}_n^+} - \frac{1}{\ddot{x}_n^-}}} \qquad \text{4-14}$$

which is concurrent to the Equation 4-3.

Case 3 in Section 3.2

If $\ddot{x}_n^- = \ddot{x}_{n+1}^-$, the minimum dynamic spacing given in the Equation 3-27 can be simplified as follows

Minimum S(t)

$$= S(t_0) + \frac{1}{2}\ddot{x}_n^+ \times (\delta' - t_1)^2 + \frac{1}{2}\ddot{x}_n^- \times (t_1 - t_0)^2 + \ddot{x}_n^- \times (t_1 - t_0)(\delta' - t_1) - \frac{1}{2}\ddot{x}_{n+1}^- \times (\delta' - \delta)^2$$

$$= S(t_0) + \frac{1}{2}\ddot{x}_n^- \times (t_1 - t_0)(\delta' - t_0) - \frac{1}{2}\ddot{x}_{n+1}^- \times (\delta' - \delta)(t_1 - \delta)$$

$$= S(t_0) - \frac{\delta - t_0}{2} \times (\Delta\dot{x}_{n+1} + \Delta\dot{x}_n) \qquad 4\text{-}15.$$

This is exactly the same as in Equation 4-10. Therefore its solution is the same as the Equation 4-13.

4.3 Local Stability

According to the definition of Rothery (Gartner, 2000), local stability is concerned with the response of a following vehicle to a fluctuation in the motion of the vehicle directly in front. Equation 4-3 shows that an initial speed disturbance

$$\Delta\dot{x}_n^0 \le \sqrt{\frac{2[S(t_0) - S_{safe}]}{\frac{1}{\ddot{x}_n^+} - \frac{1}{\ddot{x}_n^-}}}$$

will be absorbed by the spacing and the localized interaction of car-following is stable.

4.4 Asymptotic Stability for a Single Speed Disturbance

Asymptotic stability is concerned with the manner in which a fluctuation in the motion of any vehicle, say the lead vehicle of a platoon, is propagated through a line of vehicles (Gartner, 2000).

When a speed disturbance cannot be absorbed, it is propagated backward through the speed reduction of the following vehicles. This generated speed reduction has an impact on the vehicle following the following vehicleas shown in Figure 4-3.

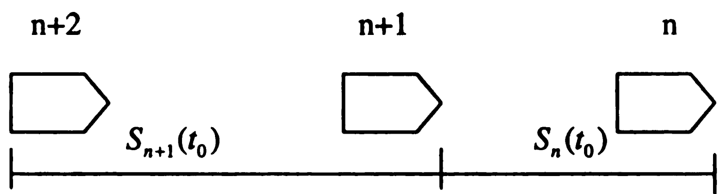


Figure 4-3 Illustration of car following of the next-nearest coupling vehicle

According to the analysis in **Section 4.2** if the generated speed disturbance is

$$\Delta\dot{x}_{n+1} \leq \sqrt{\frac{2[S_{n+1}(t_0) - S_{safe}]}{\dfrac{1}{\ddot{x}^{+}_{n+1}} - \dfrac{1}{\ddot{x}^{-}_{n+1}}}},$$

the spacing between vehicle, n+1, and its following vehicle, n+2, can absorb the rest of the speed disturbance originally produced by vehicle n and propagated through the speed reduction of the vehicle n+1, $\Delta\dot{x}_{n+1}$. Otherwise, the vehicle n+2 has to reduce its speed to respond to the generated speed disturbance $\Delta\dot{x}_{n+1}$, and in this way the original speed disturbance produced by the vehicle n is further transmitted backward through speed reductions of vehicle n+1 and its next nearest coupling vehicle n+2. The propagation of the generated speed disturbance is similar to that analyzed in **Section 4.2,** thus

$$(\Delta\dot{x}_{n+1})^2 = \frac{2[S_{n+1}(t_0) - S_{safe}]}{\frac{1}{\ddot{x}_n^+} - \frac{1}{\ddot{x}_{n+1}^-}} + (\Delta\dot{x}_{n+2})^2 \qquad 4\text{-}16.$$

If we substitute Equation 4-16 into 4-15, the original speed disturbance produced by the vehicle n is

$$(\Delta\dot{x}_n)^2 = \frac{2[S(t_0) - S_{safe}]}{\frac{1}{\ddot{x}_n^+} - \frac{1}{\ddot{x}_n^-}} + \frac{2[S_{n+1}(t_0) - S_{safe}]}{\frac{1}{\ddot{x}_n^+} - \frac{1}{\ddot{x}_{n+1}^-}} + (\Delta\dot{x}_{n+2})^2 \qquad 4\text{-}17.$$

Likewise, if the spacing behind vehicle n+2, $S_{n+2}(t_0)$, cannot absorb the speed disturbance propagated by vehicle n+2, the transmitting process will be carried on backward resulting in

$$(\Delta\dot{x}_n)^2 = \frac{2[S(t_0) - S_{safe}]}{\frac{1}{\ddot{x}_n^+} - \frac{1}{\ddot{x}_n^-}} + \frac{2[S_{n+1}(t_0) - S_{safe}]}{\frac{1}{\ddot{x}_n^+} - \frac{1}{\ddot{x}_{n+1}^-}} + \frac{2[S_{n+2}(t_0) - S_{safe}]}{\frac{1}{\ddot{x}_n^+} - \frac{1}{\ddot{x}_{n+2}^-}} + \ldots\ldots \qquad 4\text{-}18.$$

If we assume that there are N vehicles in a vehicular platoon, the upper boundary on the magnitude of the single speed disturbance produced by the leading vehicle that a vehicle platoon can absorb is

$$(\Delta\dot{x}_1)^2 = \sum_1^N (\Delta\dot{x}_i^0)^2 = \sum_1^N \frac{2[S_i(t_0) - S_{Safe}]}{\frac{1}{\ddot{x}_i^+} - \frac{1}{\ddot{x}_i^-}} \qquad 4\text{-}19.$$

Therefore, Equation 4-19 gives the upper boundary condition of asymptotic stability for a single speed disturbance.

4.5 Summary

The existence of the upper boundary on magnitude of a speed disturbance has been demonstrated by means of the minimum dynamic spacing obtained in Chapter 3.

here, we obtain the formulas required to calculate the upper boundary of the magnitude of a speed disturbance that a single spacing (or multiple spacings) can completely absorb. Moreover, the conditions for local and asymptotic stability are provided.

References

Gartner, N., G.C. Messer, and A.K. Rathi, Traffic Flow Theory, Chapter 4 of R.W. Rothery, Car Following Models, Transportation Research Board Special Report 165, Transportation Research Board, 2000, pp. 4-6, and 4-9.

Todosiev, E.P. The Action Point Model of the Driver Vehicle System. Report No. 202A-3. Ohio State University, Engineering Experiment Station, Columbus, Ohio, 1963.

CHAPTER 5 MODEL VERIFICATION

The results obtained in Chapter 4 can be tested by field, laboratory or simulation experiments. The verification of the model requires dynamic data including individual vehicular speed, spacing, and acceleration/deceleration data. In order to capture the entire process of the interaction of a following vehicle to a speed disturbance of its lead vehicle, data need to be collected over a sufficient length of a segment of a roadway and over a sufficient time period and on a group of vehicles that are following one another without lane-changing. To meet the data requirements of a model demonstration, a field or a laboratory experiment would require specialized equipment and be very costly and time consuming to perform. Therefore, a simulation approach is used.

5.1 Description of the Experiments

The simulation software used for the experiments was Traffic Simulation Integrated System (TSIS) Version 5.0 published by the FHWA in March 2001.

Two experiments were conducted. All input parameters for the two experiments were the same except the ratio of Driver Type.

The experimental site was a one-mile long, straight, level, single-lane basic freeway segment with dry concrete or dry asphalt pavement. A passenger car was selected as the test vehicle type with an average occupancy of 1.3 persons per car.

Simulated drivers were grouped into 10 types by their driving behavior from the least aggressive (ranked as 1) to the most aggressive (10). A variety of car-following sensitivity multipliers were assigned to different types of drivers with less sensitivity and larger following headways assigned to less aggressive drivers and more sensitivity and smaller following headways assigned to more aggressive drivers. The first experiment used the default values of the sensitivity factors, which assigned a ratio of 10% to each of the 10 Driver Types. To obtain a better observation of car-following behavior at the boundary conditions discussed in the previous chapters, the second experiment was conducted with the percentage of aggressive drivers increased. The distributions of Driver Types in the two experiments are summarized in Table 5-1.

Table 5-1 Percentage of Driver Types in Two Experiments

Percentage of Driver Types	Driver Types Lease aggressive									More aggressive
	1	2	3	4	5	6	7	8	9	10
Experiment 1	10	10	10	10	10	10	10	10	10	10
Experiment 2	0	0	0	0	10	10	10	20	20	30

Vehicles were generated by the simulation program with a Pearson I distribution and discharged into the experimental segment through an entry link. The hourly vehicle discharge rate was 2400 vph and the free flow speed was set at 88 ft/sec (60 mph).

Vehicle performance in acceleration/deceleration was determined according to the values for driver braking behavior under three situations (planned, anticipated but unsure when, and unexpected situations) given in Table 2-2 in Section 2.5. When the driver of a following vehicle anticipates its Expected State is unacceptable and takes a control action, the driver is most likely to perform an "anticipated but unsure when" control action. Therefore according to Table 2-2 the average deceleration rate of 15 ft/sec^2 for the "anticipated but unsure when" is used as the deceleration rate of a following vehicle in response to a speed disturbance. When a vehicle develops a speed disturbance of its own, the driver is most likely to perform a "planned" braking. Thus, according to Table 2-2 a deceleration rate 8 ft/sec^2 for a "planned" situation was assigned.

To obtain as-detailed-as-possible dynamic data, the time interval for a single step was set as 0.3 sec in the first experiment. Since the program updates speed and acceleration/deceleration data every second, to record more vehicular data the second experiment uses one second as the time interval of a single step. The total time of the simulation for each experiment was 15 minutes (900 sec).

5.2 Data

TSIS does not provide step-by-step individual vehicular speed, spacing, and acceleration and/or deceleration data in the reports. To meet the data requirement for the model verification, data were recorded manually.

5.2.1 Experiment One

During the 15 minutes of the simulation period 519 vehicles entered the experimental site. Each vehicle had at least 150 step-by-step records. Each record has three data values, namely speed, position, and acceleration/deceleration rate. If all of the vehicles are recorded the total data that needs to be recorded would be at least 519*150*3 = 233,550, which is difficult to record by hand. Therefore, a vehicle ID (number 166) was randomly selected. The dynamic movement of vehicle 166 and its following vehicles were monitored. The observation of the vehicle movements showed that vehicle 167 responded to a speed disturbance of vehicle 166. Moreover, vehicle 168 responded to the speed disturbance of vehicle 167 and so on until vehicle 171. Vehicle 171 was not in a car-following state with vehicle 170 and never responded to the speed change of vehicle 170. To obtain a picture of the car-following behavior of the vehicles following vehicle 171 (that are not in a car-following state) with the vehicle in front, three additional vehicles (172 through 174) were also monitored. Therefore, the speed, position and acceleration/deceleration of vehicle 166 through vehicle 174 were recorded in a step-by-step manner (Appendix 1).

The step-by-step spacing between each pair of vehicles, the step-by-step time headway of each vehicle, the minimum time headway of each vehicle during the 15-minute simulation, and the minimum safe distance headway maintained by the vehicles were calculated by:

Spacing = position of the lead vehicle – position of the immediately following vehicle (ft) 5-1

Time headway = spacing /speed (sec) 5-2

Minimum time headway for each vehicle during the simulations

= Minimum {Time headways of the vehicle} (sec) 5-3

Minimum distance headway maintained by each vehicle during the simulations

= the minimum time headway * the speed 5-4.

The driver type and the minimum time headway of each vehicle during the first experiment are listed in the Table 5-2. The speed interactions between each pair of adjacent vehicles are illustrated in Figure 5-1 at the end of the chapter.

Table 5-2. Driver Type and Minimum Time Headway of Each Vehicle in Experiment One

	Vehicle ID								
	166	167	168	169	170	171	172	173	174
Driver Type	7	7	7	5	10	2	2	10	7
Minimum Time Headway during the Simulation (sec)	Unknown	0.88	0.90	1.15	0.61	2.31	1.48	0.65	0.92

5.2.2 Experiment Two

During the 15 minute period of the experiment two, 597 vehicles entered the experimental site. Since the experiment two took 1 second as a single step, each vehicle took approximately 50 steps to travel through the site. A sample size of 30 vehicles was selected starting from a randomly selected vehicle ID 69. The speed, position, acceleration/deceleration rates of vehicle 69 through 98 were recorded in a step-by-step manner and the spacing between each pair of adjacent vehicles was calculated by using Equation 5-1 (Appendix 2).

The observation of the 30 vehicle movements showed that vehicles 69, 70, 77, 81, 90, 93, 94, 96, and 97 had roughly stable speeds, kept relatively large spacing from the vehicles in front, and did not respond to any speed disturbances from the leading vehicles. Their approximately constant speeds, Driver Types, and minimum time headway during the simulation are listed in Table 5-3.

Table 5-3 Driver Types, Approximately Constant Speeds, and Minimum Time Headway of Vehicles 69, 70, 77, 81, 90, 93, 94, 96, and 97 during the Simulation

	Vehicle ID								
	69	70	77	81	90	93	94	96	97
Driver Types	7	7	7	7	8	9	8	8	7
Approximately Constant Speed (ft/sec)	86	86	86	86	89	94	89	89	83
Minimum Time Headway during Simulation (sec)	Unknown	2.28	4.06	2.42	1.10	0.86	1.28	1.57	1.40

Vehicles 71 through 76 followed one another during the simulation. Each of them kept small gaps from the vehicle immediately in front once it entered a car-following mode and responded to a speed disturbance from its leading vehicle. The driver types and the minimum time headways during the simulation are listed in Table 5-4.

Table 5-4 Driver Types and Minimum Time Headways of Vehicles 71 through 76

	Vehicle ID					
	71	72	73	74	75	76
Driver's types	9	9	9	10	9	9
Minimum time headway during the simulation (sec)	0.70	0.76	0.76	0.64	0.76	0.73

Vehicle 78 developed speed disturbances of its own and vehicle 79 responded to them, which transmitted the speed disturbances from vehicle 78 backward. Vehicle 80 responded to these generated speed disturbances from vehicle 79 when the spacing between them became small. Vehicle 82 followed Vehicle 81 closely and developed speed disturbances that were transmitted backward through vehicles 83, 84, 85, 86 and 87. Vehicle 88 maintained a stable speed and large spacing from vehicle 87 until step 66 when the spacing became small. Vehicle 89 developed a speed disturbance when it moved closely to vehicle 88. The driver types and the minimum time headways of vehicles 78 through 80 and vehicles 82 through 89 are listed in Table 5-5.

Table 5-5 Driver Types and Minimum Time Headways of Vehicles 78 through 80 and Vehicles 82 through 89

	Vehicle ID										
	78	79	80	82	83	84	85	86	87	88	89
Driver Types	8	9	8	9	10	10	10	10	10	9	10
Minimum Time Headway during Simulation (sec)	0.86	0.75	0.85	0.76	0.66	0.50	0.59	0.62	0.52	0.71	0.64

Vehicles 91 and 95 developed speed disturbances of their own. Vehicle 92 responded to the speed disturbance from vehicle 91when the spacing between them was reduced to less than 75 feet, but vehicles 96, 97 and 98 did not respond to the speed disturbances from vehicle 95 because of a large spacing. The driver types and the minimum time headways of vehicles 91, 92 and 95 are listed in Table 5-6.

Table 5-6 Driver Types and Minimum Time Headways of Vehicles 91, 92, and 95

	Vehicle ID		
	91	92	95
Driver Type	9	9	9
Minimum Time Headway during Simulation (sec)	0.73	0.75	0.73

The speed interactions between each pair of the adjacent vehicles except vehicles 69 and 70, and vehicles 93 and 94 are illustrated in Figure 5-2 at the end of the chapter.

5.3 Case Study

By examining Figure 5-1 and Figure 5-2 thoroughly, one can find some cases in the experiments in which speed disturbances were absorbed completely or partially. They are identified and listed in Table 5-7 and will be discussed in the case study sections of **5.3.1**, **5.3.2**, and **5.3.3**.

Table 5-7 Cases in which Speed Disturbances Were Absorbed Completely or Partially

	Case for Scenario 1	Case for Scenario 2	Case for Scenario 3
Experiment One	Figure 5-2 e	Figure 5-2 a	Figure 5-2 d
Experiment Two	Figure 5-3 k Figure 5-3 y	Figure 5-3 i Figure 5-3 q	Figure 5-3 d Figure 5-3 e Figure 5-3 n

5.3.1 Cases for Scenario 1 - Acceptable-Acceptable Expected State

This scenario describes a car-following behavior under which the lead vehicle has a speed reduction and its nearest following vehicle does not take any control action to respond to it. Thus a reduction of the spacing between the two vehicles takes place. Therefore, the speed disturbance is completely absorbed by the spacing between the first two vehicles.

In Experiment One, Figure 5-1 e shows that vehicle 170 developed speed disturbances at steps 66-76, 82-93 and 111-118 and vehicle 171 did not respond to any of them. In Experiment Two, Figures 5-2 k and y show that vehicles 80 and 95 developed speed disturbances at steps 34-37, 43-47, 51-55, and at steps 56-58, 65-67, and 78-80. Vehicles 81, 96 did not reduce their speed to respond to them. Those speed disturbances were completely absorbed by the spacing between the vehicles. Table 5-8 summarizes the values of the speed disturbances developed by vehicle 170 in Experiment One, and by vehicles 80 and 95 in Experiment Two, the average acceleration/deceleration rates in each speed disturbance, and the spacing between vehicles 170 and 171, 80 and 81, and 95 and 96 at the beginning of the speed disturbances, the minimum distance headways during the experiments, and the upper boundary condition for speed absorption in Scenario 1 obtained by Equation 4-16. From Table 5-8 one can confirm that the speed disturbances discussed in this section are less than the upper boundary conditions calculated by Equation 4-16.

Table 5-8 Case Study for Scenario I - Acceptable-Acceptable Expected State

Experiment	Vehicle ID	Experiment, Vehicle ID, and Summary of Fata	Speed Disturbance 1	2	3
Experiment One	170	Steps in which a speed disturbance took place	66 – 76	82 – 93	111 - 118
		Minimum distance headway of vehicle 171 (ft)	198	198	198
		Acceleration (ft/sec^2) Deceleration (ft/sec^2)	2.0 1.5	3.0 4.0	1.0 1.3
		Initial spacing between 170 and 171(ft)	467	467	467
		Speed reduction (ft/sec)	4.0	5.0	1.0
		Upper speed reduction boundary condition for speed absorption (ft/sec)	22.0	30.0	17.4
Experiment Two	80	Steps in which a speed disturbance took place	34 – 37	43 – 47	51 – 55
		Minimum distance headway of vehicle 81 (ft)	208	208	208
		Acceleration (ft/sec^2) Deceleration (ft/sec^2)	4.0 2.0	3.5 2.0	4.0 1.7
		Initial spacing between 80 and 81(ft)	334	334	334
		Speed reduction (ft/sec)	4.0	4.0	4.0
		Upper speed reduction boundary condition for speed absorption (ft/sec)	29.0	29.0	28.1
	95	Steps in which a speed disturbance took place	56 – 58	65 – 67	78 – 80
		Minimum distance headway of vehicle 96 (ft)	139	139	139
		Acceleration (ft/sec^2) Deceleration (ft/sec^2)	1 1.5	2 2	1.0 1.5
		Initial spacing between 95 and 96 (ft)	181	181	181
		Speed reduction (ft/sec)	1.0	1.0	1.0
		Upper speed reduction boundary condition for speed absorption (ft/sec)	7.0	9.0	7.0

5.3.2 Cases for Scenario 2 - Acceptable-Unacceptable-Acceptable Expected State

As defined in Chapter 2 this scenario describes a car-following behavior such that when the lead vehicle has a speed disturbance (speed reduction), the Expected State of its following vehicle is acceptable, but during the recovery of this speed the Expected State of the following vehicle becomes unacceptable and the following vehicle takes a control action until the Expected State of the following vehicle returns to acceptable. In this speed interaction, the following vehicle generates a speed disturbance in response to the speed disturbance of the lead vehicle. In this case a speed disturbance of the lead vehicle can only be partially absorbed by the spacing between the first and second vehicle.

