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Feasibility Study Of Advanced Technology Hov Systems: Volume 1: Phased Implementation Of Longitudinal Control Systems

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Volume 1: Phased Impliementation of Longitudinal Control Systems

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FEASIBILITY STUDY OF **ADVANCED-TECHNOLOGY HOV** SYSTEMS

Volume 1:

Phased Implementation of Longitudinal Control Systems

by

T. Chira-Chavala

S.M. Yoo

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Contents

PHASED IMPLEMENTATION OF LONGITUDINAL CONTROL TECHNOLOGY

EXECUTIVE SUMMARY

In the face of rising urban travel demand, there is strong public perception that urban mobility in California has seriously deteriorated and that solutions for urban traffic congestion problems are urgently needed. Simply constructing more and more miles of roadways is no longer an acceptable option. Many researchers believe that advanced vehicle longitudinal control systems provide an opportunity to bring about very significant increases in the highway capacity. Longitudinal control systems range from driver-assisted intelligent cruise control systems **(ICCS's)** to fully automated systems with close-formation platooning.

STUDY OBJECTIVE

The objectives of this study are to identify strategies for early deployment of longitudinal control technologies on the highway, and to evaluate potential impacts of these strategies on traffic operation, highway capacity, and traffic accidents.

APPROACH FOR EARLY DEPLOYMENT OF LONGITUDINAL CONTROL TECHNOLOGY

One approach for early deployment of longitudinal control technologies on the highway involves incremental implementation. Initially, relatively near-term driver-assisted devices such as **ICCS's** could be adopted, and later fully automated longitudinal

control systems **with** close-formation platooning could be demonstrated in selected facilities. The approach evaluated in this study involves two phases, as follows:

Phase 1: Adopting ICCS on All Roadways

In Phase 1, vehicles on all roadways could be encouraged to adopt intelligent cruise control systems **(ICCS's)** on a voluntary basis, when **ICCS's** become available. This study defines a hypothetical ICCS to be capable of regulating vehicle speed, acceleration, and headway through both throttle and brake controls. It can achieve acceleration and deceleration of up to **0.3g** and **-0.3g,** respectively. In addition, it can also provide warnings to the driver if it estimates that the driver also has to apply extra evasive actions to avoid the impending hazard. A nominal operating headway rule for the hypothetical ICCS is shown in Table **S1.**

Phase 2: Early Deployment of Longitudinal Control Systems with Close-Formation Platooning in One-Lane Transitways

In Phase 2, longitudinal control systems with close-formation platooning could be demonstrated in high-occupancy-vehicle lanes that have exclusive right-of-way and controlled access and egress (generally known as transitways). Two hypothetical system concepts are defined for evaluation in this study. For the hypothetical **Phase-2A** system (Individual-Vehicle Dispatch), vehicles would go through vehicle check stations to have their equipment checked before entering the transitway. They could then form platoons with

Table S1: Nominal Operating Headway for Vehicles Under ICCS Control

Speed (mph)	Headway Gap* (ft)
30	25
35	30
40	40
45	50
50	60
55	75
60	94
65	124
70	168
75	228

* Clear distance between successive vehicles

one another after leaving the check stations but before entering the travel lane of the transitway, if the drivers choose to do so. For the **Phase-2A** system, vehicle-to-vehicle communication systems are required but no wayside system is needed for dispatching vehicles.' Alternatively, for the hypothetical **Phase-2B** system (Platoon Dispatch), vehicle-to-vehicle as well as **wayside-to-**vehicle communication systems would be required. Wayside computerized dispatch facilities would be employed to coordinate platoon formation and dispatches. For the **Phase-2B** system, automobiles and light-duty vehicles **(LDV's)** will be required to form platoons of some pre-specified size before they are dispatched from dispatch stations. Buses, due to their relatively lower volume, would be able to travel in the transitway as single vehicles (as opposed to close-formation platoons). The wayside computerized dispatch facilities aim to achieve the pre-specified platoon size and maximize the flow rate in the transitway.

PRINCIPAL FINDINGS FROM PEASE-1 EVALUATION OF ICCS

The evaluation in Phase 1 focuses on assessing changes in the number of traffic accidents and some traffic-operation characteristics affecting safety on the roadway, as a result of adopting the hypothetical ICCS. Traffic-operation characteristics affecting safety include the following: frequencies of hard acceleration and deceleration, harmonization of vehicle speeds, vehicle headway characteristics, and traffic perturbation characteristics. In addition, potential effect of the hypothetical

ICCS on the **highway capacity** is also addressed. The evaluation is performed for two types of the ICCS controller -- one requires data on both the headway and the speed of the vehicle in front as the control input (i.e., gap/speed controlled ICCS), and the other requires only data on the headway (i.e., gap-controlled ICCS). The evaluation of the accident impact of the hypothetical ICCS is accomplished through case-by-case analyses of police accident reports. The evaluation of the traffic-operation characteristics affecting safety, due to adopting the hypothetical ICCS, is accomplished through vehicle simulation. Primary findings from the evaluation of the ICCS include the following:

1. The hypothetical ICCS could be useful as a countermeasure for up to 7.5 percent of all accidents (on all road classes) that result in fatalities or injuries.

2. Preliminary results from the simulation of a lo-vehicle convoy indicate that the use of the hypothetical gap/speed controlled ICCS is not expected to result in traffic perturbation problems, while the use of the hypothetical gap-controlled ICCS may.

3. Preliminary results from the simulation of the lo-vehicle convoy indicate that the use of the hypothetical gap/speed controlled ICCS could reduce frequencies of hard decelerations and acceleration for equipped vehicles, enhance speed harmonization of vehicles in the traffic stream, and enable vehicles to achieve **"safe"** headway quickly with little headway fluctuation when responding to speed changes of the upstream traffic.   These

benefits are found to increase as the ICCS usage rate increases.

4. The use of the hypothetical ICCS could result in some increase in the flow rate on the highway, for speed up to 55 mph. The magnitude of this flow-rate increase depends on the ICCS usage rate.

RECOMMENDATIONS FOR FUTURE RESEARCH ON ICCS

Research is needed in the following areas to advance the understanding of the feasibility of large-scale use of **ICCS's:**

* Research is needed to assess the ability of drivers to share tasks with **ICCS's** in normal and emergency situations, as well as safety implications of such **task-sharing.**

* Research is needed to determine effects of the transfer between automated control and manual control on drivers.

* Research is needed to identify and address potential legalandliability issues/implications concerning **large-scale** use of **ICCS's.**

PRINCIPAL FINDINGS ON EARLY DEPLOYMENT OF LONGITUDINAL CONTROL SYSTEMS IN ONE-LANE TRANSITWAYS

1. The estimated flow rate in one-lane transitways, as a result of deploying longitudinal control systems with **close-formation** platooning, is sensitive to the platoon size. In addition, the estimated flow rate for the hypothetical **Phase-2A** system is also sensitive to the transitway traffic mix (i.e.,

relative proportions of cars, LDV's, and buses), and to whether cars and LDV's are allowed to form the same platoon with one another. However, the estimated flow rate for the hypothetical Phase-2B system is not sensitive to either of these two factors.

2. 'For the hypothetical Phase-2A system that does not allow cars and LDV's to form the same platoon, the estimated flow rate in one-lane transitways (at 55 mph) could be 2.6 times the currently observed flow rate in existing transitways. For the Phase-2A system that allows cars and LDV's to form the same platoon, the estimated flow rate (at 55 mph) could be 4.2 times the currently-observed flow rate, for the platoon size of 12 vehicles per platoon.

3. For the hypothetical Phase-2B system, the estimated flow rate in one-lane transitways could be significantly higher than the existing flow rate. At 55 mph, the estimated flow rate for the Phase-2B system could be 4.2 to 4.6 times the existing flow rate, for platoon sizes of 12 through 20 vehicles.

4. For the hypothetical Phase-2B system, the estimated flow rate could be affected by the nominal inter-platoon gap criteria used. For every 3-percent increase in the nominal inter-platoon gap values, the estimated flow rate could decrease by 2 percent.

5. Early deployment of the hypothetical Phase-2A and Phase-2B systems in transitways could require additional right-of-way for the transitway's access and egress sections. These additional right-of-way requirements have to be taken into account when assessing the flow-rate impact of these systems. Net increases in

the flow rate adjusted for the right-of-way for the two hypothetical systems are shown in Table S2 and Figure S1. These net increases in the flow rate adjusted for the right-of-way are found to sharply rise with increasing transitway length of up to 10 miles. The deployment of the **Phase-2A** system in lo-mile transitways could result in net flow rate at 55 mph (adjusted for the right-of-way) of 2.3 and 3.1 times the existing flow rate, if cars and **LDV's** cannot and can form the same platoon, respectively. Net flow rate at 55 mph (adjusted for the right-of-way) for the Phase-2B system is found to be 3.0 times the existing flow rate for lo-mile long transitways.

RECOMMENDATIONS FOR FUTURE RESEARCH ON LONGITUDINAL CONTROL SYSTEMS WITH CLOSE-FORMATION PLATOONING

In addition to continuing research on advanced vehicle longitudinal control systems, research is also needed in the following areas to advance the understanding of the feasibility of implementing close-formation platooning:

* Safety and human-factors research is needed to determine safe and practical nominal within-platoon and **inter-**platoon spacing. Also, as part of these research activities, safety implications of allowing different vehicle types (particularly cars, **LDV's,** and buses) to form the same platoon should be investigated.

* Human-factors research is needed to assess driver acceptance and behavior when vehicles within a platoon

Table **S2:** Net Flow-Rate Gain (at 55 mph) for Phase 2A and Phase 2B
Adjusted for Right-of-Way, Relative to Existing Flow Rate

Implementation Option	Flow Rate as Multiple of Existing Flow Rate			
	2-mile Transitway	S-mile Transitway	**10-mile** Transitway	**15-mile** Transitway
Phase 2A: cars & LDV's in different platoons	1.6	2.0	2.3	2.3
cars & LDV's in same platoon **	1.7	2.5	3.1	3.4
Phase 2B: cars & LDV's in different platoons**	1.5	2.4	3.0	3.3
cars & LDV's in same platoon **	1.6	2.5	3.1	3.4

** Based on 12-vehicle platoons.

Figure S1: Net Flow-Rate Benefit of Phase 2A and Phase 2B Adjusted for Right-of-Way

have to operate very close to one another longitudinally.

* Research is needed to investigate the transfer between automated and manual control, for example, how quickly can such transfer be achieved; how fast can drivers adjust to, and be ready for, such transfer of vehicle control?

* Research is needed to determine characteristics and consequences of accidents involving several vehicles traveling in a close-formation platoon.

* Prior accident-analysis studies reported that minor accidents in two-vehicle collisions were mostly associated with low Delta-V values. However, relatively low Delta-V values in some two-vehicle collisions could also lead to relatively severe injuries. Research is needed to assess conditions in which relatively low Delta-V values could result in severe injuries.

* Research is needed to identify and address potential legal and liability issues/implications of automated highway systems.

* Research is needed to identify cost implications of longitudinal control systems with close-formation platooning.

* Research is needed to evaluate the cost-effectiveness of **"vehicle-autonomous"** versus **"wayside"** oriented systems.

PREFACE

In the face of rising urban travel demand and public perception that urban mobility has been seriously deteriorating, many transportation professionals believe that advanced vehicle longitudinal control systems could potentially bring about significant increases in the highway capacity. Longitudinal control technologies range from driver-assisted intelligent cruise control systems (ICCS's) to automated systems with close-formation platooning. With ICCS's, drivers would remain in the control "loop" in that they still perform vehicle steering/maneuvers, and pre-set vehicle speeds. Automated longitudinal control systems could take over several driving tasks -- speed and headway control, merging, diverging, lane changing, braking, and collision avoidance. When the deployment of these systems enables vehicles to operate in close-formation platoons, significant increases in the highway capacity is possible.

Research on longitudinal control systems with close-formation platooning is at a formative stage. Implementation of these systems calls for early demonstration in existing highway facilities. This study examines possible scenarios for incremental implementation of longitudinal control related technologies, starting with ICCS's and progress toward automated longitudinal control systems. It also evaluates potential impacts of this incremental implementation plan.

Dr. Ted Chira-Chavala managed the study and drafted the Final Report. Dr. Songmin Yoo performed traffic simulations. Special thanks are for Dr. Steven Shladover, Deputy Director of California PATH, who provided technical input and comments to the researchers.

PHASED IMPLEMENTATION OF LONGITUDINAL CONTROL TECHNOLOGY

INTRODUCTION

In the face of rising urban travel demand, there is strong public perception that urban mobility in California has seriously deteriorated and that solutions for urban traffic congestion problems are urgently needed. The trend of urban traffic growth in California is expected to continue into the future. Simply constructing more and more miles of roadways is no longer a acceptable option due to high capital costs involved and adverse environmental implications. Imposing higher charges to curb travel by private vehicles also appears questionable because such measures might restrict economic growth (Shladover, 1991).

Government agencies attempting to address urban traffic congestion problems in large metropolitan areas have found that the growth in urban traffic has constantly **outpaced** new road constructions as well as traditional traffic-engineering methods for improving traffic flow conditions. Emerging advanced electronics technologies could offer promising solutions to traffic congestion problems. Potential capacity benefits of these emerging technologies are likely to vary from technology to technology. For example, advanced route guidance technologies to provide real-time traffic information and **"best"** routes may improve the utilization of roadways by 15-20 percent (Shladover, 1991). Advanced vehicle lateral control technologies may increase roadway capacity by up to 50 percent, when their applications could result in smaller lane

width requirements. (Chira-Chavala et al, 1992). Of all emerging advanced technologies, many researchers believe that vehicle longitudinal control systems could potentially bring about the greatest increase in highway capacity. Longitudinal control systems range from driver-assisted intelligent cruise control systems **(ICCS's)** to automated highway systems. **ICCS's,** which are vehicle-autonomous devices, could regulate vehicle speed, acceleration, and headway through regulating throttle and brake controls. Drivers of ICCS-equipped vehicles would remain in the control **"loop"** because they still have to perform vehicle steering and pre-set vehicle speeds. Automated highway systems could take over several driving tasks from drivers -- speed and headway control, merging, diverging, lane changing, braking, and collision avoidance. When the deployment of automated highway systems enables vehicles to operate in close-formation platoons, many-fold increases in highway capacity are possible (Shladover 1978; Frank et al 1989).

STUDY OBJECTIVES

The objectives of this study are as follows:

*   To identify possible scenarios for early deployment of longitudinal control technologies in the highway environment, particularly early deployment of **ICCS's** and advanced longitudinal control systems that are currently researched at the California PATH program.

*   To address some feasibility issues for the identified

scenarios, particularly potential impacts on traffic operation, capacity, and safety.

Currently, **ICCS's** and advanced longitudinal control systems are not in use on the road, and evidence in the literature have only identified possible system concepts. In order to meet the above objectives, this study has to define hypothetical systems for **ICCS's** and advanced longitudinal control systems for the evaluation purpose. This is accomplished by reviewing prior and related continuing studies.

ORGANIZATION OF THIS REPORT

The research results are reported in two chapters, which are preceded by the description of a plan for two-phased implementation of longitudinal control technologies. Chapter 1 focuses on the evaluation of **ICCS's,** and consists of the following sections: the definition of a hypothetical ICCS being evaluated; evaluation of the accident impact of this hypothetical ICCS; evaluation of the traffic-operation impact; and a discussion on the capacity impact. Chapter 2 evaluates longitudinal control systems with **close-**formation platooning in one-lane transitways. This chapter consists of three sections. The first section describes systems that operate without the minimum platoon size requirement (Phase 2A). Furthermore, this section describes a hypothetical system concept for Phase 2A and nominal inter-platoon gap criteria for the hypothetical system; estimates the transitway flow rate as a result of implementing the hypothetical system; and determines

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special infrastructures requirements. The second section focuses on systems that operate with the minimum platoon size requirement (Phase 2B) in order to maximize the transitway flow rate. This section also describes a hypothetical system concept for Phase 2B; estimates the transitway flow rate as a result of implementing the hypothetical system; and determines special infrastructures requirements. In Section 3, estimations of net capacity benefits, adjusting for the right-of-way, for both Phase 2A and Phase 2B are presented.

In addition, two appendices are included. Appendix A describes methodology for determining nominal safe inter-platoon gaps. Appendix B describes methodology for determining geometric dimensions of the transitway's egress section required for Phases 2A and 2B.

A PLAN FOR INCREMENTAL IMPLEMENTATION OF LONGITUDINAL CONTROL SYSTEMS

One approach for early deployment of longitudinal control technologies on the highway involves two-phased implementation, as follows:

Phase 1: Adoption of Intelligent Cruise Control Systems (ICCS's)

Initially, vehicles on all roadways could be encouraged to adopt **ICCS's** on a voluntary basis, once these devices become available. One appeal of **ICCS's** is the relative ease of deployment. **ICCS's** could be adopted on a voluntary basis, thus

both equipped and unequipped vehicles could share the same roadway. Being vehicle autonomous systems, the adoption of **ICCS's** will not require special infrastructure or wayside equipment. Potential legal and liability issues surrounding the use of **ICCS's** are likely to be less complex because these devices are extensions of the existing cruise control device. More important, favorable public acceptance of **ICCS's** can be expected because drivers would still be in the vehicle-control loop to perform vehicle steering and maneuvers, as well as to select vehicle speed. The use of **ICCS's** could familiarize drivers to the use of automated devices, a first step toward assessing public acceptance of more-advanced longitudinal control systems.

Phase 2: Early Deployment of Longitudinal Control Systems in Access-Controlled HOV lanes

Longitudinal control systems could be implemented, with a view to achieving close-formation platooning operation. In **close-**formation platoons, vehicles within platoons maintain very small intra-platoon headway while successive platoons maintain relatively large inter-platoon headway. Safety is criticalto this platooning operation. Therefore, it appears desirable that, when longitudinal control systems with platooning operation are ready for implementation, they are initially demonstrated in existing highway facilities. High-occupancy-vehicle (HOV) lanes that have exclusive right-of-way (i.e., separated from the freeway mainline by permanent barriers) are considered to be good candidates for this

purpose. These HOV lanes are generally known as transitways. For the evaluation purpose, this study started by examining a range of alternative system concepts for one-lane transitways. These alternative system concepts differed from one another in how close-formation platoons were formed. After preliminary analyses of these alternatives, two candidates were selected for further evaluations. They are Phase 2A (individual-vehicle dispatch) and Phase 2B (platoon dispatch), as follows:

Phase 2A: Individual-Vehicle Dispatch

Longitudinal control systems with close-formation platooning operation under Phase 2A require all transitway users (automobiles, light-duty vehicles or **LDV's,** and buses) to be properly equipped. Facilities to check the operating status of the vehicle and equipment are needed at the beginning of the transitway. Vehicles will pass through these check stations as **individual units,** in the order that they arrive. Then, they could form platoons with one another downstream from check stations. Drivers could choose to join (or not join) other vehicles in platoons.

Phase 2B: Platoon Dispatch

Alternatively, longitudinal control systems with close-formation platooning operation for one-lane transitways could incorporate wayside computerized dispatch facilities to coordinate close-formation platoon formation and dispatches. This would be accomplished as soon as vehicle status checks are complete. Under

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this scenario, automobiles and **LDV's** will be required to form platoons of the required size before they are dispatched from check stations. Buses, due to their relatively lower volume, could be exempted from this requirement. The purpose of integrating **computerized** dispatch facilities is to assure that some **pre-**specified minimum platoon size is achieved in order to maximize the transitway flow rate.

Detailed descriptions and evaluations of Phase-1, **Phase-2A,** and Phase-2B systems are presented in the following sections.

Chapter One

PHASE 1: ADOPTION OF INTELLIGENT CRUISE CONTROL SYSTEMS

This section presents the evaluation of the safety and traffic impacts of a hypothetical ICCS. The evaluation is preceded by an overview of the intelligent cruise control technology and a description of a hypothetical ICCS defined for the evaluation purpose.

1.1 Overview of Intelligent Cruise Control Technology

ICCS's could regulate vehicle speed and headway through throttle control alone or through both throttle and brake controls. When in use, the driver of an equipped vehicle could pre-set any desired cruise speed. When the equipped vehicle **"finds"** a vehicle in front within its **ICCS's** sensing range, its speed, acceleration, and headway will be automatically adjusted with respect to the lead vehicle. As soon as the front vehicle moves outside the **ICCS's** sensing range, the equipped vehicle will resume its pre-set speed.

The literature reports a number of plausible system concepts for **ICCS's,** which can be grouped into three categories according to their capabilities. The first category includes **ICCS's** that operate through throttle control only. These systems could use linear motors that receive instructions from microprocessors in the form of variable-width pulses. Decelerations are achieved by air friction and engine drag when the throttle is released (Hahn, 1979;

Belohoubek, 1982; and Castle Rock, 1988). A limitation of this type of ICCS's is the lack of brake control, and for closing speeds as low as 5-10 mph, drivers may be required to apply braking themselves (Castle Rock, 1988). The second category of ICCS's could incorporate both throttle control and low-g brake control. The third category of ICCS's could have throttle control and relatively high-g brake control. Controllers of ICCS's could require headway data alone, or data on both headway and speed of the lead vehicle, as the controller's input. For brevity, ICCS's that require only the headway data are called "gap-controlled" ICCS's, while those that require data on both the headway and the speed of the lead vehicle are called "gap/speed controlled" ICCS's.

1.1.1 Definition of Hypothetical ICCS

For the evaluation purpose, this study defines a hypothetical ICCS as follows:

(i) It is vehicle autonomous, requiring no inter-vehicle communication systems.

(ii) It regulates speed and headway through both throttle and brake controls, which are capable of automatically achieving maximum acceleration and deceleration rates of 0.3g and -0.3g, respectively.

(iii) It provides warnings to the driver if it estimates that the driver also has to apply extra evasive actions (including harder braking) in order to avoid the impending collision.

