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System Operations Studies for Automated Guideway Transit Systems

Quantitative Analysis of Alternative AGT Operational Control Strategies

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16. Abstract

The performance, cost, and operating characteristics of control function options for vehicle control, headway protection, longitudinal control, merge strategy and dispatch strategy were determined through analyses and experimentation at both the system and subsystem levels.

For similar vehicle performance characteristics, point follower control was found to require longer headway separation than vehicle follower control. Analytic predictions of vehicle motion and energy consumption compared well with experiments. A FIFO merge strategy resulted in the minimum flow weighted average travel time. Point follower control generally outperformed vehicle follower control during link experiments, but vehicle follower control performed better for merges and intersections.

The system level analyses showed that asynchronous longitudinal control with non-deterministic dispatch performed better than the other two combinations consisting of synchronous longitudinal control with deterministic dispatch and quasi-synchronous longitudinal control with quasi-synchronous dispatch. Also, the analysis of control-related cost showed the asynchronous combination to be the least costly, and the synchronous combination to be the more costly.

Entrainment on the guideway generally improved performance while station entrainment produced little or no difference. However, when both station and guideway entrainment were enabled, the results were varied, indicating that a more detailed analysis considering system parameters was warranted.

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PREFACE

In order to examine specific Automated Guideway Transit (AGT) developments and concepts--and to build a better knowledge base for future decision-making--the Urban Mass Transportation Administration (UMTA) undertook a new program of studies and technology investigations called the UMTA Automated Guideway Transit Technology (AGTT) program. The objectives of one segment of the AGTT program, the System Operations Studies (SOS) were to develop models for the analysis of system operations, to evaluate performance and cost, and to establish guidelines for the design and operation of AGT systems. A team headed by GM Transportation Systems Division (GM TSD) was awarded a contract by the Transportation Systems Center to pursue these objectives. The Technical Monitor for the project at TSC was Arthur Priver, who was assisted by Li Shin Yuan and Thomas Dooley.

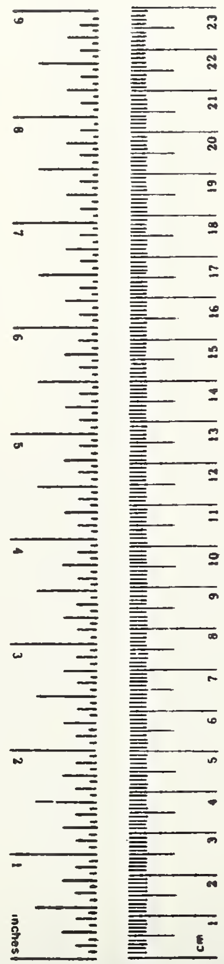
The Quantitative Analysis of Alternative AGT Operational Control Strategies report documented analyses of the performance, cost, and operating characteristics of the functions of vehicle control, headway protection, longitudinal control, merge strategy, and dispatch strategy. Several options were defined for each control function and evaluated both analytically and through experiments of vehicle motion on link, merge, and intersection guideway elements at the subsystem level. Several specific control strategy combinations were also evaluated at the system level through AGT system simulations. The performance effect of vehicle entrainment both at stations and dynamically on the guideway was also evaluated at the system level. Whenever possible, alternative strategies and/or alternative strategy combinations were compared and guidelines were stated for choosing between control alternatives.

The work reported here was performed under the direction of the SOS Program Manager, James F. Thompson, at GM TSD. The analyses and preparation of the report were performed by Loren S. Bonderson.

METRIC CONVERSION FACTORS

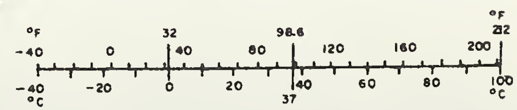
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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LIST OF ACRONYMS

AGT	Automated Guideway Transit
AGTT	Automated Guideway Transit Technology
ASYN	Asynchronous Control Combination
B	Control Block
BB	Block Vehicle Follower and Block Headway Protection
BC	Block Vehicle Follower and Continuous Headway Protection
CB	Continuous Vehicle Follower and Block Headway Protection
CC	Continuous Vehicle Follower and Continuous Headway Protection
D	Station Dock Link or Merge Decision Point
DESM	Discrete Event Simulation Model
DOCM	Detailed Operational Control Model
FIFO	First-In, First-Out
GDY	Mainline Guideway Link or Entrainment on Guideway
GM TSD	GM Transportation Systems Division
GRT	Group Rapid Transit
IGRT	Intermediate Vehicle GRT
IR	Station Input Ramp Link
IQ	Station Input Queue Link
M	Merge Point
OR	Station Output Ramp Link
OQ	Station Output Queue Link
PB	Point Follower and Block Headway Protection
PC	Point Follower and Continuous Headway Protection
Q	Downstream End of Merge Queueing Region
Q-SYN	Quasi-Synchronous Control Combination
S	Station Storage Link
SGRT	Small Vehicle GRT
SLT	Shuttle Loop Transit
SOS	System Operations Studies
STN	Entrainment at Station
STN-GDY	Entrainment at Station and on Guideway
SYN	Synchronous Control Combination

1.0 INTRODUCTION

The Automated Transit Technology System Operations Studies Program is directed toward the study of the applicability and capability of automated guideway transit systems. The AGTT-SOS program has two main thrusts:

1. To conduct comparative automated guideway system analyses of the cost, performance, and operating characteristics of several generic systems in representative urban network configurations, and

2. To develop and document a set of proven computer models that will allow the contractor to perform the analyses and allow planners to perform similar analyses of automated guideway systems.

Automated guideway transit systems in general require the functions of vehicle control, headway protection, longitudinal control, merge strategy, and dispatch strategy. The specific option utilized for each of these functions in a given system constitutes the operational control strategy combination. An important, but secondary, thrust of the AGTT-SOS program is the evaluation and computer simulation of alternative AGT operational control strategies in order to augment, compliment, and provide input to the primary system analyses.

1.1 OBJECTIVE

The objective of the operational control analysis is to evaluate the performance, cost, and operating characteristics of alternative operational control strategies in the context of the system types described in the Classification and Definition of AGT Systems report[1] and the network types identified in the Application Area Definition report[2]. The overall objective is met by a two-level analysis effort, an operational control subsystem analysis and an alternative operational control system evaluation.