Figure 5-1 a of Experiment One shows that vehicle 166 developed a speed disturbance at steps 49-63. After a two-second delay vehicle 167 responded to it at steps 55-66. Figures 5-2 i and q of Experiment Two also show that vehicle 79 and vehicle 87 developed speed disturbances at steps 37-40, and 63-70 respectively. After a time delay vehicle 80 and 88 responded to them respectively at steps 40-42, and 65-72. From the figures one can see that the speed disturbances identified in this section were partially absorbed and partially transmitted backward. Table 5-9 summarizes the acceleration/deceleration rates, the minimum distance headways during the experiments, the spacing, the speed reductions and the upper boundaries on the magnitude of a single speed disturbance that a single spacing can absorb obtained by Equation 4-17. For reader convenience in locating the cases, Table 5-9 also gives the steps during which the speed disturbances took place and the steps during which they were responded to by the following vehicles.

Table 5-9 Case Study for Scenario 2 – Acceptable-Unacceptable-Acceptable Expected State

Experiment, Vehicle ID		Summary of Data	
Experiment One	166	Steps in which a speed disturbance took place Steps in which the speed disturbance responded	49-63 55-66
		Minimum distance headway of vehicle 167 (ft)	77
		Acceleration (ft/sec^2) Deceleration (ft/sec^2)	1.5 2.0
		Initial spacing between vehicles 166 and 167 (ft)	84
		Speed reduction of 166 (ft/sec)	2.0
		Upper speed reduction boundary condition for Partial absorption of speed disturbance (ft/sec)	4.0
Experiment Two	79	Steps in which a speed disturbance took place Steps in which the speed disturbance responded	37-40 40-42
		Minimum distance headway of vehicle 80 (ft)	73.1
		Acceleration (ft/sec^2) Deceleration (ft/sec^2)	4.0 3.5
		Initial spacing between vehicles 79 and 80 (ft)	77
		Speed reduction of 80 (ft/sec)	4.0
		Upper speed reduction boundary condition for Partial absorption of speed disturbance (ft/sec)	4.0
	87	Steps in which a speed disturbance took place Steps in which the speed disturbance responded	63-70 65-72
		Minimum distance headway of vehicle 88 (ft)	60.0
		Acceleration (ft/sec^2) Deceleration (ft/sec^2)	3.3 4.3
		Initial spacing between vehicles 87 and 88 (ft)	80
		Speed reduction of 88 (ft/sec)	13
		Upper speed reduction boundary condition for Partial absorption of speed disturbance (ft/sec)	13.3

From Table 5-9 one can find that in each case the upper boundary on the magnitude of a speed disturbance which can partially be absorbed by a single spacing obtained by Equation 4-17 is larger than the corresponding speed disturbance. The values of the speed disturbances developed by vehicles 166, 79, and 87, the values of the speed disturbances absorbed by the spacing, the values of the speed disturbances propagated through their immediately following vehicles, and the upper boundary conditions for each case calculated by Equation 4-17 are listed in Table 5-10.

Table 5-10 Values of the Developed, Absorbed, Propagated, and Calculated Speed Disturbance

Vehicle	Speed Disturbance			
ID	Developed (ft/sec)	Propagated (ft/sec)	Absorbed (ft/sec)	Calculated (ft/sec)
166	2.0	2.0	0.0	4.0
79	4.0	1	3.0	4.0
87	13.0	11.0	2.0	13.3

5.3.3 Cases for Scenario 3 - Unacceptable Expected State at Target-Risk Level

Scenario 3 defined in Chapter 2 describes a situation where a vehicle follows its lead vehicle at a minimum headway and the driver of the following vehicle is always alerted and can be triggered to take an immediate control action at anytime once receiving a brake signal from the vehicle in front.

By observing Figures 5-1 and 5-2, one can find that when a vehicle is following its leading vehicle at a minimum headway, most of the time it responded to a speed disturbance from its leading vehicle with a larger speed reduction than that of the leading vehicle. In those cases Equation 4-17 can always be met.

Four cases in the simulations were found where the following vehicles followed the leading vehicle at approximately minimum time headway and responded to a speed disturbance with one-second perception-reaction delay and their speed reductions were either less than or equal to that developed by their leading vehicles. In Experiment One, Figure 5-1 d shows that when vehicle 169 developed a speed disturbance at steps 64-75 vehicle 170 maintained a small spacing from it and responded to it at steps 67-76, with a one-second perception-reaction delay. In Experiment Two, Figures 5-2 d, e, and n show that vehicles 74, 75 and 84 developed speed disturbances at steps 33-36, 40-49, and at steps 35-39 and 43-47. Vehicle 75 kept the spacing from vehicle 74 almost at its minimum safe headway and responded to the speed disturbance at steps 34-37. Vehicle 76 and vehicle 85 kept small spacing and responded to the speed disturbances at steps 42-50, and at steps 36-41 and 44-49. The perception-reaction delay for vehicles 170, 75, 76, and 85 was one second. The features of the speed disturbances and the speed interaction between vehicles 169 and 170, 74 and 75, 75 and 76, 84 and 85 and the boundary conditions calculated by Equation 4-17 are listed in Table 5-11. From Table 5-11 one can find that in each case the speed reduction is less than the corresponding upper boundary conditions calculated by Equation 4-17.

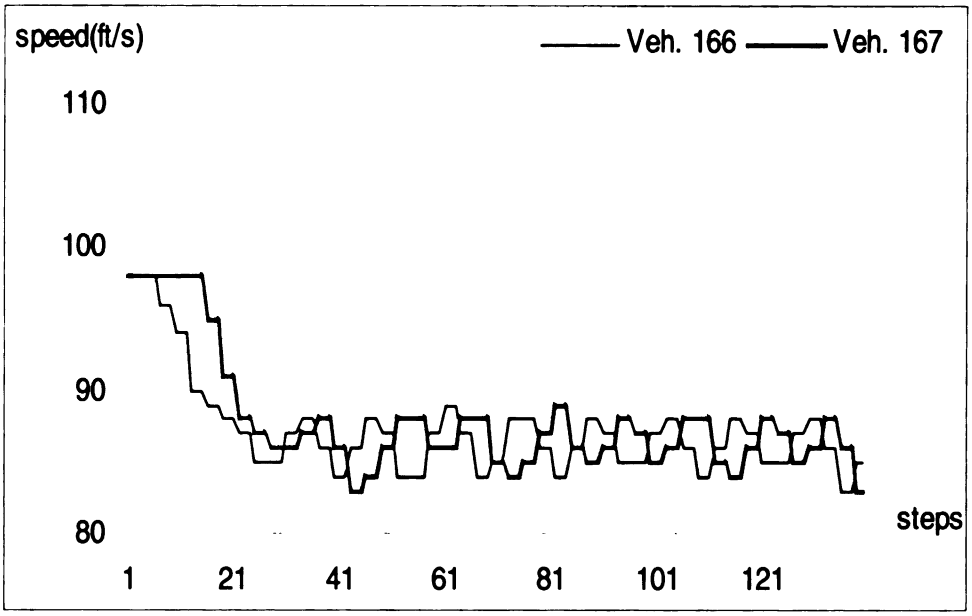
Table 5-11 Case Study for Scenario 3 - Unacceptable Expected State at Target-Risk Level

Vehicle ID		Summary of Data	
Experiment One	169	Steps in which a speed disturbance took place Steps in which the speed disturbance responded	64-75 67-76
		Speed reduction of 169 (ft/sec)	3.0
		Acceleration (ft/sec^2) / Deceleration (ft/sec^2)	2.0 / 3.0
		Initial spacing between vehicles 169 and 170 (ft)	58
		Minimum distance headway of vehicle 170 (ft)	53
		Upper boundary condition for Speed absorption (ft/sec)	4.6
Experiment Two	74	Steps in which a speed disturbance took place Steps in which the speed disturbance responded	33-36 34-37
		Speed reduction of 74 (ft/sec)	4.0
		Acceleration (ft/sec^2) / Deceleration (ft/sec^2)	3.0 / 4.0
		Initial spacing between vehicles 74 and 75 (ft)	68
		Minimum distance headway of vehicle 75 (ft)	65
		Upper boundary condition for Speed absorption (ft/sec)	4.5
	75	Steps in which a speed disturbance took place Steps in which the speed disturbance responded	41-48 42-50
		Speed reduction of 75 (ft/sec)	7.0
		Acceleration (ft/sec^2) / Deceleration (ft/sec^2)	1.8 / 3.0
		Initial spacing between vehicles 75 and 76 (ft)	77
		Minimum distance headway of vehicle 76 (ft)	63
		Upper boundary condition for Speed absorption (ft/sec)	7.0
	84	Steps in which a speed disturbance took place Steps in which the speed disturbance responded	35-39 36-41
		Speed reduction of 84 (ft/sec)	6.0
		Acceleration (ft/sec^2) / Deceleration (ft/sec^2)	3.2 / 3.2
		Initial spacing between vehicles 84 and 85 (ft)	64
		Minimum distance headway of vehicle 85 (ft)	53
		Upper boundary condition for Speed absorption (ft/sec)	7.7
	84	Steps in which a speed disturbance took place Steps in which the speed disturbance responded	43-47 44-49
		Speed reduction of 84 (ft/sec)	8
		Acceleration (ft/sec^2) / Deceleration (ft/sec^2)	4.0 / 3.7
		Initial spacing between vehicles 84 and 85 (ft)	66
		Minimum distance headway of vehicle 85 (ft)	53
		Upper boundary condition for Speed absorption (ft/sec)	9.2

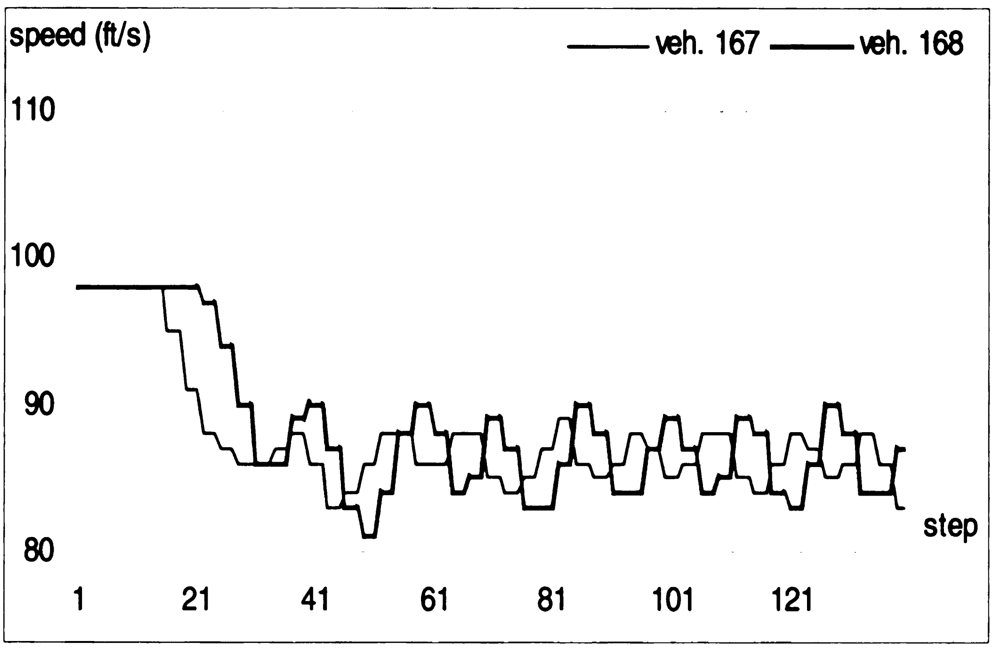
5.4 Summary

Two experiments of car-following behavior were simulated by using TSIS. The dynamic speed, position and acceleration and/or deceleration data of randomly selected lines of individual vehicles were collected in a step-by-step manner. The cases in which speed disturbances were absorbed completely or partially by spacing were identified from the experimental data and studied. The upper boundary on the magnitude of the speed disturbance that the spacing can absorb in each case was calculated by either Equation 4-16, or 4-17. The cases studied verified the models obtained in Chapter 4.

Figure 5-1 Speed Interaction between Vehicles in Experiment One

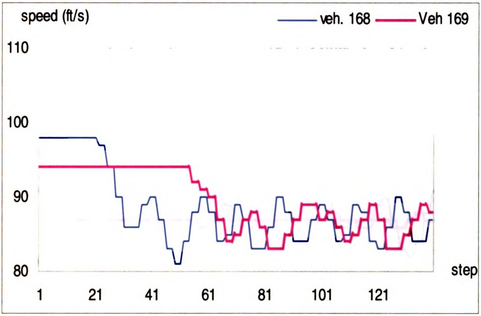


5-1 a Vehicles 166 and 167

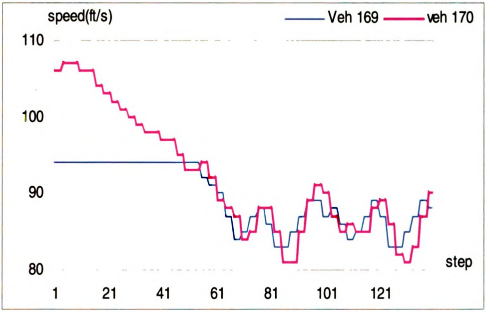


5-1 b Vehicles 167 and 168

Figure 5-1 Speed Interaction between Vehicles in Experiment One (continued)

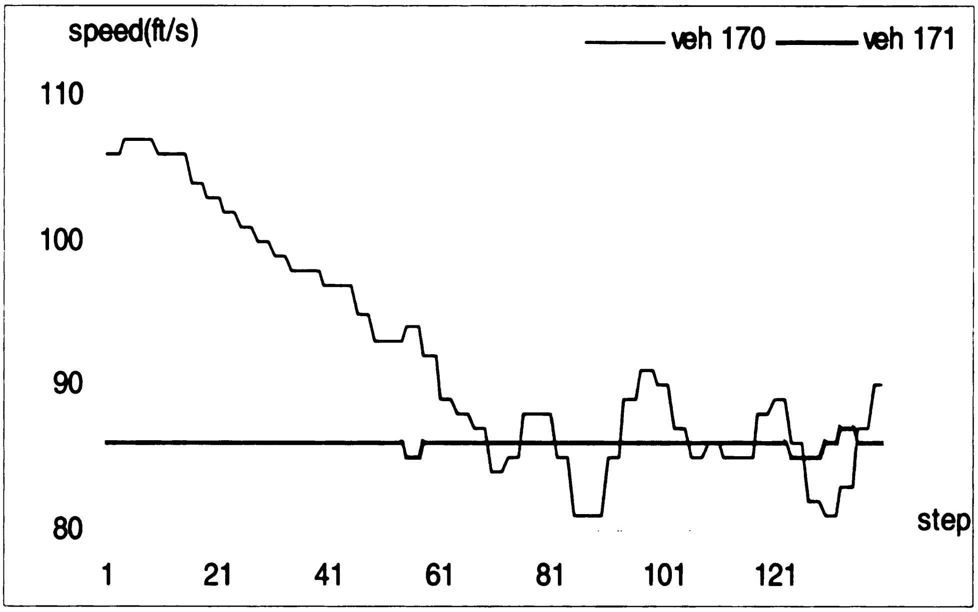


5-1 c Vehicles 168 and 169

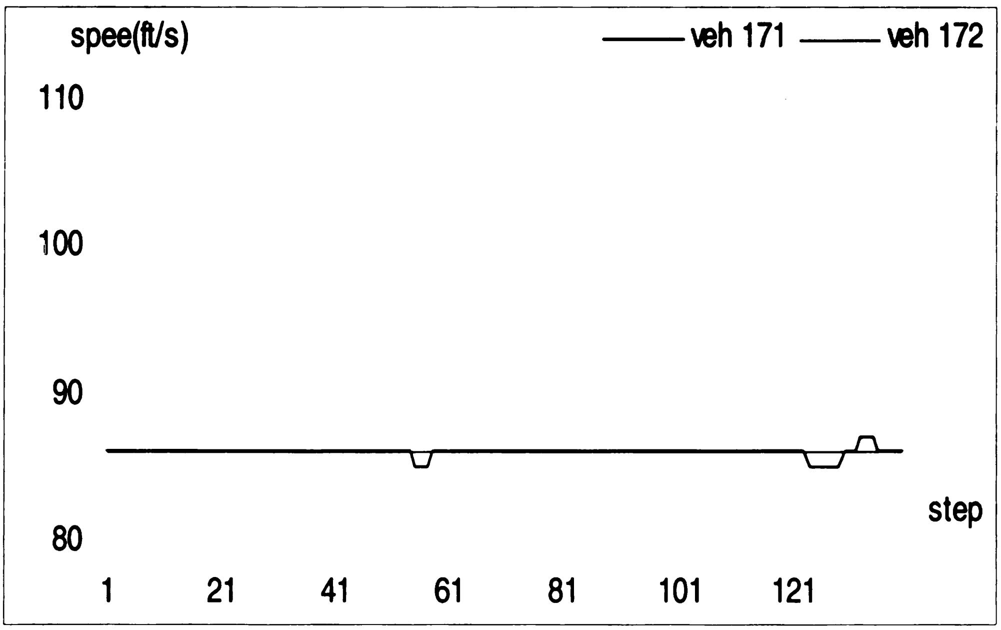


5-1 d Vehicles 169 and 170

Figure 5-1 Speed Interaction between Vehicles in Experiment One (continued)

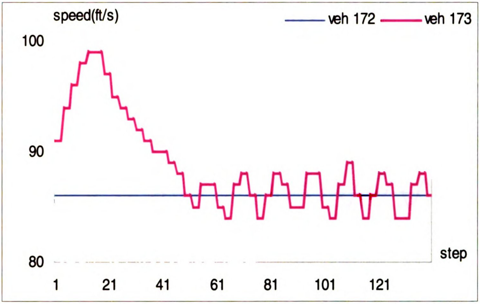


5-1 e Vehicles 170 and 171

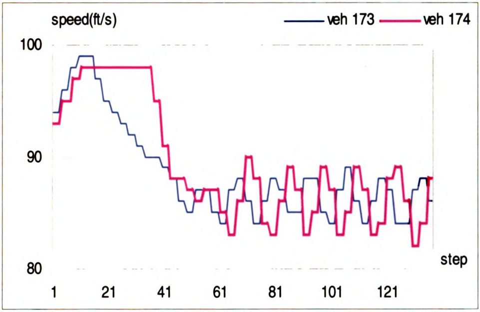


5-1 f Vehicles 171 and 172

Figure 5-1 Speed Interaction between Vehicles in Experiment One (continued)