1.2   ICCS Control Versus Driver Control

For vehicles under driver control (i.e., unequipped vehicles), driver reaction/response time significantly affects how a vehicle may respond to actions initiated by the vehicle in front.   For example, 'when the lead vehicle decelerates, the driver of the following vehicle has to determine whether the lead vehicle is slowing or stopping and then decide on an appropriate evasive action.   Driver reaction/response time is the time interval between the instant that the driver recognizes the change in the speed of the lead vehicle and the instant that he/she actually takes action. Driver reaction/response time could vary considerably from driver to driver, and could be influenced by a number of factors including the vehicle separation, driver acuity, driver natural reaction capability, **type** and condition of roadway, and surrounding environment (AASHTO, 1984).   Drivers who are alerted to potential hazards ahead exhibit a median reaction/response time of 0.7 seconds (AASHTO, 1984).   However, when hazards are unanticipated, driver reaction/response time could increase by as much as 1.0 second or more, so that the minimum driver reaction/response time under most driving conditions is likely to be closer to 1.5 seconds (AASHTO, 1984).

For vehicles under ICCS control, driver reaction/responsetime is replaced by machine **(i.e,** electrical and mechanical) response time.   Many researchers believe that machine response time for the hypothetical ICCS (the time interval between the instant that an **ICCS** detects potential hazards and the instant that it

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automatically applies control) could be as low as 0.1 second.

1.2.1 *Nominal Operating Headway for Hypothetical ICCS*

The hypothetical ICCS could automatically adjust vehicle speed and headway in accordance with some pre-specified nominal operating headway rule. Nominal operating headway for the ICCS is the minimum headway to be automatically maintained by the ICCS in following a vehicle. It is conceivable that ICCS's to be available in the future could be designed to allow drivers to select different nominal operating headway rules according to the prevailing driving conditions and driving style. Magnitude of nominal operating headway for the ICCS could have important safety and capacity implications. On the one hand, very large nominal operating headway could ensure that, if the lead vehicle suddenly stops, the ICCS would be able to bring the vehicle to a safe stop. On the other hand, large nominal headway invariably reduces traffic density and highway capacity. Furthermore, large nominal headway could also induce undesirable maneuvers by encouraging vehicles in adjacent lanes to merge into the larger gap. This tradeoff suggests that practical nominal headway for the ICCS should be just large enough to assure that the ICCS could bring a vehicle to stop safely in response to a vehicle in front stopping in normal driving, but not too large to result in reductions of the highway capacity.

Nominal operating headway rules for ICCS's have not been established in the literature. For evaluation purposes, this study

expresses a nominal operating headway for the hypothetical ICCS as the clear distance between vehicles (or headway gap). These nominal operating headway gaps are shown in Table 1, which are calculated based on the following assumptions:

(a) The ICCS is capable of automatically **applying** acceleration and deceleration up to **0.3g** and **-0.3g**, respectively. When the ICCS estimates that an deceleration rate in excess of **-0.3g** is required to stop the vehicle, it will signal warnings to the driver to take extra evasive actions.

(b) Machine response time for the ICCS is 0.1 seconds.

Nominal operating headway gaps shown in Table 1 imply that:

o The hypothetical ICCS should be able to bring the equipped vehicle to stop safely when the vehicle in front decelerates or comes to a stop in normal driving, or as long as the lead vehicle's deceleration rate is not in excess of **-0.45g**, without the driver of the equipped vehicle having to apply brakes or take other evasive actions.

o Under worse-case situations characterized by the lead vehicle suddenly stopping at a deceleration rate of **-0.6g** and the driver of the following vehicle takes no extra evasive action after the ICCS sounds a warning, a collision between the two vehicles, if occurs, would result in a Delta-V value no more than 15 mph. Delta-V of 15 mph is chosen as the cut-off point because Gimotty et al (1980) reported that, for Delta-V of 15 mph or

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Table I: Nominal Operating Headway for Vehicles Under ICCS Control

Speed (mph)	Headway Gap* (ft)
30	25
35	30
40	40
45	50
50	60
55	75
60	94
65	124
70	168
75	228

* Clear distance between successive vehicles

less, the probabilities of occupants receiving serious injuries were less than 20 percent. **O'Day** et al (1985) showed that less than 0.5 percent of all occupant fatalities in highway accidents were associated with Delta-V values up to 15 mph. However, if the driver of the following vehicle could also apply additional or take extra evasive actions after receiving the warning from the ICCS, he/she may be able to avoid the pending collision.

1.3 Evaluation of Safety Impact of Hypothetical ICCS

The most direct measure of traffic safety is the number of traffic accidents. Because there are currently no **ICCS's** in use on the road, accident data for ICCS-equipped vehicles do not exist for the safety evaluation. This study evaluates the potential safety impact of the hypothetical ICCS using a two-forked approach. First, possible changes in the number of traffic accidents, as a result of adopting the hypothetical ICCS, are determined from an in-depth analysis of police accident reports. This accident analysis aims to determine whether the ICCS (if it had been used) could have intervened and possibly altered the accident outcome for each accident under examination. Second, effects of the hypothetical ICCS on some traffic operation characteristics affecting safety (e.g., frequencies of hard acceleration and deceleration, degree of traffic perturbation in response to some upstream disturbances, speed harmonization among vehicles, and

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headway characteristics) are evaluated by vehicle simulation.

The assessment of changes in traffic accidents as a result of adopting the hypothetical ICCS is presented below. Potential changes in traffic operation characteristics affecting safety as a result of adopting the hypothetical ICCS are presented in the subsequent section.

1.3.1 Usefulness of Hypothetical ICCS in Reducing Accidents

The use of the hypothetical ICCS could bring about reductions in traffic accidents in a number of ways. For example:

(i)   When the vehicle equipped with the hypothetical ICCS senses another vehicle in front, the ICCS would automatically and continuously adjust speed and acceleration to assure that the equipped vehicle maintain the nominal headway with respect to the vehicle in front. In this way, the use of the ICCS could reduce the incidence of **"tail-gate"** and **"excessive"** speed with respect to the prevailing traffic condition, two common contributing factors to crashes.

(ii) With the ICCS activated, driver reaction and response time would be replaced by much smaller machine response time. This could help to reduce the probability of collision because the ICCS can detect the hazard and apply braking in a fraction of a second.

1.3.2 Accident Analysis Procedure

Potential changes in traffic accidents due to adopting the

hypothetical ICCS are assessed by examining accident data of the existing vehicle population, and determining whether the accident outcome could have been altered by the use of the hypothetical **ICCS,** had it been used. Such determination calls for the construction of a sequence of events that culminated in the accident from available accident data. If the ICCS were to be able to alter the accident outcome, there must exist at least one *point of intervention* along this sequence of events that would respond to the ICCS.

Computerized accident data for California were examined, but were found to lack details essential for the above analysis. However, hard-copy police accident reports (PAR's) were found to be more satisfactory in terms of the available detail. This is because, in addition to information on coded variables typically found in computerized accident data, **PAR's** also have the following details:

* Every PAR has at least one detailed accident diagram prepared by the police officer.

* Every PAR has a summary of the police's interviews with the drivers, occupants, and witnesses concerning the accident and how it happened.

* Every PAR contains a narrative (by the police officer) on the crash location characteristics; traffic and roadway conditions; events before, during, and after the crash; driver actions/inaction; and vehicle movements before and after the crash.

* Most **PAR's** have the police's account of the drivers' conditions prior to and during the crash.

* A small percent of **PAR's** have diagrams and dimensions of vehicle skid marks, as well as the police's own calculations of vehicles speeds prior to the crash based on accident reconstructions.

Therefore, in-depth examinations of hard-copy **PAR's** were performed in an attempt to determine what proportion of total accidents might the hypothetical ICCS be applicable as a possible countermeasure. The case-by-case examination of **PAR's** involves two tasks as follows:

Task 1: For each accident, available information in the PAR is synthesized to construct a sequence of events and driver actions that culminated in the accident.

Task 2: The researchers make judgment whether there exists at least one point along this sequence of events that the hypothetical ICCS could have intervened and altered the accident outcome (had the ICCS been used). If so, the hypothetical ICCS is considered to be a possible countermeasure for that accident.

1.3.3 *Sample Design*

The case-by-case examination of PAR's is time-consuming, which tends to limit the number of cases that can be analyzed in-depth. This in turn influences the size of the accident population

selected for this study. The selected study population consists of all accidents occurring on all roadways within four major counties of California (Los Angeles, Orange, San Diego, and San Francisco counties), from September through December of 1990. This population has 18,187 reported accidents that resulted in at least visible-injury accidents. Of these accidents, 537 were reported fatal accidents, 2,153 reported severe-injury accidents, and 15,497 reported visible-injury (i.e., non-severe) accidents. **Property-**damage-only (PDO) accidents are excluded because they tend to be under-reported to a greater extent than injury and fatal accidents.

A probability sample of this accident population is obtained through a random selection process stratified by three reported accident severity levels (i.e., fatal accidents, severe-injury accidents, and visible-injury accidents). These are definitions of severity levels used by the California Highway Patrol in reporting traffic accidents. A stratified random sample is employed to ensure that the selected sample of accidents would contain sufficient numbers of more-severe accidents.

The sample size used is 379 accidents, with the following breakdown by severity levels:

* 22.75 percent of fatal accidents for the study's population (or 118 PAR's)

* 5.20 percent of "severe-injury" accidents for the study's population (or 112 PAR's)

* 0.96 percent of "visible-injury" accidents for the study's population (or 149 PAR's)

1.3.4 Assumptions for In-Depth Examination of PAR's

The following assumptions are made in determining whether the hypothetical ICCS might be a possible accident countermeasure for the accidents under investigation. These assumptions, which were used by prior studies in assessing potential benefits of new technologies (e.g., Hitchcock **1991),** are necessary because there are currently no **ICCS's** in use on the road and no accident data of ICCS-equipped vehicles.

(a) The hypothetical ICCS will perform as intended.

(b) Changes in driver behavior resulting from adopting the hypothetical ICCS, if any, cannot be predicted at this time, and thus are not taken into consideration in the analysis.

(c) New hazards that could occur as a result of failures of the ICCS cannot be predicted at this time, and thus are not taken into consideration.

1.3.5 Results of In-Depth Examination of PAR's

The in-depth examination of **PAR's** reveals that the task of constructing a sequence of events that culminated in the accident (Task 1) is relatively easy for most accidents, thanks to the accident diagrams and detailed accident narratives contained in **PAR's.** On the other hand, the task of determining whether the hypothetical ICCS could have intervened and altered the accident outcome (Task 2) is more difficult. This is because **PAR's** do not contain key *quantitative* information such as the following: exact

vehicle separation. before collision;   exact instant when the
driver(s) perceives the hazard (if at all) and applies braking;
the magnitude of deceleration; accurate speed information (vehicle
speeds prior to the crash usually come from the drivers, occupants,
or witnesses, with unknown accuracy).   In the absence of this
quantitative information, judgment has to be made whether there
exists at least one point along the identified sequence of events
that the ICCS could have intervened and altered the accident
outcome.   However, the absence of such information makes it
impossible to compute the probability with which each accident
could have been prevented by the hypothetical ICCS.

The lack of the above *quantitative* information, unfortunately,
is true for all existing accident data programs in the U.S. In
light of the above data limitation, together with the above
assumptions (a) through (c), estimates of the number of accidents
for which the hypothetical ICCS could be considered a possible
countermeasure presented below should be viewed as **"upper-bound"**
estimates.

Table 2 shows the numbers of total accident and accidents for
which the ICCS could be a possible countermeasure for the sample
under investigation, by the accident severity. Table 2 indicates
that the usefulness of the hypothetical ICCS as a possible accident
countermeasure could vary, depending on the accident severity. The
hypothetical ICCS is found to be a possible countermeasure for up
to 5.08 and 4.46 percent of fatal and severe-injury accidents,
respectively;   this proportion is 8.05 percent for visible-injury

Table 2: Numbers of Sampled Total Accidents and Accidents That May Respond to ICCS

Severity	# of Total Accidents	# of Rearend Accidents	# of Accidents That May Respond to ICCS
Fatal accidents	118	11	6
Severe-injury accidents	112	9	5
Visible-injury accidents	149	24	12
Total	379	44	23

Note: The study population consists of a total of 18,187 reported fatal, severe-injury, and visible-injury accidents.

accidents.

The numbers of accidents shown in Table 2 are based on a stratified random sample, with unequal weighting for the three severity levels. To estimate the percent of accidents for which the hypothetical ICCS could be a possible countermeasure for this population, the numbers in Table 2 are weighted by appropriate sampling factors. The weighted results indicate that the proportion of all accidents for which the hypothetical ICCS could be a possible countermeasure is up to 7.54 percent.

The accidents for which the hypothetical ICCS is found to be a possible countermeasure are primarily **rearend** collisions. This paper defines a **"rearend"** collision as a crash involving two or more vehicles *in transport,* in which at least one of them is struck from behind. Vehicles *in transport* are those that are being operated by drivers, which may be in motion or stopped in traffic at the time of the accident. Vehicles *in transport* do not include parked vehicles, which are usually driver-less and left on the shoulder or the roadside.

1.4 Evaluation of Traffic-operation Characteristics Affecting Safety

The use of the hypothetical ICCS could affect speed, acceleration, and headway characteristics of equipped vehicles (relative to unequipped vehicles) when responding to some actions of the vehicle in front. The extent of such impacts could be affected by the type of input requirement for the ICCS controller

-- whether the ICCS generates control instructions from headway input data alone (i.e., gap-controlled ICCS), or from input data on both the headway and the speed of the front vehicle (i.e., gap/speed controlled ICCS).

The evaluation aims at assessing:

0   Traffic perturbation characteristics of the hypothetical gap controlled and gap/speed controlled ICCS's

0   Effects of the hypothetical ICCS on frequencies of hard accelerations and decelerations, speed harmonization among vehicles in the traffic stream, and vehicle headway characteristics

The evaluation is accomplished by means of vehicle simulation. Models for ICCS-controlled and for driver-controlled vehicles used in the simulation are described below.

1.4.1 Model for ICCS-Controlled Vehicles

Figures 1 and 2 are block diagrams for the gap-controlled ICCS and gap/speed controlled ICCS, respectively. For both types of controllers, the vehicle headway is known and speed of the equipped vehicle is also known. In addition, speed of the vehicle in front is also known for the gap/speed controlled ICCS, but not for the gap-controlled ICCS.

An "error" term for the two types of ICCS at any time interval can be expressed as (Ogata, 1970):

$$e_g (t) = G(h_{req}) - G (h_{cur}) \tag{1.1}$$

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Figure 1: Control Diagram for Gap-Controlled ICCS

Leading Vehicle

P_n +   −

V_n

P_{n+1}

+ V_{n+1}

−

h_{cur}

G

$G(h_{cur})$

−

+

+

+

e^{-b}

A*

a_{n+1}

$\dfrac{1}{s}$

V_{n+}

$\dfrac{1}{s}$

L

P_{n+1}

$G(h_{req})$

G

h_{req}

Nonlinear
Block
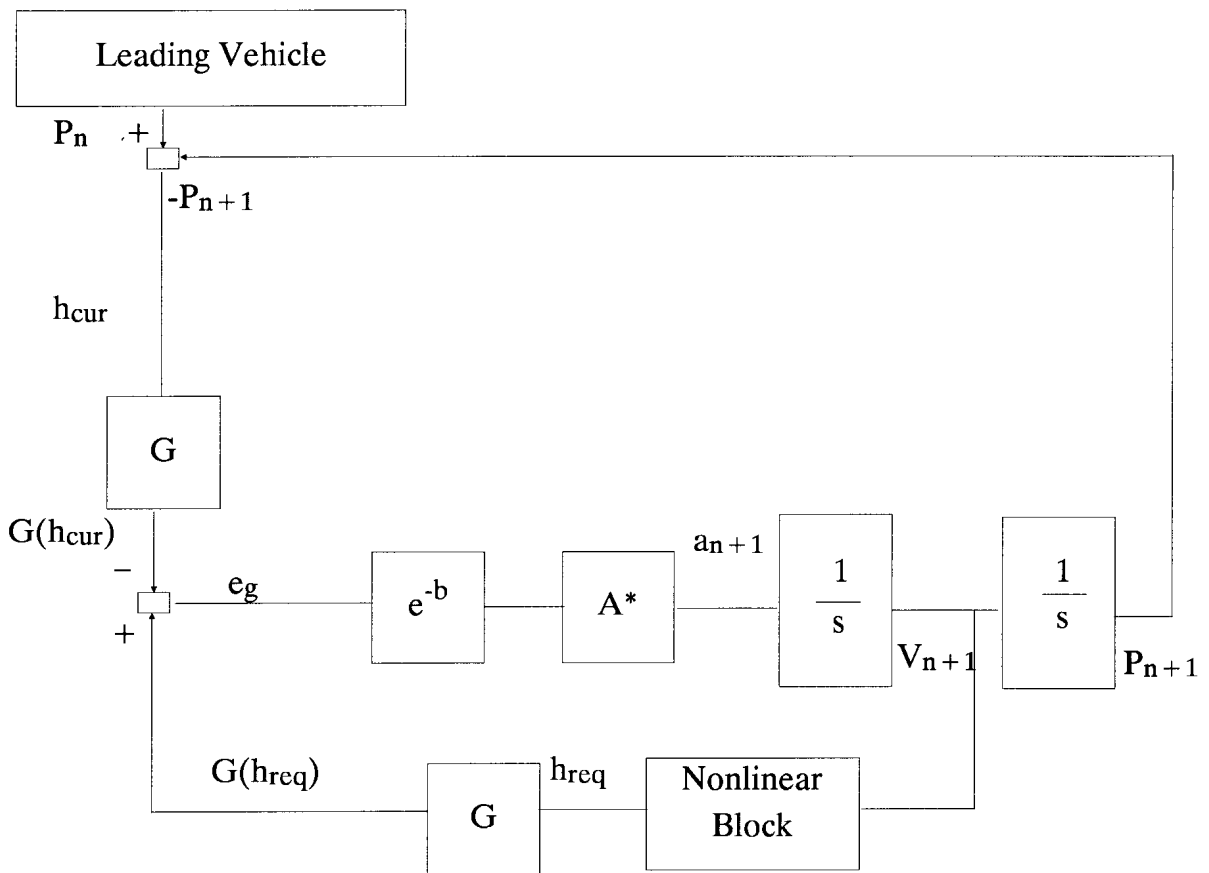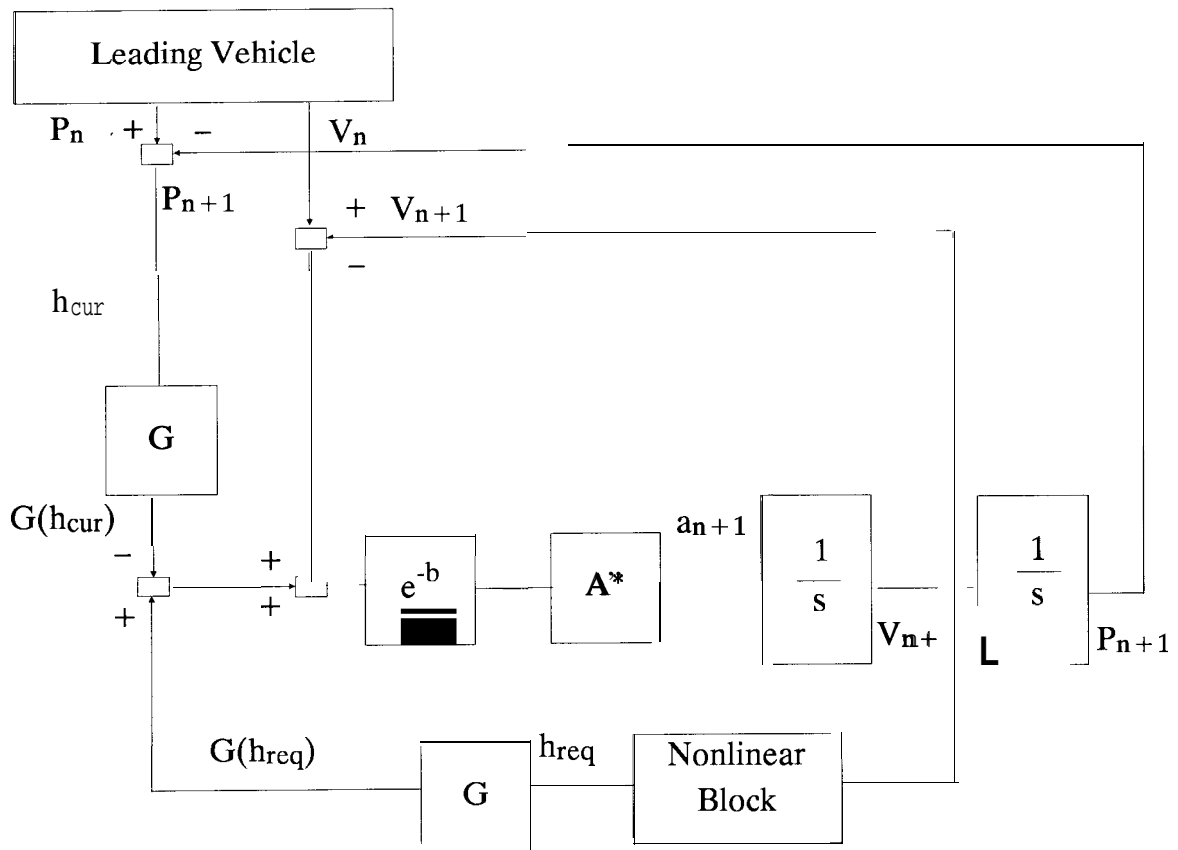
A* : Control block

$$K_p + \frac{K_i}{S} + K_d * s$$

Figure 2:   Control Diagram for Gap/Speed Controlled ICCS

$$e_v(t) = G(h_{req}) - G(h_{cur}) + [V_n - V_{n+1}] \qquad (1.2)$$

where:

$e_g(t)$ is error term for gap-controlled ICCS

$e_v(t)$ is error term for gap/speed controlled ICCS

G is speed estimation function

$G(h_{req})$ is speed estimated from the nominal operating headway

$G(h_{cur})$ is speed estimated from headway measured by the sensor

V_n is speed of the lead vehicle

V_{n+1} is speed of the following vehicle

h_{req} is nominal headway gap

h_{cur} is headway gap measured by the sensor

Once the error term is determined, the controller generates acceleration (or deceleration), a(t), which can be expressed as:

$$a(t + b) = k_p * e(t) + k_i \int_0^t e(p)\,dp + k_d * d[e(t)]/dt \qquad (1.3)$$

where b is the response delay; k_p, k_i, k_d are control gains; and the second term on the right-hand side of the equation is the accumulated error limit range.