1.2 SCOPE

An overview of the operational control analyses showing their interrelationship and their relationship to other portions of the AGTT-SOS program is provided in Figure 1-1. The first level of analysis, the operational control subsystem analysis, consists of a higher level definition of algorithms and the hardware and software components for the alternative control strategies and a performance analysis. The performance analysis, consisting of parametric analysis and network subelement experiments, provides the detailed description of vehicle dynamic behavior required as input to the system trade-off analysis and to the system-level analysis, which constitutes the second level of the alternative operational control strategies analysis. The second level of analysis, the alternative operational control system evaluation, consists of three evaluation studies. The first study, alternative

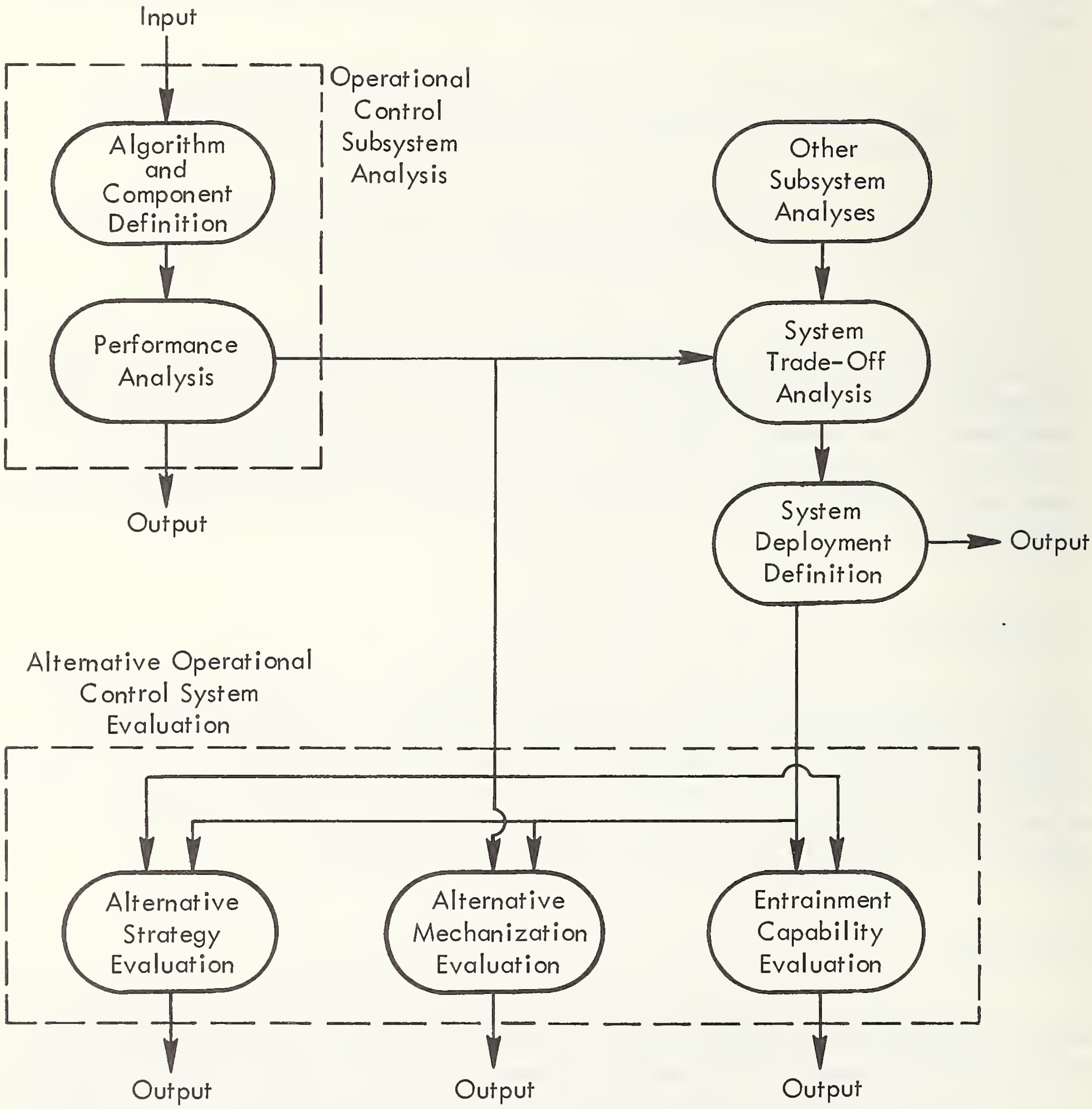


FIGURE 1-1. OPERATIONAL CONTROL ANALYSIS

strategy evaluation, considers the system performance and cost effects of alternative operational control strategies in the context of a single system deployment. The alternative mechanization evaluation, the second study, compares the software and hardware mechanizations of the alternative control strategies in the context of the same baseline system deployment. The third study, entrainment capability evaluation, evaluates the dynamic system performance effects of operational entrainment capabilities using the same baseline system deployment.

As shown, each of the three evaluation studies requires input from the operational control subsystem analysis and from the system trade-off analysis. The baseline system used in the system evaluations is an altered version of one system from the group of representative system deployments studied in the system trade-off analysis. Whenever possible, alternative strategies and/or alternative strategy combinations are compared and guidelines are stated for choosing between control alternatives.

The analytical and experimental tasks performed in these subsystem and system level studies were done in the context of a large body of work already done in the field of operational control. Section 6.0 is a Bibliography of reports and articles, which while not specifically referenced in this report, were found to be very useful.

2.0 OPERATIONAL CONTROL SUBSYSTEM ANALYSIS

The objective of the operational control subsystem analysis is twofold. First a higher level definition of the various algorithms used for controlling vehicle position, velocity, safety, merging and dispatching along with an identification of the components and computation required to implement the algorithms is given. Once a specific set of algorithms is available a performance analysis consisting of parametric analysis and network subelement experiments using the Detailed Operational Control Model (DOCM) is performed. The purpose of this analysis at the subsystem level is to make direct comparisons between algorithms whenever possible through experiments which focus only on the performance of single vehicles or single guideway elements. These subsystem analyses provide detailed descriptions of vehicle dynamic behavior required for input to the System Trade-Off Analysis and to the system-level analysis of operational control.

2.1 ALGORITHM AND COMPONENT DEFINITION

In this section alternative algorithms are identified for vehicle control, headway protection, longitudinal control, merge strategy and dispatch strategy. The various alternatives are not all mutually compatible. Compatible combinations are identified in in this section. An underlying theme of these control strategies is vehicle safety. Vehicle safety is assumed to be equivalent to the maintenance of a minimum headway between vehicles under all conditions and if not maintained an emergency response is invoked. The definition of this minimum headway is thus made in this section.

Once the alternative algorithms are identified, a higher level definition of the hardware and software requirements to realize the algorithms in actual practice is made.

2.1.1 Minimum Headway

The minimum operational headway associated with a specific combination of operational control strategies depends on the strategies chosen. That is, for example, a point follower control constrains the minimum operational headway in a different way than does a vehicle follower control. These effects are presented in detail in a following section. In this section two expressions, one rather general and the other a very useful special case of the general expression, for the minimum head-to-head distance between vehicles considering only the dynamics of braking to a safe stop, are presented.