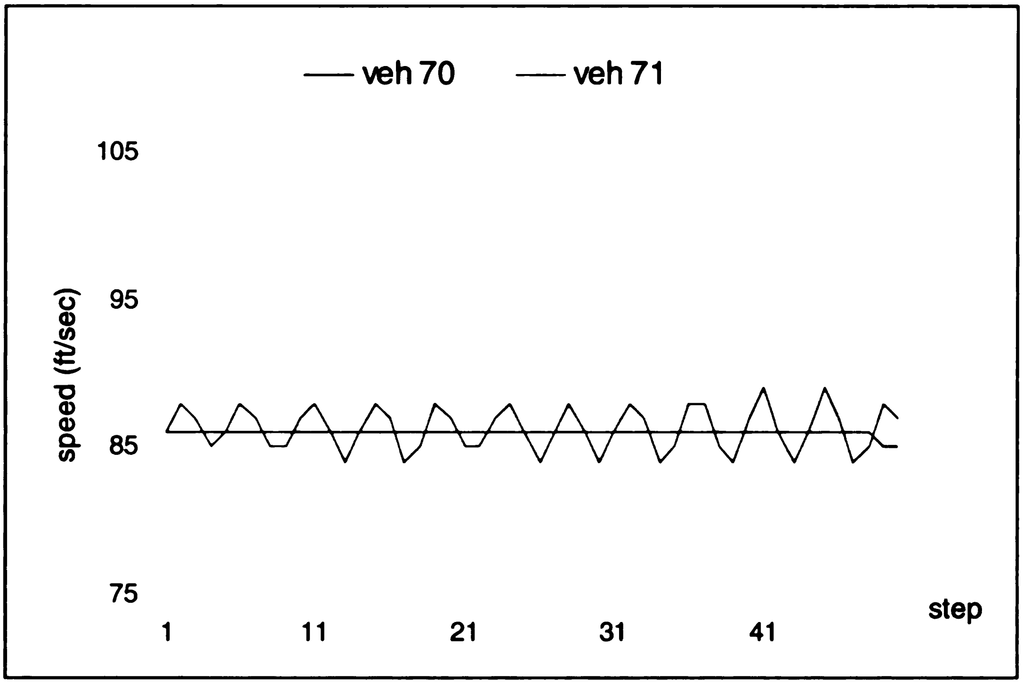


5-1 g Vehicles 172 and 173

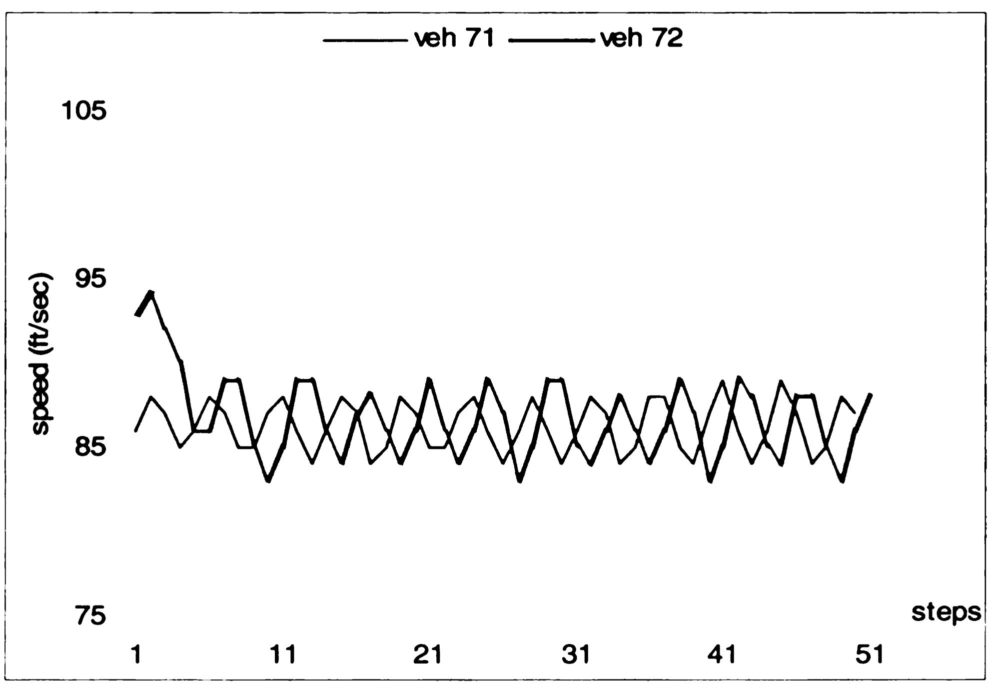


5-1 h Vehicles 173 and 174

Figure 5-2 Speed Interactions between Vehicles in Experiment Two

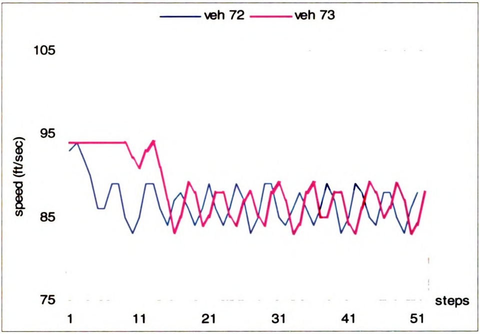


5-2 a Vehicles 70 and 71

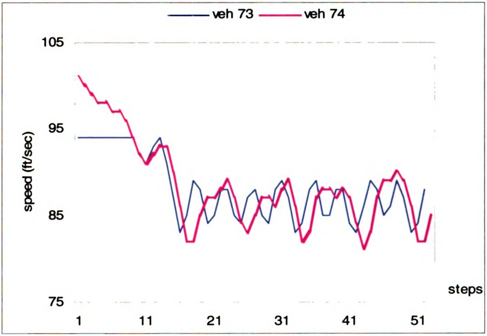


5-2 b. Vehicles 71 and 72

Figure 5-2 Speed Interactions between Vehicles in Experiment Two (continued)

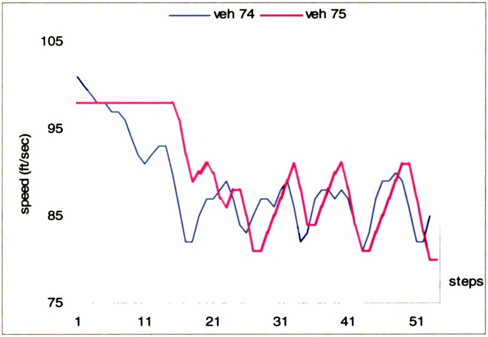


5-2 c Vehicles 72 and 73

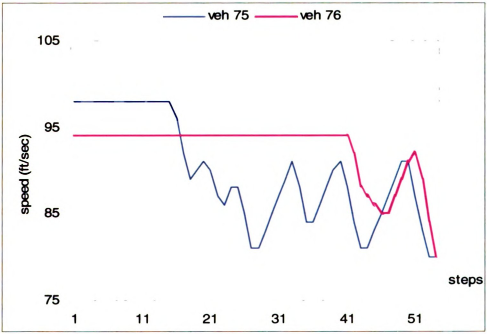


5-2 d Vehicles 73 and 74

Figure 5-2 Speed Interactions between Vehicles in Experiment Two (continued)

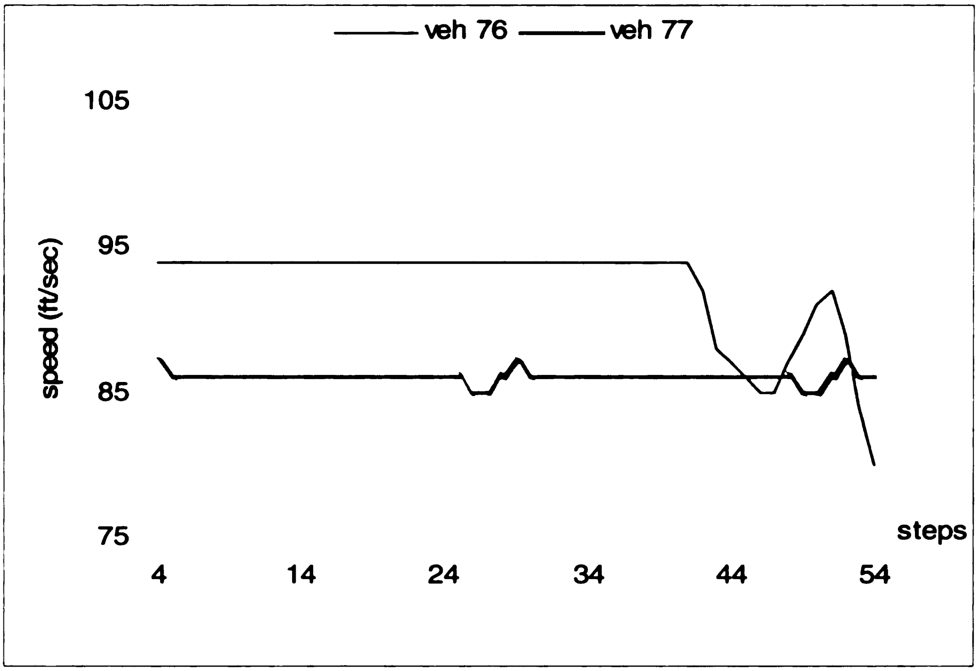


5-2 e Vehicles 74 and 75

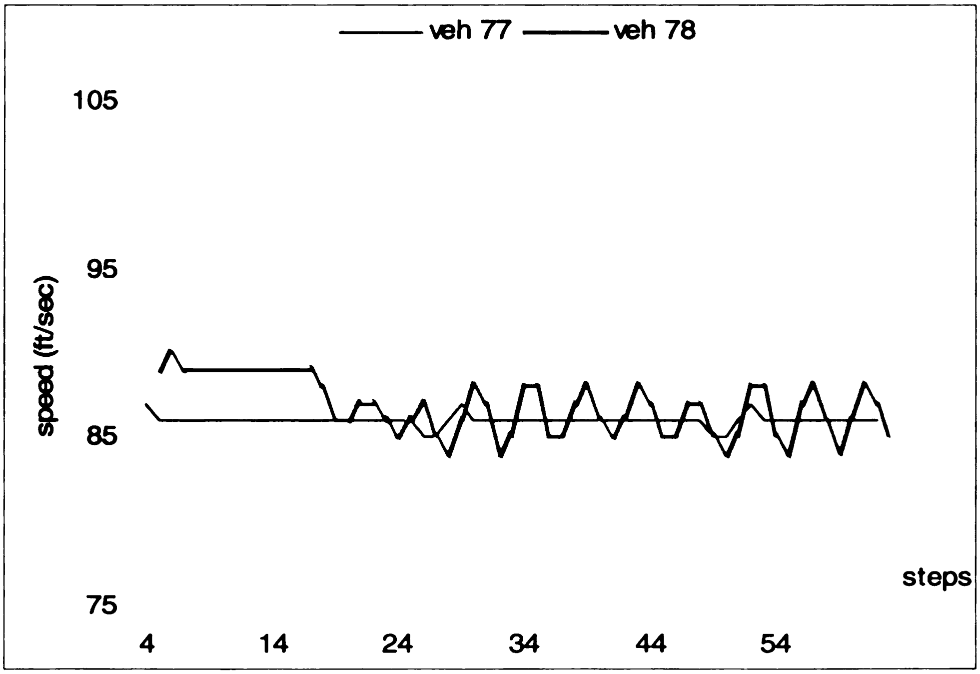


5-2 f Vehicles 75 and 76

Figure 5-2 Speed Interactions between Vehicles in Experiment Two (continued)

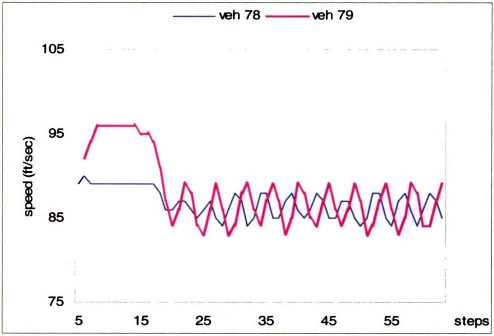


5-2 g Vehicles 76 and 77

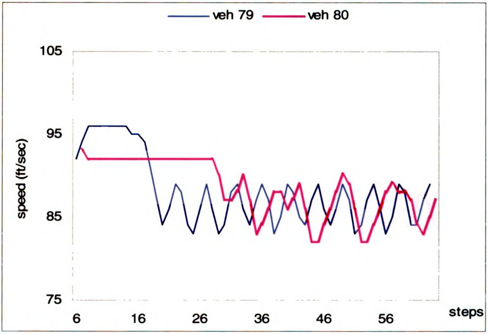


5-2 h Vehicles 77 and 78

Figure 5-2 Speed Interactions between Vehicles in Experiment Two (continued)

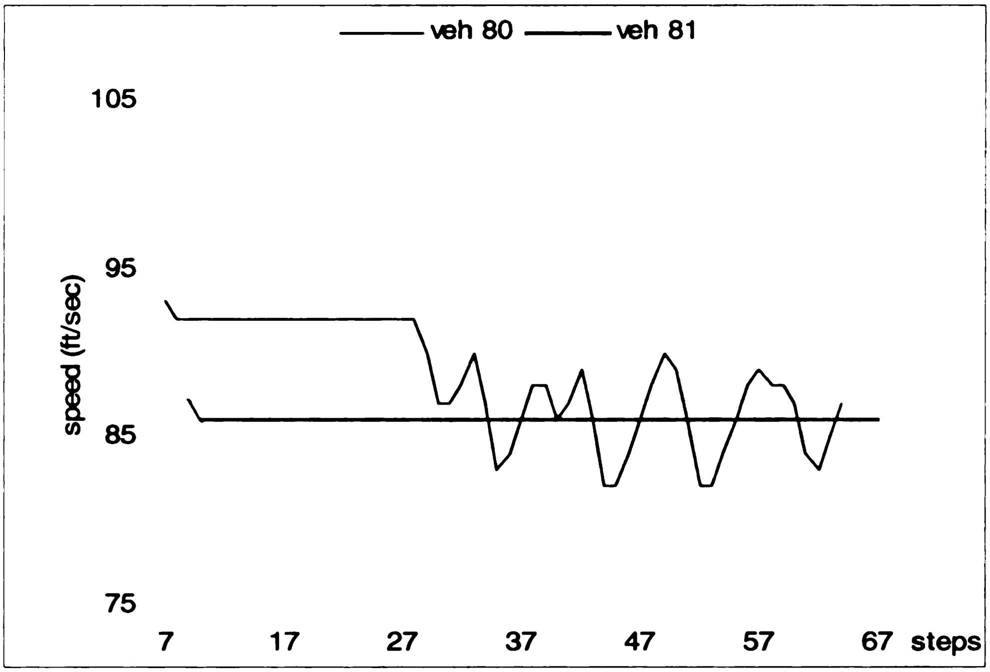


5-2 i   Vehicles 78 and 79

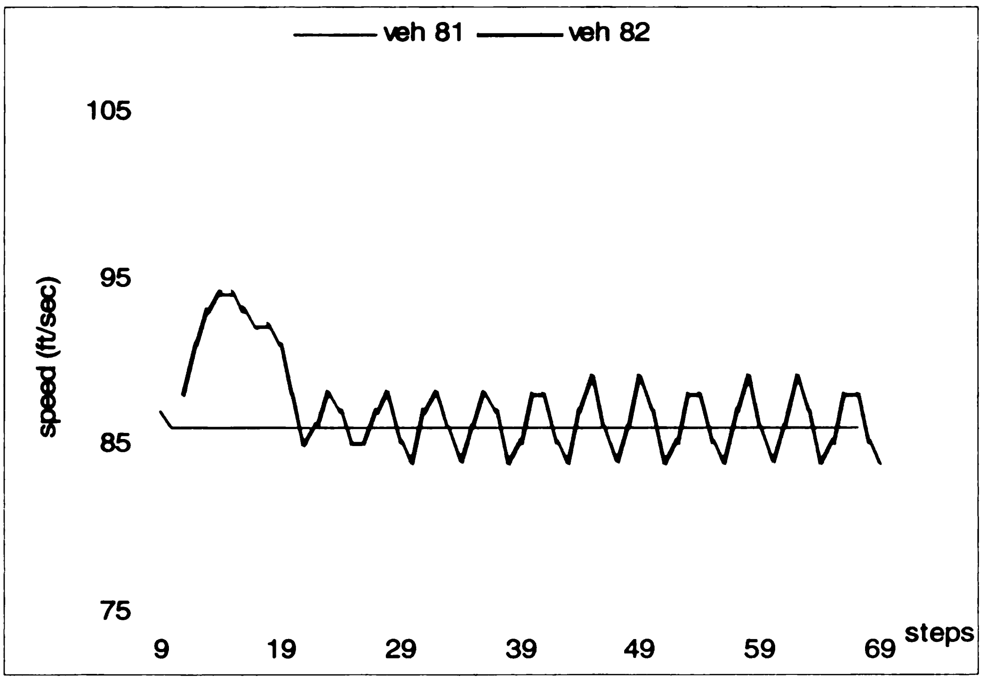


5-2 j   Vehicles 79 and 80

Figure 5-2 Speed Interactions between Vehicles in Experiment Two (continued)

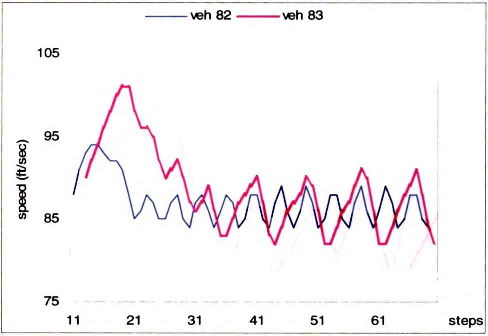


5-2 k Vehicles 80 and 81

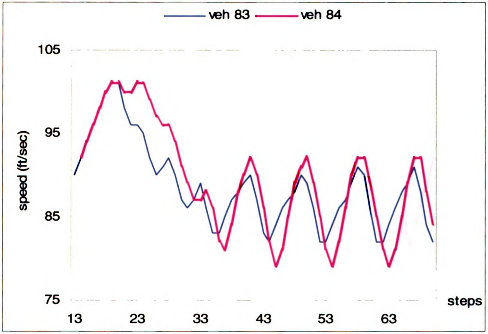


5-2 l Vehicles 81 and 82

Figure 5-2 Speed Interactions between Vehicles in Experiment Two (continued)

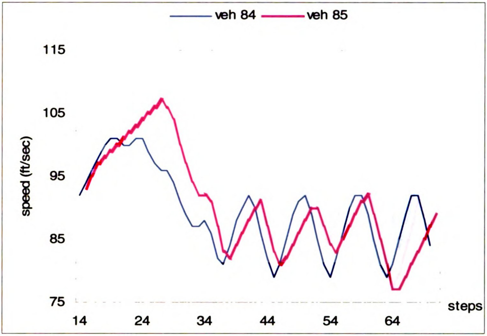


5-2 m Vehicles 82 and 83

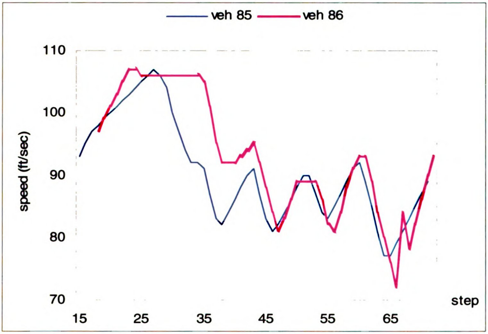


5-2 n Vehicles 83 and 84

Figure 5-2 Speed Interactions between vehicles in Experiment Two (continued)

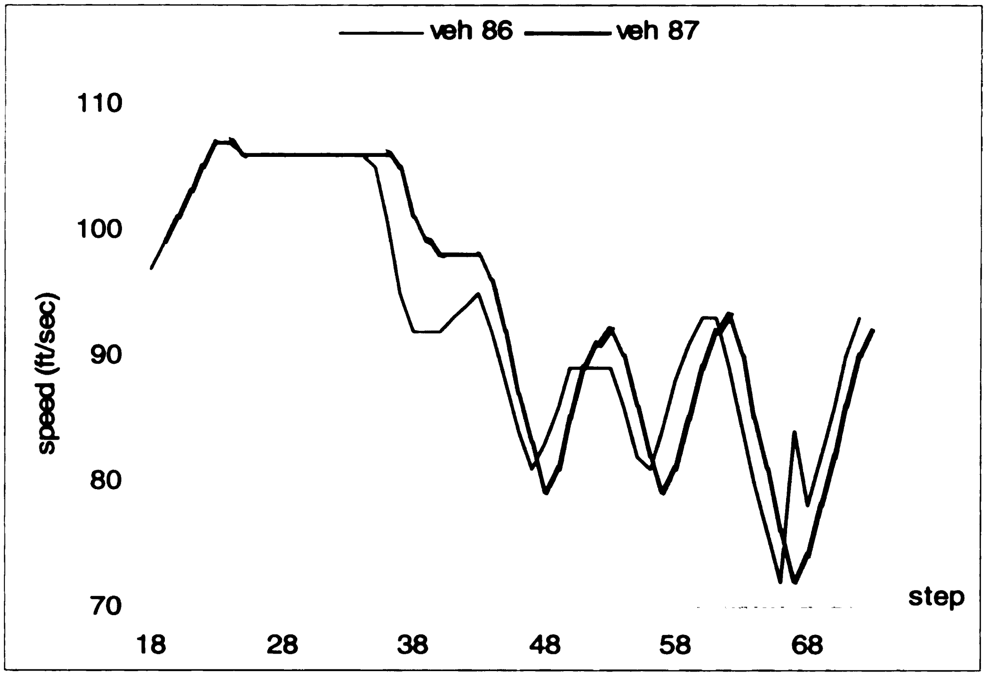


5-2 o Vehicles 84 and 85

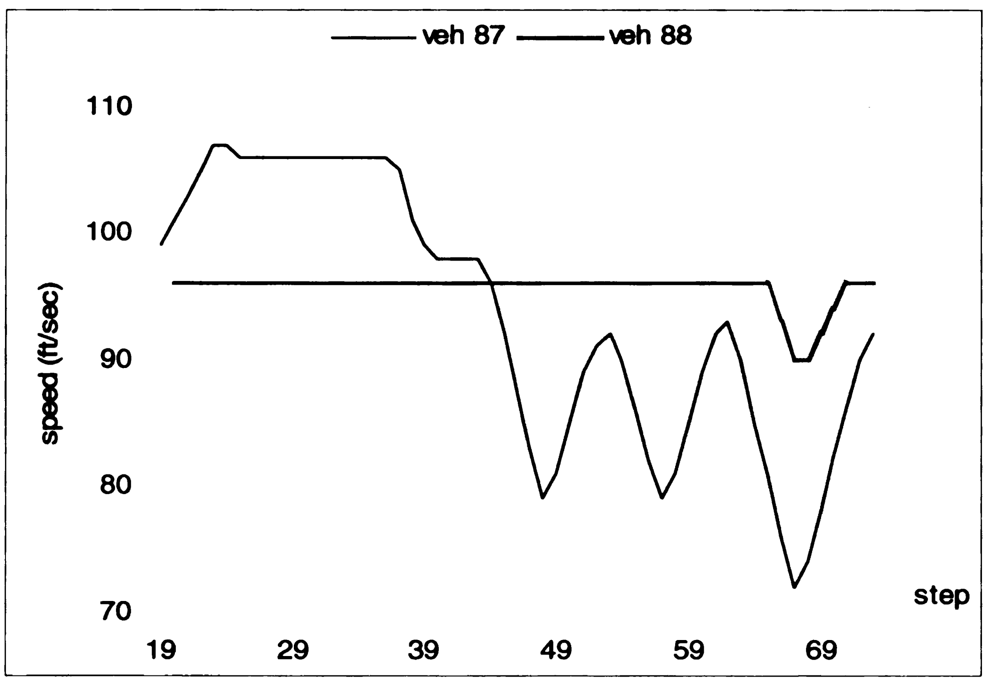


5-2 p Vehicles 85 and 86

Figure 5-2 Speed Interactions between Vehicles in Experiment Two (continued)