The amount of control instructions is assumed to change within a jerk limit of 0.3 **g/sec** as follows:

$$\frac{a(t+At) - a(t)}{At} \leq 0.3g \qquad (1.4)$$

Once the acceleration (or deceleration) is computed, the vehicle speed and position can be updated, as follows:

$$V_{n+1}(t+\Delta t) \quad = V_{n+1}(t) + a(t)*\Delta t \qquad\qquad (1.5)$$

$$p_{n+1}(t+\Delta t) \quad = p_{n+1}(t) + [V_{n+1}(t+\Delta t) + V_{n+1}(t)]/2*\Delta t$$
$$= p_{n+1}(t) + V_{n+1}(t)*\Delta t + a(t)/2*\Delta t^2 \qquad (1.6)$$

where:

$p_{n+1}(t)$ is position of the following vehicle

Δt is sampling time

Simulation Model for Vehicles Under Driver Control

Speed, acceleration, and headway characteristics for vehicles under driver control (i.e., vehicles not equipped with the ICCS) are needed to provide the baseline for assessing changes in traffic operation characteristics as a result of adopting the hypothetical ICCS. In high-flow conditions, driver reaction time is known to affect how a vehicle may respond to actions initiated by the vehicle in front. Prior studies (e.g. TRB 1975; May 1990) have reported that vehicles under driver control interacted with one another in a manner that could be approximated by the car-following principle. One functional form of the car-following principle is as follows:

$$\ddot{x}_{n+1}(t+T) = \frac{a_0}{x_n(t) - x_{n+1}(t)}[\dot{x}_n(t) - \dot{x}_{n+1}(t)] \qquad (1.7)$$

where:

    $\ddot{x}(t)$ is acceleration at time t, in feet per second^2

    $\dot{x}(t)$ is velocity at time t, in feet per second

    x(t) is the vehicle position at time t, in feet

    a_0 is driver sensitivity, in feet per second

    T   is driver reaction time, in seconds

    n   denotes the order of the vehicle position in the traffic

        stream;   for example, Vehicle (n+1) is downstream of

        Vehicle n.

This study assumes that trajectories of vehicles under driver control in high-flow conditions could be approximated by the above car-following model. Some prior studies (e.g., Leutzbach, 1988) hypothesized that drivers, out of concern for their own safety, might react more alertly to headway closing (i.e., when the vehicle in front decelerates) than to headway lengthening (i.e., when the vehicle in front accelerates). Unfortunately, no prior study ever reported numerical values concerning how different driver reaction times might be between these two situations. Herman et al (1961) reported average values of driver reaction time and driver sensitivity measured from experiments conducted in Holland Tunnel and Lincoln Tunnel, one value for each tunnel. These reported values for the two tunnels differ slightly from one another. In an

attempt to account for possible effects of different driver
reaction times on the car-following behavior between the **headway-**
closing situation and the headway-lengthening situation, this study
adopts the smaller driver reaction time value reported by Herman et
al for headway closing and the larger driver reaction time value
for headway lengthening, as follows:

* When the vehicle in front decelerates (i.e., the gap is closing for the following vehicle), T is assumed to be *1.2* seconds. The corresponding a_0 value of 20.3 mph reported for this reaction time is also adopted.

* When the vehicle in front accelerates (i.e., the gap is lengthening for the following vehicle), T is assumed to be 1.4 seconds with a corresponding a_0 value of 18.1 mph.

1.4.3 Simulation Procedure

Vehicle speed, acceleration, and headway profiles can be
estimated from the simulation for vehicles under ICCS control and
those under driver control. The simulation is performed using a
traffic stream consisting of 10 vehicles. This traffic stream is
assumed to be moving along on a roadway lane at 40 mph initially.
The lead vehicle then reduces its speed to 30 mph, with a
deceleration rate of **-0.15g.** After the lead vehicle reaches 30
mph, it cruises at that speed until the 60th second. It then
increases its speed to 40 mph again, by accelerating at a rate of
0.15g. The speed profile of this lead vehicle is shown in Figure
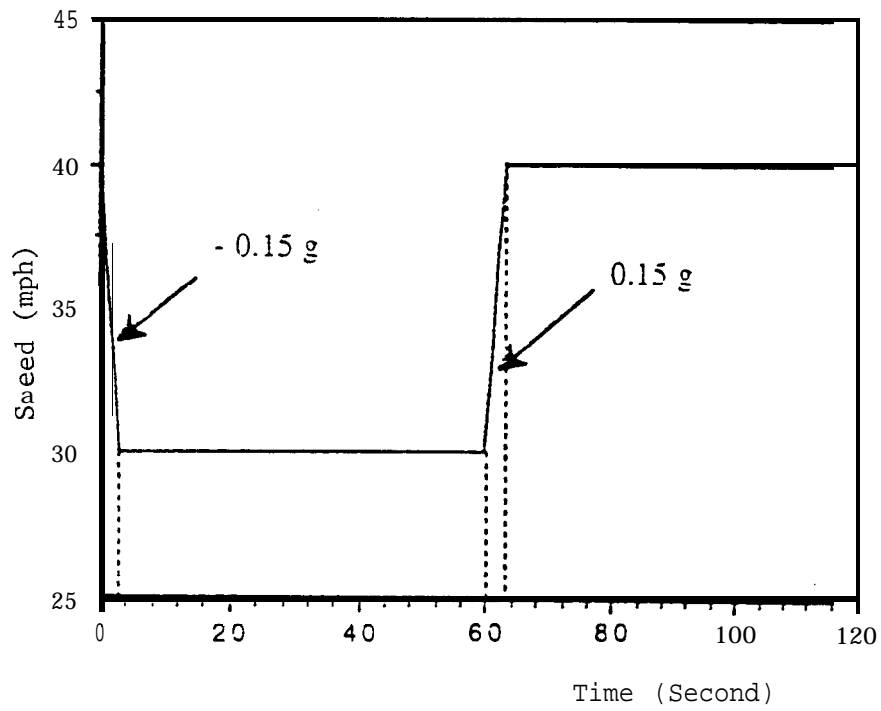*3.* For simplicity, the simulation assumes that none of the other

Figure 3:   Speed Profile for Lead Vehicle During Simulation

nine vehicles in the convoy changes lane during the simulation period. Acceleration, speed, and headway profiles for these nine vehicles can be estimated, and the profiles of the traffic stream adopting the ICCS can be compared with those of the traffic stream without the ICCS.

1.5 Simulation Results

1.5.1 *Use of Hypothetical ICCS and Traffic Perturbation*

As the lead vehicle changes its speed, ICCS's on the other vehicles in the assumed lo-vehicle stream would automatically adjust their accelerations and speeds in order to maintain the pre-specified nominal operating headway. For stability, the lead vehicle's deceleration (or acceleration) must not be amplified by the downstream vehicles. Otherwise, unsafe driving conditions can result.

Perturbation characteristics of ICCS-equipped vehicles are investigated for a case in which all vehicles in the traffic stream are assumed to be equipped with the ICCS (i.e., 100-percent ICCS market penetration. This represents the worst-case scenario, if the use of the hypothetical ICCS could potentially result in perturbation problems. Initially, when the lo-vehicle stream is traveling at 40 mph, successive vehicles are maintaining 55-foot headway-gaps from one another (i.e., the nominal headway gap for 40 mph from Table 1). The lead vehicle then reduces its speed from 40 mph to 30 mph and cruises at 30 mph until the 60th second, at which

time it starts to accelerate up to 40 mph and cruise at 40 mph until the end of the simulation at the 120th second.

Deceleration and acceleration profiles, as well as overshoots, for the 9 following equipped vehicles responding to the lead vehicle's actions are presented below, separately for gap/speed controlled and gap controlled ICCS's.

1.5.1.1 For Gap/Speed Controlled ICCS

Figure 4 shows a plot of deceleration versus time for the fifth vehicle during the speed-reduction phase (from 40 to 30 mph, between 0 and 60 seconds). The shape of deceleration-time plots for other vehicles are similar to this profile, in that each exhibits a peak deceleration, followed immediately by a slight overshoot, and then a steady state is reached. Table 3 summarizes peak decelerations and overshoots for all10 ICCS-equipped vehicles during the speed reduction phase. Vehicle 1 designates the lead vehicle, while vehicle 10 designates the last vehicle in the traffic stream.   Table 2 indicates that the lead vehicle's deceleration is quickly dampened by the downstream vehicles, as evidenced by the decreases in peak decelerations for vehicles 2 through 10.   Deceleration overshoots (which are much smaller in magnitude than the peak decelerations) slightly increase for downstream vehicles up to the 8th vehicle, and then level off for subsequent vehicles.

Figure 5 is a plot of acceleration versus time for Vehicle 5 during the speed-increasing phase (from 30 to 40 mph, between 60
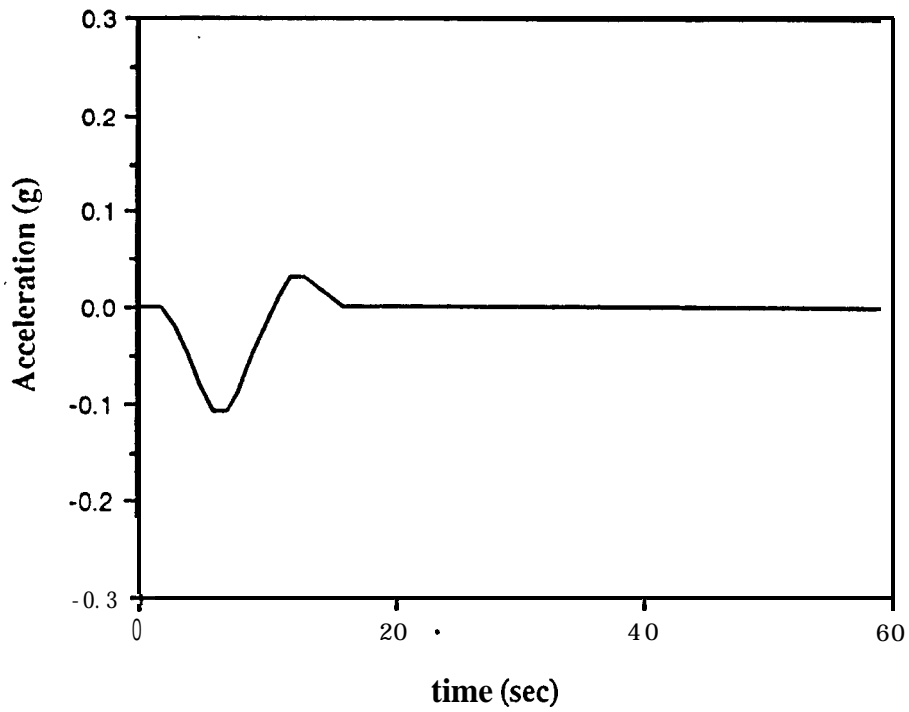
Figure 4: Deceleration Profile **of** Vehicle 5 **Equipped** With Gap/Speed
Controlled ICCS
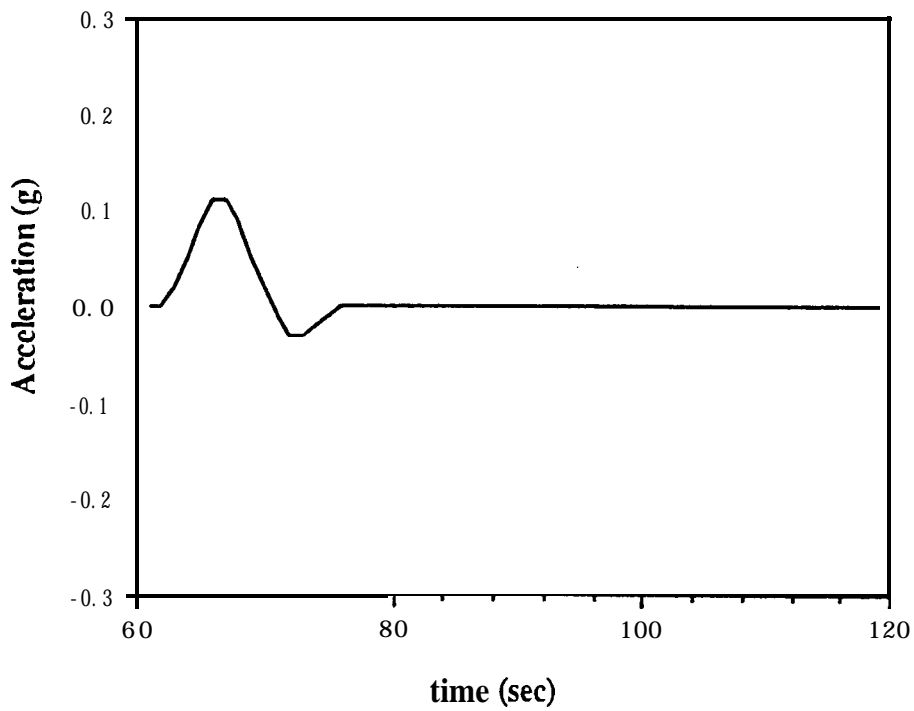
Figure 5: Acceleration Profile of Vehicle 5 Equipped With Gap/Speed
Controlled ICCS

Table 3:. Peak Decelerations and Overshoots
for Speed-Reduction Phase (Gap/Speed-Controlled ICCS)

Vehicle Order	Peak Deceleration	Overshoot
1	-0.15	0
' 2	-0.15	0.01
3	-0.13	0.02
4	-0.12	0.03
5	-0.11	0.03
6	-0.11	0.04
7	-0.11	0.04
8	-0.11	0.05
9	-0.11	0.05
10	-0.11	0.05

and 120 seconds). The shape of this plot is also typical for vehicles 2 through 9, in that it is characterized by a peak acceleration, followed immediately by a small overshoot and then the steady state. Table 4 summarizes peak accelerations and overshoots for all 10 ICCS-equipped vehicles during the speed-increasing phase. The table indicates that the acceleration of the lead vehicle is quickly dampened by downstream vehicles.

The above results imply that ICCS's that generate control instructions from data on both the headway and the speed of the front vehicle could achieve dampened perturbation quickly. Therefore, the use of the hypotheticalgap/speed controlled ICCS is not expected to result in perturbation problems.

1.5.1.2 For Gap-Controlled ICCS

Figure 6 is a deceleration-time plot for Vehicle 5, during a speed-reduction phase. The shape of this deceleration profile is typical for all vehicles in the traffic stream. It shows that the vehicle first undergoes a moderate deceleration rate at the start of the speed-reduction phase. This is then followed by a large overshoot, after which the deceleration/acceleration oscillate for a relatively long time before the steady state is reached. Comparison of Figure 6 with Figure 4 reveals that vehicles equipped with the gap-controlled ICCS could exhibit acceleration oscillations of the magnitude and duration not observed for vehicles equipped with the gap/speed controlled ICCS. Table 5 summarizes peak decelerations and overshoots for all 10 vehicles

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Table 4: **Peak** Accelerations and Overshoots for
Speed-Increasing Phase (Gap/Speed-Control ICCS)

Vehicle Order	Peak Acceleration	Overshoot
1	0.15	0
2	0.15	-0.01
3	0.13	-0.02
4	0.12	-0.03
5	0.11	-0.03
6	0.11	-0.04
7	0.11	-0.04
8	0.11	-0.05
9	0.11	-0.05
10	0.11	-0.05
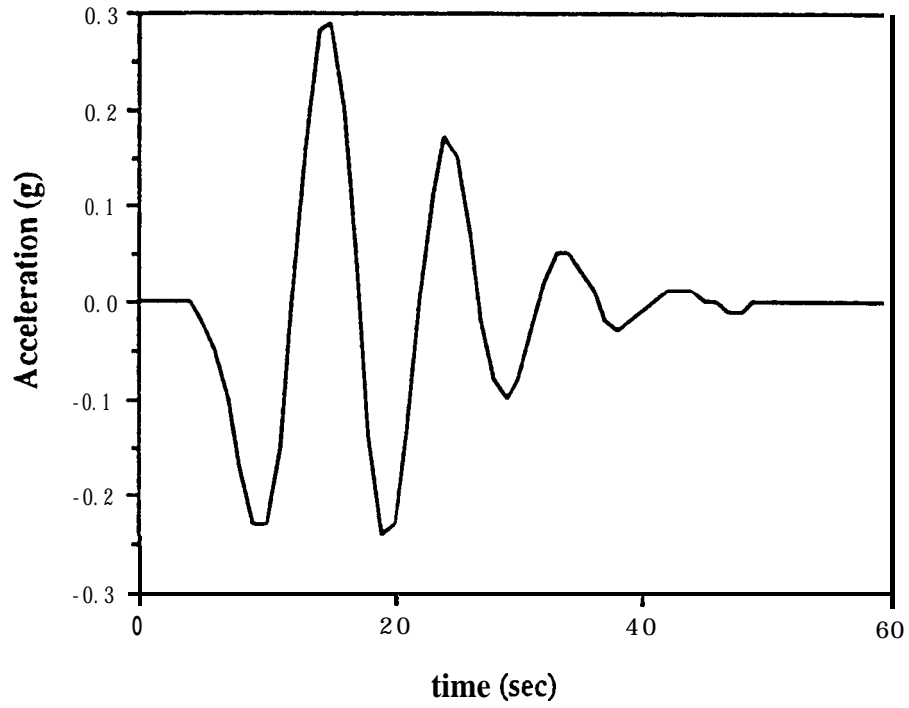
Figure 6: Deceleration Profile of Vehicle 5 Equipped With Gap
Controlled ICCS
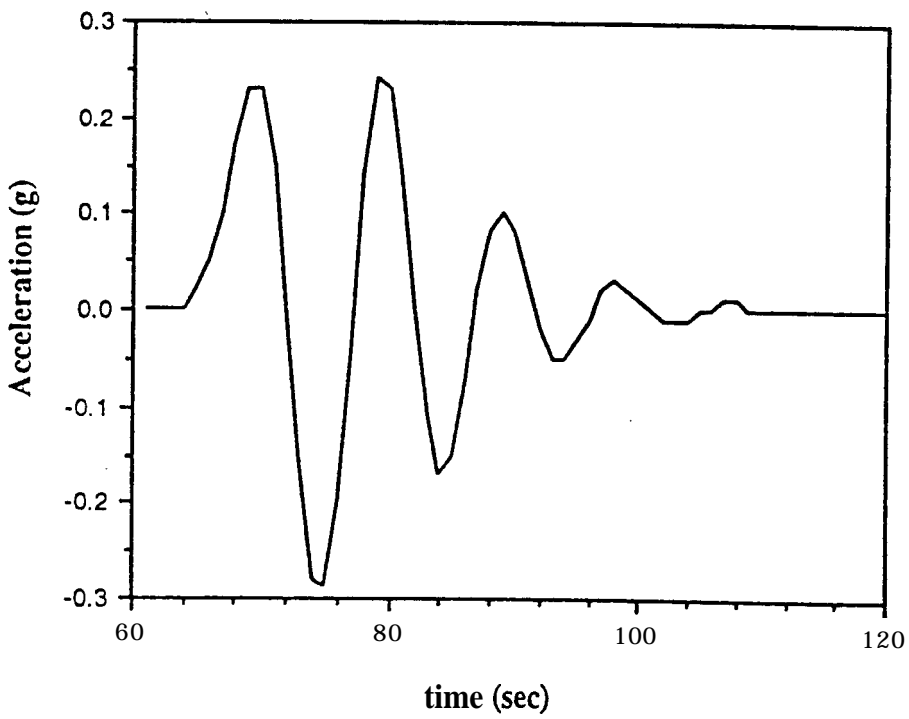
Figure 7: Acceleration Profile of Vehicle 5 Equipped With Gap
Controlled ICCS

Table **5:** Peak Decelerations and Overshoots
for Speed-Reduction Phase (Gap-Controlled ICCS)

Vehicle Order	Peak Deceleration	Overshoot (g)
1	-0.15	0
' 2	-0.17	0.06
3	-0.18	0.12
4	-0.21	0.20
5	-0.24	0.29
6	**-0.62***	*
7	**	**
8	**	**
9	**	**
10	**	**

* Deceleration rate is very high, a potential hazard

**Simulation is terminated

equipped with the gap-controlled ICCS during the speed reduction phase. The table indicates that the lead vehicle's deceleration could be significantly amplified by the downstream vehicles. Figure 7 shows an acceleration-time plot for Vehicle 5 during the speed-increasing phase. The shape of this acceleration profile is typical for all vehicles in the traffic stream during the **speed-increase** phase. As in the speed-reduction phase, acceleration oscillation could be quite pronounced in both the magnitude and the duration. Table 6 summarizes peak accelerations and overshoots for all 10 vehicles equipped with the gap-controlled ICCS during the speed-increasing phase. As with the speed-reduction phase, the lead vehicle's acceleration could be significantly amplified for the downstream vehicles.

The above results suggest that the use of the ICCS that generates control instructions from the headway input data alone requires further research and evaluations. Preliminary simulation results suggest that there may be perturbation problems associated with the use of this type of ICCS.

1.5.2 Impact of Hypothetical ICCS on Frequencies of Hard
Accelerations and Decelerations

Possible changes in acceleration characteristics of individual vehicles in the traffic stream adopting the hypothetical ICCS are investigated. The simulation uses the same lo-vehicle convoy. The simulation results for the traffic stream adopting lo-percent ICCS market penetration are compared with those for the traffic stream

Table 6: Peak Accelerations and Overshoots for
Speed-Increasing Phase (Gap-Control ICCS)

Vehicle Order	Peak Acceleration (g)	Peak Overshoot (g)
1	0.15	0
2	0.17	-0.06
3	0.18	-0.12
4	0.21	-0.20
5	0.24	-0.29
6	*	*
7	*	*
8	*	*
9	*	*
10	*	*

* Simulation is terminated due to potential hazard during the
speed-reduction phase (see Table 5)

without the ICCS (i.e., the existing traffic). For lo-percent market penetration, Vehicle 5 is assumed to be equipped, while the other 9 vehicles are not. Initial headway gaps among the 10 vehicles for the lo-percent market penetration are shown in Figure 8. Acceleration profiles for individual vehicles, in response to the lead vehicle changing its speed (first reducing from 40 to 30 **mph,** and then increasing to 40 mph), were estimated.