The idealized worst case head-to-head distance that must be allowed in order for the trailing vehicle to brake to a stop without colliding with a failed lead vehicle is[3]:

$$D_m = \frac{v^2}{2A_e} + \frac{vA_e}{2J_e} + \tau v + \frac{vA_f}{J_e} + \frac{vA_f^2}{2A_eJ_e} + \frac{\tau vA_f}{A_e}$$

$$+ \frac{\tau A_f^3}{2A_eJ_e} + \frac{A_f^4}{8A_eJ_e^2} + \frac{\tau^2 A_f^2}{2A_e} + \frac{A_eA_f^2}{4J_e^2}$$

$$+ \frac{\tau A_eA_f}{2J_e} + \frac{A_f\tau^2}{2} + \frac{A_f^3}{3J_e^2} + \frac{A_f^2\tau}{J_e} + L \qquad (2\text{-}1)$$

where

D_m	=	Head-to head vehicle distance
v	=	Trailing vehicle velocity at the time of failure detection
A_e	=	Trailing vehicle emergency deceleration (DOCM variable ANEACC)
J_e	=	Trailing vehicle emergency jerk (DOCM variable ANEJRK)
τ	=	Reaction delay after failure detection (DOCM variable ANEDLY)
A_f	=	Trailing vehicle acceleration at failure
L	=	Preceding vehicle (or consist) length (DOCM variable IDVLEN)

The acceleration time history for such a braking situation is shown in Figure 2-1. This expression also assumes "brickwall" stops for the failed lead vehicle; that is, its deceleration rate is infinite. This expression is very conservative and a commonly used subcase assumes that the trailing vehicle acceleration at failure is zero. This is not unrealistic since first, a vehicle's acceleration limit at maximum design velocity is usually less than its low velocity acceleration capability and secondly, because a nonzero value at maximum design velocity implies a double failure event. The double failure event is that the lead vehicle has failed and the trailing vehicle is in an acceleration mode at minimum acceptable spacing, itself a failure event. The expression when A_f is zero becomes:

$$D_m = \frac{v^2}{2A_e} + \frac{vA_e}{2J_e} + \tau v + L \qquad (2\text{-}2)$$

The safe headway distance D in all DOCM algorithms is

$$D = BD_m \tag{2-3}$$

where Equation 2-2 is the expression used for D_m and B is the user input variable ANBFCT.

When head-to-head vehicle distance becomes less than this value an emergency procedure is enabled. Thus, the commanded spacing for vehicle control algorithms must be greater than this distance.

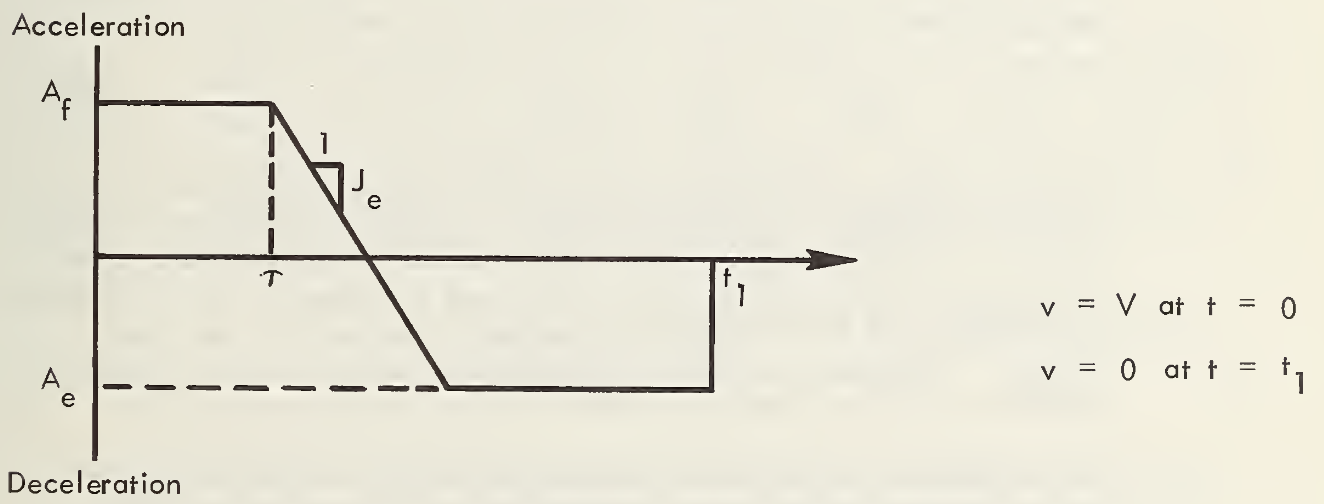


FIGURE 2-1. ACCELERATION TIME HISTORY ASSOCIATED WITH EQUATION 2-1

2.1.2 Control Algorithms

A specific combination of vehicle control, longitudinal control, and headway protection methods operating in conjunction with network merge and dispatch policies constitutes an operational control strategy. The individual strategy options identified during this study and implemented in at least one specific form for simulation using either the DOCM or Discrete Event Simulation Model (DESM) are defined in this section. Those algorithms which are documented in other reports are referenced and those algorithms not concisely documented in other reports are detailed in this section.

2.1.2.1 Vehicle Control - Vehicle control provides for regulation of vehicle position, velocity, acceleration, and jerk through acceleration and deceleration commands to the vehicle's propulsion and braking systems. The three regulation alternatives considered are:

1. Vehicle follower vehicle control implemented by fixed guideway blocks - For the purpose of vehicle control, the guideway is divided into discrete blocks, hardwired to the guideway. Vehicle location, accurate only to the length of a fixed block, is determined from block occupancy data. A vehicle utilizes data on the occupancy status of preceding blocks and possibly data on its own velocity and position within a block to determine appropriate propulsion and braking commands. Central or local control may alter the algorithm which determines the propulsion and braking commands provided that the limits imposed by the headway protection strategy and maximum line speed are not violated.

   The specific control algorithm implemented in the DOCM is an acceleration command

$$a_c = a_3 E_x + a_4 E_t \tag{2-4}$$

   where a_3 and a_4 are elements of the user input gain vector ANGAIN 1, E_t is the difference of reference velocity and vehicle tachometer velocity, and E_x is the time integral of E_t. The reference velocity is determined by applying a line speed factor to the normal line speed. The line speed factor to be used for a given block separation number is a user input quantity. Emergency and service deceleration commands are available as special cases of the line speed factor and thus override Equation 2-4.

2. Vehicle follower vehicle control implemented by continuous state measurements - Measurement equipment on board the vehicle provides essentially continuous measurement of intervehicle distance and relative velocity. These data along with nominal line speed data are used to determine propulsion and braking commands for the vehicle. When the intervehicle distance exceeds a function of safe stopping distance, the control is based entirely upon the nominal line velocity and the vehicle controller is said to be in the velocity command mode.