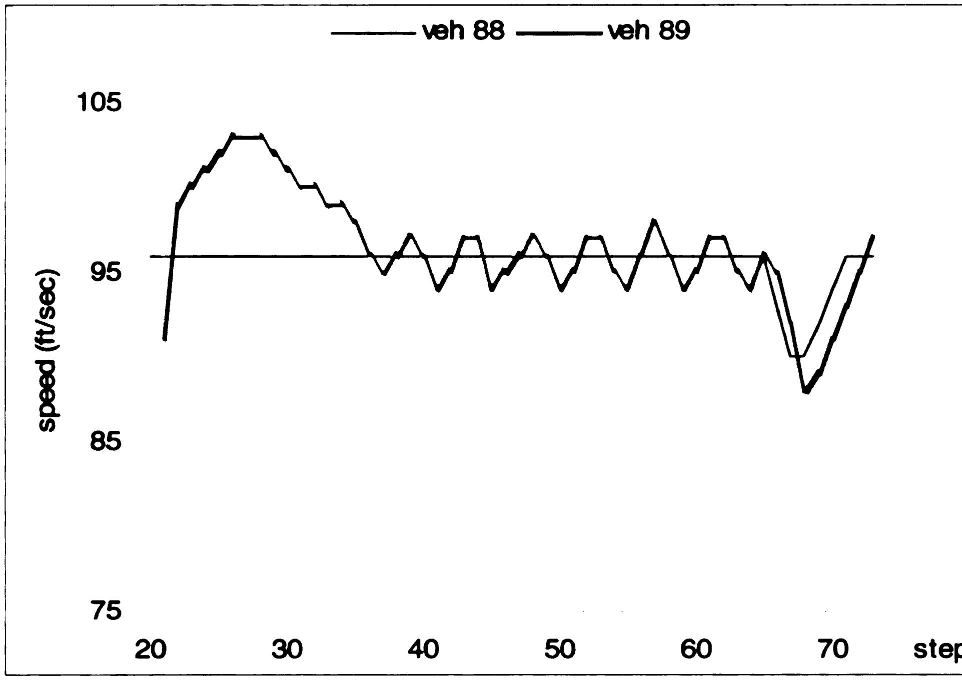


5-2 q Vehicles 86 and 87

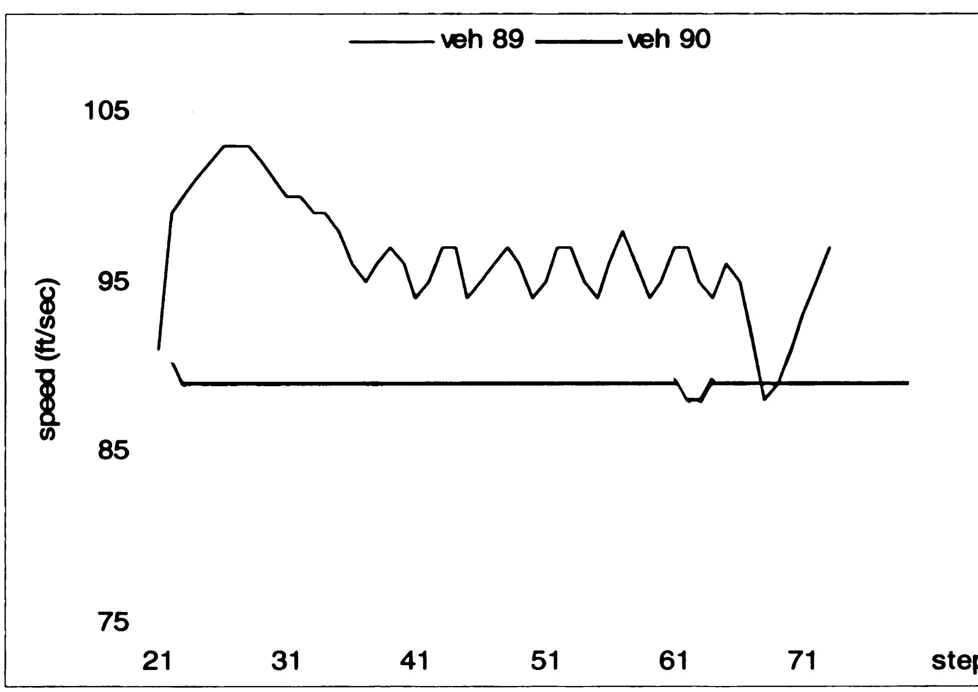


5-2 r Vehicles 87 and 88

Figure 5-2 Speed Interactions between Vehicles in Experiment Two (continued)

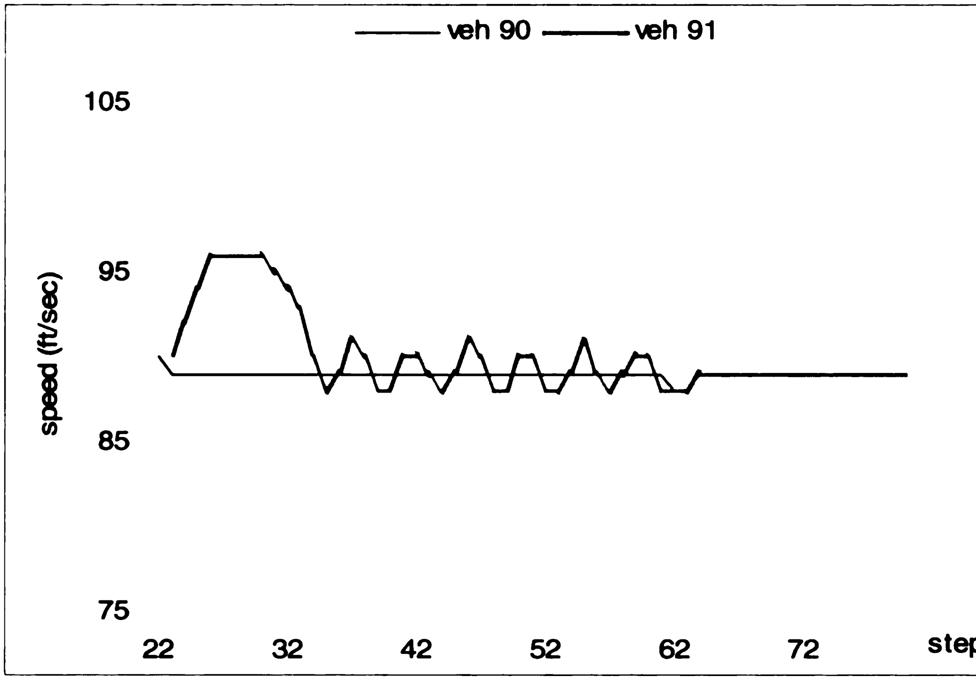


5-2 s   Vehicles 88 and 89

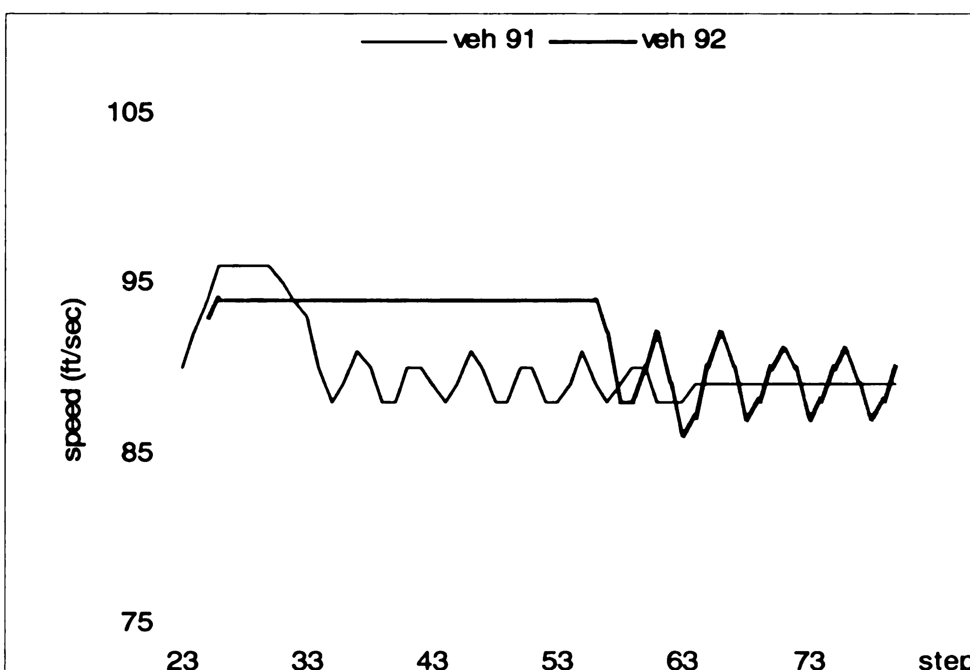


5-2 t   Vehicles 89 and 90

Figure 5-2 Speed Interactions between Vehicles in Experiment Two (continued)

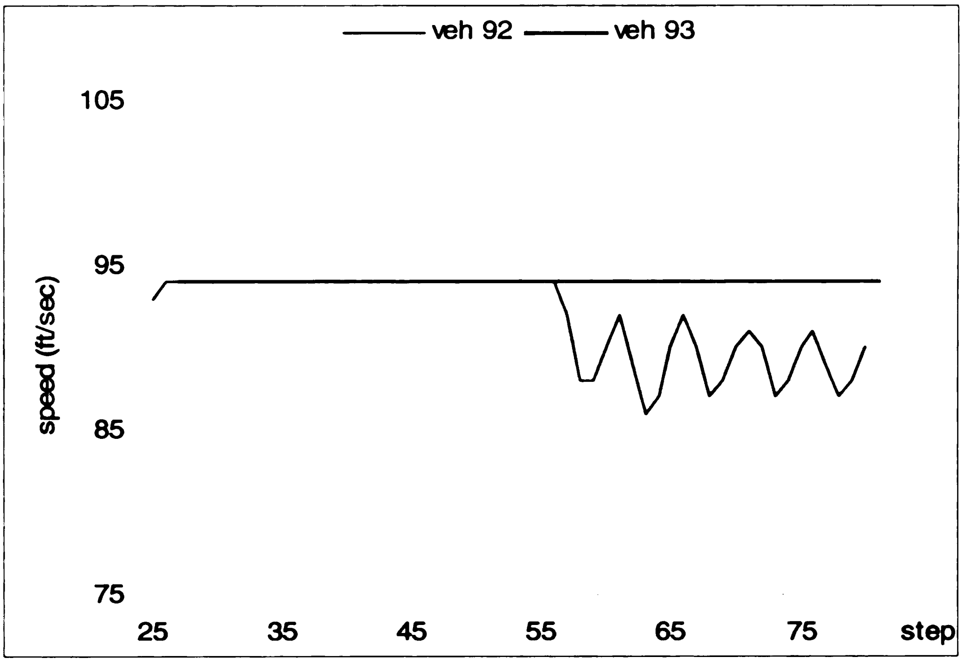


5-2 u   Vehicles 90 and 91

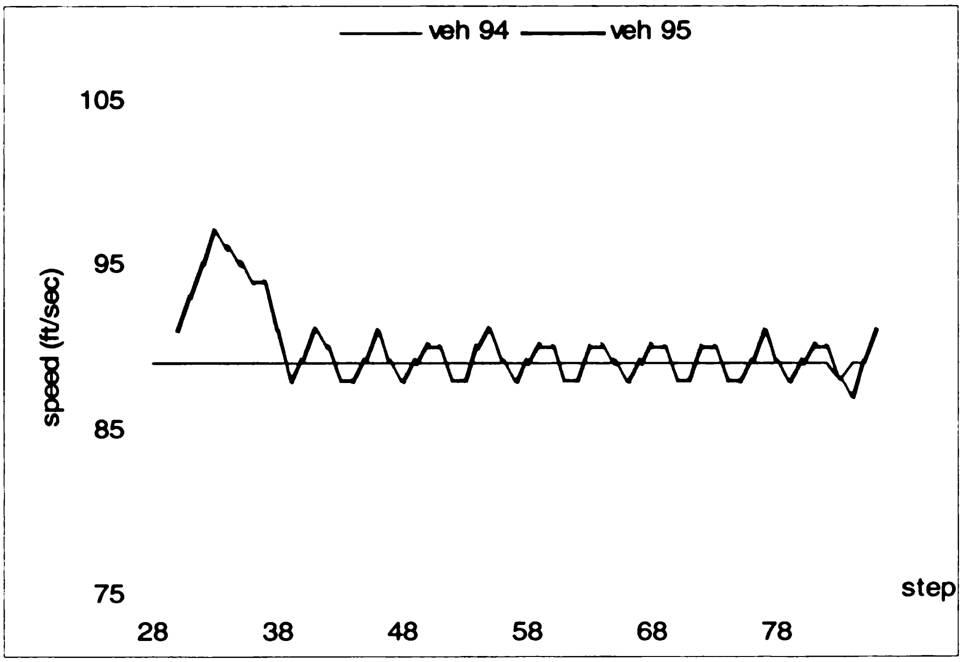


5-2 v   Vehicles 91 and 92

Figure 5-2 Speed Interactions between Vehicles in Experiment Two (continued)

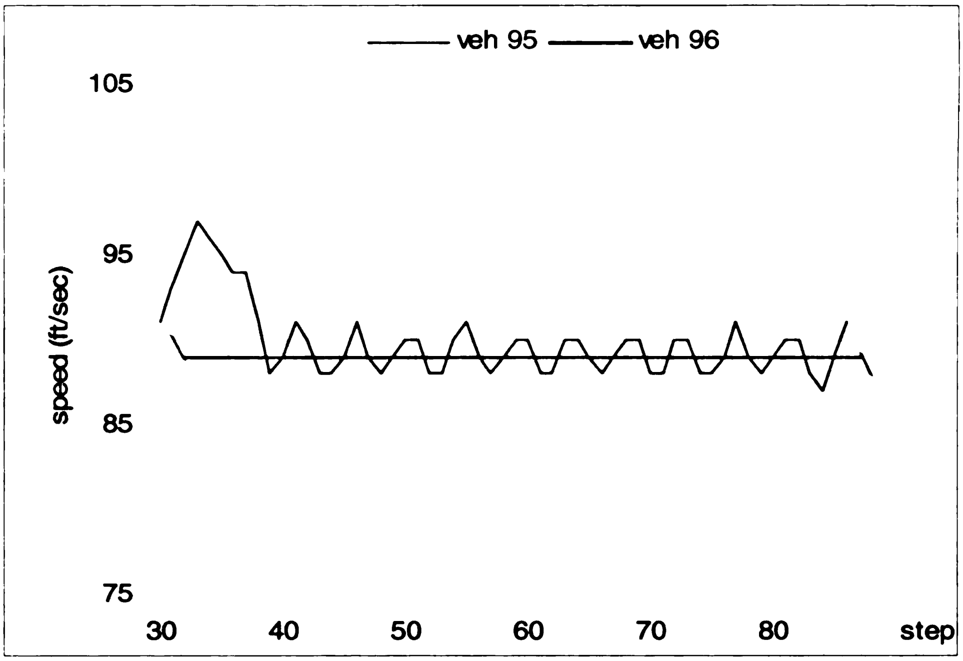


5-2 w   Vehicles 92 and 93



5-2 x   Vehicles 94 and 95

Figure 5-2 Speed Interactions between Vehicles in Experiment Two (continued)



5-2 y Vehicles 95 and 96

CHAPTER 6 FINDINDS AND RECOMMENDATIONS

6.1 Findings

The study discussed the single-lane car following behavior when a speed disturbance from a lead vehicle occurs. A concept of Expected State-Control Action Chains and three scenarios of single-lane car-following behavior situations were developed (Table 2-1). The minimum dynamic spacing for each scenario was analyzed and defined (Table 3-1). The existence of an upper boundary of a speed disturbance that a spacing can absorb was proved through Theory 4-1, Lemma 4-1 and Theory 4-2. The mathematical models were obtained to calculate the upper boundary of the magnitude of a speed disturbance that a single spacing or multiple spacings can absorb (Equations 4-4, 4-13. Moreover, the conditions for local and asymptotic stability were determined (Equations 4-16 and 4-17). Two simulation experiments were conducted and studied. The cases identified from the experimental data verified the models obtained in Chapter 4. The most important findings of this work are summarized in Table 6-1.

The findings of this work demonstrate that speed fluctuations of individual vehicles do play a role in traffic stability, and can be used in car-following analysis to find upper boundary conditions for the stability at the microscopic level.

Table 6-1 Summary of Findings

Findings	Reference Numbers of Figures, Tables, or Equations in the Contents
Concept of Expected State-Control Action Chain (Car-Following Prcess)	Table 2-1
Minimum Dynamic Spacing	Table 3-1
Existence of an Upper Boundary of a Speed Disturbance that a Spacing Can Absorb	Definitions 4-1 through 4-6 Theories 4-1 and 4-2, Lemma 4-1
Mathematical Models to Calculate an Upper Boundary of the Magnitude of a Speed Disturbance that a Single Spacing Can Absorb	Equations 4-4, 4-13
Conditions for Local and Asymptotic Stability	Equations 4-16 and 4-17
Model Verification	Sample Cases from the Two Simulation Experiments

6.2 Recommendations for Further Research

This work discussed a single speed disturbance and its absorption at microscopic level. The findings established a basic framework for the research on multiple speed disturbances and their absorption. As we pointed out in Chapter 2, errors and deviation from the assessment or control skill of human beings are unavoidable. When a following vehicle, n+1, reduces its speed in response to a speed disturbance from the lead vehicle, n, vehicle n+1 may create a speed disturbance of its own because of the errors. In other words the speed reduction of a following vehicle includes two parts: speed reduction in response to the speed disturbance from the lead vehicle and speed disturbance from its assessing and/or controlling errors. The errors of assessment and/or control can be regarded as a speed disturbance produced by the following vehicle n+1. Therefore, further research is needed to understand the phenomenon of multiple speed disturbances and their absorption in a group of vehicles that follow one another. The upper boundary conditions of multiple speed disturbances that can be absorbed by a vehicular platoon will result in a macroscopic model for traffic stability.