Figures 9 shows three acceleration-time plots for Vehicle 5, representing the following three cases:

* Traffic I: existing traffic in which the ICCS is not used on any of the vehicles in the convoy.
* Traffic II: lo-percent ICCS market penetration, in which Vehicle 5 is equipped with the gap/speed controlled ICCS.
* Traffic III: lo-percent ICCS market penetration, in which Vehicle 5 is equipped with the gap-controlled ICCS.

Figure 9 shows that Vehicle 5 under Traffic II and III exhibits less deceleration oscillation and smaller peak decelerations than Vehicle 5 under Traffic I, during the speed reduction phase. That is, the peak deceleration of Vehicle 5 under Traffic II is only about 0.45 times that of Vehicle 5 under Traffic I; the peak deceleration of Vehicle 5 under Traffic III is about 0.75 that of Vehicle 5 under Traffic I. These results imply that, relative to the existing traffic, the hypothetical ICCS could help to reduce frequencies of hard decelerations for equipped vehicles, when responding to stopping traffic ahead. During the **speed-**increase phase, differences in peak accelerations of Vehicle 5
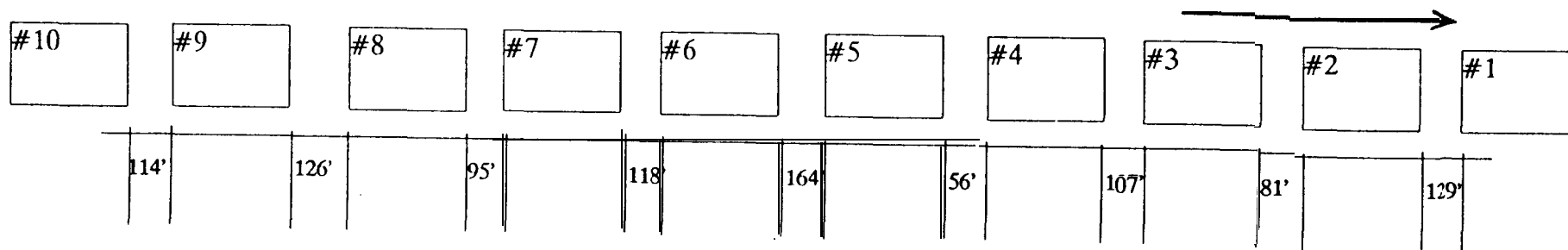
31

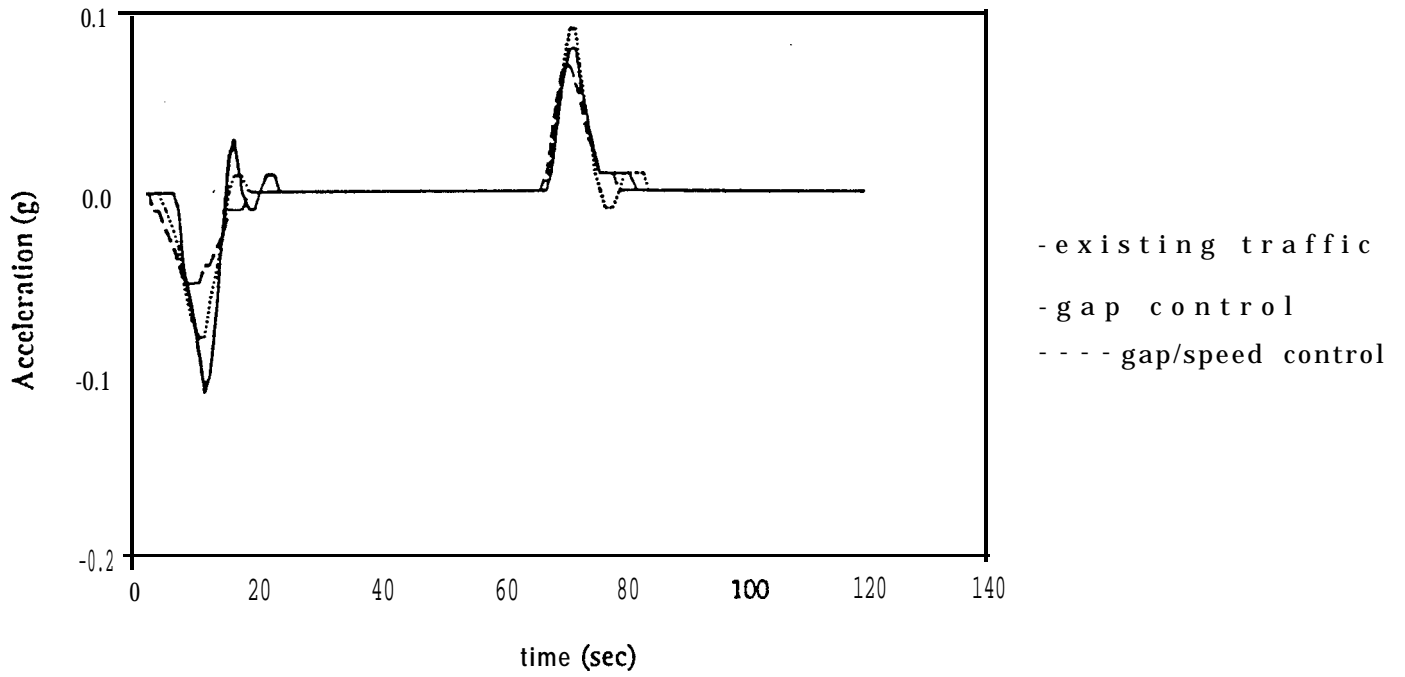Fig 8. Headway-Gap (Feet), 10-Vehicle Stream

Figure 9: Acceleration/Time Plots for Vehicle **5** (10% Market
          Penetration)

among Traffic I, II, and III are small.

1.5.3 *Impact of Hypothetical ICCS on Speed Harmonization*

The simulation uses the same lo-vehicle convoy. The convoy **adopting 10-percent** ICCS market penetration is compared with the convoy without the ICCS. Initial headway gaps for the convoy adopting lo-percent ICCS market penetration are as previously shown in Figure 8. Figure 10 shows three speed-time plots for Vehicle 5, for Traffic I, II, and III. Under Traffic I, Vehicle 5 is not equipped with the ICCS; for Traffic II and III, Vehicle 5 is equipped with the gap/speed controlled and gap-controlled ICCS respectively. Examination of Figure 10 indicates that:

* Relative to the existing traffic situation, the gap/speed controlled ICCS could help the equipped vehicle to converge to the desired steady-state speed quickly with little speed fluctuation.

* The gap-controlled ICCS does not appear to reduce speed fluctuation of the equipped vehicle, relative to unequipped vehicles under the existing traffic.

Figure 11 shows four plots of the mean speed (among the 10 vehicles in the convoy) versus time, for four levels of market penetration of the gap/speed controlled ICCS (10, 20, 40, and 100 percent). The figure indicates that as the market penetration of the gap/speed controlled ICCS increases, this entire convoy could converge to the desired steady-state speed more quickly and with less speed fluctuation. Therefore, a higher usage rate of the

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Control rule

-existing traffic

——— gap control
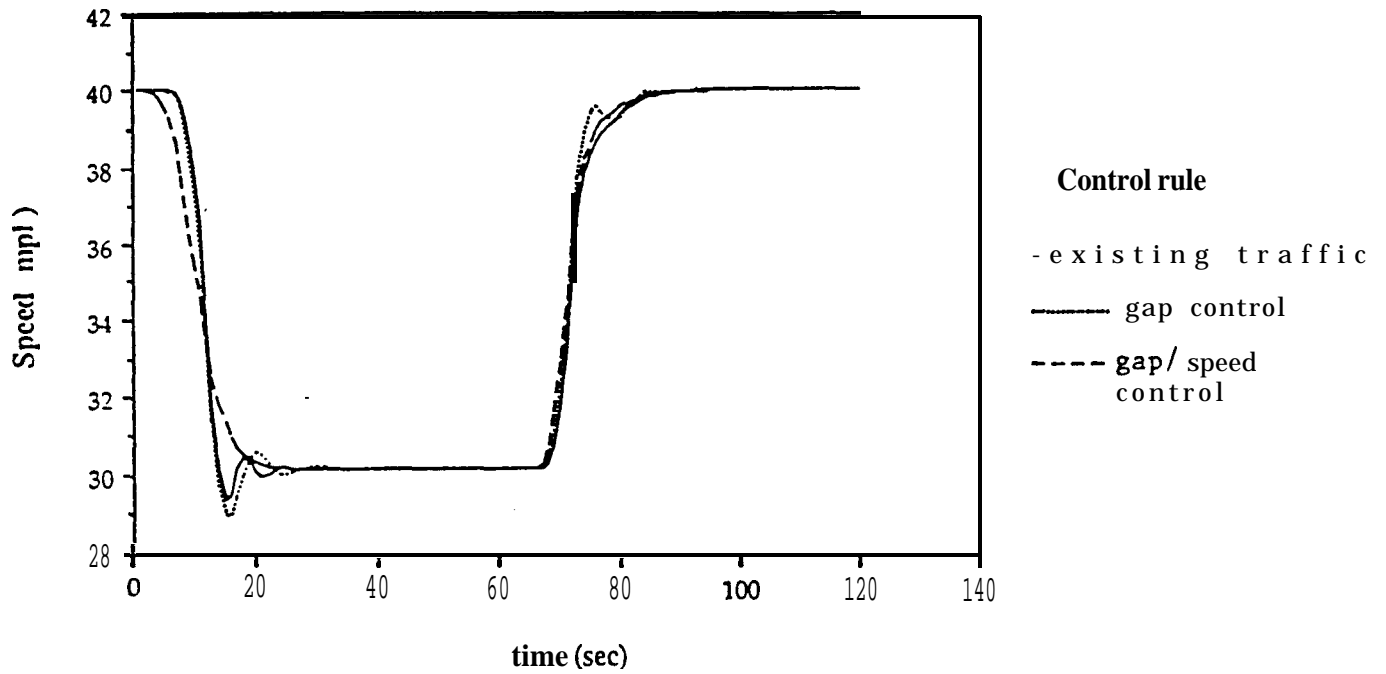
- - - - gap/ speed
control

Figure 10:   Speed/Time   Plots   for   Vehicle   **5**   (10% Market
Penetration)

market penetration

——— 10 %

········· 20 %

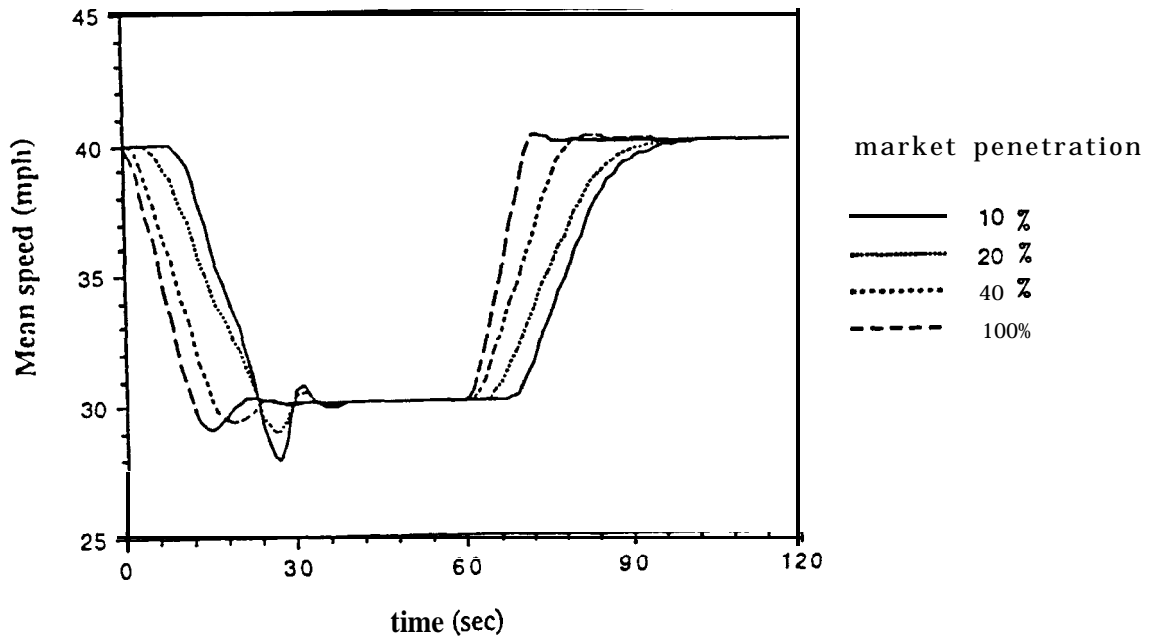········· **40** %

- - - - - **100%**

Figure 11:   Mean Speed versus Time of lo-vehicle **Stream** for
Various Market Penetration (Gap/Speed Controlled
ICCS)

gap/speed controlled ICCS could result in a higher degree of speed harmonization among all vehicles in the traffic stream.

Figure 12 shows four plots of the standard deviation of speeds (among the 10 vehicles) versus time, for the four levels of market penetration for the gap/speed controlled ICCS. This figure indicates that the standard deviation of speeds decreases as the market penetration increases. This lends support to the above finding that as more and more vehicles are equipped with the gap/speed controlled ICCS, speed harmonization for all vehicles in the traffic stream could be further enhanced.

1.5.4   *Impact of Hypothetical ICCS on Headway Characteristics*

Simulation results for the convoy adopting lo-percent ICCS market penetration are compared with those for the convoy without the ICCS. Figure 13 shows three plots of headway-gap versus time for Vehicle 5, under Traffic I, II, and III. Under Traffic I (the existing traffic), Vehicle 5 responds to the lead vehicle's **speed-**reduction by immediately exhibiting some oscillation in the headway-gap size, which becomes as low as 18 feet (or less than 0.75 seconds in equivalent time-headway for 30 mph). After this initial oscillation which lasts for about 10 seconds, the **headway-**gap reaches a stable value of 20 feet (or about 0.8 seconds in equivalent time-headway for 30 mph). From the traffic safety perspective, both **18-foot** and **20-foot** headway gaps may be deemed **"less** safe" for vehicles under driver control for some drivers. When the lead vehicle speeds up to 40 mph, this Vehicle 5 achieves

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market penetration
10 %
20 %
40 %
100 %
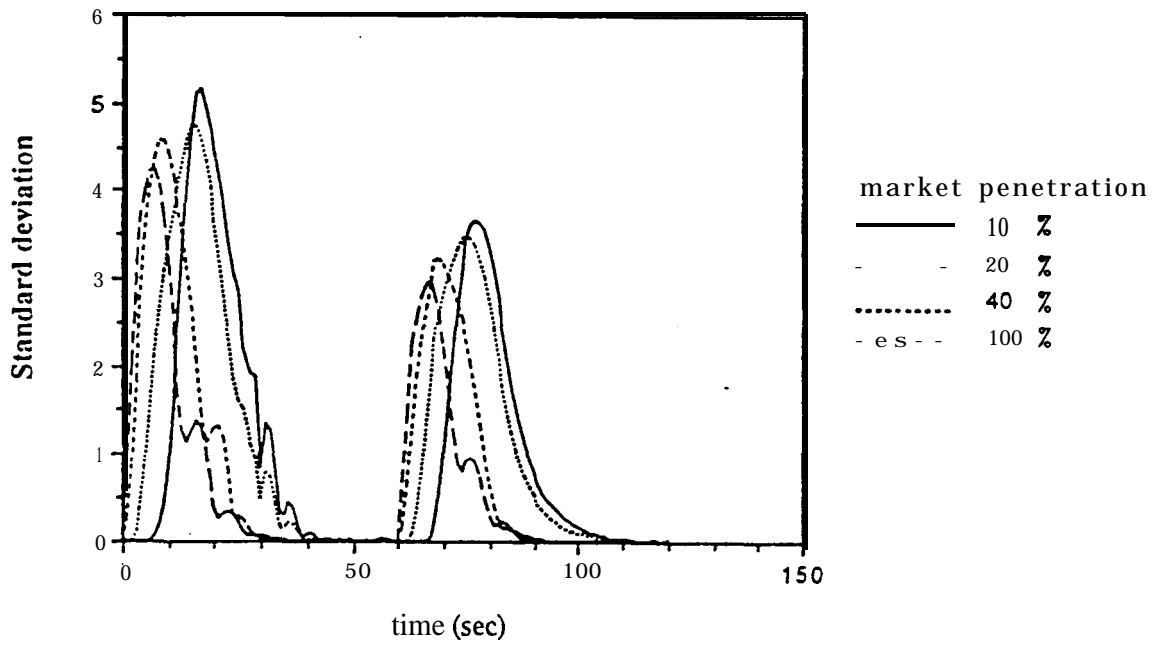
Figure 12:   Standard Deviation of Speeds of **10-Vehicle** Stream
                  for   Various   **Market**   Penetration   **(Gap/Speed**
                  controlled **ICCS)**

Control rule

——— existing traffic

·········· gap control
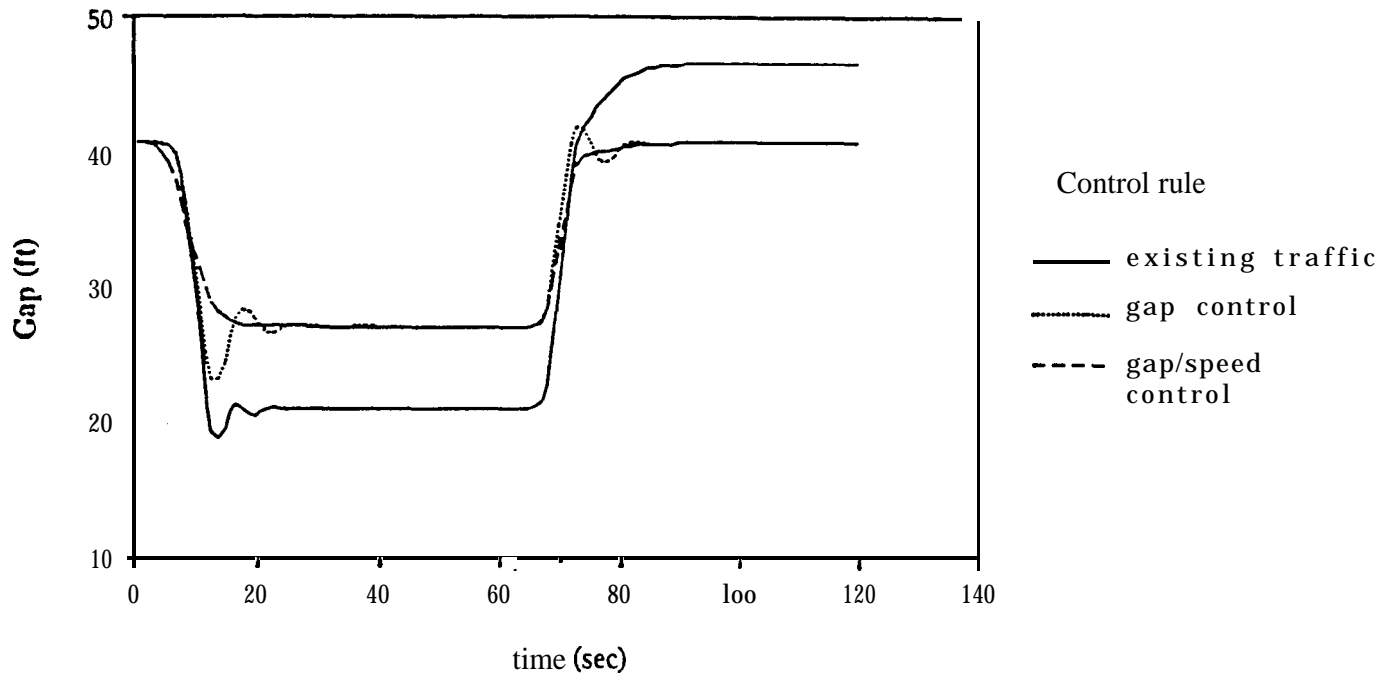
– – – gap/speed control

Figure 13:   Headway-Gap Profiles for Vehicle 5 (10% Market
                  Penetration)

headway-gap of 47 feet (or about 1.1 second in equivalent **time-**headway for 40 mph).

Vehicle 5 under Traffic II (equipped with the gap/speed controlled ICCS) responds to the lead vehicle's speed-reduction phase by'quickly converging to headway-gap of 26 feet (i.e., the nominal headway-gap), with little fluctuation in the gap size. This Vehicle 5 behaves similarly in responding to the lead vehicle speeding up to 40 mph. Under Traffic III, Vehicle 5 (equipped with the gap-controlled ICCS) exhibits some initial fluctuation in the headway-gap size, in response to the lead vehicle' speed changes. For example, it takes Vehicle 5 about 40 seconds to finally reach the steady-state nominal headway;   and for about 4-5 seconds initially, this vehicle could undergo headway smaller than the nominal headway.

The above results imply that:

*   The gap/speed controlled ICCS could help equipped vehicles to converge quickly to the nominal headway, in response to the lead vehicle's speed changes, with little fluctuation in the headway-gap size. This in turn could help to reduce the occurrence of small **"less safe"** headway (or "tail-gate"), and to enhance traffic safety.

*   The gap-controlled ICCS appears to exhibit some initial fluctuation in the headway-gap size, in responding to the lead vehicle's speed changes. Therefore, the use of the gap-controlled ICCS in the highway environment requires further research and evaluation.

1.6 Impact of Hypothetical ICCS on Highway Capacity

At least one prior study (Broqua et al, 1991) attempted to investigate the impact of ICCS's on the highway capacity, using microscopic vehicle simulation. Broqua et al assessed changes in the capacity of two-lane freeways, by examining four scenarios made up of two levels of ICCS market penetration (20 and 40 percent) and two ICCS nominal headway rules (time-headway of 1 and 2 seconds). From their simulation results, Broqua et al reported that the capacity impact of ICCS's depended on both the ICCS market penetration and nominal headway rule, as follows:

* For ICCS's using the 1-second nominal headway rule, the flow rate could increase with a higher ICCS usage rate. Specifically, 6-percent and 13-percent increases in the flow rate, relative to the existing traffic situation, were reported for the market penetration of 20 and 40 percent, respectively.

* For ICCS's using the 2-second nominal headway rule, lower flow rates could result. Specifically, 3-percent and 6-percent decreases in the flow rate were reported for the ICCS market penetration of 20 and 40 percent, respectively.