   The specific control algorithm implemented in the DOCM is that of Equation 2-4 when in the velocity command mode, and

$$a_c = a_2 E_x + a_1 E_{xx} + a_4 E_t + a_5 E_v \tag{2-5}$$

   when in the vehicle follower mode. The gains a_1, a_2, a_4, and a_5 are elements of the user input gain vector ANGAIN 2, E_x is the difference of lead vehicle position and the sum of following vehicle position and desired safe spacing S_o. E_{xx} is the time integral of E_x, E_t is the difference of the linespeed velocity and the vehicle tachometer velocity, and E_v is the difference of the lead vehicle velocity and the following vehicle velocity. The desired safe spacing S_o is related to D of Equation 2-3 by

$$S_o = KD \tag{2-6}$$

where K is the user input variable ANKFCT.

The vehicle is in the vehicle follower mode whenever its head-to-head spacing with the preceding vehicle is less than $K_t S_o$, where K_t is the user input variable ANKTO. Once in the vehicle following mode it remains in that mode.

3. Point follower vehicle control - Each vehicle follows a predetermined velocity and position profile. These profiles may be interpreted as defining a virtual moving control point. On board measurement equipment provides essentially continuous measurements of the vehicle's position and velocity errors in tracking this control point, which are then used to determine propulsion and braking commands to keep the vehicle within a virtual slot having the control point as its center.

   The specific control algorithm implemented is an acceleration command

$$a_c = a_2 E_x + a_1 E_{xx} + a_4 E_v + a_6 E_A \tag{2-7}$$

   where a_1, a_2, a_4, and a_6 are elements of the user input gain vector ANGAIN 1, E_x is the difference of vehicle position and the control point position, E_{xx} is the time integral of E_x, E_v is the difference of vehicle velocity and the control point velocity, and E_A is the vehicle acceleration. Special cases of control are available when a point follower is forced to queue or maneuver from one control point to another. These cases are covered in the DOCM's User Manual[4] and should be clear once the basic control is understood.

2.1.2.2 Headway Protection - Headway protection provides a fail-safe means of preventing intervehicle collisions. The two alternatives considered are:

1. Fixed block headway protection - For the purpose of headway protection, the guideway is divided into discrete segments or blocks, hardwired to the guideway. A vehicle is protected from colliding with a preceding vehicle through the imposition of velocity limit and braking commands based upon occupancy data received from preceding blocks. These commands specify a velocity envelope which may not be exceeded by the vehicle controller. The velocity limit and service or emergency braking commands to be used for a given block separation number are user input quantities. If the velocity limits are exceeded, the headway protection commands an

emergency deceleration; or, if the block separation distance corresponds to a service or emergency brake situation, that command is issued.

2. Moving block headway protection - Measurement equipment on board the vehicle provides essentially continuous measurement of intervehicle distance and the vehicle's velocity. The velocity determines a minimum safe spacing D as given by Equations 2-2 and 2-3. If the intervehicle distance becomes less than D an emergency braking command is given by this algorithm.

2.1.2.3 Longitudinal Control - Longitudinal control provides for the orderly movement of vehicles along the guideway and especially allows for the orderly merging of vehicles at merges and intersections. The three alternatives considered are:

1. Synchronous longitudinal control - Vehicles operate under point follower vehicle control, always tracking an initially assigned reference point.

2. Quasi-synchronous longitudinal control - Vehicles normally operate under point follower vehicle control but are allowed to advance or slip from the initial reference point to another control point. This maneuver is performed upstream of a merge in a maneuver region and is made to resolve a merge conflict.

3. Asynchronous longitudinal control - Vehicles operated under vehicle follower vehicle control and are allowed to change velocity and position relative to the surrounding vehicular states to resolve a potential merge conflict.

These three commonly identified longitudinal control strategies are actually a higher level description of combinations of vehicle control and merge strategy.

2.1.2.4 Merge Strategy - Merge strategy refers to the logic used to resolve potential merge conflicts. The three basic alternatives considered are:

1. Scheduled merge - The dispatch time for each vehicle is chosen so that as long as a vehicle adheres to its schedule, no merge conflicts will occur. If a vehicle can not maintain its schedule, a conflict may occur and must be resolved by one of the other merge strategies. Deterministic dispatching, which is described in the next section, is invoked to effect a scheduled merge maneuver. There is no algorithm associated with scheduled merge.

2. First-in/first-out merge (FIFO) - Vehicles are allowed to proceed through a merge based upon the time order in which they enter a data acquisition area (or zone of influence) located upstream of the merge point.

A FIFO merge algorithm suitable for vehicles operating under vehicle control implemented by fixed guideway blocks has been implemented in the DOCM. Figure 2-2 pictorially represents the merge geometry and location of the velocity control blocks.

Points A_1 and A_2 are the upstream ends of the analysis regions on links 1 and 2, respectively. Points D_1 and D_2 are the decision points on links 1 and 2, respectively. M is the merge location. The points A_1, A_2, D_1, D_2 may be located independently; however, A_1 and A_2 are at or upstream of D_1 and D_2, respectively, and D_1 and D_2 must be at least some minimum number of blocks upstream of M. The minimum number of blocks is such that a vehicle located in the block just upstream of M will not cause a brake command or a reduced speed command for any block upstream of the decision point. Safe merge control is accomplished by assigning a phantom vehicle to the block just upstream of M to either link 1 or link 2 vehicles at the time they reach their respective decision points.[15] The idea of a phantom vehicle is that the vehicle control and headway protection systems are made to respond as if an actual vehicle were located in the control block to which a phantom vehicle is assigned. The logic is as follows:

- When passing D_1, a link 1 vehicle is assigned a phantom if there are any link 2 vehicles between D_2 and M. At the same time, the ID of the link 2 vehicle between D_2 and M which is the most upstream is determined. The phantom for the link 1 vehicle is removed when the vehicle of determined ID passes M.
- The logic for link 2 vehicles is equivalent.
- The order of processing exact ties in arrival is random.