APPENDICE

APPENDIX 1 DATA OF EXPERIMENT ONE

Data of Single-Lane Car Following Simulation - Experiment One

# of	veh. 166 (DT=7)			veh.167 (DT=7)			spacing	veh. 168 (DT=7)			spacing	veh. 169 (DT=5)			spacing	veh. 170 (DT=10)			spacing
steps	mi pt (ft)	Acce. (ft/s/s)	speed (ft/s)	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh 166	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh 167	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh 168	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh 169
1	1160	0	98	1050	0	98	110	936	0	98	114	780	0	94	156	605	2	106	175
2	1192	0	98	1082	0	98	110	968	0	98	114	811	0	94	157	640	2	106	171
3	1225	0	98	1115	0	98	110	1001	0	98	114	843	0	94	158	676	2	106	167
4	1258	0	98	1148	0	98	110	1034	0	98	114	875	0	94	159	712	0	107	163
5	1290	0	98	1180	0	98	110	1067	0	98	113	906	0	94	161	747	0	107	159
6	1323	0	98	1213	0	98	110	1100	0	98	113	937	0	94	163	783	0	107	154
7	1356	-1	96	1246	0	98	110	1133	0	98	113	969	0	94	164	819	0	107	150
8	1388	-1	96	1278	0	98	110	1165	0	98	113	1000	0	94	165	854	0	107	146
9	1420	-1	96	1311	0	98	109	1198	0	98	113	1032	0	94	166	890	0	107	142
10	1452	-2	94	1344	0	98	108	1231	0	98	113	1064	0	94	167	926	0	106	138
11	1482	-2	94	1376	0	98	106	1263	0	98	113	1095	0	94	168	961	0	106	134
12	1513	-2	94	1409	0	98	104	1296	0	98	113	1126	0	94	170	996	0	106	130
13	1544	-3	90	1442	0	98	102	1329	0	98	113	1158	0	94	171	1032	0	106	126
14	1574	-3	90	1474	0	98	100	1361	0	98	113	1189	0	94	172	1067	0	106	122
15	1607	-3	90	1507	0	98	100	1394	0	98	113	1220	0	94	174	1102	0	106	118
16	1634	0	89	1540	-4	95	94	1427	0	98	113	1252	0	94	175	1138	-1	104	114
17	1663	0	89	1571	-4	95	92	1459	0	98	112	1283	0	94	176	1172	-1	104	111
18	1693	0	89	1602	-4	95	91	1492	0	98	110	1315	0	94	177	1207	-1	104	108
19	1723	0	88	1633	-4	91	90	1525	0	98	108	1347	0	94	178	1242	-1	103	105
20	1752	0	88	1663	-4	91	89	1557	0	98	106	1378	0	94	179	1276	-1	103	102
21	1781	0	88	1693	-4	91	88	1590	0	98	103	1409	0	94	181	1310	-1	103	99
22	1811	-1	87	1723	-2	88	88	1623	0	97	100	1441	0	94	182	1345	-1	102	96
23	1840	-1	87	1752	-2	88	88	1655	0	97	97	1472	0	94	183	1378	-1	102	94
24	1869	-1	87	1781	-2	88	88	1687	0	97	94	1503	0	94	184	1412	-1	102	91
25	1898	-1	85	1811	0	87	87	1720	-4	94	91	1535	0	94	185	1446	-1	101	89
26	1926	-1	85	1840	0	87	86	1750	-4	94	90	1566	0	94	184	1479	-1	101	87
27	1954	-1	85	1869	0	87	85	1781	-4	94	88	1598	0	94	183	1513	-1	101	85
28	1983	0	85	1898	0	86	85	1812	-4	90	86	1630	0	94	182	1547	0	100	83
29	2012	0	85	1926	0	86	86	1841	-4	90	85	1661	0	94	180	1580	0	100	81

Data of Single-Lane Car Following Simulation - Experiment One (continued)

# of steps	veh. 166 (DT=7) mi pt (ft)	veh. 166 (DT=7) Acce. (ft/s/s)	veh. 166 (DT=7) speed (ft/s)	veh.167 (DT=7) mi pt (ft)	veh.167 (DT=7) Acce (ft/s/s)	veh.167 (DT=7) speed (ft/s)	spacing from veh 166	veh. 168 (DT=7) mi pt (ft)	veh. 168 (DT=7) Acce (ft/s/s)	veh. 168 (DT=7) speed (ft/s)	spacing from veh 167	veh. 169 (DT=5) mi pt (ft)	veh. 169 (DT=5) Acce (ft/s/s)	veh. 169 (DT=5) speed (ft/s)	spacing from veh 168	veh. 170 (DT=10) mi pt (ft)	veh. 170 (DT=10) Acce (ft/s/s)	veh. 170 (DT=10) speed (ft/s)	spacing from veh 169
30	2041	0	85	1955	0	86	86	1870	-4	90	85	1692	0	94	178	1613	0	100	79
31	2070	2	87	1984	0	86	86	1900	-4	86	84	1724	0	94	176	1647	0	99	77
32	2099	2	87	2013	0	86	86	1928	-4	86	85	1755	0	94	173	1680	0	99	75
33	2128	2	87	2042	0	86	86	1957	-4	86	85	1787	0	94	170	1713	0	99	74
34	2158	0	88	2071	1	87	87	1986	1	86	85	1819	0	94	167	1746	0	98	73
35	2187	0	88	2100	1	87	87	2015	1	86	85	1850	0	94	165	1778	0	98	72
36	2216	0	88	2130	1	87	86	2044	1	86	86	1881	0	94	163	1811	0	98	70
37	2246	-3	86	2160	0	88	86	2073	4	89	87	1913	0	94	160	1844	0	98	69
38	2274	-3	86	2189	0	88	85	2103	4	89	86	1944	0	94	159	1876	0	98	68
39	2302	-3	86	2218	0	88	84	2133	4	89	85	1975	0	94	158	1909	0	98	66
40	2331	0	84	2248	-4	86	83	2164	0	90	84	2007	0	94	157	1942	0	97	65
41	2359	0	84	2276	-4	86	83	2193	0	90	83	2038	0	94	155	1972	0	97	66
42	2388	0	84	2304	-4	86	84	2223	0	90	81	2070	0	94	153	2006	0	97	64
43	2417	2	86	2332	-1	83	85	2253	-4	87	79	2102	0	94	151	2039	0	97	63
44	2446	2	86	2360	-1	83	86	2281	-4	87	79	2133	0	94	148	2071	0	97	62
45	2475	2	86	2388	-1	83	87	2309	-4	87	79	2164	0	94	145	2103	0	97	61
46	2504	1	88	2416	2	84	88	2338	-4	83	78	2196	0	94	142	2136	-1	95	60
47	2533	1	88	2444	2	84	89	2365	-4	83	79	2227	0	94	138	2167	-1	95	60
48	2563	1	88	2472	2	84	91	2392	-4	83	80	2259	0	94	133	2199	-1	95	60
49	2593	-2	87	2501	2	86	92	2420	0	81	81	2291	0	94	129	2231	-1	93	60
50	2621	-2	87	2530	2	86	91	2447	0	81	83	2322	0	94	125	2262	-1	93	60
51	2650	-2	87	2559	2	86	91	2474	0	81	85	2353	0	94	121	2294	-1	93	59
52	2679	-2	84	2589	2	88	90	2502	4	84	87	2385	0	94	117	2324	0	93	61
53	2707	-2	84	2618	2	88	89	2531	4	84	87	2416	0	94	115	2355	0	93	61
54	2735	-2	84	2647	2	88	88	2560	4	84	87	2447	0	94	113	2386	0	93	61
55	2763	1	84	2677	-1	88	86	2589	4	88	88	2478	-1	92	111	2418	1	94	60
56	2791	1	84	2706	-1	88	85	2618	4	88	88	2509	-1	92	109	2449	1	94	60
57	2820	1	84	2735	-1	88	85	2648	4	88	87	2540	-1	92	108	2480	1	94	60
58	2849	3	87	2765	-2	86	84	2678	2	90	87	2571	0	91	107	2512	-2	92	59

Data of Single-Lane Car Following Simulation - Experiment One (continued)

# of steps	veh. 166 (DT=7) mi pt (ft)	Acce. (ft/s/s)	speed (ft/s)	veh.167 (DT=7) mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	spacing from veh 166	veh. 168 (DT=7) mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	spacing from veh 167	veh. 169 (DT=5) mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	spacing from veh 168	veh. 170 (DT=10) mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	spacing from veh 169
59	2878	3	87	2793	-2	86	85	2708	2	90	85	2601	0	91	107	2542	-2	92	59
60	2908	3	87	2821	-2	86	87	2738	2	90	83	2631	0	91	107	2573	-2	92	58
61	2938	1	89	2850	1	86	88	2769	-4	88	81	2662	0	90	107	2604	-3	89	58
62	2967	1	89	2879	1	86	88	2798	-4	88	81	2692	0	90	106	2633	-3	89	59
63	2996	1	89	2908	1	86	88	2827	-4	88	81	2722	0	90	105	2663	-3	89	59
64	3026	-3	87	2938	2	88	88	2856	-4	84	82	2752	-4	87	104	2693	0	88	59
65	3054	-3	87	2967	2	88	87	2884	-4	84	83	2780	-4	87	104	2722	0	88	58
66	3083	-3	87	2996	2	88	87	2912	-4	84	84	2809	-4	87	103	2751	0	88	58
67	3112	-2	84	3026	-1	88	86	2940	3	85	86	2838	-2	84	102	2780	-1	87	58
68	3140	-2	84	3055	-1	88	85	2969	3	85	86	2866	-2	84	103	2808	-1	87	58
69	3168	-2	84	3084	-1	88	84	2998	3	85	86	2894	-2	84	104	2837	-1	87	57
70	3197	1	85	3113	-3	85	84	3028	3	89	85	2923	2	85	105	2866	-2	84	57
71	3225	1	85	3141	-3	85	84	3057	3	89	84	2951	2	85	106	2894	-2	84	57
72	3254	1	85	3169	-3	85	85	3087	3	89	82	2980	2	85	107	2922	-2	84	58
73	3283	3	88	3197	0	84	86	3117	-4	87	80	3009	2	87	108	2951	2	85	58
74	3312	3	88	3225	0	84	87	3145	-4	87	80	3038	2	87	107	2980	2	85	58
75	3342	3	88	3253	0	84	89	3174	-4	87	79	3068	2	87	106	3009	2	85	59
76	3372	0	88	3282	2	85	90	3203	-4	83	79	3098	0	88	105	3038	4	88	60
77	3401	0	88	3311	2	85	90	3230	-4	83	81	3127	0	88	103	3067	4	88	60
78	3430	0	88	3340	2	85	90	3258	-4	83	82	3156	0	88	102	3097	4	88	59
79	3460	-3	86	3369	2	87	91	3286	1	83	83	3186	-4	86	100	3127	-1	88	59
80	3488	-3	86	3398	2	87	90	3314	1	83	84	3214	-4	86	100	3156	-1	88	58
81	3516	-3	86	3428	2	87	88	3342	1	83	86	3242	-4	86	100	3185	-1	88	57
82	3545	0	84	3458	0	89	87	3370	4	86	88	3267	-2	83	103	3215	-4	85	52
83	3573	0	84	3487	0	89	86	3399	4	86	88	3297	-2	83	102	3243	-4	85	54
84	3601	0	84	3516	0	89	85	3429	4	86	87	3325	-2	83	104	3271	-4	85	54
85	3630	2	86	3546	-3	86	84	3459	4	90	87	3353	2	83	106	3299	-4	81	54
86	3659	2	86	3574	-3	86	85	3489	4	90	85	3381	2	83	108	3326	-4	81	55
87	3688	2	86	3603	-3	86	85	3519	4	90	84	3409	2	83	110	3353	-4	81	56

Data of Single-Lane Car Following Simulation - Experiment One (continued)

# of steps	veh. 166 (DT=7) mi pt (ft)	veh. 166 Acce. (ft/s/s)	veh. 166 speed (ft/s)	veh.167 (DT=7) mi pt (ft)	veh.167 Acce (ft/s/s)	veh.167 speed (ft/s)	spacing from veh 166	veh. 168 (DT=7) mi pt (ft)	veh. 168 Acce (ft/s/s)	veh. 168 speed (ft/s)	spacing from veh 167	veh. 169 (DT=5) mi pt (ft)	veh. 169 Acce (ft/s/s)	veh. 169 speed (ft/s)	spacing from veh 168	veh. 170 (DT=10) mi pt (ft)	veh. 170 Acce (ft/s/s)	veh. 170 speed (ft/s)	spacing from veh 169
88	3718	2	88	3632	0	85	86	3549	-4	88	83	3438	2	85	111	3380	1	81	58
89	3747	2	88	3660	0	85	87	3578	-4	88	82	3466	2	85	112	3407	1	81	59
90	3776	2	88	3688	0	85	88	3607	-4	88	81	3495	2	85	112	3435	1	81	60
91	3806	-2	87	3717	2	86	89	3636	-4	84	81	3524	2	87	112	3463	4	85	61
92	3835	-2	87	3746	2	86	89	3664	-4	84	82	3553	2	87	111	3492	4	85	61
93	3864	-2	87	3775	2	86	89	3692	-4	84	83	3583	2	87	109	3521	4	85	62
94	3893	-2	85	3805	2	88	88	3720	1	84	85	3613	2	89	107	3550	4	89	63
95	3921	-2	85	3834	2	88	87	3748	1	84	86	3643	2	89	105	3580	4	89	63
96	3949	-2	85	3863	2	88	86	3777	1	84	86	3673	2	89	104	3610	4	89	63
97	3978	0	85	3893	-2	87	85	3806	4	87	87	3703	-1	89	103	3641	1	91	62
98	4006	0	85	3922	-2	87	84	3835	4	87	87	3732	-1	89	103	3671	1	91	61
99	4035	0	85	3951	-2	87	84	3865	4	87	86	3761	-1	89	104	3702	1	91	59
100	4064	3	87	3980	-2	85	84	3895	0	89	85	3791	-1	87	104	3733	-1	90	58
101	4093	3	87	4008	-2	85	85	3924	0	89	84	3820	-1	87	104	3762	-1	90	58
102	4122	3	87	4036	-2	85	86	3954	0	89	82	3849	-1	87	105	3792	-1	90	57
103	4152	0	88	4065	2	86	87	3984	-4	87	81	3879	0	88	105	3822	-4	87	57
104	4181	0	88	4094	2	86	87	4012	-4	87	82	3908	0	88	104	3851	-4	87	57
105	4210	0	88	4123	2	86	87	4041	-4	87	82	3937	0	88	104	3880	-4	87	57
106	4240	-2	86	4152	2	88	88	4070	-2	84	82	3967	-2	86	103	3909	0	85	58
107	4268	-2	86	4181	2	88	87	4098	-2	84	83	3995	-2	86	103	3937	0	85	58
108	4297	-2	86	4210	2	88	87	4126	-2	84	84	4024	-2	86	102	3966	0	85	58
109	4326	-1	84	4240	0	88	86	4154	4	85	86	4053	-1	84	101	3995	1	86	58
110	4354	-1	84	4269	0	88	85	4183	4	85	86	4081	-1	84	102	4023	1	86	58
111	4382	-1	84	4298	0	88	84	4212	4	85	86	4109	-1	84	103	4052	1	86	57
112	4411	2	86	4328	-3	85	83	4242	4	89	86	4137	2	85	105	4081	-1	85	56
113	4440	2	86	4356	-3	85	84	4272	4	89	84	4166	2	85	106	4109	-1	85	57
114	4469	2	86	4384	-3	85	85	4302	4	89	82	4195	2	85	107	4138	-1	85	57
115	4498	2	88	4412	0	84	86	4332	-4	88	80	4224	2	87	108	4167	0	85	57
116	4527	2	88	4440	0	84	87	4360	-4	88	80	4253	2	87	107	4195	0	85	58

Data of Single-Lane Car Following Simulation - Experiment One (continued)

# of steps	veh. 166 (DT=7) mi pt (ft)	veh. 166 (DT=7) Acce. (ft/s/s)	veh. 166 (DT=7) speed (ft/s)	veh.167 (DT=7) mi pt (ft)	veh.167 (DT=7) Acce (ft/s/s)	veh.167 (DT=7) speed (ft/s)	spacing from veh 166	veh. 168 (DT=7) mi pt (ft)	veh. 168 (DT=7) Acce (ft/s/s)	veh. 168 (DT=7) speed (ft/s)	spacing from veh 167	veh. 169 (DT=5) mi pt (ft)	veh. 169 (DT=5) Acce (ft/s/s)	veh. 169 (DT=5) speed (ft/s)	spacing from veh 168	veh. 170 (DT=10) mi pt (ft)	veh. 170 (DT=10) Acce (ft/s/s)	veh. 170 (DT=10) speed (ft/s)	spacing from veh 169
117	4557	2	88	4469	0	84	88	4389	-4	88	80	4283	2	87	106	4224	0	85	59
118	4587	-1	87	4498	2	86	89	4418	-4	84	80	4313	1	89	105	4253	4	88	60
119	4616	-1	87	4527	2	86	89	4446	-4	84	81	4342	1	89	104	4282	4	88	60
120	4645	-1	87	4556	2	86	89	4474	-4	84	82	4372	1	89	102	4312	4	88	60
121	4674	-2	85	4585	2	88	89	4502	0	83	83	4402	-4	87	100	4342	0	89	60
122	4702	-2	85	4614	2	88	88	4530	0	83	84	4430	-4	87	100	4371	0	89	59
123	4723	-2	85	4644	2	88	79	4558	0	83	86	4458	-4	87	100	4401	0	89	57
124	4759	0	85	4674	-1	87	85	4587	4	86	87	4487	-3	83	100	4431	-4	86	56
125	4787	0	85	4703	-1	87	84	4616	4	86	87	4514	-3	83	102	4459	-4	86	55
126	4816	0	85	4732	-1	87	84	4645	4	86	87	4542	-3	83	103	4487	-4	86	55
127	4845	2	87	4761	-2	85	84	4675	3	90	86	4570	2	83	105	4516	-4	82	54
128	4874	2	87	4789	-2	85	85	4705	3	90	84	4598	2	83	107	4543	-4	82	55
129	4903	2	87	4817	-2	85	86	4735	3	90	82	4626	2	83	109	4570	-4	82	56
130	4933	0	88	4846	1	86	87	4765	-4	88	81	4654	2	85	111	4598	0	81	56
131	4962	0	88	4875	1	86	87	4794	-4	88	81	4683	2	85	111	4625	0	81	58
132	4991	0	88	4904	1	86	87	4823	-4	88	81	4712	2	85	111	4652	0	81	60
133	5021	-3	86	4933	2	88	88	4852	-4	84	81	4741	2	87	111	4680	4	83	61
134	5049	-3	86	4962	2	88	87	4880	-4	84	82	4770	2	87	110	4708	4	83	62
135	5077	-3	86	4991	2	88	86	4908	-4	84	83	4800	2	87	108	4737	4	83	63
136	5105	-1	83	5021	-2	86	84	4936	2	84	85	4830	2	89	106	4766	4	87	64
137	5133	-1	83	5049	-2	86	84	4964	2	84	85	4859	2	89	105	4795	4	87	64
138	5161	-1	83	5077	-2	86	84	4993	2	84	84	4889	2	89	104	4825	4	87	64
139	5189	2	85	5106	-3	83	83	5022	2	87	84	4916	-2	88	106	4855	2	90	61
140	5218	2	85	5133	-3	83	85	5051	2	87	82	4948	-2	88	103	4885	2	90	63
141	5247	2	85	5161	-3	83	86	5080	2	87	81	4977	-2	88	103	4915	2	90	62

Note: DT = Driver's Types ranking from 1 (least aggressive driver) to 10 (most aggressive driver)

Data of Single-Lane Car Following Simulation - Experiment One (continued)