The nominal headway gaps for the hypothetical ICCS (in feet) of Table 1 can be converted into equivalent time-headway (in seconds). When this is done assuming that the vehicle length is 15 feet, it is found that nominal time-headway for the hypothetical ICCS ranges from 0.9 to 1.1 seconds for speeds between 30 and 55

35

mph. At 70 mph, the nominal time-headway is about 1.8 seconds. By interpolating the findings reported by Broqua et al, one can infer that the use of the hypothetical ICCS could result in some increase in the flow rate for speeds up to 55 mph. The magnitude of this increase depends on the ICCS market penetration.

1.7 Summary of Chapter One

ICCS's are capable of regulating vehicle speed, acceleration, and headway, without taking over driving tasks from the drivers. Evidence indicates that ICCS's could become available for use on the road in the foreseeable future. Appeals of ICCS's include: the ease of adoption; usage flexibility (voluntary adoption, and drivers can choose to turn the device on/off); and relatively less-complicated legal and liability implications because ICCS's are extensions of the existing cruise control device. In addition, the use of ICCS's would allow drivers to become familiar with using driver-assisted devices, an initial step toward studying driver acceptance of more-advanced longitudinal control systems.

This study attempts to evaluate potential impacts of a hypothetical ICCS on traffic accidents and some traffic-operation characteristics affecting safety.   In this regard, relative performance between the ICCS controller that requires input data on both the headway and speed of the front vehicle (i.e., gap/speed controlled ICCS) and the ICCS controller that requires only input data on the headway (i.e., gap-controlled ICCS) is also evaluated.

The hypothetical ICCS is capable of regulating vehicle speed

and headway through both throttle and brake controls. It can achieve maximum acceleration and deceleration rates of **0.3g** and **-0.3g,** respectively. In addition, it can also provide warnings to the driver when it estimates that the driver has to also apply extra evasive actions in order to avoid the impending collision. A nominal headway rule for this hypothetical ICCS is shown in Table 1. Principal findings from the evaluation include:

1. The hypothetical ICCS could be useful as a countermeasure for up to 7.54 percent of all accidents that result in fatalities or injuries. It is particularly effective as a countermeasure for **rearend** crashes.

2. Preliminary results from the simulation of a lo-vehicle convoy indicate that the use of the hypothetical ICCS that requires data on both the headway and the speed of the vehicle in front as the control input (i.e., gap/speed controlled ICCS) is not expected to result in traffic perturbation problems.

3. Preliminary results from the simulation of the lo-vehicle convoy indicate that the hypothetical gap/speed controlled ICCS could reduce frequencies of hard accelerations and decelerations for equipped vehicles, enhance speed harmonization among vehicles, and enable equipped vehicles to achieve **"safe"** headway quickly, in response to the lead vehicle changing its speed. Higher usage rate of this hypothetical ICCS is found to result in greater benefits.

4. Based on a synthesis of the literature, it is expected that the use of the hypothetical ICCS defined in this study could result in some increase in the flow rate, for average highway

speeds of up to 55 mph. The extent of this increase depends on the ICCS market penetration.

The above results are based on two implicit assumptions: (i) the use of the hypothetical ICCS does not result in changes in driver behavior; and (ii) drivers are able to share tasks with the ICCS as intended.   Research is clearly needed to verify such assumptions, and to advance the understanding of the feasibility of large-scale use of **ICCS's.**   Future research should include the following:

* ***** Research is needed to assess the ability of drivers to share tasks with **ICCS's** in normal and emergency situations, as well as implications of such task-sharing.
* * Research is needed to determine effects of the transfer between automated headway control and manual headway control on drivers.
* * Research is needed to identify and address potential legalandliability issues/implications concerning **large-**scale use of **ICCS's.**

Chapter Two

Section One

PHASE 2A: EARLY DEPLOYMENT OF LONGITUDINAL CONTROL SYSTEMS WITH PLATOONING OPERATION IN TRANSITWAYS (INDIVIDUAL-VEHICLE DISPATCH)

This chapter assesses potential capacity benefit of, and special infrastructure requirements for, deploying longitudinal control systems with close-formation platooning in one-lane transitways. This chapter consists of three sections. Section One focuses on the evaluation of a hypothetical system for Phase 2A. The evaluation of a hypothetical system for Phase 2B is presented in the next section. The final section presents the assessment of net capacity benefit adjusted for the right-of-way requirement for the systems of Phase 2A and Phase 2B.

2.1 Overview of Longitudinal Control Systems

Vehicle longitudinal control systems require measurements on both vehicle headway and closing/opening rates as input to generate control instructions for automatic throttle and braking controls. Shock-wave dampening could be achieved by means of inter-vehicle communication systems, which enable trailing vehicles to start and stop at essentially the same time as leading vehicles. In this way, longitudinal control systems could allow vehicles to operate in close-formation platoons. Methods for achieving longitudinal control have been explored by many prior studies. Fenton et al. (1981) developed and tested a longitudinal control system using

1965 Plymouth passenger vehicles. Communications between vehicles, as well as between vehicle and a wayside computer, were accomplished by using **"off-the-shelf"** commercial products.   The vehicle controller used was Intel 8085A based micro-computer. Tests were conducted at maximum vehicle speed of 86.4 km per hour (55 mph).   Observed velocity errors were reported to be within ± 0.06 meters per second, while the maximum position error was 1.0 meter.

There is considerable research on vehicle longitudinal control systems at the California's PATH program.   The following studies are some of such research efforts. Hauksdottir (1985) designed a controller for operating speeds up to 108 km per hour (70 mph) using a 1969 model Plymouth sedan, and reported that position errors were 0.63 meters for on-ramp maneuvers and 0.15 meters for mainline maneuvers. **McMahan** et al. (1990) developed a controller using a vehicle nonlinear model that incorporated vehicle aerodynamic resistance and tire-road friction. The simulation of two-vehicle platoons yielded position errors up to 4.5 cm (with respect to 1 meter spacing) for speed of 88 km/h (55 mph). Tests under varying operating conditions indicated that inter-vehicular spacing of 1 meter could be maintained with position errors no more than 4.7 cm at 55 mph. Frank et al. (1989) performed simulations of 15-vehicle platoons using a linear vehicle model. Velocity errors of less than 4 percent for speeds up to 30 meters per second (or 67 mph) were reported. Sheikholeslam et al (1990) performed simulation of platoons consisting of 4, 11, and 16 identical

vehicles. The simulation results indicated that deviations from the vehicles' pre-assigned position were less than 0.22 m (0.67 feet). The authors reported that, by choosing appropriate controller coefficients, deviations in vehicle spacing from their steady-state values were not magnified from the front to the end of the platoon. Sheikholeslam et al (1991) developed control laws for longitudinal control in the event of loss of communication between vehicles. For 15-vehicle platoons, a maximum vehicle position error less than 0.08 meters (for nominal spacing of 1 meter) was reported, suggesting that the controller is likely to be robust in the event of failures of the communication systems within platoons. At the present time, on-the-road tests of two-vehicle platoons are being conducted at PATH, using a non-linear sliding mode controller. These tests are aimed at validating results from simulation studies.

Components of Longitudinal Control Systems

Major components of longitudinal control systems include the following:

o Sensins systems: Vehicle sensors measure the status of current and preceding vehicles -- headway, speeds, accelerations, and steering angles. Onboard transmitters transmit signals to the preceding vehicles. Headway can be determined by measuring the time it takes for signals to travel from the transmitter to the receiver. Vehicle speeds, accelerations, and steering angles can be measured by speedometers, accelerometers, and turn angle

sensors. **Antenna servo** mechanism can be used to regulate the antenna direction toward the object. These sensors are all commercially available. Sensors for measuring headway and closing rates could use radar or laser signals. Prior studies (e.g., **Pollard, 1988;** and Stein, 1989) reported that performance of existing radar systems needed to be improved for highway deployments. Tests of laser systems have not been widely reported.

o   <u>Data Processing Unit</u>:   Information detected by vehicle sensors, as well as that transmitted from other vehicles, is directed into the **onboard** data processing unit. This unit processes the information, and then generates instructions to the braking system and/or propulsion system (throttle). Another important component of the data processing unit is the controller unit, which is embedded within the logic of the data processor. Sliding mode controllers using a non-linear vehicle model is being investigated at PATH (Chang et al, 1992).

o   <u>Actuators</u>:   Vehicle actuators include braking and acceleration control units, operated by electro-mechanical servo mechanisms. Stopping and decelerations are accomplished by the brake servo system applying brake pressure to the wheels. Vehicle accelerations are achieved by opening the throttle and the propulsion servo mechanism supplying more fuel. Experiments and tests conducted at PATH to date have used commercially available actuators.

o   <u>Communication systems</u>:   Communication systems transmit information between vehicles, as well as between wayside and

vehicles. Ultrasonic, optical (infra-red), and various radio links are among possible communication technologies reported in the literature.   Ongoing research on communication systems at PATH includes the feasibility assessment of communication systems using radar signals to transmit information between vehicles (Chang et al, **1992),** and the development of detailed communication layers for longitudinal control systems (Hsu et al, 1991).

In addition to the above-mentioned devices, the implementation of longitudinal control systems is likely to also require the integration of vehicle lateral control systems (Sanders et al, 1967;   Carson et al, 1978;   Fenton, 1970;   Parsons et al, 1988; Zhang et al 1988;   Peng et al, 1990;   Peng et al **1991),** to perform vehicle steering and for safety reasons. Considerable research in lateral control systems has also been on going at the California's PATH program.

2.2   Early Deployment in Transitways

In Phase **2A,** longitudinal control systems with close-formation platooning could be demonstrated in one-lane transitways, which usually have controlled access and egress (in the form of at-grade slip ramps or special grade-separated ramps).   All vehicles are required to be properly equipped to enable them to engage in **close-**formation platooning operation while traveling in the transitway. For close-formation platooning, vehicles within any one platoon would maintain very small within-platoon headway. A gap of about 3 feet has been suggested by Shladover (1978 and **1991),** with a

rationale that thissmallwithin-platoon headway would minimize the seriousness of collisions among vehicles *within* platoon in case of system failures. Headway between successive platoons, on the other hand, would be large enough to prevent collisions *among* different platoons'in case of system failures. Vehicles would engage in close-formation platooning operation only while traveling within the transitway. Before leaving the transitway, vehicles within platoons will separate from one another, and automatic control will be shifted to driver control.

Transitways are selected for demonstrating longitudinal control systems with close-formation platooning for the following reasons:

(a)   Longitudinal control systems with close-formation platooning require **all** vehicles to be properly equipped with devices that are in a good working order. The permanent barriers and controlled access of transitways make it relatively easy to set up facilities to screen vehicles and check the operating status of the equipment before they are allowed to enter the transitways. In this way, unqualified vehicles can be prevented from inadvertently entering the transitway.

(b) The access control of transitways assures that any system mishaps would be contained within the transitway, and not affect vehicles in the mainline.

(c)   Prior to implementing the new system, it may be necessary to conduct extensive system testing on the facility. It is relatively easy to close transitways for testing during off-peak

periods without causing serious traffic disruption.

2.3 System Concept for Phase 2A

For the evaluation purpose, this study defines a hypothetical system concept for Phase **2A**, for early deployment in one-lane transitways. The transitway can be divided into four contiguous sections (Figure 14): access ramps (complete with vehicle check stations at the beginning of the access ramps); transition or merge section; main section (or the transitway proper); and egress section.

All vehicles wishing to use the transitway must pass through vehicle check stations. The check routines (which could include both static and dynamic tests) could verify the operating status of components such as the sensing systems, communication systems, data processing unit and **onboard** computing mechanisms, and braking and propulsion actuators. All devices are to be activated before vehicles go through the check stations. Vehicles that pass the inspection will proceed along the access ramp toward the merge section. Those failing the inspection will be guided out of the transitway. Research is needed to configure automated vehicle check facilities. At this time, it suffices to assume that vehicles could probably pass through check stations at a relatively low speed (possibly about 25 mph).

After leaving the check station, successive vehicles (that are of the same vehicle type) on each access ramp could form a **close-**formation platoon right away, before they reach the merge section.

access ramps

merge section

main section

gress section

egress section

egress ramps

$\mathcal{C}$: vehicle check station
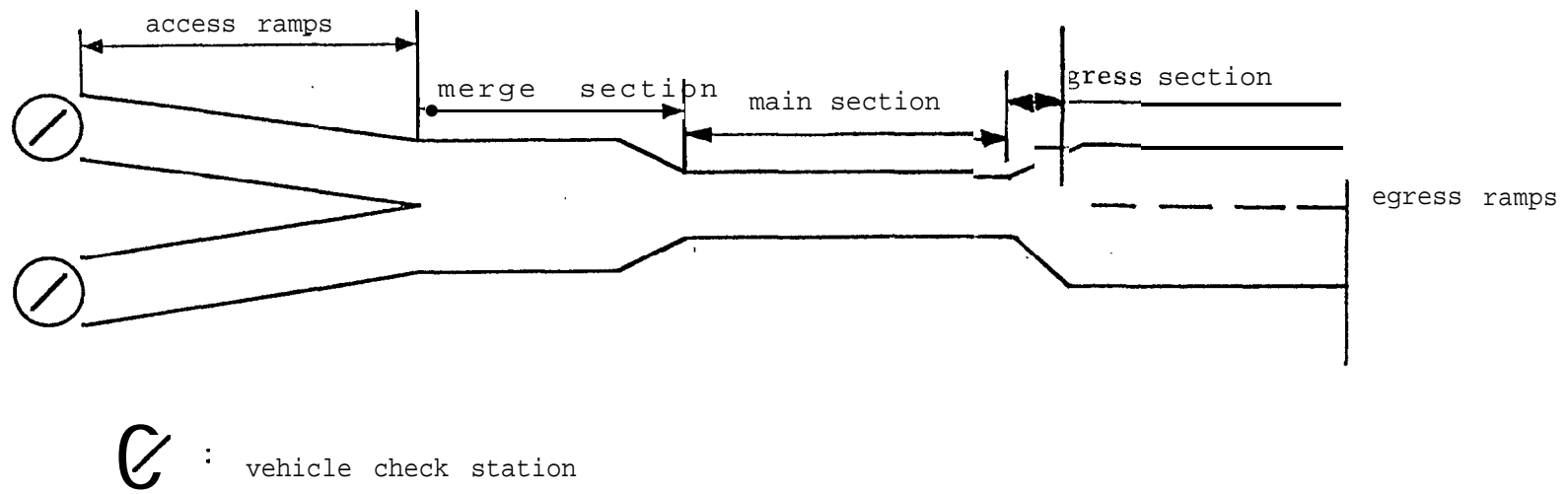
Figure 14:   A Conceptual Structure of Advanced 1-Lane **HOV**
                Facility Under Phase 2A

For safety reasons, it may be desirable in early deployment of close-formation platooning not to allow successive vehicles that are of different vehicle types to form a close-formation platoon with one another. This is because within any one platoon, vehicles could collide with one another in case of system failures, due to the very small within-platoon gap. Shladover (1978) showed that collision speeds association with collisions of vehicles within a platoon would be quite low due to the very small within-platoon gap. Nevertheless, collisions involving vehicles of vastly different dimensions could lead to undesirable secondary crash events (e.g., underrides, overrides, bumper bars of the larger vehicles striking windscreens of the smaller vehicles, etc). Such secondary crash events by themselves could result in injuries to vehicle occupants, regardless of the crash speed involved. Therefore, different vehicle types would form their own platoons, and maintain at least the nominal inter-platoon gap from successive platoons.

Platoons and individual vehicles from the two access ramps will merge as they are about to enter the main section of the transitway. This merging will take place in the merge section. There are a number of merging possibilities, depending on the arrivals at the merge area, as follows:

* Two platoons from the two access ramps that are of the same vehicle type could merge into one larger platoon
* An individual vehicle from one ramp could join a platoon that has the same vehicle type from the other ramp

*   Individual vehicles that are of the same vehicle type
        from the two ramps could form a platoon
  *   No platoon is formed because individual vehicles from the
   two ramps are of different types.

The 'merging rule is diagrammatically shown in Figure 15.   The merge section can be 600-800 feet long.

2.3.1 Nominal Inter-Platoon Gap

Safety is critical in close-formation platooning operation, both in normal operation and in case of vehicle or system failures. The gap maintained by successive platoons (**i.e.,** the clear distance separating successive platoons) could influence the probability of collisions between different platoons in case of system failures, and, therefore, is an important system specification.   In case of system failures, collisions between platoons (if occur) could have potentially catastrophic consequences, because they could involve a large number of vehicles crashing into one another at relatively high collision speeds.   Shladover (1978) reasoned that collisions between platoons should be prevented, by specifying nominal **inter-**platoon gaps for close-formation platooning that are large enough to enable trailing platoons to come to a safe stop should the lead platoon suddenly fail or abruptly stop. Nominal inter-platoon gaps adopted for the hypothetical system of Phase 2A are shown in Table 7. Methodology for computing these nominal inter-platoon gaps is presented in Appendix A.   Table 7 is based on the following assumptions:

Figure 15

First Come/First Merge Rule
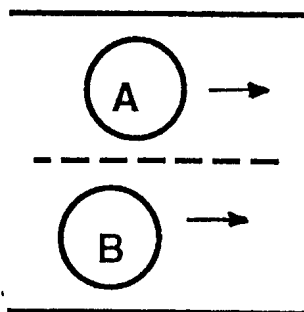
A	B	Maneuver
car	car	Form one platoon
car	van	Accel A
car	bus	Accel A
van	van	Form one platoon
van	car	Decel B
van	bus	Accel A
bus	bus	Form one platoon
bus	car	Decel B
bus	van	Decel B

Table 7: . Nominal Inter-Platoon Gap Requirement
for Platooning Operation

Speed (mph)	Nominal Inter-Platoon Gap* (ft)
25	64
30	88
35	118
40	152
45	190
50	232
55	278
60	328
65	382
70	440

* Values assume: vehicle fails at -1.2 g's; following platoons
  decelerate at -0.3 **g's;** and electrical/mechanical delay for
  longitudinal control systems is 0.3 seconds.

*   In case of system failures, the failed platoon is assumed
     to decelerate at a rate up to -1.2 g, a very high
     deceleration rate.   Such a rate is not observed even
     during emergency panic braking, and may represent an
 unusual incident (e.g., the engine or extremely heavy
     objects falling off a vehicle).

*   Trailing platoons are assumed to respond to the failed
     platoon with deceleration rates of up to 0.3 g, a
     comfortable deceleration rate for most drivers.

*   Electronic/mechanical delay time of longitudinal control
     systems is assumed to be 0.3 seconds.   This value is
     considered conservative for advanced vehicle control
     systems, in which a target value closer to 0.1 seconds
     has been typically reported.   Nevertheless, this study
     intentionally airs on the conservative side by adopting
     a value of 0.3 second for the analysis of Phase-2
     systems.   This is because the safety of close-formation
     platoons is very critical.

2.4   Estimation of Flow Rate due to Adopting Phase-PA System
     The flow rate within one-lane transitways, as a result of
deploying close-formation platooning, is estimated by simulation.
The following is the data input for the simulation:

Transitway Traffic Mix
     The simulation assumes that cars, LDV's, and buses are users

of the transitway: The simulation is performed for the traffic comprised of a fixed hourly volume of buses of 45 buses per hour, and the ratio of cars to LDV's of 8.5 : 1.5.

Speed and Acceleration Capabilities of Transitway Vehicles

Acceleration capabilities of cars, LDV's, and buses assumed for the flow-rate analysis are shown in Table 8.

Transitway Travel Speed

A range of transitway travel speeds are simulated. They range from 35 to 65 mph, with an increment of 5 mph.

2.4.1 Simulation Procedure

The simulation involves the following steps:

1. For each level of the hourly transitway demand (i.e., the number of vehicles per hours arriving at the transitway), vehicle arrival intervals at a check station are randomly generated from Shifted Negative Exponential Distribution that has the minimum headway of 0.6 seconds.

2. After passing through the check stations, vehicles follow the maneuvers as described in Section 2.3. Status of all vehicles is updated every 0.1 seconds.

3. The simulation is conducted for 60 minutes, after which the traffic density (the number of vehicles per mile of the transitway) is calculated. Flow rate is then calculated as the product between the traffic density and the transitway speed.

Table 8
Acceleration Capabilities of Cars, LDV's, Buses

Vehicle Type	Time to Accelerate From Zero to 60 mph (seconds)
Cars	9.0
LDV's	18.0
Buses	40.0

4. Steps 1 through 3 are then repeated for a higher level of transitway demand, until no higher flow rate in the transitway is achieved.

2.5 Simulation Results

The estimated flow rate in one-lane transitways as a result of deploying the hypothetical Phase-2A system is shown in Table 9, by the transitway speed. The table indicates that the estimated flow rate is sensitive to the transitway speed. For example, a flow rate of 3,850 vehicles per hour (vph) is possible at a speed of 35 mph. The estimated flow rate then decreases by an average of 11 percent for every 10 mph increase in the transitway speed. At 55 mph, the estimated flow rate is found to be 3,090 vehicles per hour.

Field data collected for existing one-lane transitways generally indicate that practical capacity of one-lane transitways is about 1,500 vehicle per hour; and that at 55 mph, the observed flow rate is about 1,200 vph. Therefore, the results of Table 9 suggests that the flow rate in one-lane transitways at 55 mph, due to the deployment of the hypothetical Phase-2A system, could be 2.6 times the currently observed flow rate. Flow rates at 55 mph or higher speeds are of interest for transitway operation, because transitways are aimed to enable high-occupant vehicles to travel at speeds higher than that prevailed on the freeway mainline during congestion.

The estimated flow rate for the Phase-2A system is sensitive

Table 9: Estimated Flow Rate for Phase-2A System

Speed (mph)	Flow Rate (vph)
35	3850
45	3520
55	3090
65	2710

to variation in the traffic mix (i.e., relative proportions of buses, cars, and LDV's). The simulation results reveal that, relative to the above-mentioned traffic mix, more-diverse traffic mixes (i.e., more buses and LDV's but fewer cars, such as 90 buses per hour'with the ratio of cars to LDV's of 7.0 : 3.0) could yield lower estimated flow rates. On the other hand, less-diverse traffic mixes (i.e., fewer buses and LDV's but more cars, such as 30 buses per hour and the ratio of cars to LDV's of 9.0 : 1.0) could yield higher estimated flow rates. This sensitivity of the estimated flow rate to variation in the traffic mix is attributable to the fact that the less diverse traffic generally yields higher average platoon size, which in turn leads to a higher traffic density (because less road space is taken up by large inter-platoon gaps). This results in a higher flow rate.