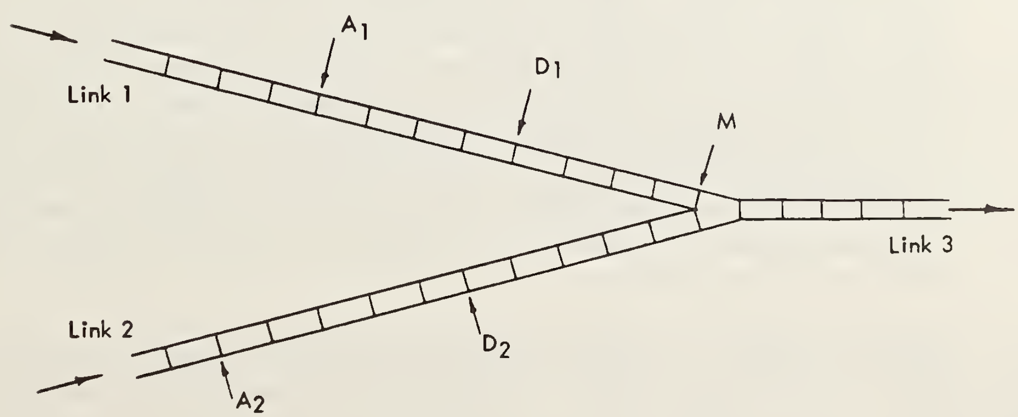


FIGURE 2-2. MERGE GEOMETRY AND VELOCITY CONTROL BLOCKS

A FIFO merge algorithm suitable for vehicles operating under vehicle follower vehicle control implemented by continuous state measurements has also been implemented in the DOCM. The algorithm is the Brown algorithm and is documented in Section A.4.2 of the DOCM Technical Specification [5]. (Also see Bibliography, entry 4.)

A FIFO merge algorithm suitable for vehicles operating under point follower vehicle control has also been implemented in the DOCM. The algorithm is the Chu algorithm documented in Section A.4.1 of the DOCM Technical Specification[5]. (Also see Bibliography, entries 10 and 11).

3. Priority merge - Vehicles in a data acquisition area located upstream of the merge point are allowed to proceed through the merge in an order based upon a method of assigning priority other than time order of arrival. Some examples of priority assignment are one favored link, loaded vehicles favored, moving vehicles favored, queued vehicles favored, random choice, alternating choice, etc.

   The priority merge algorithm which has been implemented in the DOCM for vehicles operating under vehicle follower vehicle control gives priority to vehicles in the analysis region of one link over the vehicles in the analysis region of the other link. This may be accomplished with the already defined FIFO merge algorithms by defining the new location of the decision point for the priority link to be the same as the upstream end of the priority link's analysis region. Thus, referring to Figure 2-2, all vehicles in the analysis region of link 1, those vehicles between A_1 and D_1, may be given priority over vehicles in the link 2 analysis region by moving the decision point D_1 to coincide with A_1 and then applying the normal FIFO merge algorithms.

   The freedom to independently locate the decision points and analysis regions on the two merge input links is not compatible with the Chu algorithm for FIFO merging under point follower vehicle control. However, simultaneous vehicle arrivals at the two decision points is a common occurrence under point follower vehicle control and thus the default order of processing links can have an important effect on this algorithm. The order of processing links, and thus priority in the event of ties, is a user input to the DOCM. Optional advance modes are also available in the DOCM implementation of the Chu merge algorithm and thus provide additional user flexibility in designing a merge strategy for point follower vehicle control.

2.1.2.5 <u>Dispatch Strategy</u> - Dispatch strategy governs the degree of merge conflict resolution that is accomplished before a vehicle is launched onto the main line. A dispatch strategy is not implemented in the DOCM. Injections to the DOCM simulations are either individually user specified or are randomly generated to satisfy input distribution statistics. As a simulator of isolated network elements no dispatch strategy is required. The following three alternatives are implemented in the DESM and documented in Section 2.2.2.15.1 of the DESM Technical Specification[6]:

1. Deterministic dispatch - All merge conflicts are resolved before launch, and barring failures, each vehicle is assured of traversing the network on a preassigned path in a predetermined time.

2. Quasi-deterministic dispatch - Merge conflicts are not resolved prior to launch, but information about the future state of the network is used to launch vehicles at times which provide a high probability of efficient merging.

3. Non-deterministic dispatch - Potential conflicts at merges are not considered before launch but are resolved locally in data acquisition and maneuver areas upstream of each merge.

2.1.2.6 Compatible Combinations - A specific combination of the control strategies just defined constitutes the system operational control policy. The individual strategies, however, are not completely independent; that is, certain combinations are not feasible. Synchronous and quasi-synchronous longitudinal control may use only point follower vehicle control and asynchronous longitudinal control may use either of the two forms of vehicle follower vehicle control. Synchronous longitudinal control is only compatible with a deterministic dispatch strategy; and a deterministic dispatch strategy is only compatible with a point follower vehicle control. Since a deterministic dispatch stragegy implies that all merge conflicts have been resolved at the time a vehicle enters the guideway, the only compatible merge strategy is scheduled merge. The vehicle control and headway protection combination consisting of a vehicle follower vehicle control implemented using fixed block occupancy data and moving block headway protection is included for study although it does not appear to use data in an efficient manner.

These restrictions reduce the number of possible operational control combinations to 28. Six primary types of operational control are identified based upon the choice of longitudinal control and dispatch strategy as shown in Tables 2-1 and 2-2. Specifically, all Type 1 policies correspond to the definition of synchronous, all Type 2 policies correspond to the definition of hybrid, all Type 3 and 4 policies correspond to the definition of quasi-synchronous, and all Type 5 and 6 policies correspond to the definition of asynchronous.

TABLE 2-1. PRIMARY TYPES OF OPERATIONAL CONTROL

Longitudinal Control	Deterministic	Quasi-Deterministic	Non-Deterministic
Synchronous	Type 1	---	---
Quasi-Synchronous	Type 2	Type 3	Type 4
Asynchronous	---	Type 5	Type 6

Within each of these operational control types, there are alternate configurations which are feasible for practical implementation. Types 1, 2, 3, and 4 have point follower vehicle control and may have either fixed or moving block headway protection. Types 5 and 6 may each have the following four combinations of vehicle control and headway protection:

1. Fixed block headway protection and vehicle follower vehicle control implemented by fixed block measurements

2. Fixed block headway protection and vehicle follower vehicle control implemented by continuous measurements

3. Moving block headway protection and vehicle follower vehicle control implemented by continuous measurements

4 Moving block headway protection and vehicle follower vehicle control implemented by fixed block measurements

In addition to these subtype differences, Types 3, 4, 5, and 6 operational control may have either a first-in/first-out, or priority merge strategy; Types 1 and 2 operate under a scheduled merge policy. Potential operational control policies resulting from a combination of individual compatible strategies are summarized in Table 2-2. Since dispatching is a control concept applicable to a system as an entity, it is not practical to use subsystem analysis or simulation to determine the combined effect of dispatch strategy and the other elements of operational control. Also, the observed result of deterministic dispatch used to create scheduled merges is the absence of merge conflicts. This could be simulated at the subsystem level but would produce no results of interest. Thus, at the subsystem level, the combinations identified in Table 2-2 reduce to those identified in Table 2-3.