# of steps	veh. 171 (DT=2) mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	spacing from veh 170	veh. 172 (DT=2) mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	spacing from veh 171	veh. 173 (DT=10) mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	spacing from veh 172	veh. 174 (DT=7) mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	spacing from veh 173
1	406	0	86	199	277	0	86	129	104	4	91	173				
2	435	0	86	205	306	0	86	129	135	4	91	171				
3	464	0	86	212	335	0	86	129	166	4	91	169				
4	493	0	86	219	364	0	86	129	197	2	94	167	75	2	93	122
5	512	0	86	235	392	0	86	120	229	2	94	163	106	2	93	123
6	550	0	86	233	421	0	86	129	261	2	94	160	138	2	93	123
7	579	0	86	240	450	0	86	129	293	2	96	157	170	2	95	123
8	608	0	86	246	479	0	86	129	325	2	96	154	202	2	95	123
9	637	0	86	253	508	0	86	129	357	2	96	151	234	2	95	123
10	666	0	86	260	537	0	86	129	390	2	98	147	266	2	95	124
11	695	0	86	266	566	0	86	129	423	2	98	143	289	2	97	134
12	724	0	86	272	595	0	86	129	456	2	98	139	331	2	97	125
13	753	0	86	279	624	0	86	129	489	1	99	135	364	1	97	125
14	782	0	86	285	653	0	86	129	522	1	99	131	396	1	98	126
15	811	0	86	291	682	0	86	129	555	1	99	127	429	1	98	126
16	840	0	86	298	711	0	86	129	589	-1	99	122	462	0	98	127
17	868	0	86	304	739	0	86	129	621	-1	99	118	495	0	98	126
18	897	0	86	310	768	0	86	129	654	-1	99	114	528	0	98	126
19	926	0	86	316	797	0	86	129	687	-1	97	110	561	0	98	126
20	955	0	86	321	826	0	86	129	719	-1	97	107	593	0	98	126
21	984	0	86	326	855	0	86	129	751	-1	97	104	626	0	98	125
22	1013	0	86	332	884	0	86	129	784	-1	95	100	659	0	98	125
23	1042	0	86	336	913	0	86	129	815	-1	95	98	691	0	98	124
24	1071	0	86	341	942	0	86	129	847	-1	95	95	724	0	98	123
25	1100	0	86	346	971	0	86	129	879	-1	94	92	757	0	98	122
26	1129	0	86	350	1000	0	86	129	910	-1	94	90	789	0	98	121
27	1158	0	86	355	1029	0	86	129	941	-1	94	88	822	0	98	119
28	1187	0	86	360	1058	0	86	129	973	-1	93	85	855	0	98	118
29	1215	0	86	365	1086	0	86	129	1004	-1	93	82	887	0	98	117

Data of Single-Lane Car Following Simulation - Experiment One (continued)

# of steps	veh. 171 (DT=2) mi pt (ft)	veh. 171 (DT=2) Acce (ft/s/s)	veh. 171 (DT=2) speed (ft/s)	spacing from veh 170	veh. 172 (DT=2) mi pt (ft)	veh. 172 (DT=2) Acce (ft/s/s)	veh. 172 (DT=2) speed (ft/s)	spacing from veh 171	veh. 173 (DT=10) mi pt (ft)	veh. 173 (DT=10) Acce (ft/s/s)	veh. 173 (DT=10) speed (ft/s)	spacing from veh 172	veh. 174 (Dt=7) mi pt (ft)	veh. 174 (Dt=7) Acce (ft/s/s)	veh. 174 (Dt=7) speed (ft/s)	spacing from veh 173
30	1244	0	86	369	1115	0	86	129	1035	-1	93	80	920	0	98	115
31	1273	0	86	374	1144	0	86	129	1066	0	92	78	953	0	98	113
32	1302	0	86	378	1173	0	86	129	1096	0	92	77	986	0	98	110
33	1331	0	86	382	1202	0	86	129	1127	0	92	75	1019	0	98	108
34	1360	0	86	386	1231	0	86	129	1158	0	91	73	1052	0	98	106
35	1389	0	86	389	1260	0	86	129	1188	0	91	72	1084	0	98	104
36	1418	0	86	393	1289	0	86	129	1218	0	91	71	1117	0	98	101
37	1447	0	86	397	1318	0	86	129	1249	0	90	69	1150	0	98	99
38	1476	0	86	400	1347	0	86	129	1279	0	90	68	1182	0	98	97
39	1509	0	86	400	1376	0	86	133	1309	0	90	67	1214	0	98	95
40	1534	0	86	408	1405	0	86	129	1339	0	90	66	1247	-4	95	92
41	1562	0	86	410	1433	0	86	129	1369	0	90	64	1278	-4	95	91
42	1591	0	86	415	1462	0	86	129	1399	0	90	63	1309	-4	95	90
43	1620	0	86	419	1491	0	86	129	1429	0	89	62	1340	-4	91	89
44	1649	0	86	422	1520	0	86	129	1458	0	89	62	1370	-4	91	88
45	1678	0	86	425	1549	0	86	129	1488	0	89	61	1400	-4	91	88
46	1707	0	86	429	1578	0	86	129	1518	-1	88	60	1430	-1	88	88
47	1736	0	86	431	1607	0	86	129	1547	-1	88	60	1459	-1	88	88
48	1765	0	86	434	1636	0	86	129	1576	-1	88	60	1488	-1	88	88
49	1794	0	86	437	1665	0	86	129	1606	-2	86	59	1518	0	88	88
50	1823	0	86	439	1694	0	86	129	1634	-2	86	60	1547	0	88	87
51	1852	0	86	442	1723	0	86	129	1663	-2	86	60	1576	0	88	87
52	1881	0	86	443	1752	0	86	129	1692	0	85	60	1606	-1	87	86
53	1909	0	86	446	1780	0	86	129	1720	0	85	60	1635	-1	87	85
54	1938	0	86	448	1809	0	86	129	1749	0	85	60	1664	-1	87	85
55	1967	-1	85	451	1838	0	86	129	1778	1	87	60	1693	0	86	85
56	1995	-1	85	454	1867	0	86	128	1807	1	87	60	1721	0	86	86
57	2024	-1	85	456	1896	0	86	128	1836	1	87	60	1750	0	86	86
58	2053	0	86	459	1925	0	86	128	1866	0	87	59	1779	1	87	87

Data of Single-Lane Car Following Simulation - Experiment One (continued)

	veh. 171 (DT=2)			spacing	veh. 172 (DT=2)			spacing	veh. 173 (DT=10)			spacing	veh. 174 (Dt=7)			spacing
# of steps	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh 170	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh 171	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh 172	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh 173
59	2081	0	86	461	1953	0	86	128	1895	0	87	58	1808	1	87	87
60	2110	0	86	463	1982	0	86	128	1924	0	87	58	1837	1	87	87
61	2139	0	86	465	2011	0	86	128	1953	-2	85	58	1867	0	87	86
62	2168	0	86	465	2039	0	86	129	1981	-2	85	58	1896	0	87	85
63	2196	0	86	467	2068	0	86	128	2009	-2	85	59	1925	0	87	84
64	2226	0	86	467	2097	0	86	129	2037	0	84	60	1954	-3	85	83
65	2255	0	86	467	2126	0	86	129	2065	0	84	61	1982	-3	85	83
66	2284	0	86	467	2156	0	86	128	2094	0	84	62	2010	-3	85	84
67	2313	0	86	467	2184	0	86	129	2123	3	87	61	2038	0	83	85
68	2342	0	86	466	2213	0	86	129	2152	3	87	61	2066	0	83	86
69	2371	0	86	466	2242	0	86	129	2182	3	87	60	2094	0	83	88
70	2400	0	86	466	2271	0	86	129	2212	0	88	59	2123	4	86	89
71	2429	0	86	465	2300	0	86	129	2241	0	88	59	2152	4	86	89
72	2458	0	86	464	2329	0	86	129	2270	0	88	59	2181	4	86	89
73	2487	0	86	464	2358	0	86	129	2300	-3	86	58	2211	4	90	89
74	2515	0	86	465	2386	0	86	129	2328	-3	86	58	2241	4	90	87
75	2544	0	86	465	2415	0	86	129	2356	-3	86	59	2271	4	90	85
76	2573	0	86	465	2444	0	86	129	2385	-1	84	59	2302	-4	88	83
77	2602	0	86	465	2473	0	86	129	2413	-1	84	60	2331	-4	88	82
78	2631	0	86	466	2502	0	86	129	2441	-1	84	61	2360	-4	88	81
79	2660	0	86	467	2531	0	86	129	2470	3	86	61	2389	-4	84	81
80	2689	0	86	467	2560	0	86	129	2499	3	86	61	2417	-4	84	82
81	2718	0	86	467	2589	0	86	129	2528	3	86	61	2445	-4	84	83
82	2747	0	86	468	2618	0	86	129	2558	1	88	60	2473	0	83	85
83	2776	0	86	467	2647	0	86	129	2587	1	88	60	2501	0	83	86
84	2805	0	86	466	2676	0	86	129	2616	1	88	60	2529	0	83	87
85	2834	0	86	465	2705	0	86	129	2646	-2	87	59	2557	4	86	89
86	2862	0	86	464	2733	0	86	129	2675	-2	87	58	2586	4	86	89
87	2891	0	86	462	2762	0	86	129	2704	-2	87	58	2616	4	86	88

Data of Single-Lane Car Following Simulation - Experiment One (continued)

# of steps	veh. 171 (DT=2) mi pt (ft)	veh. 171 Acce (ft/s/s)	veh. 171 speed (ft/s)	spacing from veh 170	veh. 172 (DT=2) mi pt (ft)	veh. 172 Acce (ft/s/s)	veh. 172 speed (ft/s)	spacing from veh 171	veh. 173 (DT=10) mi pt (ft)	veh. 173 Acce (ft/s/s)	veh. 173 speed (ft/s)	spacing from veh 172	veh. 174 (Dt=7) mi pt (ft)	veh. 174 Acce (ft/s/s)	veh. 174 speed (ft/s)	spacing from veh 173
88	2920	0	86	460	2791	0	86	129	2733	-2	85	58	2646	2	89	87
89	2949	0	86	458	2820	0	86	129	2761	-2	85	59	2675	2	89	86
90	2978	0	86	457	2849	0	86	129	2789	-2	85	60	2705	2	89	84
91	3007	0	86	456	2878	0	86	129	2817	2	85	61	2735	-4	87	82
92	3036	0	86	456	2907	0	86	129	2846	2	85	61	2763	-4	87	83
93	3065	0	86	456	2936	0	86	129	2875	2	85	61	2792	-4	87	83
94	3094	0	86	456	2965	0	86	129	2904	2	88	61	2821	-3	83	83
95	3123	0	86	457	2994	0	86	129	2933	2	88	61	2849	-3	83	84
96	3152	0	86	458	3023	0	86	129	2963	2	88	60	2877	-3	83	86
97	3181	0	86	460	3052	0	86	129	2993	-1	88	59	2905	4	85	88
98	3209	0	86	462	3080	0	86	129	3022	-1	88	58	2934	4	85	88
99	3238	0	86	464	3109	0	86	129	3051	-1	88	58	2963	4	85	88
100	3267	0	86	466	3138	0	86	129	3080	-3	85	58	2992	4	89	88
101	3296	0	86	466	3167	0	86	129	3108	-3	85	59	3022	4	89	86
102	3325	0	86	467	3196	0	86	129	3136	-3	85	60	3052	4	89	84
103	3354	0	86	468	3225	0	86	129	3165	0	84	60	3082	-4	87	83
104	3383	0	86	468	3254	0	86	129	3193	0	84	61	3110	-4	87	83
105	3412	0	86	468	3283	0	86	129	3222	0	84	61	3139	-4	87	83
106	3441	0	86	468	3312	0	86	129	3251	4	87	61	3168	-4	83	83
107	3470	0	86	467	3341	0	86	129	3280	4	87	61	3196	-4	83	84
108	3499	0	86	467	3370	0	86	129	3310	4	87	60	3224	-4	83	86
109	3528	0	86	467	3399	0	86	129	3340	0	89	59	3252	4	85	88
110	3556	0	86	467	3427	0	86	129	3369	0	89	58	3281	4	85	88
111	3585	0	86	467	3456	0	86	129	3398	0	89	58	3310	4	85	88
112	3614	0	86	467	3485	0	86	129	3428	-4	86	57	3339	4	89	89
113	3643	0	86	466	3514	0	86	129	3456	-4	86	58	3369	4	89	87
114	3672	0	86	466	3543	0	86	129	3484	-4	86	59	3399	4	89	85
115	3701	0	86	466	3572	0	86	129	3513	-1	84	59	3429	-4	87	84
116	3730	0	86	465	3601	0	86	129	3541	-1	84	60	3457	-4	87	84

Data of Single-Lane Car Following Simulation - Experiment One (continued)

# of steps	veh. 171 (DT=2) mi pt (ft)	veh. 171 (DT=2) Acce (ft/s/s)	veh. 171 (DT=2) speed (ft/s)	spacing from veh 170	veh. 172 (DT=2) mi pt (ft)	veh. 172 (DT=2) Acce (ft/s/s)	veh. 172 (DT=2) speed (ft/s)	spacing from veh 171	veh. 173 (DT=10) mi pt (ft)	veh. 173 (DT=10) Acce (ft/s/s)	veh. 173 (DT=10) speed (ft/s)	spacing from veh 172	veh. 174 (Dt=7) mi pt (ft)	veh. 174 (Dt=7) Acce (ft/s/s)	veh. 174 (Dt=7) speed (ft/s)	spacing from veh 173
117	3759	0	86	465	3630	0	86	129	3569	-1	84	61	3486	-4	87	83
118	3788	0	86	465	3659	0	86	129	3597	4	86	62	3515	-4	83	82
119	3817	0	86	465	3688	0	86	129	3626	4	86	62	3542	-4	83	84
120	3846	0	86	466	3717	0	86	129	3655	4	86	62	3570	-4	83	85
121	3875	0	86	467	3746	0	86	129	3684	1	88	62	3589	2	84	95
122	3903	0	86	468	3774	0	86	129	3714	1	88	60	3627	2	84	87
123	3932	0	86	469	3803	0	86	129	3744	1	88	59	3656	2	84	88
124	3961	-1	85	470	3832	0	86	129	3774	-2	87	58	3685	4	88	89
125	3989	-1	85	470	3861	0	86	128	3802	-2	87	59	3714	4	88	88
126	4017	-1	85	470	3890	0	86	127	3831	-2	87	59	3744	4	88	87
127	4046	1	85	470	3919	0	86	127	3860	-2	84	59	3774	0	89	86
128	4075	1	85	468	3947	0	86	128	3888	-2	84	59	3803	0	89	85
129	4104	1	85	466	3976	0	86	128	3916	-2	84	60	3832	0	89	84
130	4133	0	86	465	4005	0	86	128	3944	1	84	61	3862	-4	86	82
131	4162	0	86	463	4033	0	86	129	3972	1	84	61	3890	-4	86	82
132	4191	0	86	461	4062	0	86	129	4001	1	84	61	3918	-4	86	83
133	4226	0	87	454	4091	0	86	135	4030	3	87	61	3947	-3	82	83
134	4249	0	87	459	4120	0	86	129	4059	3	87	61	3974	-3	82	85
135	4278	0	87	459	4149	0	86	129	4089	3	87	60	4002	-3	82	87
136	4307	0	86	459	4178	0	86	129	4119	0	88	59	4030	4	84	89
137	4336	0	86	459	4206	0	86	130	4148	0	88	58	4095	4	84	53
138	4365	0	86	460	4235	0	86	130	4177	0	88	58	4088	4	84	89
139	4394	0	86	461	4264	0	86	130	4206	-3	86	58	4117	4	88	89
140	4422	0	86	463	4293	0	86	129	4234	-3	86	59	4146	4	88	88
141	4451	0	86	464	4322	0	86	129	4263	-3	86	59	4176	4	88	87

Note: DT = Driver's Types ranking from 1 (least aggressive driver) to 10 (most aggressive driver)

APPENDIX 2 DATA OF EXPERIMENT TWO

Data of Single-Lane Car Following Simulation - Experiment Two

# of step	veh 69 (DT=7) mi pt (ft)	veh 69 (DT=7) Acce. (ft/s/s)	veh 69 (DT=7) speed (ft/s)	veh 70 (DT=7) mi pt (ft)	veh 70 (DT=7) Acce (ft/s/s)	veh 70 (DT=7) speed (ft/s)	spacing from veh 69	veh 71 (DT=9) mi pt (ft)	veh 71 (DT=9) Acce (ft/s/s)	veh 71 (DT=9) speed (ft/s)	spacing from veh 70	veh 72 (DT=9) mi pt (ft)	veh 72 (DT=9) Acce (ft/s/s)	veh 72 (DT=9) speed (ft/s)	spacing from veh 71	veh 73 (DT=9) mi pt (ft)	veh 73 (DT=9) Acce (ft/s/s)	veh 73 (DT=9) speed (ft/s)	spacing from veh 72
1	1152	0	86	950	0	86	202	885	2	86	65	796	0	93	89	656	0	94	140
2	1238	0	86	1041	0	86	197	973	1	88	68	890	0	94	83	751	0	94	139
3	1325	0	86	1128	0	86	197	1061	-2	87	67	984	-2	92	77	845	0	94	139
4	1412	0	86	1215	0	86	197	1147	-1	85	68	1075	-3	90	72	939	0	94	136
5	1499	0	86	1301	0	86	198	1232	1	86	69	1164	-3	86	68	1034	0	94	130
6	1585	0	86	1388	0	86	197	1319	2	88	69	1250	0	86	69	1128	0	94	122
7	1672	0	86	1475	0	86	197	1408	-1	87	67	1337	3	89	71	1223	0	94	114
8	1759	0	86	1562	0	86	197	1495	-2	85	67	1427	-2	89	68	1317	0	94	110
9	1846	0	86	1648	0	86	198	1580	0	85	68	1515	-4	85	65	1411	0	94	104
10	1932	0	86	1735	0	86	197	1666	2	87	69	1599	-2	83	67	1505	-3	92	94
11	2019	0	86	1822	0	86	197	1754	0	88	68	1682	4	85	72	1596	0	91	86
12	2106	0	86	1909	0	86	197	1842	-3	86	67	1770	4	89	72	1689	2	93	81
13	2193	0	86	1995	0	86	198	1927	0	84	68	1859	-1	89	68	1783	0	94	76
14	2279	0	86	2082	0	86	197	2013	2	86	69	1947	-4	86	66	1876	-3	91	71
15	2366	0	86	2169	0	86	197	2101	1	88	68	2032	0	84	69	1965	-4	87	67
16	2453	0	86	2250	0	86	203	2189	-2	87	61	2118	4	87	71	2051	-3	83	67
17	2540	0	86	2342	0	86	198	2275	-1	84	67	2206	0	88	69	2135	4	85	71
18	2626	0	86	2429	0	86	197	2360	2	85	69	2294	-4	86	66	2222	3	89	72
19	2713	0	86	2516	0	86	197	2447	2	88	69	2379	0	84	68	2312	-3	88	67
20	2800	0	86	2603	0	86	197	2536	-1	87	67	2464	4	86	72	2398	-4	84	66
21	2887	0	86	2689	0	86	198	2622	-2	85	67	2552	1	89	70	2483	2	85	69
22	2973	0	86	2776	0	86	197	2707	1	85	69	2641	-3	86	66	2569	4	88	72
23	3060	0	86	2863	0	86	197	2794	0	87	69	2726	-1	84	68	2658	-1	88	68
24	3147	0	86	2950	0	86	197	2882	0	88	68	2811	4	86	71	2745	-4	85	66
25	3234	0	86	3037	0	86	197	2970	-3	86	67	2899	2	89	71	2830	0	84	69
26	3320	0	86	3123	0	86	197	3055	0	84	68	2988	-3	87	67	2916	4	87	72
27	3407	0	86	3210	0	86	197	3140	3	86	70	3074	-3	83	66	3004	0	88	70
28	3494	0	86	3297	0	86	197	3229	1	88	68	3157	4	85	72	3091	-4	85	66
29	3581	0	86	3384	0	86	197	3317	-3	86	67	3245	4	89	72	3176	1	84	69
30	3667	0	86	3470	0	86	197	3403	-1	84	67	3335	-2	89	68	3262	4	88	73
31	3754	0	86	3557	0	86	197	3487	2	86	70	3422	-4	85	65	3351	0	89	71
32	3841	0	86	3644	0	86	197	3575	2	88	69	3507	0	84	68	3440	-4	87	67