Note:

In the deployment of the hypothetical Phase-2A system, the requirement prohibiting the three different vehicle types from forming the same platoon with one another results in a smaller average platoon size than if cars and LDV's are allowed to form the same platoon. Other things being equal, smaller average platoon sizes yield lower flow rates. If cars and LDV's were allowed to form the same platoon, the estimated flow rate for one-lane transitways, due to the deployment of Phase-2A system, could be substantially higher than the flow rate shown in Table 9. Because the transitway's traffic is made up almost entirely of cars and

LDV's, allowing cars and **LDV's** to form the same platoon could result in the platoon size becoming indefinitely large. Therefore, if cars and **LDV's** were allowed in the same platoon, a limit on the maximum allowable platoon size would have to be specified. Then, the estimated flow rate would depend on this maximum allowable platoon size. For example, the platoon size of 12 vehicles could result in the estimated flow rate within one-lane transitways of about 5,000 vehicles per hour (at 55 mph), and even higher flow rates for the platoon size greater than 12 vehicles per platoon.

2.6 Geometric Requirements for Egress Section

The egress section is located at the end of the main section (see Figure 14). It enables close-formation platoons to get ready to leave the transitway. Within this egress section, vehicles in platoons will separate from one another, and the automated control will be shifted to driver control. The egress section for one-lane transitways can consist of more than one channel. The length and the number of egress channels required are determined below.

2.6.1 Platoon Disengagement Rules

At the end of the main section, each platoon could be guided into an egress channel, possibly by reference markers embedded in the pavement. Once inside the egress channel, vehicles within platoons would start breaking away from one another. There are numerous possible strategies for platoon disengagement. This study initially considered three strategies, as follows:

o <u>Rear-to-Front Disengagement</u>:   This rule involves the last vehicle of the platoon starts breaking off first by decreasing its speed, as soon as it enters the egress channel.   Then, the disengagement proceeds toward the front of the platoon.

o <u>Front-to-Rear Disensagement</u>:   This platoon disengagement starts with the frontmost vehicle of a platoon breaking away first by increasing its speed, as soon as it enters the egress channel. Then the process proceeds toward the rear of the platoon.

o <u>Front/Rear Disensasement</u>:   This involves vehicles at both ends of the platoon simultaneously breaking away from the platoon. As soon as the first vehicle enters the egress channel, it will start to accelerate to initiate the platoon break-off.   Then the second vehicle will do likewise, and so on.   In the meantime, as soon as the last vehicle enters the egress channel, it will decelerate to start breaking away from the platoon.   Then the second to the last vehicle will do likewise, and so on.   Therefore, the platoon disengagement proceeds from both ends toward the middle of the platoon.

Of the above three disengagement rules, the Front/Rear Disengagement rule is the most efficient, in terms of the time and distance it takes for platoons to complete the disengagement. Therefore, only this rule is used for the determination of the length and the number of the egress channels.   The other two rules are excluded from further consideration.   Further detail of the

platoon disengagement rule is described below.

Let the transitway speed be denoted by v_0:

1. As soon as the frontmost vehicle (Vehicle Xl) enters the egress channel, it starts to accelerate away from the platoon until it achieves a certain time-headway, h,, from the next vehicle. h_f is the desired time-headway (in seconds) under driver control. At this time, speed of Vehicle **X1** will be v_1 $(v_1 > v_0)$. Vehicle **X1** will maintain this headway, h_f, until the shift from automated control to driver control is complete.

2. As soon as the last vehicle of the platoon (Vehicle **Z1**) enters the egress channel, it starts to decelerate away from the platoon, until it achieves the headway of h_f with respect to the second last vehicle. At this time, speed of Vehicle **Z1** will be v_2 $(v_2 < v_0)$.

3. Next vehicles at both ends of the platoon follow similar actions, as the platoon break-away proceeds from both ends toward the middle of the platoon.

4. After all vehicles in the platoons are separated from one another, all vehicles will begin to adjust their speeds toward v_0 again. That is, vehicles cruising at v_1 will reduce speed from v_1 toward v_0, while those cruising at v_2 will increase the speed toward v_0. Once this process is complete, the vehicles will start to shift from automated control to driver control. At the moment when the manual control is achieved, all the vehicles would have time-headway around h,. The rationale for having all vehicles achieve similar velocity of v_0 before the control shift takes place

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is in order to assure safety during and after the control shift.

2.6.2 Estimated Length and Number of Egress Channels Required

The length and number of the egress channels required for the platoon disengagement can be determined from the formulas shown below. Derivations of these formulas are presented in Appendix B.

The number of egress channels required can be estimated from:

$$N*h_f \;\le\; M*[\{N*(L+h)+H-h\}/v_0] \qquad\qquad (2.1)$$

where   M is the number of egress channels required

h_f is the desired time-headway for vehicles under driver
     control (seconds)

N is the platoon size

L is vehicle length (feet)

h is the within-platoon gap (3 feet)

H is the nominal inter-platoon gap (feet)

v_0 is the transitway speed (feet per second)

The length of the egress channels can be expressed as:

$$D = P/a - v_1 Q/a + \{(N-1)v_1/2Q\}\{h_f v_0 + (L+h)R/v_0\} \qquad (2.2)$$

where all terms are as previously defined, and

a   is the absolute value of the acceleration and deceleration
     employed (assumed to be the same) during the platoon

disengagement

$$P \quad = \quad (v_1{}^2 - v_0{}^2)$$

$$Q \quad = \quad (v_1 - v_0)$$

$$R \quad = \quad (v_1 - 2v_0)$$

Based on Equations (2.1) and **(2.2)**, the number and length of egress channels required are determined for the hypothetical **Phase-2A** system by the platoon size, as shown in Table 10. Table 10 is based on the vehicle length (L) of 20 feet (for **LDV's)**, a of **0.075g,** v_0 of 55 mph, and v_1 of 65 mph. A LDV platoon is the critical platoon for the determinations of the number and length of the egress channels because **LDV's** are generally longer than cars, and because buses are expected to travel mostly as individual vehicles (as opposed to in close-formation platoons).

For the Phase-2A system that allows only vehicles of the same type to form the same platoon, the simulation results indicate that about 85 percent of such platoons are expected to have fewer than 6 vehicles per platoon. Therefore, Table 10 suggests that:

- 0   For Phase **2A,** two egress channels are expected to be sufficient to accommodate the platoon disengagement and the transfer from automated control to driver control.
- 0   The length of egress channels required could be about 2,155 feet (or about 0.4 mile).

Table **10:** Length and Number of Egress Channels
Required for Phase 2A by Platoons Size

Platoon Size	Length of Egress Channels (feet)*	No. of Egress Channels Required
4	1490	2
6	2155	2
8	2825	3
10	3480	3
12	4155	3
14	4825	3
16	5490	3
18	6160	4
20	6825	4

* **For transitway speed of 55 mph**

Chapter Two

Section Two

**PHASE 2B: EARLY DEPLOYMENT OF LONGITUDINAL CONTROL SYSTEMS
WITH PLATOONING OPERATION IN TRANSITWAYS (PLATOON DISPATCH)**

This section presents the evaluation of another hypothetical system concept for early deployment of longitudinal control systems with close-formation platooning in one-lane transitways.   This system aims to achieve even a higher flow rate than that achieved by the hypothetical system in Phase 2A. The hypothetical system in Phase 2B differs from the system in Phase 2A in the strategies for platoon formation and dispatch.

The system concept for Phase 2B is described below. This is followed by the analysis of the flow rate in one-lane transitways due to deploying the Phase-2B system, and the determination of the geometric requirements for the access and egress sections.

3.1   System Concept for Phase 2B

In addition to the equipment mentioned for the hypothetical system in Phase 2A, the phase-2 system is likely to also require wayside computerized dispatch facilities for coordinating the platoon formation and dispatch, as well as for issuing speed and position commands to vehicles/platoons. In this way, merging and diverging of close-formation platoons can be facilitated. In addition, communication systems between the vehicles and wayside facilities may also be required.

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A system concept for deploying the hypothetical **Phase-2B** system in one-lane transitway is shown in Figure 16. The transitway can be divided into four contiguous sections: transitway access ramp (complete with vehicle check stations), transition section, main section, and egress section. These are described below.

Transition Section

The transition section is located after vehicle check stations (possibly toward the end of the transitway access ramps). It consists of multiple channels, each is designated for a particular vehicle type (cars, **LDV's,** or buses). The designation of different channels for different vehicle types is to facilitate the platoon formation and dispatch, due to a requirement that only vehicles of the same type can form the same platoon with one another.

Vehicles that pass the inspection will proceed toward the transition section. Those failing the checkup will be guided out of the transitway before reaching the transition section. Computerized vehicle dispatch systems are located after vehicle check stations. The **Phase-2B** system requires that cars and **LDV's** form platoons of the pre-specified size at dispatch stations in their designated transition channels, before they are dispatched. Buses could be dispatched as single vehicles, as soon as they arrive at the dispatch station without having to form a bus platoon. Within the transition section, platoons in each channel will maintain inter-platoon spacing no smaller than some **pre-**
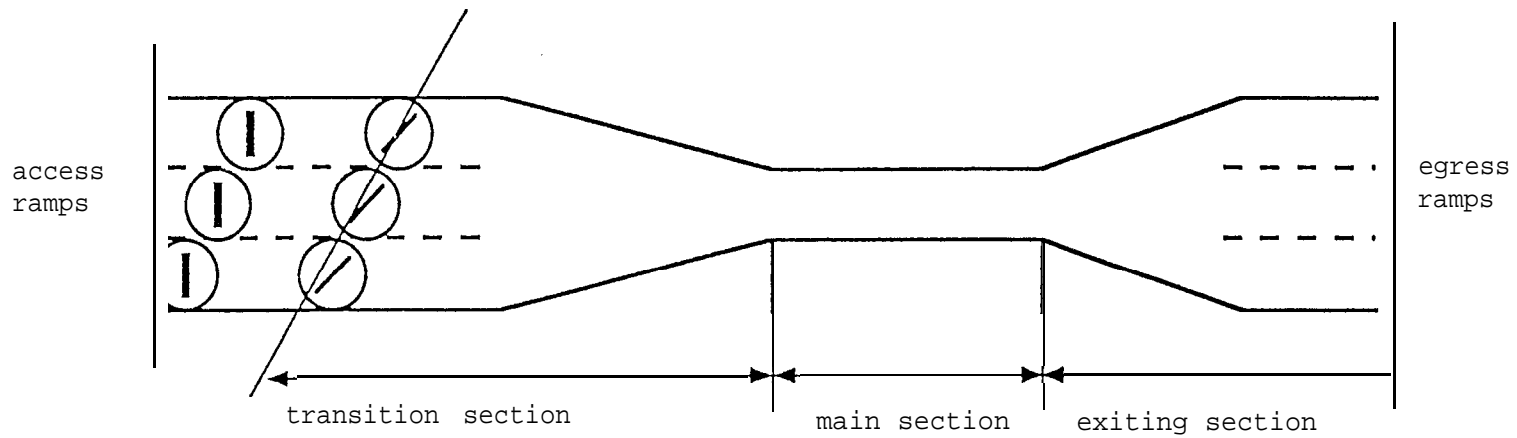
access
ramps

egress
ramps

transition section   main section   exiting section

ℓ :Vehicle dispatch station

0 : Vehicle check station

Figure 16:   A Conceptual Structure of **Advanced** l-Lane HOV
                  Facility Under Phase 2B

specified nominal inter-platoon headway.

Towards the end of the transition section, platoons and individual buses within multiple channels will start to merge into single file, in preparation to enter the main section of the transitway. Roadway references embedded in individual channels could guide platoons and individual buses during this merge phase. The computerized dispatch system would regularly update vehicle speeds and positions as soon as vehicles leave the dispatch stations. It will also issue speed and position commands to platoons and individual buses to facilitate smooth merging.

Main Section

This is the transitway proper. Within this section, platoons and individual buses are assumed to all travel at some advisory speed for the transitway. For one-lane transitways, the main section consists of one travel lane.

Egress Section

The egress section for the **Phase-2B** system serves similar purposes as that for the Phase-2A system. Before platoons could leave the transitway and merge into the freeway traffic, vehicles in each platoon have to be separated, and the automatic control shifted to driver control. The egress section, which comes after the main section, facilitates these actions.

3.2 Estimation of Flow Rate

Flow rate as a result of deploying the hypothetical Phase-2B system in one-lane transitways is estimated by simulation. The simulation assumes that cars, LDV's, and buses have acceleration capabilities as previously shown in Table 8. A model employed in the simulation is described below.

3.2.1 Dispatch-Decision Criteria

The simulation assumes that vehicles arrive randomly at dispatch stations, in channels designated for particular vehicle types. Figure 17 is a diagrammatic illustration of the coordinated platoon dispatch for the hypothetical Phase-2B system. If H is the nominal inter-platoon gap (feet), then the nominal inter-platoon time-headway corresponding to H is:

$$Ht(N,L) = \{(N-1)h + NL + H\} / V \qquad (2.3)$$

where   Ht(N,L) is nominal inter-platoon time-headway (seconds)

H is nominal inter-platoon gap (feet)

h is within-platoon gap (assumed to be 3 feet)

N is platoon size

L is vehicle length (feet)

v is travel speed in the transitway (feet per second)

As vehicles arrive at the dispatch station in each channel, the computerized dispatch system would hold these vehicles until enough of the same type arrive and form a platoon of the required

transition
section

main section
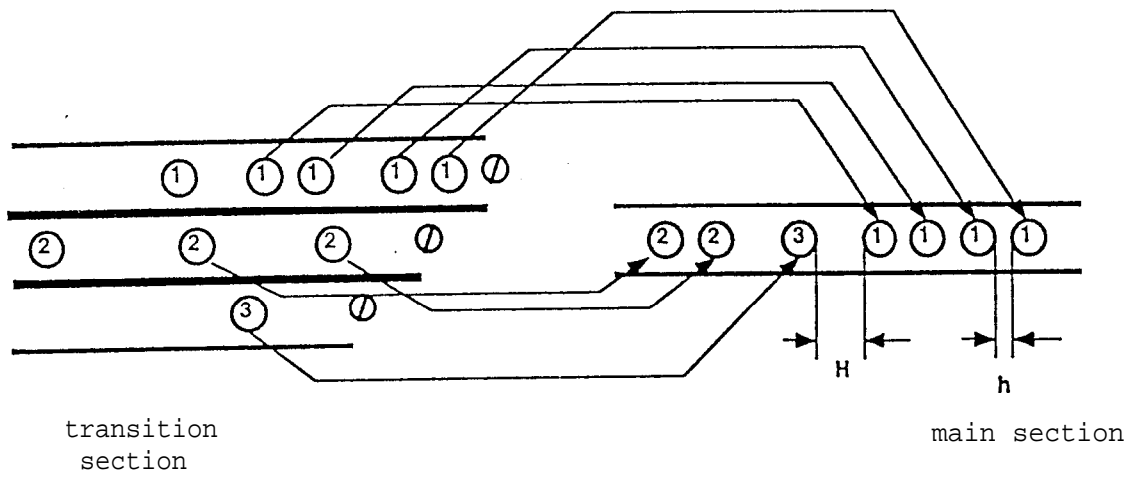
⊘ vehicle dispatch station

H is nominal inter-platoon gap

h is within-platoon gap (3 feet)

Figure 17: **Diagrammatic Illustration of Platoon Dispatch concept Under Phase 2B**

minimum size. The computer would then calculate the time that the platoon is expected to reach the merge area, and determine whether this platoon would be able to merge between other platoons already been dispatched in the other channels.   If so, the platoon is dispatched, and the computer would update information concerning the platoon position and speed. Otherwise, that platoon would have to wait for dispatch at a later time interval.

Consider a situation in which three platoons of cars, **LDV's,** and buses (in that sequence) have already been dispatched into the transition section in three different channels, with actual **inter-**platoon headway larger than the nominal inter-platoon headway. Expected arrival time at the merge area for these three platoons could be determined from their respective acceleration rates. Let **p1, p2,** and **p3** be the expected arrival time (clock time) for the car, LDV, and bus platoons, respectively. The decision to dispatch another platoon (Platoon M) that has just been formed at a dispatch station depends on the vehicle type and Platoon **M's** expected arrival time at the merge area.

If Platoon **M's** expected arrival time at the merge area is **p4** (clock time), the following paragraphs describe dispatch-decision criteria for Platoon M as a car, LDV, or bus platoon, respectively.

<u>If Platoon M is a Car Platoon</u>:   **p4** must be larger than p1. Platoon M can be dispatched and either merge between the car and the LDV platoons, merge between the LDV platoon and the bus, or trail the bus, depending on its expected arrival time at the merge

area.   The following conditions must be satisfied before
dispatching Platoon M:

(a)   If Platoon M is expected to reach the merge area before
the LDV platoon that has already been dispatched in another
channel, p4 must be smaller than p2. Platoon M has to maintain at
least the nominal inter-platoon headway relative to the first car
platoon and the first LDV platoon, as follows:

$$p2 - p4 > Ht(N,L2)$$

and

$$p4 - p1 > Ht(N,L1) \qquad (2.4)$$

where   L1 is length of cars

L2 is length of LDV's

The first requirement of Eqn (2.4) is to satisfy the **inter-**
platoon headway requirement between the LDV platoon and Platoon M.
The second requirement is to satisfy the inter-platoon headway
requirement between the first car platoon and Platoon M.

(b)   If Platoon M is expected to reach the merge area after
the LDV platoon but before the bus, both of which have already been
dispatched in other channels, p4 is larger than p2 but smaller than
p3. Platoon M have to maintain at least the nominal inter-platoon
headway between the LDV platoon and the bus, as follows:

$$p4 - p2 > Ht(N,L1)$$

and

$$P3 - p4 > Ht(1,L3) \tag{2.5}$$

where.   L3 is length of buses

(c)   If Platoon M is expected to reach the merge area after the bus that has already been dispatched in another channel, **p4** is larger than **p3**.   Platoon M have to maintain the inter-platoon headway relative to the bus as follows:

$$P4 - p3 > Ht(N,L1) \tag{2.6}$$

If Platoon M is a LDV Platoon: **p4** must be larger than **p2**. Platoon M can be dispatched and either merge between the LDV platoon and the bus or trail the bus, depending on its expected arrival time at the merge area.   The following conditions are required for dispatching Platoon M:

(d)   If Platoon M is expected to reach the merge area before the bus that has already been dispatched in another channel, **p4** is smaller than **p3**.   The following has to be satisfied:

$$P4 - p2 > Ht(N,L2)$$

and

$$P3 - p4 > Ht(1,L3) \tag{2.7}$$

(e)   If Platoon M is expected to reach the merge area after the bus that has already been dispatched, **p4** is larger than **p3**. The following must be satisfied in order to dispatch Platoon M:

$$p4 - p3 > Ht(N,L2) \qquad\qquad\qquad (2.8)$$

If Platoon M is a Bus: It would be dispatched immediately without a need to form a platoon.   Platoon M would enter the merge area trailing the three platoons earlier dispatched because buses have the lowest acceleration rate among the three vehicle types.

3.2.2 Simulation Procedure

The estimation of the flow rate involves the following steps:

1) For each level of the hourly transitway demand (i.e., the number of vehicles per hour wishing to use the transitway), three random number processes generate three sequences of arrival times at dispatch stations for cars, **LDV's,** and buses.   These arrival time intervals can be expressed as (Shannon, 1975):

$$\text{Interval} = -3600 \; / \; u \; * \; \ln (r) \qquad\qquad (2.10)$$

where   u is the number of vehicles per hour

ln is log to base e

r is random number between 0 and 0.1

2)   As soon as a platoon of the required minimum size is formed, dispatch-decision criteria (a) through (e) are checked. If the criteria are satisfied, this platoon is dispatched. Otherwise, it would be held at the dispatch station until the next time interval.

3)   Steps 1 through 2 are repeated for 60 minutes, using a one-second interval.   Then, the flow rate is computed for that

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level of the transitway demand, from:

$$Flow = k * v \qquad\qquad\qquad (2.9)$$

where

k is traffic density obtained from the simulation

v is travel speed within the transitway

4) Steps 1 through 3 are then repeated for another higher hourly volume, and the entire process is repeated until no higher flow rate is achieved.

3.2.3 Simulation Results

The flow rate in one-lane transitways as a result of deploying the hypothetical **Phase-2B** system is estimated, by assuming that the system operates with the nominal inter-platoon gaps of Table 7. Unlike the hypothetical system in Phase **2A,** the simulation results indicate that the estimated flow rate for the Phase-2B system is not sensitive to the transitway traffic mix. This is because the Phase-2B system incorporates coordinated platoon dispatch, while the **Phase-2A** system does not. As a result, it is possible for the **phase-2B** system to achieve any pre-specified platoon size and platoon arrangement aimed at maximizing the traffic density.