TABLE 2-2. COMPATIBLE OPERATIONAL CONTROL STRATEGY COMBINATIONS

Type	Longitudinal Control	Dispatch	Vehicle Control	Headway Protection	Merge
1a	SY	D	PF	FB	S
1b	SY	D	PF	MB	S
2a	QS	D	PF	FB	S
2b	QS	D	PF	MB	S
3a	QS	QD	PF	FB	F, P*
3b	QS	QD	PF	MB	F, P
4a	QS	N	PF	FB	F, P
4b	QS	N	PF	MB	F, P
5a	A	QD	VFB	FB	F, P
5b	A	QD	VFC	FB	F, P
5c	A	QD	VFC	MB	F, P
5d	A	QD	VFB	MB	F, P
6a	A	N	VFB	FB	F, P
6b	A	N	VFC	FB	F, P
6c	A	N	VFC	MB	F, P
6d	A	N	VFB	MB	F, P

*First-In/First-Out and Priority merge strategies are both compatible, resulting in two combinations

Legend

A - Asynchronous
D - Deterministic
F - First-In/First-Out
FB - Fixed block
MB - Moving block
N - Non-Deterministic
P - Priority
PF - Point follower
QD - Quasi-Deterministic
QS - Quasi-Synchronous
S - Scheduled
SY - Synchronous
VFB - Fixed block vehicle follower
VFC - Continuous vehicle follower

TABLE 2-3. OPERATIONAL CONTROL STRATEGY COMBINATIONS AT THE SUBSYSTEM LEVEL

Vehicle Control	Headway Protection	Merge
PF	FB	F
PF	FB	P
PF	MB	F
PF	MB	P
VFB	FB	F
VFB	FB	P
VFB	MB	F
VFB	MB	P
VFC	FB	F
VFC	FB	P
VFC	MB	F
VFC	MB	P

Legend

F - First-In/First-Out
FB - Fixed block
MB - Moving block
P - Priority
PF - Point Follower
VFB - Fixed block vehicle follower
VFC - Continuous vehicle follower

2.1.3 Component and Computation Requirements

In this section a higher level component and computation requirement definition for each of the operational control strategies is given. Computation requirements are identified on vehicles, at the central control facility, and at localized control facilities such as at merges, intersections and major portions of guideway. No attempt has been made to quantify the requirements, except to identify a low, medium and high level of computation requirement. These levels are not to be interpreted across locations but are to be interpreted across strategies. That is, for example, a high level of on board vehicle computation is not comparable to a high level of central control computation,but a similar high level of on board computation is required for both continuous vehicle follower at short headway and point follower at short headway.

The vehicle control and headway protection strategies which require continuous measurement of variables are divided into short and medium headway systems because the hardware requirements change. For state-of-the-art systems, the dividing headway time of 3 to 5 seconds was chosen for this study.

The results of this higher level component definition and computation requirement analysis are presented in Table 2-4.

2.2 PERFORMANCE ANALYSIS

The performance analysis consists of parametric analysis and network link, merge and intersection subelement experiments using the DOCM. The parametric analysis addresses minimum operational headway as a function of control algorithms, the selection of control parameters, and the calculation of detailed vehicle dynamics and energy usage. The experiments using the DOCM consist of single vehicle on links to confirm vehicle dynamics and energy useage and multiple vehicle experiments on links, merges, and intersections. The multiple vehicle experiments consist of both transient event experiments to test stability, headway protection, and start up procedures and flow experiments in which statistics are gathered over moderately long periods of time to predict steady state performance. The merge experiments are specifically structured to allow a comparison of the chosen merge strategies.

2.2.1 Minimum Operational Headway Analysis

The minimum operational headway is the closest head-to-head spacing of vehicles for a particular combination of vehicle control and headway protection, safety factor, and vehicle dynamic parameters. The distance D_m of either Equation 2-1 or 2-2 is the distance which allows a safe stop of the following vehicle for a "brickwall" stop of a failed lead vehicle. The DOCM uses this distance in establishing the headway distance, Equation 2-3, and the commanded intervehicle spacing, Equation 2-6. The user, however, must choose the multiplicative constants and reasonable block lengths and slot times where applicable. The following subsections present the results of the analysis of operational headway.

TABLE 2-4. HIGHER LEVEL COMPONENT AND COMPUTATION REQUIREMENTS OF EACH STRATEGY

	VFB	VFC-S	VFC-M	PF-S	PF-M	FB	MB-S	MB-M	SY-S	QS-S	QS-F	QS-P	A-F	A-P	D	QD	N
Vehicle Mounted																	
Guideway Data Receiving Equipment	X	X	X	X	X	X		X			X	X	X	X	X	X	X
Vehicle Data Sending Equipment			X					X							X	X	X
Direct Intervehicle Distance Measurement		X					X										
Bench Mark Detector			X	X	X			X	X	X							
Velocity Measurement	X	X	X	X	X	X	X	X									
Other State Variable Measurement		X		X		X	X	X									
Computation	L	H	M	H	M	L	M	M	L	L	L	L	L	L	L	L	L
Propulsion Actuator	X	X	X	X	X												
Braking Actuator	X	X	X	X	X	X	X	X									
Guideway Mounted																	
Vehicle Data Receiving Equipment			X					X									
Guideway Data Sending Equipment	X	X	X	X	X	X		X			X	X	X	X			
Benchmarks			X	X	X			X	X	X							
Presence Detectors	X					X					X	X	X	X	X	X	
Interblock Data Links	X					X											
Station Mounted																	
Vehicle Data Receiving Equipment															X	X	X
Dispatch Data Sending Equipment															X	X	X
Presence Detectors															X	X	X
Localized Control																	
Computation	L	M	M	M	M	L					H	H	L	L	L	L	L
Signal Generation	X	X	X	X	X	X					X	X	X	X	X	X	X
Data Link With Station																	X
Central Control																	
Computation			L	L											H	M	L
Data Link With Station															X	X	
Data Link With Localized Control			X	X											X	X	X

Legend

A-F	First-In/First-Out Merge Strategy for Asynchronous System
A-P	Priority Merge Strategy for Asynchronous System
D	Deterministic Dispatch Strategy
FB	Fixed Block Headway Protection
H	High Level of Computation Required
L	Low Level of Computation Required
M	Medium Level of Computation Required
MB-M	Moving Block Headway Protection for Medium Headways
MB-S	Moving Block Headway Protection for Short Headways
N	Non-Deterministic Dispatch Strategy
PF-M	Point Follower Vehicle Control for Medium Headways
PF-S	Point Follower Vehicle Control for Short Headways
QD	Quasi-Deterministic Dispatch Strategy
QS-F	First-In/First-Out Merge Strategy for Quasi-Synchronous System
QS-P	Priority Merge Strategy for Quasi-Synchronous System
QS-S	Scheduled Merge Strategy for Quasi-Synchronous System
SY-S	Scheduled Merge Strategy for Synchronous System
VFB	Fixed Block Vehicle Follower Vehicle Control
VFC-M	Continuous Vehicle Follower Vehicle Control for Medium Headways
VFC-S	Continuous Vehicle Follower Vehicle Control for Short Headways
X	Required