Data of Single-Lane Car Following Simulation - Experiment Two (continued)

	veh 69 (DT=7)			veh 70 (DT=7)			spacing	veh 71 (DT=9)			spacing	veh 72 (DT=9)			spacing	veh 73 (DT=9)			spacing
# of steps	mi pt (ft)	Acce. (ft/s/s)	speed (ft/s)	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh 69	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh 70	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh 71	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh 72
33	3928	0	86	3731	0	86	197	3664	-2	87	67	3592	4	86	72	3525	-4	83	67
34	4015	0	86	3817	0	86	198	3750	-3	84	67	3680	1	88	70	3608	4	84	72
35	4101	0	86	3904	0	86	197	3835	1	85	69	3768	-3	86	67	3695	4	88	73
36	4188	0	86	3991	0	86	197	3921	3	88	70	3854	-1	84	67	3785	-1	89	69
37	4275	0	86	4078	0	86	197	4010	0	88	68	3939	4	86	71	3872	-4	85	67
38	4362	0	86	4164	0	86	198	4098	-4	85	66	4027	1	89	71	3958	1	85	69
39	4448	0	86	4251	0	86	197	4183	0	84	68	4116	-4	87	67	4045	4	88	71
40	4535	0	86	4338	0	86	197	4268	4	87	70	4201	-3	83	67	4134	-2	88	67
41	4622	0	86	4425	0	86	197	4356	1	89	69	4285	4	85	71	4220	-4	84	65
42	4709	0	86	4511	0	86	198	4445	-4	86	66	4372	4	89	73	4304	0	83	68
43	4795	0	86	4598	0	86	197	4530	-2	84	68	4461	-1	88	69	4388	4	86	73
44	4882	0	86	4685	0	86	197	4615	3	86	70	4549	-4	85	66	4476	2	89	73
45	4969	0	86	4772	0	86	197	4703	2	89	69	4633	0	84	70	4565	-1	88	68
46	5055	0	86	4858	0	86	197	4792	-3	87	66	4720	4	88	72	4653	-3	85	67
47	5141	0	86	4945	0	86	196	4878	-3	84	67	4809	0	88	69	4738	2	86	71
48				5032	0	86		4962	2	85	70	4896	-4	85	66	4826	2	89	70
49				5118	-1	85		5049	3	88	69	4981	-1	83	68	4915	-4	87	66
50				5204	1	85		5137	-2	87	67	5066	4	86	71	5000	-4	83	66
51												5153	1	88		5083	3	84	70
52																5170	4	88	
53																			
54																			
55																			
56																			
57																			
58																			
59																			
60																			
61																			
62																			
63																			
64																			

Data of Single-Lane Car Following Simulation - Experiment Two (continued)

	veh 74 (DT=10)			spacing	veh 75 DT=9)			spacing	veh 76 (DT=9)			spacing	veh 77 (DT=7)			spacing	veh 78 (DT=8)			spacing
# of step	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh 73	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh 74	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh75	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh 76	mi pt (ft)	Acce. (ft/s/s)	speed (ft/s)	from veh 77
1	564	0	101	92	423	0	98	141	227	0	94	196								
2	665	0	100	86	521	0	98	144	321	0	94	200								
3	765	0	99	80	619	0	98	146	415	0	94	204								
4	864	0	98	75	717	0	98	147	510	0	94	207	157	-1	87	353				
5	962	0	98	72	815	0	98	147	604	0	94	211	244	0	86	360	130	1	89	114
6	1060	0	97	68	914	0	98	146	698	0	94	216	331	0	86	367	220	0	90	111
7	1158	0	97	65	1012	0	98	146	793	0	94	219	417	0	86	376	310	0	89	107
8	1254	-1	96	63	1110	0	98	144	887	0	94	223	504	0	86	383	399	0	89	105
9	1350	-2	94	61	1208	0	98	142	981	0	94	227	591	0	86	390	489	0	89	102
10	1443	-1	92	62	1306	0	98	137	1076	0	94	230	678	0	86	398	578	0	89	100
11	1535	0	91	61	1405	0	98	130	1170	0	94	235	764	0	86	406	668	0	89	96
12	1627	0	92	62	1503	0	98	124	1265	0	94	238	851	0	86	414	758	0	89	93
13	1720	2	93	63	1601	0	98	119	1359	0	94	242	938	0	86	421	847	0	89	91
14	1814	0	93	62	1699	0	98	115	1453	0	94	246	1025	0	86	428	937	0	89	88
15	1907	-4	90	58	1797	0	98	110	1548	0	94	249	1111	0	86	437	1026	0	89	85
16	1995	-4	86	56	1895	-2	96	100	1642	0	94	253	1198	0	86	444	1116	0	89	82
17	2080	-4	82	55	1989	-4	92	91	1736	0	94	253	1285	0	86	451	1206	0	89	79
18	2162	1	82	60	2080	-1	89	82	1831	0	94	249	1372	0	86	459	1295	-2	88	77
19	2246	4	85	66	2169	1	90	77	1925	0	94	244	1458	0	86	467	1382	-1	86	76
20	2333	1	87	65	2260	1	91	73	2020	0	94	240	1545	0	86	475	1468	0	86	77
21	2421	0	87	62	2352	-1	90	69	2114	0	94	238	1632	0	86	482	1554	1	87	78
22	2509	0	88	60	2441	-3	87	68	2208	0	94	233	1719	0	86	489	1642	0	87	77
23	2598	1	89	60	2528	0	86	70	2303	0	94	225	1805	0	86	498	1729	-1	86	76
24	2687	2	87	58	2615	2	88	72	2397	0	94	218	1892	0	86	505	1815	0	85	77
25	2773	-4	84	57	2704	0	88	69	2492	0	94	212	1979	0	86	513	1901	1	86	78
26	2856	0	83	60	2791	-4	85	65	2586	0	94	205	2065	-1	85	521	1989	0	87	76
27	2940	4	85	64	2875	-4	81	65	2680	0	94	195	2151	-1	85	529	2076	-2	85	75
28	3027	1	87	64	2956	2	81	71	2775	0	94	181	2237	0	86	538	2161	0	84	76
29	3115	0	87	61	3038	2	83	77	2869	0	94	169	2324	0	87	545	2246	3	86	78
30	3203	-1	86	59	3123	2	85	80	2963	0	94	160	2411	0	86	552	2334	1	88	77
31	3290	3	88	61	3210	2	87	80	3058	0	94	152	2498	0	86	560	2422	-2	87	76
32	3379	0	89	61	3298	2	89	81	3152	0	94	146	2585	0	86	567	2508	-1	84	77

Data of Single-Lane Car Following Simulation - Experiment Two (continued)

	veh 74 (DT=10)			spacing	veh 75 DT=9)			spacing	veh 76 (DT=9)			spacing	veh 77 (DT=7)			spacing	veh 78 (DT=8)			spacing
# of steps	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh 73	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh 74	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh75	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh 76	mi pt (ft)	Acce. (ft/s/s)	speed (ft/s)	from veh 77
33	3467	-4	86	58	3389	1	91	78	3247	0	94	142	2671	0	86	576	2593	-2	85	78
34	3552	-4	82	56	3480	-4	88	72	3341	0	94	139	2758	0	86	583	2680	2	88	78
35	3634	2	83	61	3566	-4	84	68	3435	0	94	131	2845	0	86	590	2769	-1	88	76
36	3720	4	87	65	3650	1	84	70	3530	0	94	120	2932	0	86	598	2856	-2	85	76
37	3803	0	88	69	3736	2	86	67	3624	0	94	112	3018	0	86	606	2941	0	85	77
38	3897	0	88	61	3823	2	88	74	3718	0	94	105	3105	0	86	613	3027	2	87	78
39	3985	0	87	60	3912	2	90	73	3813	0	94	99	3192	0	86	621	3115	0	88	77
40	4073	1	88	61	4003	0	91	70	3907	0	94	96	3279	0	86	628	3203	-2	86	76
41	4161	-2	87	59	4094	-3	88	67	4002	0	94	92	3365	0	86	637	3289	0	85	76
42	4247	-4	84	57	4180	-4	84	67	4095	-3	92	85	3452	0	86	643	3373	2	86	79
43	4330	-2	81	58	4263	-2	81	67	4186	-3	88	77	3539	0	86	647	3462	1	88	77
44	4412	4	83	64	4344	1	81	68	4273	0	87	71	3626	0	86	647	3550	-1	87	76
45	4497	4	87	68	4427	2	83	70	4360	0	86	67	3712	0	86	648	3636	-1	85	76
46	4586	0	89	67	4512	2	85	74	4447	-1	85	65	3799	0	86	648	3722	1	85	77
47	4675	0	89	63	4599	2	87	76	4532	0	85	67	3886	0	86	646	3808	2	87	78
48	4765	1	90	61	4687	2	89	78	4619	2	87	68	3973	0	86	646	3896	0	87	77
49	4855	-1	89	60	4778	2	91	77	4707	2	89	71	4059	-1	85	648	3983	-2	85	76
50	4944	-4	86	56	4870	-1	91	74	4797	2	91	73	4144	1	85	653	4068	-1	84	76
51	5028	-4	82	55	4960	-4	87	68	4889	0	92	71	4231	0	86	658	4153	2	85	78
52	5110	1	82	60	5046	-4	83	64	4981	-4	89	65	4318	0	87	663	4240	2	88	78
53	5194	4	85		5128	-3	80	66	5067	-4	84	61	4405	0	86	662	4329	-4	88	76
54					5208	2	80		5150	-4	80	58	4491	0	86	659	4416	-3	85	75
55													4578	0	86		4501	0	84	77
56													4665	0	86		4587	3	87	78
57													4752	0	86		4675	0	88	77
58													4838	0	86		4763	-3	86	75
59													4925	0	86		4848	-1	84	77
60													5012	0	86		4934	2	86	78
61													5099	0	86		5021	1	88	78
62													5185	0	86		5110	-2	87	75
63																	5196	-2	85	
64																				

Data of Single-Lane Car Following Simulation - Experiment Two (continued)

	veh 79 (DT=9)			spacing	veh 80 (DT=8)			spacing	veh 81 (DT=7)			spacing	veh 82 (DT=9)			spacing	Veh 83 (DT=10)			spacing
# of step	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh 78	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh 79	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh 80	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh81	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh 82
1																				
2																				
3																				
4																				
5																				
6	78	2	92	142																
7	171	2	94	139	60	0	93	111												
8	266	2	96	133	153	-1	92	113												
9	363	0	96	126	246	0	92	117	35	0	87	211								
10	460	0	96	118	338	0	92	122	122	0	86	216								
11	556	0	96	112	431	0	92	125	209	0	86	222	88	4	88	121				
12	652	0	96	106	523	0	92	129	295	0	86	228	178	2	91	117				
13	749	0	96	98	616	0	92	133	382	0	86	234	270	2	93	112	106	2	90	164
14	845	0	96	92	708	0	92	137	469	0	86	239	364	1	94	105	198	2	92	166
15	941	0	95	85	801	0	92	140	556	0	86	245	459	0	94	97	292	2	94	167
16	1037	0	95	79	893	0	92	144	642	0	86	251	553	-1	93	89	388	2	96	165
17	1131	0	94	75	986	0	92	145	729	0	86	257	647	-1	92	82	486	2	98	161
18	1224	-4	91	71	1078	0	92	146	816	0	86	262	739	0	92	77	586	1	100	153
19	1314	-4	87	68	1170	0	92	144	903	0	86	267	831	0	91	72	687	1	101	144
20	1399	-1	84	69	1263	0	92	136	989	0	86	274	921	-4	88	68	788	0	101	133
21	1485	3	86	69	1355	0	92	130	1076	0	86	279	1008	-2	85	68	889	-4	98	119
22	1573	3	89	69	1448	0	92	125	1163	0	86	285	1093	2	86	70	986	0	96	107
23	1663	-3	88	66	1540	0	92	123	1250	0	86	290	1181	2	88	69	1082	0	96	99
24	1749	-4	84	66	1633	0	92	116	1336	0	86	297	1269	-2	87	67	1178	-1	95	91
25	1833	0	83	68	1725	0	92	108	1423	0	86	302	1356	-2	85	67	1272	-3	92	84
26	1918	4	86	71	1818	0	92	100	1510	0	86	308	1441	1	85	69	1364	0	90	77
27	2006	1	89	70	1910	0	92	96	1597	0	86	313	1527	3	87	70	1455	1	91	72
28	2095	-4	86	66	2003	0	92	92	1683	0	86	320	1616	0	88	67	1547	0	92	69
29	2180	-3	83	66	2095	-2	90	85	1770	0	86	325	1703	-3	85	67	1639	-2	90	64
30	2263	4	84	71	2184	-3	87	79	1857	0	86	327	1788	0	84	69	1727	-1	87	61
31	2349	4	88	73	2271	0	87	78	1944	0	86	327	1874	3	87	70	1814	0	86	60
32	2439	0	89	69	2359	2	88	80	2030	0	86	329	1962	0	88	68	1901	2	87	61

Data of Single-Lane Car Following Simulation - Experiment Two (continued)

	veh 79 (DT=9)			spacing	veh 80 (DT=8)			spacing	veh 81 (DT=7)			spacing	veh 82 (DT=9)			spacing	Veh 83 (DT=10)			spacing
# of steps	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh 78	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh 79	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh 80	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh81	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh 82
33	2527	-4	86	66	2448	1	90	79	2117	0	86	331	2051	-3	86	66	1990	1	89	61
34	2612	0	84	68	2538	-4	87	74	2204	0	86	334	2136	-1	84	68	2078	-3	86	58
35	2697	4	87	72	2624	-4	83	73	2291	0	86	333	2221	2	86	70	2163	-3	83	58
36	2786	1	89	70	2707	2	84	79	2377	0	86	330	2309	2	88	68	2245	2	83	64
37	2875	-4	87	66	2792	2	86	83	2464	0	86	328	2397	-2	87	67	2330	2	85	67
38	2960	-3	83	67	2879	2	88	81	2551	0	86	328	2484	-2	84	67	2417	2	87	67
39	3044	4	85	71	2967	0	88	77	2638	0	86	329	2568	1	85	70	2505	0	88	63
40	3132	4	89	71	3055	-1	86	77	2724	0	86	331	2655	3	88	69	2594	2	89	61
41	3222	-2	88	67	3142	2	87	80	2811	0	86	331	2744	-1	88	67	2684	0	90	60
42	3309	-4	85	64	3231	0	89	78	2898	0	86	333	2831	-3	85	67	2773	-4	87	58
43	3393	0	84	69	3319	-4	86	74	2985	0	86	334	2916	0	84	69	2859	-4	83	57
44	3478	4	87	72	3404	-3	82	74	3071	0	86	333	3002	3	87	69	2942	0	82	60
45	3567	1	89	69	3486	2	82	81	3158	0	86	328	3090	0	89	68	3025	2	84	65
46	3655	-4	86	67	3570	2	84	85	3245	0	86	325	3179	-4	86	66	3111	2	86	68
47	3741	-2	84	67	3656	2	86	85	3332	0	86	324	3264	-1	84	68	3198	0	87	66
48	3825	4	86	71	3744	2	88	81	3418	0	86	326	3348	3	86	70	3286	1	88	62
49	3913	2	89	70	3834	2	90	79	3505	0	86	329	3436	2	89	69	3376	1	90	60
50	4002	-4	87	66	3925	-2	89	77	3592	0	86	333	3525	-3	87	67	3466	-1	89	59
51	4087	-4	83	66	4013	-4	86	74	3679	0	86	334	3612	-3	84	67	3554	-4	86	58
52	4170	3	84	70	4097	-4	82	73	3765	0	86	332	3696	2	85	69	3638	-4	82	58
53	4256	4	87	73	4179	1	82	77	3852	0	86	327	3783	3	88	69	3720	2	82	63
54	4345	0	89	71	4263	2	84	82	3939	0	86	324	3872	-1	88	67	3804	2	84	68
55	4434	-4	86	67	4348	2	86	86	4026	2	86	322	3959	-4	85	67	3889	2	86	70
56	4519	-2	83	68	4436	2	88	83	4112	0	86	324	4044	0	84	68	3976	0	87	68
57	4603	4	85	72	4525	0	89	78	4199	0	86	326	4129	4	87	70	4045	2	89	84
58	4691	3	89	72	4615	-1	88	76	4286	0	86	329	4218	1	89	68	4156	1	91	62
59	4781	-3	88	67	4703	0	88	78	4373	0	86	330	4306	-4	86	67	4247	-2	90	59
60	4868	-4	84	66	4791	0	87	77	4459	0	86	332	4392	-2	84	67	4335	-4	86	57
61	4952	0	84	69	4877	-3	84	75	4546	0	86	331	4476	3	86	70	4419	-4	82	57
62	5038	4	87	72	4961	0	83	77	4633	0	86	328	4564	3	89	69	4501	2	82	63
63	5127	0	89	69	5045	2	85	82	4720	0	86	325	4653	-3	87	67	4585	2	84	68
64					5132	2	87		4806	0	86	326	4740	-3	84	66	4671	2	86	69

Data of Single-Lane Car Following Simulation - Experiment Two (continued)

	veh 79 (DT=9)			spacing	veh 80 (DT=8)			spacing	veh 81 (DT=7)			spacing	veh 82 (DT=9)			spacing	Veh 83 (DT=10)			spacing
# of step	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh 78	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh 79	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh 80	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh81	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh 82
65									4893	0	86		4824	2	85	69	4758	1	88	66
66									4980	0	86		4910	4	88	70	4847	2	89	63
67									5067	0	86		4999	-1	88	68	4938	0	91	61
68													5087	-4	85		5028	-4	88	59
69													5172	0	84		5115	-4	84	57
70																	5198	-1	82	
71																				
72																				
73																				
74																				
75																				
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93																				
94																				

Data of Single-Lane Car Following Simulation - Experiment Two (continued)

	veh 84 (DT=10)			spacing	veh 85 (DT=10)			spacing	veh 86 (DT=10)			spacing	veh 87 (DT=10)			spacing	veh 88 (DT=9)			spacing
# of step	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh 83	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh 84	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh 85	mi pt (ft)	Acce. (ft/s/s)	speed (ft/s)	from veh 86	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh 87
1																				
2																				
3																				
4																				
5																				
6																				
7																				
8																				
9																				
10																				
11																				
12																				
13																				
14	88	2	92	110																
15	182	2	94	110	31	2	93	151												
16	278	2	96	110	125	2	95	153												
17	374	2	98	112	222	2	97	152												
18	476	2	100	110	320	1	98	156	105	2	97	215								
19	577	0	101	110	420	1	99	157	204	2	99	216	87	2	99	117				
20	679	0	101	109	520	1	100	159	305	2	101	215	188	2	101	117	96	0	96	92
21	780	0	100	109	621	1	101	159	408	2	103	213	290	2	103	118	192	0	96	98
22	881	0	100	105	724	1	102	157	512	2	105	212	395	2	105	117	288	0	96	107
23	982	0	101	100	827	1	103	155	619	0	107	208	501	1	107	118	385	0	96	116
24	1083	0	101	95	932	1	104	151	726	0	107	206	608	0	107	118	481	0	96	127
25	1183	-1	99	89	1037	1	105	146	833	0	106	204	715	0	106	118	577	0	96	138
26	1282	-2	97	82	1143	0	106	139	940	0	106	203	822	0	106	118	673	0	96	149
27	1379	0	96	76	1250	0	107	129	1046	0	106	204	929	0	106	117	770	0	96	159
28	1475	0	96	72	1357	0	106	118	1153	0	106	204	1035	0	106	118	866	0	96	169
29	1571	-2	94	68	1463	-3	104	108	1260	0	106	203	1142	0	106	118	962	0	96	180
30	1664	-2	91	63	1565	-3	100	99	1367	0	106	198	1249	0	106	118	1059	0	96	190
31	1755	-1	89	59	1664	-3	97	91	1474	0	106	190	1356	0	106	118	1155	0	96	201
32	1843	-2	87	58	1760	-2	94	83	1580	0	106	180	1463	0	106	117	1251	0	96	212