The estimated flow rate (at speed of 55 mph) is shown in Table 11 and Figure 18, for a transitway traffic mix comprised of 90 buses per hour with the ratio of cars to **LDV's** of **7:3.** Table 11 and Figure 18 indicate that the platoon size significantly influences the estimated flow rate, as would be expected. The flow

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Table.11: Estimated Flow Rates for One-Lane
Transitways (Phase 2B)

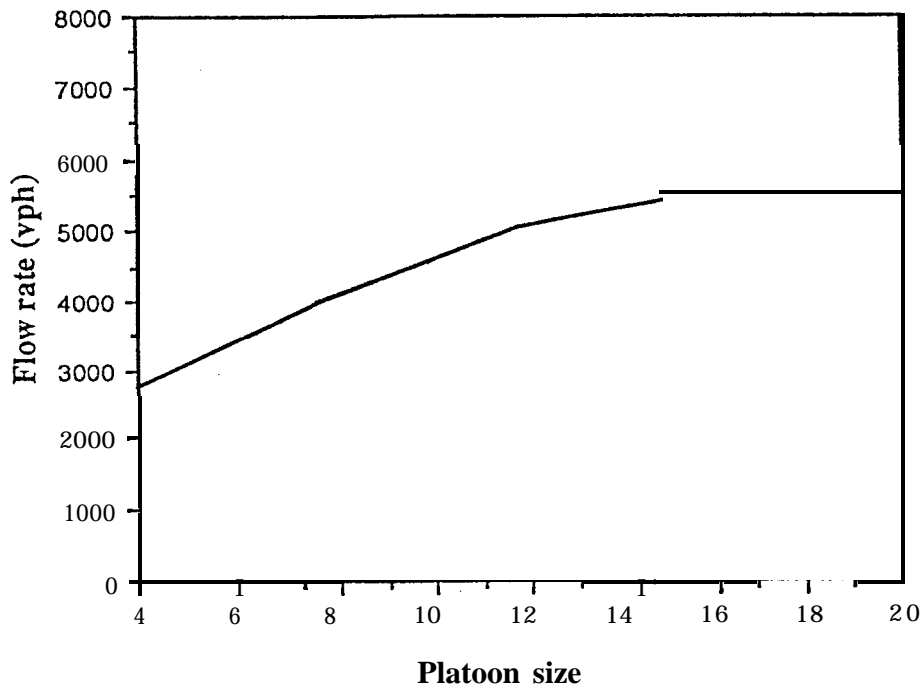| Platoon Size	Flow Rate (vph)
4	2720
6	3340
8	4000
10	4510
12	5010
14	5200
16	5330
18	5420
20	5540

Figure 18: **Estimated Flow Rate versus Platoon Size at 55 mph**

rate increases sharply with the platoon size of up to 12 vehicles per platoon. Beyond this platoon size, the estimated flow rate still increases (but less sharply) with increasing platoon sizes.

Simulation is also performed to investigate how variation in the nominal inter-platoon gap values might affect the estimated flow rate. In this regard, another more safety-conservative nominal inter-platoon gap criteria is specified, which is based on an assumption that, in case of system failures resulting in the failed platoon decelerating at an extremely high rate of -2.0g (as opposed to the previously assumed value of **-1.2g)**, following platoons would be able to safely stop. The assumption of -2.0g deceleration yields the nominal inter-platoon gap values about 12 percent larger than the values based on **-1.2g** deceleration (previously shown in Table 7). The estimated flow rate based on this more safety-conservative criteria is found to be about 8 percent lower than the estimated flow rate shown in Table 11. That is, for every 3 percent increase in the nominal headway-gap value, the estimated flow rate in one-lane transitways (due to deploying the Phase-2B system) could decrease by about 2 percent.

3.2.4 A Note on Estimated Flow Rates for Phase-2B System
The above estimated flow rate for the hypothetical **Phase-2B** system is based on an assumption that the three different vehicle types (cars, **LDV's,** and buses) are not allowed to form the same platoon. This assumption is primary out of concern for safety in

case of system failures.   If cars and **LDV's** were allowed to form the same platoon, the simulation performed indicates that the estimated flow rate could be about 4 percent higher.

3.3   **Comparison** of **Estimated Flow Rate with Results from Prior Studies**

The estimated flow rate (of Table 11) is compared with results reported by two prior studies (Shladover 1978; and Karaaslan et al 1990) in Figures 19(a) and 19(b), for platoon sizes of 4 and 12 vehicles per platoon, respectively. It is to be noted that both of these prior studies estimated flow rates for close-formation platoons comprised solely of cars (i.e, they did not consider the presence of **LDV's** or buses in the traffic stream).   The figures indicate that the estimated flow rate obtained in this study are about 10 percent and 18 percent lower than those reported by Shladover and Karaaslan, respectively.   Such differences can be attributed to :   (i) both prior studies assumed just one vehicle type (i.e., cars) in close-formation platooning operation with uniform vehicle dimensions and acceleration capability, whereas this study include buses, **LDV's,** and cars in the analysis (which have different vehicle dimensions and acceleration capabilities); and (ii) the analysis in this study assumes that buses would be given priorities in the coordinated dispatch over cars and **LDV's.**

Figures 19 (a) and 19(b) also show speed-flow curves obtained from the Highway Capacity Manual (1986) for multiple-lane freeways. Comparison of the estimated flow rate with the curves from the
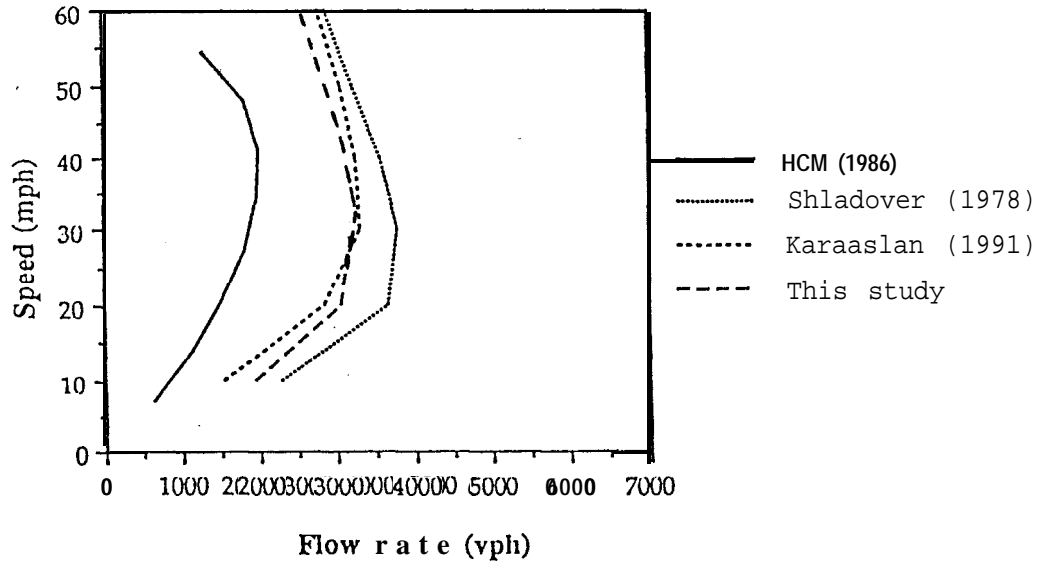
Figure 1%:   Comparison of Speed-Flow Curves Between This Study
              and Prior Studies (for Platoon Size of 4 Vehicles)
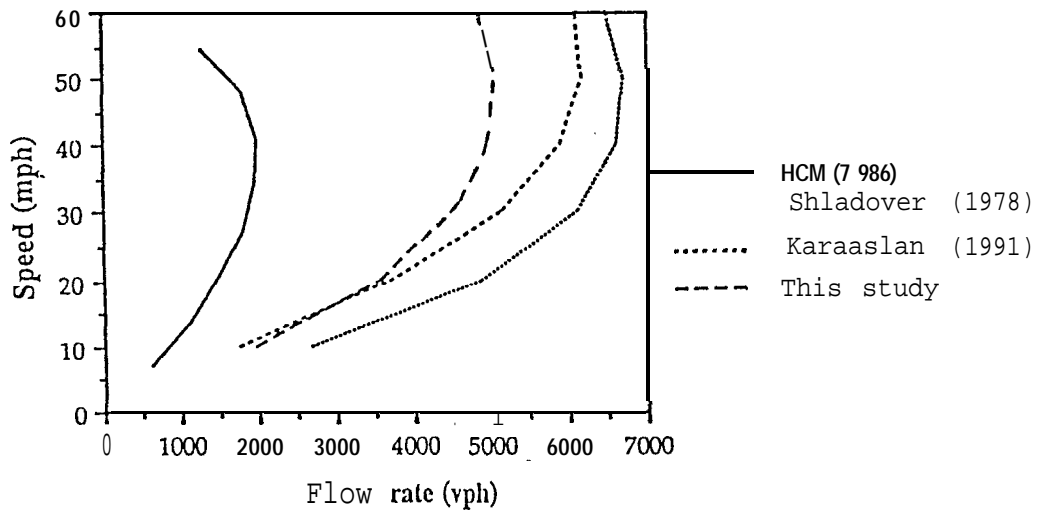

Figure 19b: Comparison of Speed-Flow Curves Between This Study
              and Prior Studies (for Platoon Size of 12 Vehicles)

Highway Capacity Manual reveals that, relative to the existing traffic, the hypothetical system of Phase 2B could increase the flow rate in one-lane transitways significantly. The magnitude of such increases varies, depending on the platoon size. For example, the flow'rate for 4-vehicle and **12-vehicle** platoons could be 1.9 and 3.6 times the existing flow rate. Please note that the **HCM's** speed-flow curves shown in Figures 19(a) and 19(b) are applicable for multiple-lane freeways. Observed flow rates in existing **one-**lane transitways are generally lower -- the flow rate at 55 mph is typically about 1,200 vph, as opposed to **1,400-1,500** vph. This implies that, if the Phase-2B system is implemented, the flow rate at 55 mph in one-lane transitways could be as much as 4.2 times the existing flow rate (for the platoon size of 12 vehicles per platoon).

3.4 Geometric Requirements of Transition Section

As previously mentioned, the transition section of **the** transitway in Phase 2B could consist of multiple channels. The number and length of these transition channels can be determined as follows:

3.4.1 Length of Transition Section

The transition section should have sufficient length for close-formation platoons of cars and **LDV's,** or individual buses that leave the dispatch station to accelerate up to a reasonable speed when entering the main section. The required minimum length

of the transition section, D, can be calculated from:

$$D = v^2/2a + h(N-1) + NL \qquad (2.11)$$

where   ´ v is transitway speed

a is acceleration capability of a particular vehicle type
(Table 8)

L is length of that vehicle type

N is platoon size

h is within-platoon gap (assumed to be 3 feet)

Among cars, **LDV's,** and buses with assumed acceleration capabilities as shown in Table 8, the bus is the critical vehicle because of its relatively low acceleration capability compared with those for cars and **LDV's.** To reach a speed of 55 mph at the beginning of the main section, buses could require the transition section length of 1,800 feet.

3.4.2 *Number of Channels for Transition Section*

The number of transition channels required depends on the traffic volume to be served by the transitway, as well as on the platoon size. If only vehicles of the same type are allowed to form the same platoon with one another, a minimum of three channels will be required, one each for cars, **LDV's,** and buses. Table 12 shows the number of transition channels required for the Phase-2B system for traffic volumes between 2,000 and 5,000 vehicles per

Table .**12:** Number of Transition Channels
Required for Phase 2B
(Platoon Size $\geq$ 12 Vehicles)

Transitway Demand (vph)	No. of Transition Channels	
	Cars, **LDV's** cannot form same platoon	Cars, **LDV's** can form same platoon
2,000	3	2
3,000	3	2
4,000	3	2
5,000	3	3

hour, for the platoon size of at least 12 vehicles per platoon.

If cars and **LDV's** were allowed to form the same platoon, a minimum of two channels would be required (one for cars and **LDV's,** and the other for buses).   Table 12 also shows the number of transition channels required under this operating assumption.

3.5 Geometric Requirements for Egress Section

The egress section, located at the end of the main section, is needed to allow vehicles in platoons to disengage and shift from automated control to driver control in preparation for leaving the transitway.   The determination of the number and length of egress channels was previously presented in Section 2.6, with Table 10 showing the number and length of the egress channels required. Table 10 is also applicable for the hypothetical Phase-2B system.

Chapter Two

Section Three

Net Benefits of Phases 2A and 2B Adjusted for
Right-of-Way Requirement

The estimated flow rates in one-lane transitways, as a result
of deploying the hypothetical Phase-2A and **Phase-2B** longitudinal
control systems with close-formation platooning, have been shown to
be significantly higher than the flow rate currently observed in
existing one-lane transitways. It has also been shown that the
deployment of both the **Phase-2A** and **Phase-2B** systems in transitways
would require additional right-of-way for the egress and access
sections. Net changes in the transitway flow rate adjusted for the
right-of-way requirement for the **Phase-2A** and Phase-2B systems,
relative to existing transitways, are determined in this section.

Right-of-Way Requirements for Phase 2A and Phase 2B

Transitways are aimed to provide a travel-time advantage for
transitway users, relative to general traffic on freeway mainlanes,
when the freeways are congested. This means that travel speed in
transitways should not fall substantially below 55 mph.   The
assessment of net flow-rate benefits adjusted for the right-of-way
for **Phase-2A** and **Phase-2B** systems is based on evaluating changes in
the transitway flow rate at 55 mph, as a result of deploying **Phase-
2A** and **Phase-2B** systems.

Additional right-of-way required for the **transitway's** access

and egress as a result of deploying the two hypothetical systems (for transitway speed of 55 mph) is summarized in Table 13. For each phase, Table 13 shows the right-of-way requirements for the case in which cars and LDV's are not allowed to form the same platoon, 'as well as for the case in which cars and LDV's are allowed to do so. Table 13 indicates that whether or not car and LDV's are allowed to from the same platoon could make a difference in the right-of-way requirement for Phase 2A, which is not so for Phase 2B.

Net Flow-Rate Benefits Adjusted for Right-of-Way

Net increases in the flow rate adjusted for the right-of-way for Phase 2A and Phase 2B, relative to existing transitways, can be determined from:

$$G = (q_2/q_1) * (W_1/W_2) \tag{2.12}$$

where

q_1 is flow rate in existing transitways (no advanced technology)

q_2 is estimated flow rate for Phase 2A (or Phase 2B)

W_1 is right-of-way for existing transitways (no advanced technology)

W_2 is right-of-way required for Phase 2A (or Phase 2B)

Using the information shown in Table 13, net increases in the flow rate adjusted for the right-of-way for Phase 2A and Phase 2B are determined, as shown in Table 14. Table 14 expresses the net

Table 13: Infrastructural Requirements for Phase 2A and Phase 2B,
Relative to Existing Transitways

	Existing l-lane Transitway	Phase 2A		Phase 2B	
		Cars & LDV's in different platoons	Cars & LDV's in same platoon	Cars & LDV's in different platoons	Cars & LDV's in same platoon
Flow rate at 55 mph (vph)	12,00	3,090	5,000*	5,010"	5,210*
Access ramps: Number of ramps Length of each ramp (ft)	1 1,000	2 1,000	3 1,000	3 1,000	3 1,000
Transition section: Number of channels Length of each channel (ft)	n/a n/a	2 800	3 800	3 1,800	3 1,800
Egress section: Number of channels Length of each channel (ft)	n/a n/a	2 2,155	3 4,155	3 4,155	3 4,155
Egress ramps: Number of channels Length of each channel (ft)	1 1,200	2 1,200	3 1,200	3 1,200	3 1,200

* Based on 12-vehicle platoons

Table 14: Net Flow-Rate Gain (at 55 mph) for Phase 2A and Phase 2B Adjusted for Right-of-Way, Relative to Existing Flow Rate

Implementation Option	Flow Rate as Multiple of Existing Flow Rate			
	P-mile Transitway	**5-mile** Transitway	lo-mile Transitway	**15-mile** Transitway
Phase 2A:				
cars & LDV's in different platoons	1.6	2.0	2.3	2.3
cars & LDV's in same platoon **	1.7	2.5	3.1	3.4
Phase 2B:				
cars & LDV's in different platoons**	1.5	2.4	3.0	3.3
cars & LDV's in same platoon **	1.6	2.5	3.1	3.4

** Based on 12-vehicle platoons.

flow rate **adjusted** for the right-of-way at 55 mph as the multiple of the flow rate for existing transitways, for a range of the transitway length from 2 through 15 miles. Because the amounts of additional right-of-way required at the access and egress sections for Phase 2A and Phase 2B do not vary with the length of the transitway, net increases in the flow rate adjusted for the two phases are expected to become more substantial as the transitway length increases. The results of Table 14 are also plotted in Figure 20. Examination of Table 14 and Figure 20 indicates that:

* The net flow rate at 55 mph adjusted for the right-of-way rises sharply with increasing length of the transitway, up to about 10 miles. Beyond 10 miles, the net flow-rate benefit begins to taper off.

* For transitway length of two miles, the net flow rate at 55 mph adjusted for the right-of-way are almost similar for all four new system options (and range from 1.5 to 1.7 times the flow rate for existing transitways).

* For transitway length of five miles, the net flow rate at 55 mph adjusted for the right-of way for Phase 2A in which different vehicle types are not allowed to form the same platoon is found to be 2.0 times the flow rate for existing transitways. Such net flow rates are about 2.5 times the flow rate for existing transitways for Phase 2B, as well as for Phase 2A in which cars and LDV's are allowed to form the same platoon.

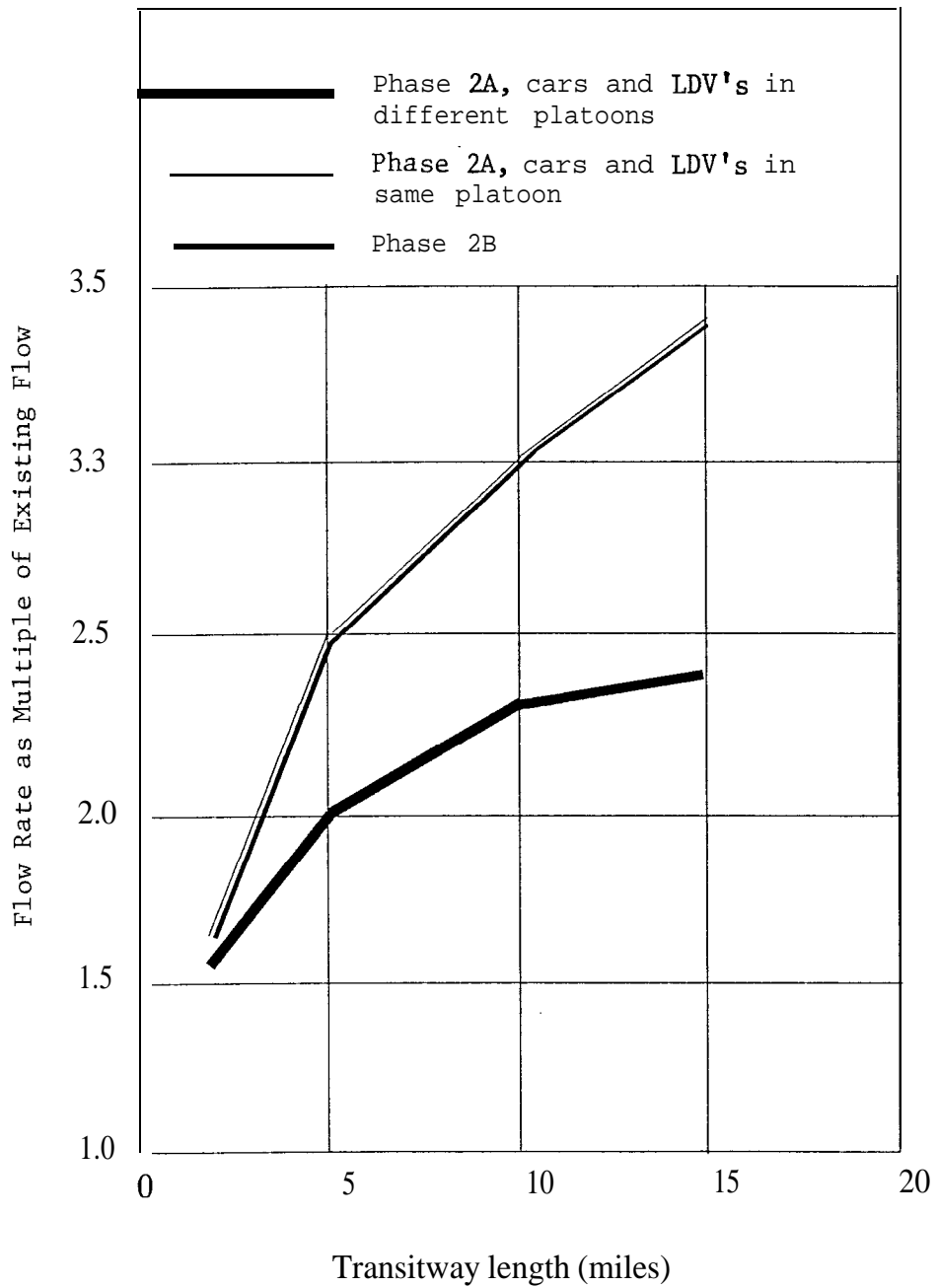* For lo-mile long transitways, the net flow rate at 55 mph

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Figure 20 Net Flow-Rate Benefit of Phase 2A and Phase 2B Adjusted for Right-of-Way

adjusted for the right-of-way for Phase 2B is about 3.0 times the flow rate for existing transitways. Such net flow rates for Phase 2A could be 2.3 or 3.1 times the existing flow rate, depending on whether cars and LDV's are allowed to form the same platoon.

*   For 15-mile long transitways, the net flow rate at 55 mph adjusted for the right-of-way for Phase 2B could be 3.3-3.4 times the existing flow rate.

The above findings indicate that, in order to maximize the net flow rate benefit (adjusted for the right-of-way) from the hypothetical longitudinal control systems with close-formation platooning, these systems should be deployed in transitways that are about 10 miles long, but as a minimum about 5 miles long.

Summary and Conclusions for Chapter Two

Chapter two evaluates two alternative strategies for early deployment of longitudinal control systems with close-formation platooning in one-lane transitways. The evaluation includes assessments of potential changes in the transitway flow rate and special infrastructure requirements. The evaluation assumes that longitudinal control systems with close-formation platooning can be safely configured, even though current research on longitudinal control systems is still at a formative stage.

The rationale for proposing early deployment of longitudinal control systems with close-formation platooning in one-lane transitways is based on a believe that it is essential to

demonstrate safety.and public acceptance of such advanced systems in exclusive right-of-way facilities before their large-scaled use on freeways can take place. Because characteristics of transitways and freeways differ greatly, it is conceivable that the implementation of such systems in transitways and on freeways could differ in the systems concept, deployment strategy, and infrastructure requirement. Therefore, results obtained in this study may not be directly applicable to the eventual deployment on freeways. Further, the magnitude of the estimated impacts is also likely to be influenced by the assumptions employed in the analysis, such as: the hypothetical system structure, geometric design of the transitway, platoon-formation characteristics, nominal within-platoon and inter-platoon spacing criteria, traffic mix, and speed and acceleration capabilities of various vehicle types.