2.2.1.1 Parametric Expressions — The consist length and the distance traveled by the failed vehicle before it stops are subtracted from the distance D_m as obtained from either Equation 2-1 or 2-2. The expression used for the stopping distance assumes a constant level of failed vehicle deceleration A_{LF} . The same velocity is used for the trailing vehicle since the maximum safe guideway velocity is reasonable for both vehicles. Finally, the head-to-tail spacing due to stopping requirements, X_s, is related by a safety factor to the above difference.

$$X_s = K_s \left(D_m - L - \frac{v^2}{2A_{LF}} \right) \qquad (2\text{-}8)$$

For $K_s \geq 1$ the allowed spacing distance is greater than or equal to the exact amount required for a no collision stop. For $K_s < 1$ the allowed spacing is less than the exact amount required for a no collision stop.

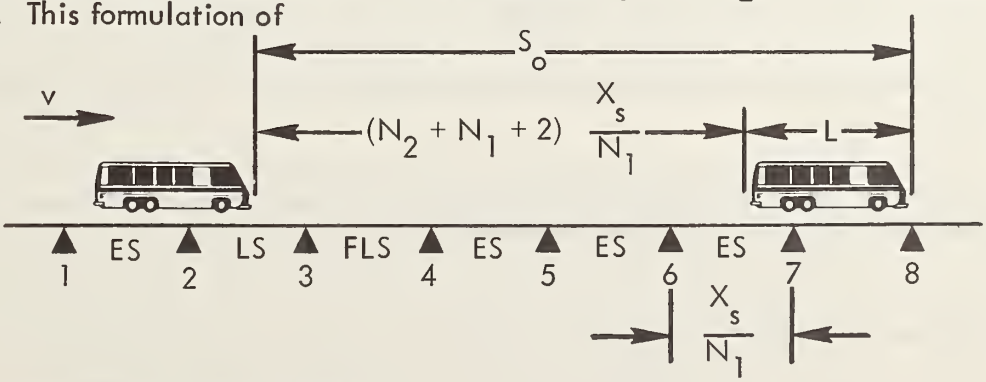
For the control combination of block vehicle follower and block headway protection the minimum operational headway distance is

$$S_o = (N_1 + N_2 + 2) \frac{X_s}{N_1} + L \qquad (2\text{-}9)$$

The minimum operational headway time in all cases is

$$h = \frac{S_o}{v} \qquad (2\text{-}10)$$

The stopping distance X_s is divided into N_1 equal blocks. The nominal distance between the end of the preceding train and the front of the following train is $N_1 + N_2 + 2$ of these blocks. N_1 blocks account for the emergency braking command portion and the 2 additional blocks are the minimum number to allow smooth operation. One of these two blocks allows vehicles to be in the center of their respective blocks and the other is normally devoted to a fractional line speed command to accommodate normal differences of vehicle performance. $N_2 = 0$ is the minimum spacing case. Controllers can use a $N_2 \neq 0$ to provide a finer block quantization and thus smoother control. The case for $N_1 = 2$, $N_2 = 0$ is illustrated in Figure 2-3. This formulation of



ES = Emergency stop command
LS = Line speed command
FLS = Fractional line speed command

FIGURE 2-3. OPERATIONAL HEADWAY FOR BLOCK VEHICLE FOLLOWER AND BLOCK HEADWAY PROTECTION operational headway, as well as the cases to follow, assumes that stations are off-line and thus do not constrain guideway headway. The average operational case is illustrated, but the lengths are chosen based upon the worst case of the preceeding train stopped just forward of block boundary 6. As can be seen, if the following train achieves an actual velocity greater than the other train, it will receive a fractional line speed command at some time and thus drop back to the desired average spacing. Clearly, a command of emergency stop is not acceptable for the first reduction of the block aspect number, since this is a frequent occurrence for this combination of control.

For the control combination of block vehicle follower and continuous headway protection, the minimum operational headway distance is the same as the previous Equation 2-9. However, in D_m there should be a second delay term $\tau_c'v$ where τ_c' is the time for the continuous headway equipment to detect a headway violation. Continuous headway equipment generally requires more calculation and transmission of signals than does the case of simple block occupancy headway protection logic.

Rather than modify Equations 2-1 and 2-2 or change the definition of τ in those equations, the minimum operational headway for this case is written as

$$S_o = (N_1 + N_2 + 2)\frac{X_s}{N_1} + L + \tau_c v \tag{2-11}$$

where

$$\tau_c = \frac{K_s (N_1 + N_2 + 2)\ \tau'_c}{N_1} \tag{2-12}$$

The block length is now

$$\text{Block Length} = \frac{X_s}{N_1} + \frac{\tau_c v}{(N_1 + N_2 + 2)} \tag{2-13}$$

As for the previous case, the minimum spacing case is $N_2 = 0$ but $N_2 \neq 0$ may be desired for smoother control.

For the control combination of continuous vehicle follower and block headway protection the minimum operational headway is

$$S_o = (N_1 + N_2 + 1)\frac{X_s}{N_1} + L + \Delta x \tag{2-14}$$

The minimum spacing case is $N_2 = 0$. The case for $N_1 = 2$ and $N_2 = 0$ is illustrated in Figure 2-4.

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16. Abstract

The objectives of the Systems Operation Studies (SOS) for automated guideway transit (AGT) systems are to develop models for the analysis of system operations, to evaluate performance and cost, and to establish guidelines for the design and operation of AGT systems. This report documents analyses of the performance, cost, and operating characteristics of the functions of vehicle control, headway protection, longitudinal control, merge strategy, and dispatch strategy. Several options were defined for each control function and evaluated both analytically and through experiments of vehicle motion on link, merge, and intersection guideway elements at the subsystem level. Several specific control strategy combinations were also evaluated at the system level through AGT system simulations. The performance effect of vehicle entrainment both at stations and on the guideway was also evaluated at the system level. Alternative strategies/combinations were compared and guidelines were stated for choosing between control alternatives.

The minimum operational headway analysis showed that the vehicle control and headway protection combination consisting of continuous moving block headway protection and fixed block vehicle follower vehicle control offers no advantage over the simpler combination using fixed blocks for both functions. In all cases, point follower control was found to require longer headway separation than vehicle follower control because of the focusing distance phenomenon during line speed changes.