Data of Single-Lane Car Following Simulation - Experiment Two (continued)

	veh 84 (DT=10)			spacing	veh 85 (DT=10)			spacing	veh 86 (DT=10)			spacing	veh 87 (DT=10)			spacing	veh 88 (DT=9)			spacing
# of steps	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh 83	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh 84	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh 85	mi pt (ft)	Acce. (ft/s/s)	speed (ft/s)	from veh 86	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh 87
33	1931	0	87	59	1854	0	92	77	1687	0	106	167	1569	0	106	118	1347	0	96	222
34	2019	1	88	59	1947	0	92	72	1794	0	106	153	1676	0	106	118	1444	0	96	232
35	2107	-4	86	56	2039	-2	91	68	1900	-1	105	139	1783	0	106	117	1540	0	96	243
36	2192	-4	82	53	2128	-4	87	64	2004	-5	101	124	1890	0	106	114	1636	0	96	254
37	2273	0	81	57	2213	-3	83	60	2102	-4	95	111	1996	-2	105	106	1733	0	96	263
38	2355	4	84	62	2296	0	82	59	2196	-2	92	100	2099	-4	101	97	1829	0	96	270
39	2442	4	88	63	2380	2	84	62	2289	0	92	91	2200	-1	99	89	1925	0	96	275
40	2531	2	90	63	2465	2	86	66	2381	0	92	84	2298	0	98	83	2021	0	96	277
41	2623	1	92	61	2552	2	88	71	2474	0	93	78	2396	0	98	78	2118	0	96	278
42	2715	-3	90	58	2642	2	90	73	2569	1	94	73	2495	0	98	74	2214	0	96	281
43	2804	-4	86	55	2733	0	91	71	2664	0	95	69	2593	0	98	71	2310	0	96	283
44	2889	-4	82	53	2823	-4	87	66	2758	-3	92	65	2691	-2	96	67	2407	0	96	284
45	2970	-3	79	55	2909	-3	83	61	2848	-4	88	61	2785	-4	92	63	2503	0	96	282
46	3050	4	81	61	2991	-1	81	59	2934	-4	84	57	2876	-4	87	58	2599	0	96	277
47	3133	4	85	65	3073	2	82	60	3017	-2	81	56	2961	-4	83	56	2695	0	96	266
48	3221	4	89	65	3157	2	84	64	3099	3	83	58	3043	-4	79	56	2792	0	96	251
49	3312	2	91	64	3242	2	86	70	3183	4	86	59	3123	4	81	60	2888	0	96	235
50	3404	0	92	62	3330	2	88	74	3272	2	89	58	3206	4	85	66	2984	0	96	222
51	3496	-3	89	58	3419	2	90	77	3362	0	89	57	3294	4	89	68	3081	0	96	213
52	3583	-4	85	55	3510	0	90	73	3452	0	89	58	3384	2	91	68	3177	0	96	207
53	3667	-4	81	53	3599	-4	87	68	3541	0	89	58	3477	0	92	64	3273	0	96	204
54	3748	-1	79	56	3695	-2	84	53	3629	-4	86	66	3568	-3	90	61	3369	0	96	199
55	3828	4	82	61	3768	0	83	60	3714	-4	82	54	3656	-4	86	58	3466	0	96	190
56	3912	4	86	64	3853	2	85	59	3796	0	81	57	3741	-4	82	55	3562	0	96	179
57	4000	4	90	45	3940	2	87	60	3879	4	84	61	3821	-1	79	58	3658	0	96	163
58	4093	2	92	63	4028	2	89	65	3966	4	88	62	3901	4	81	65	3755	0	96	146
59	4186	0	92	61	4116	2	91	70	4056	2	91	60	3985	4	85	71	3851	0	96	134
60	4277	-4	89	58	4211	0	92	66	4149	2	93	62	4073	4	89	76	3947	0	96	126
61	4356	-4	85	63	4303	-4	89	53	4242	-1	93	61	4164	2	92	78	4044	0	96	120
62	4449	-4	81	52	4391	-4	85	58	4334	-4	89	57	4257	1	93	77	4140	0	96	117
63	4529	-1	79	56	4474	-4	81	55	4421	-4	84	53	4350	-5	90	71	4236	0	96	114
64	4609	4	81	62	4553	-4	77	56	4503	-4	80	50	4438	-4	85	65	4332	0	96	106

Data of Single-Lane Car Following Simulation - Experiment Two (continued)

	veh 84 (DT=10)			spacing	veh 85 (DT=10)			spacing	veh 86 (DT=10)			spacing	veh 87 (DT=10)			spacing	veh 88 (DT=9)			spacing
# of steps	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh 83	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh 84	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh 85	mi pt (ft)	Acce. (ft/s/s)	speed (ft/s)	from veh 86	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh 87
65	4693	4	85	65	4630	2	77	63	4582	-4	76	48	4521	-4	81	61	4427	-2	95	94
66	4781	4	89	66	4709	2	79	72	4656	-3	72	53	4600	-4	77	56	4520	-4	92	80
67	4872	2	92	66	4790	2	81	82	4729	4	74	61	4677	0	77	52	4610	-4	88	67
68	4964	-1	92	64	4872	2	83	92	4806	4	78	66	4756	3	80	50	4696	-4	84	60
69	5055	-4	88	60	4957	2	85	98	4886	4	82	71	4838	4	84	48	4772	-4	80	66
70	5142	-4	84	56	5043	2	87	99	4971	4	86	72	4924	4	88	47	4853	1	81	71
71					5132	1	89		5060	4	90	72	5013	2	90	47	4934	2	83	79
72									5152	2	93		5103	0	90	49	5018	2	85	85
73													5194	2	92		5104	2	87	90
74																				
75																				
76																				
77																				
78																				
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Data of Single-Lane Car Following Simulation - Experiment Two (continued)

	veh 89 (DT=10)			spacing	veh 90 (DT=8)			spacing	veh 91 (DT=9)			spacing	veh 92 (DT=9)			spacing	veh 93 (DT=9)			spacing
# of step	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh 88	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh 89	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh 90	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh 91	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh 92
1																				
2																				
3																				
4																				
5																				
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7																				
8																				
9																				
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11																				
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13																				
14																				
15																				
16																				
17																				
18																				
19																				
20																				
21	62	2	91	130																
22	160	2	99	128	61	0	90	99												
23	260	1	100	125	151	0	89	109	25	2	90	126								
24	361	1	101	120	240	0	89	121	117	2	92	123								
25	463	1	102	114	330	0	89	133	211	2	94	119	39	2	93	172				
26	566	1	103	107	419	0	89	147	306	1	96	113	134	0	94	172				
27	670	0	103	100	509	0	89	161	403	0	96	106	229	0	94	174	39	0	94	190
28	773	-1	103	93	599	0	89	174	500	0	96	99	323	0	94	177	133	0	94	190
29	876	0	102	86	688	0	89	188	596	0	96	92	417	0	94	179	228	0	94	189
30	978	0	101	81	778	0	89	200	692	0	96	86	512	0	94	180	322	0	94	190
31	1079	0	100	76	868	0	89	211	788	0	95	80	606	0	94	182	416	0	94	190
32	1179	0	100	72	957	0	89	222	883	0	94	74	701	0	94	182	511	0	94	190

Data of Single-Lane Car Following Simulation - Experiment Two (continued)

	veh 89 (DT=10)			spacing	veh 90 (DT=8)			spacing	veh 91 (DT=9)			spacing	veh 92 (DT=9)			spacing	veh 93 (DT=9)			spacing
# of steps	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh 88	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh 89	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh 90	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh 91	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh 92
33	1279	0	99	68	1047	0	89	232	977	-1	93	70	795	0	94	182	605	0	94	190
34	1378	0	99	66	1136	0	89	242	1069	-3	90	67	889	0	94	180	700	0	94	189
35	1477	-1	98	63	1226	0	89	251	1158	-1	88	68	984	0	94	174	794	0	94	190
36	1574	-2	96	62	1316	0	89	258	1247	2	89	69	1078	0	94	169	888	0	94	190
37	1670	0	95	63	1405	0	89	265	1337	1	91	68	1172	0	94	165	983	0	94	189
38	1765	1	96	64	1495	0	89	270	1428	-2	90	67	1267	0	94	161	1077	0	94	190
39	1863	0	97	62	1584	0	89	279	1518	-2	88	66	1361	0	94	157	1171	0	94	190
40	1960	-2	96	61	1674	0	89	286	1606	1	88	68	1456	0	94	150	1266	0	94	190
41	2055	-1	94	63	1764	0	89	291	1695	2	90	69	1550	0	94	145	1360	0	94	190
42	2150	2	95	64	1853	0	89	297	1786	0	90	67	1644	0	94	142	1455	0	94	189
43	2247	0	97	63	1943	0	89	304	1876	-2	89	67	1739	0	94	137	1549	0	94	190
44	2345	-1	97	62	2032	0	89	313	1965	0	88	67	1833	0	94	132	1643	0	94	190
45	2441	-2	94	62	2122	0	89	319	2054	2	89	68	1927	0	94	127	1738	0	94	189
46	2535	0	95	64	2212	0	89	323	2144	0	91	68	2022	0	94	122	1832	0	94	190
47	2631	2	96	64	2301	0	89	330	2235	-1	90	66	2116	0	94	119	1926	0	94	190
48	2729	0	97	63	2391	0	89	338	2324	-1	88	67	2211	0	94	113	2010	0	94	201
49	2826	-2	96	62	2481	0	89	345	2412	1	88	69	2305	0	94	107	2115	0	94	190
50	2922	-1	94	62	2570	0	89	352	2502	2	90	68	2399	0	94	103	2210	0	94	189
51	3017	2	95	64	2663	0	89	354	2593	0	90	70	2494	0	94	99	2304	0	94	190
52	3113	2	97	64	2749	0	89	364	2683	-2	88	66	2588	0	94	95	2398	0	94	190
53	3211	-1	97	62	2839	0	89	372	2771	0	88	68	2683	0	94	88	2493	0	94	190
54	3308	-2	95	61	2929	0	89	379	2860	2	89	69	2777	0	94	83	2587	0	94	190
55	3402	0	94	64	3018	0	89	384	2951	0	91	67	2871	0	94	80	2681	0	94	190
56	3498	2	96	64	3108	0	89	390	3041	-2	89	67	2966	0	94	75	2776	0	94	190
57	3595	1	98	63	3197	0	89	398	3130	-1	88	67	3059	-2	92	71	2870	0	94	189
58	3693	-2	96	62	3287	0	89	406	3219	1	89	68	3150	-4	88	69	2965	0	94	185
59	3789	-2	94	62	3377	0	89	412	3309	1	90	68	3238	1	88	71	3059	0	94	179
60	3883	2	95	64	3466	0	89	417	3400	-1	90	66	3327	2	90	73	3153	0	94	174
61	3980	2	97	64	3556	0	89	424	3489	-2	88	67	3418	1	92	71	3248	0	94	170
62	4077	0	97	63	3645	-1	88	432	3577	0	88	68	3510	-4	89	67	3342	0	94	168
63	4174	-2	95	62	3733	1	88	441	3666	1	88	67	3598	-3	86	68	3437	0	94	161
64	4269	0	94	63	3823	0	89	446	3755	0	89	68	3684	3	87	71	3531	0	94	153

Data of Single-Lane Car Following Simulation - Experiment Two (continued)

	veh 89 (DT=10)			spacing	veh 90 (DT=8)			spacing	veh 91 (DT=9)			spacing	veh 92 (DT=9)			spacing	veh 93 (DT=9)			spacing
# of steps	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh 88	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh 89	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh 90	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh 91	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh 92
65	4364	2	96	63	3912	0	89	452	3845	0	89	67	3773	2	90	72	3625	0	94	148
66	4457	-2	93	63	4002	0	89	455	3935	0	89	67	3865	1	92	70	3720	0	94	145
67	4548	-4	89	62	4092	0	89	456	4025	0	89	67	3956	-3	90	69	3812	0	94	144
68	4635	-4	85	61	4181	0	89	454	4114	0	89	67	4045	-2	87	69	3908	0	94	137
69	4718	-4	81	54	4271	0	89	447	4204	0	89	67	4133	2	88	71	4003	0	94	130
70	4798	-2	80	55	4361	0	89	437	4293	0	89	68	4222	2	90	71	4097	0	94	125
71	4877	-2	78	57	4450	0	89	427	4383	0	89	67	4313	1	91	70	4192	0	94	121
72	4961	2	83	57	4540	0	89	421	4473	0	89	67	4404	-2	90	69	4286	0	94	118
73	5045	2	85	59	4629	0	89	416	4562	0	89	67	4493	-2	87	69	4380	0	94	113
74					4719	0	89		4652	0	89	67	4581	2	88	71	4475	0	94	106
75					4809	0	89		4742	0	89	67	4670	2	90	72	4569	0	94	101
76					4898	0	89		4831	0	89	67	4761	0	91	70	4663	0	94	98
77					4988	0	89		4920	0	89	68	4852	-2	89	68	4758	0	94	94
78					5078	0	89		5010	0	89	68	4941	-1	87	69	4852	0	94	89
79					5167	0	89		5100	0	89	67	5029	2	88	71	4947	0	94	82
80									5190	0	89		5119	2	90	71	5041	0	94	78
81																	5135	0	94	
82																				
83																				
84																				
85																				
86																				
87																				
88																				
89																				
90																				
91																				
92																				
93																				
94																				

Data of Single-Lane Car Following Simulation - Experiment Two (continued)

	veh 94 (DT=8)			spacing	veh 95 (DT=9)			spacing	veh 96 (DT=8)			spacing	veh 97 (DT=7)			spacing	veh 98 (DT=7)			spacing
# of step	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh 93	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh 94	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh 95	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh 96	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh 97
1																				
2																				
3																				
4																				
5																				
6																				
7																				
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22																				
23																				
24																				
25																				
26																				
27																				
28	19	0	89	114																
29	108	0	89	120																
30	198	0	89	124	88	2	91	110												
31	288	0	89	128	181	2	93	107	40	0	90	141								
32	377	0	89	134	275	2	95	102	130	0	89	145								

Data of Single-Lane Car Following Simulation - Experiment Two (continued)

	veh 94 (DT=8)			spacing	veh 95 (DT=9)			spacing	veh 96 (DT=8)			spacing	veh 97 (DT=7)			spacing	veh 98 (DT=7)			spacing
# of steps	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh 93	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh 94	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh 95	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh 96	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh 97
33	467	0	89	138	372	1	97	95	220	0	89	152	104	0	83	116				
34	556	0	89	144	469	-1	96	87	309	0	89	160	188	0	83	121				
35	646	0	89	148	565	0	95	81	399	0	89	166	272	0	83	127	87	2	87	185
36	736	0	89	152	660	0	94	76	489	0	89	171	356	0	83	133	175	0	87	181
37	825	0	89	158	754	0	94	71	578	0	89	176	440	0	83	138	262	0	86	178
38	915	0	89	162	847	-3	91	68	668	0	89	179	524	0	83	144	349	0	86	175
39	1005	0	89	166	937	-1	88	68	758	0	89	179	608	0	83	150	435	0	86	173
40	1094	0	89	172	1025	2	89	69	847	0	89	178	692	0	83	155	522	0	86	170
41	1184	0	89	176	1115	2	91	69	937	0	89	178	776	0	83	161	609	0	86	167
42	1273	0	89	182	1207	-1	90	66	1026	0	89	181	859	0	83	167	695	0	86	164
43	1363	0	89	186	1296	-2	88	67	1116	0	89	180	943	0	83	173	728	0	86	215
44	1453	0	89	190	1384	0	88	69	1206	0	89	178	1027	0	83	179	869	0	86	158
45	1542	0	89	196	1474	2	89	68	1295	0	89	179	1111	0	83	184	956	0	86	155
46	1632	0	89	200	1564	0	91	68	1385	0	89	179	1195	0	83	190	1042	0	86	153
47	1721	0	89	205	1655	-2	89	66	1474	0	89	181	1279	0	83	195	1129	0	86	150
48	1811	0	89	199	1744	-1	88	67	1564	0	89	180	1363	0	83	201	1216	0	86	147
49	1901	0	89	214	1832	1	89	69	1654	0	89	178	1447	0	83	207	1303	0	86	144
50	1990	0	89	220	1922	1	90	68	1743	0	89	179	1531	0	83	212	1389	0	86	142
51	2083	0	89	221	2013	-1	90	70	1833	0	89	180	1614	0	83	219	1476	0	86	138
52	2169	0	89	229	2103	-2	88	66	1923	0	89	180	1698	0	83	225	1563	0	86	135
53	2259	0	89	234	2191	0	88	68	2010	0	89	181	1782	0	83	228	1650	0	86	132
54	2349	0	89	238	2280	2	90	69	2102	0	89	178	1866	0	83	236	1736	0	86	130
55	2438	0	89	243	2370	0	91	68	2191	0	89	179	1950	0	83	241	1823	0	86	127
56	2528	0	89	248	2462	-2	89	66	2281	0	89	181	2034	0	83	247	1910	0	86	124
57	2618	0	89	252	2550	-1	88	68	2371	0	89	179	2118	0	83	253	1997	0	86	121
58	2707	0	89	258	2639	1	89	68	2460	0	89	179	2202	0	83	258	2083	0	86	119
59	2797	0	89	262	2729	1	90	68	2550	0	89	179	2286	0	83	264	2170	0	86	116
60	2886	0	89	267	2820	-1	90	66	2639	0	89	181	2370	0	83	269	2257	0	86	113
61	2976	0	89	272	2909	-2	88	67	2729	0	89	180	2453	0	83	276	2344	0	86	109
62	3066	0	89	276	2998	-1	88	68	2819	0	89	179	2537	0	83	282	2430	0	86	107
63	3155	0	89	282	3087	2	90	68	2908	0	89	179	2621	0	83	287	2517	0	86	104
64	3245	0	89	286	3178	0	90	67	2998	0	89	180	2705	0	83	293	2604	0	86	101

Data of Single-Lane Car Following Simulation - Experiment Two (continued)

	veh 94 (DT=8)			spacing	veh 95 (DT=9)			spacing	veh 96 (DT=8)			spacing	veh 97 (DT=7)			spacing	veh 98 (DT=7)			spacing
# of steps	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh 93	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh 94	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh 95	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh 96	mi pt (ft)	Acce (ft/s/s)	speed (ft/s)	from veh 97
65	3334	0	89	291	3268	-2	89	66	3087	0	89	181	2789	0	83	298	2691	0	86	98
66	3424	0	89	296	3357	0	88	67	3177	0	89	180	2873	0	83	304	2778	0	86	95
67	3514	0	89	298	3445	2	89	69	3267	0	89	178	2957	0	83	310	2864	0	86	93
68	3603	0	89	305	3536	1	90	67	3356	0	89	180	3041	0	83	315	2951	0	86	90
69	3693	0	89	310	3626	-1	90	67	3446	0	89	180	3125	0	83	321	3038	0	86	87
70	3783	0	89	314	3716	-1	88	67	3536	0	89	180	3208	0	83	328	3124	-1	85	84
71	3872	0	89	320	3804	1	88	68	3625	0	89	179	3292	0	83	333	3209	-1	83	83
72	3962	0	89	324	3894	2	90	68	3715	0	89	179	3376	0	83	339	3292	0	83	84
73	4051	0	89	329	3985	0	90	66	3804	0	89	181	3460	0	83	344	3376	1	84	84
74	4141	0	89	334	4075	-2	88	66	3894	0	89	181	3544	0	83	350	3461	0	84	83
75	4231	0	89	338	4163	0	88	68	3984	0	89	179	3628	0	83	356	3545	-1	83	83
76	4320	0	89	343	4252	0	89	68	4073	0	89	179	3712	0	83	361	3628	0	83	84
77	4410	0	89	348	4342	0	91	68	4163	0	89	179	3796	0	83	367	3712	0	83	84
78	4499	0	89	353	4433	-2	89	66	4252	0	89	181	3880	0	83	372	3796	0	84	84
79	4589	0	89	358	4522	-1	88	67	4342	0	89	180	3963	0	83	379	3880	0	84	83
80	4679	0	89	362	4610	1	89	69	4432	0	89	178	4047	0	83	385	3964	0	83	83
81	4768	0	89	367	4700	1	90	68	4521	0	89	179	4131	0	83	390	4048	0	83	83
82	4858	0	89		4791	-1	90	67	4611	0	89	180	4215	0	83	396	4131	0	84	84
83	4947	-1	88		4881	-2	88	66	4701	0	89	180	4299	0	83	402	4216	0	84	83
84	5036	0	89		4969	0	87	67	4790	0	89	179	4383	0	83	407	4300	0	83	83
85	5125	0	89		5057	2	89	68	4880	0	89	177	4467	0	83	413	4383	0	83	84
86					5147	2	91		4969	0	89	178	4551	0	83	418	4467	0	83	84
87									5059	0	89		4635	0	83	424	4551	0	84	84
88									5148	-1	88		4719	0	83	429	4635	0	84	84
89													4802	0	83		4719	0	83	83
90													4886	-1	83		4801	0	83	85
91													4969	0	83		4886	0	83	83
92													5053	0	83		4969	0	83	84
93													5137	0	84		5053	0	84	84
94																	5137	0	84	