Two hypothetical longitudinal control systems with **close-**formation platooning are evaluated in this study. They are:

* Phase 2A assumes that vehicles would enter the transitway and form platoons with one another after they go through check stations, in the order that they leave the check stations. Drivers could have the option to join (or not to join) platoons with other vehicles. For this hypothetical Phase-2A system, the average platoon size (and thus the flow rate) could be influenced by the mix of the transitway traffic (i.e., relative proportions of cars, **LDV's,** and buses). The more diverse the traffic

mix is, the lower the estimated flow rate will tend to be.

* Phase 2B requires that cars and **LDV's** arriving at the transitway form platoons of some pre-specified minimum size, before they are dispatched. Buses are exempted from having to form platoons, and would be given priorities in the dispatch over car or LDV platoons (i.e., buses could be dispatched as individual vehicles, as soon as they complete the vehicle checks). Computerized dispatch facilities would be required to coordinate the platoon dispatch. An advantage of Phase 2B (over Phase 2A) is that much larger platoon sizes than that attainable in Phase 2A could be assured in order to further increase the flow rate.

Primary findings from the evaluation in Chapter 2 include:

1. The estimated flow rate is sensitive to the platoon size, for both the Phase-2A and Phase-2B systems. In addition, the estimated flow rate for the hypothetical **Phase-2A** system is also sensitive to the transitway traffic mix and to whether cars and **LDV's** are allowed to form the same platoons.

2. For the **Phase-2A** system that does not allow cars and **LDV's** to form the same platoon, the estimated flow rates within one-lane transitways (for travel speed of 55 mph) could be on the order of 2.6 times that currently observed in existing one-lane transitways. For the **Phase-2A** system that allows cars and **LDV's** to form the same platoon, the estimated flow rate (for 55 mph) could be 4.2 times

the currently observed flow rate, for the platoon sizes of at least 12 vehicles per platoon.

3. For the **Phase-2B** system, the estimated flow rate could be much higher than the existing flow rate. For speed of 55 mph, the estimated flow rate could be 4.2 to 4.6 times the currently observed flow rate for platoon sizes of 12 through 20 vehicles.

4. For the **Phase-2B** system, the estimated flow rate could be affected by the nominal inter-platoon gap criteria used (a **system-**specification parameter). It is found that for every 3 percent increase in the nominal inter-platoon gap values, the estimated flow rate could decrease by 2 percent.

5. The implementation of Phase-2A and Phase-2B systems in transitways would require special infrastructures at thetransitway access and egress sections, and thus extra right-of-way. Such extra right-of-way requirements means that the estimated increase in the flow rate due to adopting Phase-2A and Phase-2B systems must be discounted accordingly. Net flow-rate benefits adjusted for the right-of-way for **Phase-2A** and **Phase-2B** systems, relative to existing transitways, are shown in Table 14 and Figure 20. The net flow rate at 55 mph adjusted for the right-of-way requirement is found to be sensitive to the transitway length in a range up to 10 miles. The deployment of the **Phase-2A** system in a lo-mile transitway could yield the net flow rate at 55 mph (adjusted for the right-of-way) of 2.3 and 3.1 times the flow rate in existing transitways, if cars and **LDV's** are not, and are, allowed to form the same platoon respectively. Net flow rate at 55 mph adjusted

for the right-of-way for the Phase-2B system is found to be about 3.0 times the existing flow rate, for lo-mile long transitways.

Recommendations for Further Research on Longitudinal Control Systems

In addition to continuing research in the technology development of advanced vehicle control systems, research is also needed in the following areas to advance the understanding of the feasibility of early deployment of longitudinal control systems with close-formation platooning:

* Safety and human-factors research is needed to determine safe and practical nominal within-platoon and inter-platoon spacing. Also, as part of these research activities, safety implications of allowing different vehicle types (particularly cars and LDV's) to form the same platoon should be investigated.

* Human-factors research is needed to assess driver acceptance and behavior when vehicles within a platoon have to operate very close to one another longitudinally.

* Research is needed to investigate the transfer between automated and manual control, for example, how quickly can such transfer be achieved; how fast can drivers adjust to, and be ready for, such transfer of vehicle control ?

* Research is needed to determine characteristics and consequences of accidents involving several vehicles

traveling in close-formation platoons, in case of system failures.

*   Prior accident-analysis studies (e.g., Gimotty et al) reported that less-severe (or minor) accidents in two-
'   vehicle collisions were mostly associated with low **Delta-**V values. However, that same study also indicated that relatively low Delta-V values of a-vehicle collisions could sometimes lead to severe injuries.   Research is needed to assess conditions in which relatively low Delta-V values could result in severe injuries.

*   Research is needed to identify and address potential legal and liability issues/implications of automated highway systems.

*   Research is needed to identify cost implications of longitudinal control systems with platooning operation

*   Research is needed to evaluate the cost-effectiveness of **"vehicle-autonomous"** versus **"wayside"** oriented systems.

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Collision Speed and Delta V

Vehicle collision speed and speed variation between before and after the collision (Delta V) can be found as follows:

1. Collision speed

Given the initial headway, performance and vehicle dimension, collision speed between vehicles can be found. If the leading vehicle fails, the following vehicle can be involved in three situations:

- **o** Collision with the first vehicle while the first vehicle is decelerating

- **o** Collision with the first vehicle after the first vehicle stops

- **o** No collision

Shladover (1979) defined basic parameters involved in the collision analysis as:

h = headway **(sec)**

vo = vehicle speed or speed before failure

L = vehicle length

af = failed vehicle deceleration

ae = following vehicle deceleration rate

d = following vehicle braking delay

vc = collision speed

t = time after failure

tc = collision **time**

ts1 = time elapse until the first vehicle (failed

vehicle) stops

ts2   = time elapse until the second vehicle stops

The time required to stop the failed vehicle can be calculated as

ts1 = - VO/af

ts2 ' = - VO/ae

1.1. Collision while moving (d < tc < ts1)

This is a situation in which the leading vehicle and the following vehicle collide while the lead vehicle is still moving (decelerating). The collision time, tc, can be found by solving the following quadratic equation:

(af-ae)/2*tc*tc + ae*d*tc + (Vo-L-ae/2*d*d) = 0

Then, the collision speed, vc, can be found as:

vc = ae*(tc-d) - af*tc

Solutions to the above equation should satisfy the requirements:

d < tc < ts1, and 0 < vc < VO

1.2 Collision after failed vehicle stops (ts1 < tc)

If a collision happens after the failed vehicle has stopped. The collision time, tc, can be found by solving the quadratic equation:

ae/2*tc*tc+(v0-ae*d)(tc+(V0*V0/2/af+L-V0*h+ad/2*d*d)=0

Then, the collision speed can be found as:

vc = VO+ae*(tc-d)

To be a reasonable solution, the collision time and collision speed have to satisfy the following requirements.

ts1 < tc < ts2, and 0 < vc < VO

1.3 No collision .

If the solution in (1.1) and (1.2) does not satisfy the requirements, the initial headway, h, is large enough that no collision occurs. The collision speed is zero.

2. Delta v

Speed variation before and after the collision is calculated by the following relationships:

DV1 = vc * m2/(m1+m2)

DV2 = vc * m1/(m1+m2)

where   DV1 = Speed variation of the first vehicle

DV2 = Speed variation of the second vehicle

ml = mass of the first vehicle

m2 = mass of the second vehicle

3. Safe headway with delta v of 15 mph

Safe headway which assures a Delta-V value no larger than 15 mph can be found using formulas in (1) and (2). The procedure consists of the following steps:

1) Change vehicle **headways** from 15 ft. to 500 ft. with increment of 5 ft.

2) Find the collision speed corresponding to each initial headway chosen with respect to certain vehicle speed

3) Find the delta v

4) Find the maximum value of initial headway which has delta v lower than 15 mph

5) Repeat above steps with respect to various vehicle speeds.

METHODOLOGY FOR DETERMINING NUMBER AND LENGTH

OF EGRESS CHANNELS FOR PHASES 2A AND 2B

The'egress section is located at the end of the main section. It serves as a transition for vehicles to get ready to leave the automated transitway. Within the egress section, vehicles in platoons will separate from each other and the automated control shifted to driver control. The egress section could consist of multiple channels. The length and the number of these channels required are determined below.

Determination of Length and Number of Egress Channels (Under Simultaneous Front/Rear Platoon Disengagement)

At the end of the main section, each platoon could be guided into an egress channel, possibly by reference markers embedded in the pavement. Once inside the egress channel, vehicles within platoons would start breaking away from one another. There are numerous possible strategies for platoon disengagement. This study initially considered three stratagies, as follows:

(i) The first platoon disengagement strategy considered involves the last vehicle of the platoon starts breaking off first, as soon as it enters the egress channel, by decreasing its speed. Then, the disengagement proceeds toward the front of the platoon.

(ii) The second platoon disengagement strategy starts with the frontmost vehicle of a platoon breaking away first, as soon as

it enters the egress channel, by increasing its speed.   Then the process proceeds toward the rear of the platoon.

(iii)   The third disengagement strategy involves vehicles at both ends of the platoon simultaneously breaking away from the platoon. ˙As soon as the first vehicle enters the egress channel, it will start accelerate to initiate the platoon break-off.   Then the second vehicle will do likewise, and so on.   In the meantime, as soon as the last vehicle enters the egress channel, it will decelerate to start breaking away from the platoon.   Then the second last vehicle will do likewise, and so on.   Therefore, the platoon disengagement proceeds from both end toward the middle of the platoon.

Of the above three disengagement strategies, the third strategy is the most efficient, in terms of the time and distance it takes for platoons to complete the disengagement.   Therefore, this rule is selected for the determination of the length and the number of the exiting channels.   The other two ruless are excluded from further consideration.

Detail of the platoon disengagement strategy assumed in the analsyis follows:

Let the transitway speed be denoted by v_0:

1.   As soon as the frontmost vehicle (Vehicle Xl) enters the egress channel, it starts to accelerate away from the platoon until it achieves time-headway from the next vehicle of h,, where h_f is the desired time-headway (in seconds) under driver control. At this time, speed of Vehicle X1 will be v_1 ($v_1 > v_0$).   Vehicle X1 will maintain this headway, h,, until the shift from automated

control to driver control is complete.

2. As soon as the last vehicle of the platoon (Vehicle **Z1**) enters the egress channel, it starts to decelerate away from the platoon, until it achieves the headway of h_f with respect to the second last vehicle. At this time, speed of Vehicle **Z1** will be v_2 ($v2 < v_0$).

3. Next vehicles at both ends of the the platoon follow similar actions, as the platoon break-away proceeds from both ends toward the middle of the platoon.

4. After all vehicles in the platoons are separated from one another, all vehicles will begin to adjust their speeds toward v_0 again. That is, vehicles cruising at v_1 will reduce speed from v_1 toward v_0, while those cruising at v_2 will increase the speed toward v_0. Once this process is complete, the vehicles will start to shift from automated control to driver control. At the moment when the manual control is achieved, all the vehicles would have time-headway around h,.

Figure B.l is a diagrammatic illustration of the positions of successive platoons within the transitways as they approach the egress section. Figure B.2 is a speed-time profile for the frontmost vehicle (Vehicle Xl), as soon as it enters the egress channel until the moment just before it switches from the automated control to the driver control. The figure indicates that during time t,, Vehicle Xl accelerates from speed v_o to speed v_1 to break away. Then, it cruises at speed v_1 for a period of t_2 until all vehicles in that platoon are separated. Then, it takes time t_3 for Vehicle Xl to decelerates toward v_0 again. It is assumed that the
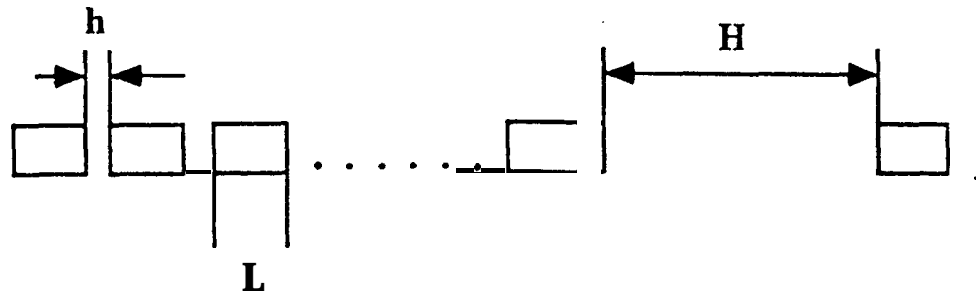
h is within-platoon gap
H is inter-platoon gap
L is vehicle length

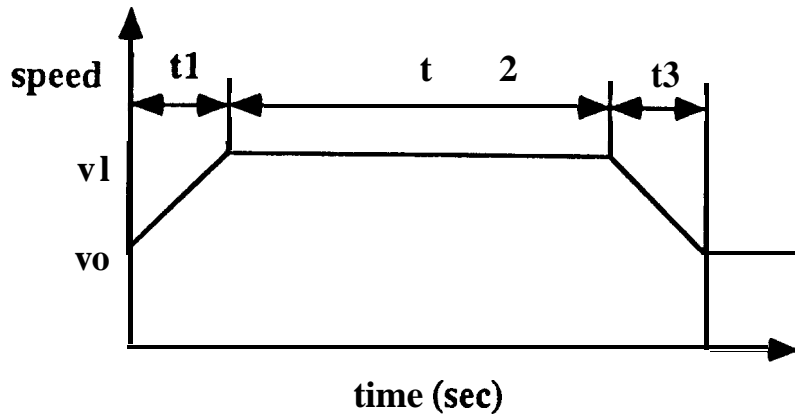Figure B1: Vehicle and Platoon Arrangements Before Egress Section

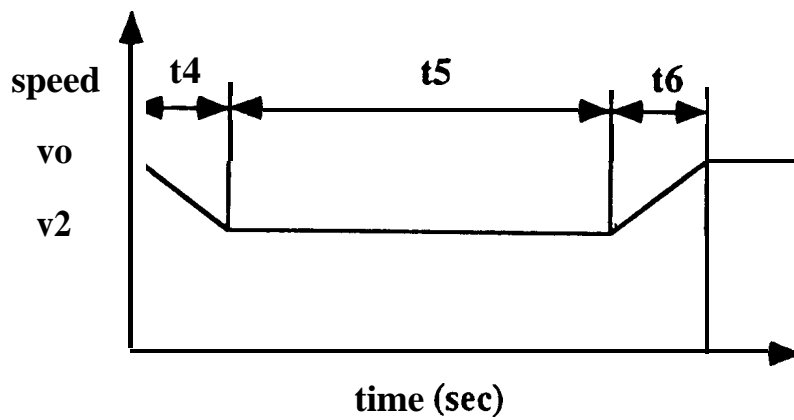Figure B2: Speed-Time Diagram for First Vehicle of the Platoon

Figure B3: Speed-Time Diagram for Last Vehicle of the Platoon

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acceleration and deceleration rates of Vehicle Xl are the same in their absolute values **("a")**. Therefore, t_1 and t_3 are equal, and:

$$t_1 = t_3 = (v_1 - v_0)/a \qquad\qquad (B.1)$$

Figure B.3 shows a speed-time profile for the **rearmost** vehicle of the same platoon (Vehicle **Z1**), as it enters the exiting channel until the moment just before it switches from automated to driver control. Acceleration and deceleration rates of Vehicle **Z1** are also assumed to be equal in the absolute value, **"a"**. Therefore,

$$t_4 = t_6 = (v_0 - v_2)/a \qquad\qquad (B.2)$$

The distance travelled by Vehicle Xl during the time interval $(t_1+t_2+t_3)$ is:

$$S_1 = (v_0+v_1)/2 * (t_1+t_3) + (v_1*t_2)$$
$$= (v_0+v_1)*t_1 + v_1*t_2 \qquad\qquad (B.3)$$

The distance travelled by Vehicle **Z1** during the time interval $(t_4+t_5+t_6)$ is:

$$S_2 = (v_0+v_2)*t_4 + v_2*t_5 \qquad\qquad (B.4)$$

Since Vehicle **Z1** enters the egress channels after Vehicle Xl does, $(t_1+t_2+t_3)$ is not equal to $(t_4+t_5+t_6)$, and the difference can be expressed as:

$$t_c = 2t_1 + t_2 + 2t_4 - t_5 = (L + h)(n - 1)/v_0 \quad (B.5)$$

where   L   is the vehicle length

h   is the within-platoon gap (assumed to be 3 feet)

$\cdot$ N   is the platoon size

If the speed changes by Vehicle X1 and Vehicle Z1 are assumed to be identical in the magnitude, then $(v_1 - v_0) = (v_0 - v_2)$, and Equation (5) can be simplified to:
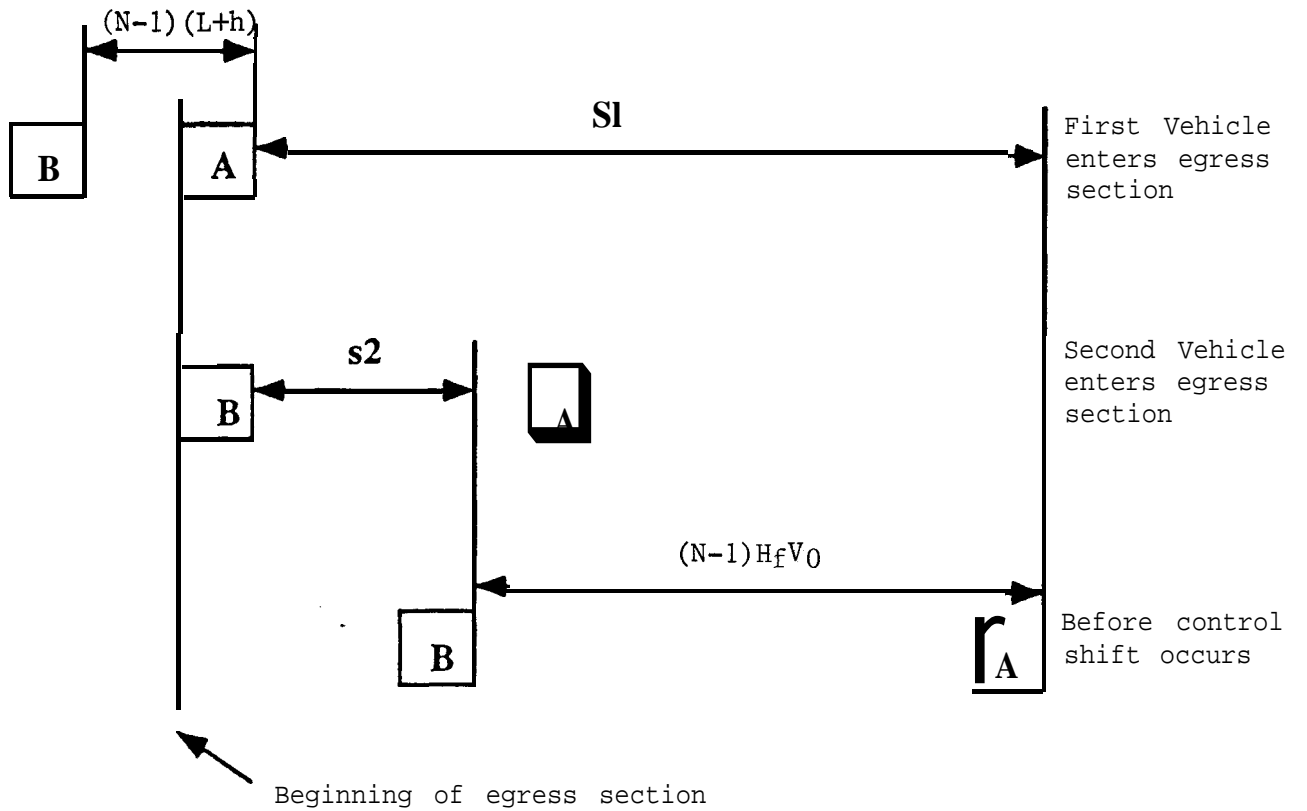
$$t_2 = t_5 + (L+h)(N-1)/v_0 \quad (B.6)$$

The final arrangements of vehicles at an instant just before the control shift takes place is shown in Figure B.4. The final separation between these two vehicles after the completion of the platoon disengagement is $(N-1)*v_0*h_f$. Therefore,

$$S_1 - S_2 = (N-1)v_0h_f \quad (B-7)$$

Length Requirement of Egress Section

The egress section for platoon disengagement must have sufficient length to accommodate the distance travelled by the frontmost vehicle of the platoon (Vehicle X1), or S_1. Therefore, S_1 is the minimum length required for the egress section. Solving simultaneous Equations (1) through (7):

$$D = P/a - v_1Q/a + \{(N-1)v_1/2Q\}\{h_fv_0 + (L+h)R/v_0\} \quad (B.8)$$

$(N-1)(L+h)$

Sl

B

A

First Vehicle
enters egress
section

s2

B

A

Second Vehicle
enters egress
section

$(N-1)H_f V_0$

B

A

Before control
shift occurs

Beginning of egress section

A: First vehicle
B: Last vehicle

Figure B4: Positions of Vehicles at the Start and End of Platoon
            Disengagement

where

a   is the absolute value of the acceleration and deceleration (assumed to be the same) during the platoon disengagement

$P = (v_1^2 - v_0^2)$

$Q = (v_1 - v_0)$

$R = (v_1 - 2v_0)$

M   is the number of egress channels

h_f is the desired time-headway under driver control (seconds)

N   is the platoon size

L   is vehicle length (feet)

h   is the within-platoon gap (3 feet)

H   is the nominal inter-platoon gap (feet)

v_0 is the transitway speed (feet per second)

v_0, v_1, **a**, H, h_f, N, and L are all know implementation or system-specification parameters, thus S_1 can be calculated, as shown in Table B.1. Table B.1 is based on v_0 = 55 mph, v_1 = 65 mph, a = 0.075 g, and L = 20 feet. Table B.1 indicates that as the platoon size increases, so will the length of the egress channels required, as would be expected.

Number of Egress Channels Required

Consider two successive platoons within the egress section. In order for the lead platoon to complete the platoon disengagement and all disengaged vehicles to maintain time-headway of h_f from one another, the time-separation between the frontmost vehicle of the first platoon and the frontmost vehicle of the following platoon must be at least Nh_f. Therefore, the number of egress channels, M,

required can be determined from the following equation:

$$M\{N(L+h)+H-h\}/v_0 \geq N*h_f \qquad \text{(B.9)}$$

where all' symbols are as previously defined.