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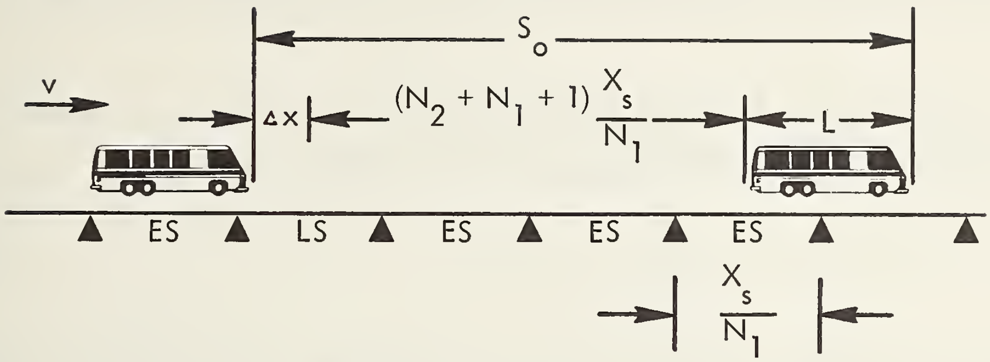


FIGURE 2-4. OPERATIONAL HEADWAY FOR CONTINUOUS VEHICLE FOLLOWER AND BLOCK HEADWAY PROTECTION

The continuous vehicle follower controller can control for a desired head-to-tail distance of the stopping requirement plus one headway block plus Δx. The term Δx is the maximum safe variation of the controller's ability to space vehicles. As shown, the addition of this Δx allows the block headway protection to use an abrupt command change from full line speed to emergency stop with only a unit change in the block aspect number. This is possible because the following vehicle will never see a reduction of the normal aspect number except under a true emergency situation.

For the combination of continuous vehicle follower and continuous headway protection the minimum operational headway is

$$S_o = X_s + \tau_c v + L + \Delta x \tag{2-15}$$

This case is illustrated in Figure 2-5

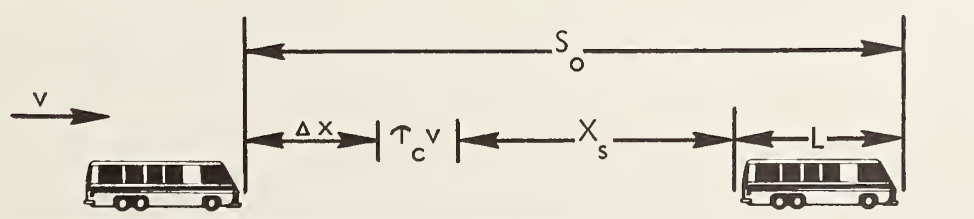


FIGURE 2-5. OPERATIONAL HEADWAY FOR CONTINUOUS VEHICLE FOLLOWER AND CONTINUOUS HEADWAY PROTECTION

The controller uncertainty Δx and the distance traveled before failure detection are added to the distance required for stopping and the consist length to obtain the operational headway distance.

For the case of point follower vehicle control with block headway protection and no on-line speed reductions the minimum operational headway is

$$S_o' = (N_1 + N_2 + 1)\frac{X_s}{N_1} + L + 2\Delta x \tag{2-16}$$

This is similar to Equation (2-14) for the case of a continuous vehicle follower with block headway protection except that an extra Δx is included to account for the characteristic of a point follower control system which independently controls the location of the two vehicles. This is contrasted to the vehicle follower control which controls so as to establish an intervehicle spacing.

When linespeed velocity changes are allowed under point follower control a velocity reduction will result in a decrease of vehicle spacing with the following vehicle retaining a high linespeed until it reaches the point of speed reduction. In vehicle follower control, the following vehicle can immediately begin to compensate its velocity to retain a desired safe spacing. Thus, in point follower control, because the vehicles are oblivious of each other, the commanded spacing at all times must account for the focusing distance which occurs during a velocity reduction. The results obtained by Hinman and Pitts[3] are used in this analysis. A velocity reduction of Δv is considered at a service deceleration limit of A_s and service jerk limit of J_s. For this case the minimum operational headway is

$$S_o = \frac{S_o' - \frac{\Delta v}{2} t'}{1 - \frac{\Delta v}{v}}$$

if

$$\frac{S_o}{v} \geq t' \tag{2-17}$$

or

$$S_o = \frac{v^2}{\Delta v} t' - \sqrt{\left(\frac{v^2}{\Delta v} t'\right)^2 - \frac{2S_o' v^2 t'}{\Delta v}}$$

if

$$\frac{S_o'}{v} < t'$$

where S_o' is the operational headway for no speed reduction on-line, that is Equation 2-16, and

$$t' = \frac{\Delta v}{A_s} + \frac{A_s}{J_s} \qquad (2\text{-}18)$$

For the case of point follower vehicle control with continuous headway protection and no on-line speed reductions the minimum operational headway is

$$S_o' = X_s + \tau_c v + 2\Delta x + L \qquad (2\text{-}19)$$

This is similar to the vehicle follower case of Equation 2-15 except for the additional Δx because the point follower control independently positions two vehicles. When on-line speed reductions are allowed the minimum operational headway S_o is given by Equations 2-17, 2-18, and 2-19.

When on-line stations are to be used the vehicle dwell time in the station very strongly affects the minimum operational headway for point follower vehicle control. It also affects the maximum steady state flow of systems using vehicle follower control but does not affect the minimum operational headway because following vehicles can slow down and queue outside of stations if necessary under vehicle follow control. However, because steady state flow capability is of primary importance, both types of control are considered together for this case.

As also reported in the report, Analysis of SLT Systems Volume III[7], the minimum operational headway for all cases of on-line stations in this analysis will use the expressions of Bergmann[8]. Several cases exist, depending on a relationship between the consist length L and the maximum linespeed v.

$$S_o = \frac{v^2}{2A_e} + \frac{v^2}{2A_s} + \frac{v^2}{2A_m} + \tau v + \tau_d v + L$$

if

$$L_1 \leq L \leq \infty$$

$$S_o = \sqrt{\frac{2v^2}{A_m}\left(L + \frac{v^2}{2A_e} - \frac{v^2}{2A_s}\right)} + \frac{v^2}{A_s} + \tau v + \tau_d v \qquad (2\text{-}20)$$

if

$$L_2 \leq L \leq L_1$$

$$S_o = \sqrt{\frac{2v^2 L \left(1 + \frac{A_m}{A_s} - \frac{A_s}{A_e} \right)}{A_m \left(1 - \frac{A_s}{A_e} \right)}} + \tau v + \tau_d v$$

if

$$L \leq L_2$$

where

$$L_1 = \frac{v^2}{2A_m} + \frac{v^2}{2A_s} - \frac{v^2}{2A_e}$$

$$L_2 = \left(1 - \frac{A_s}{A_e} \right)^2 \frac{v^2}{2A_m} + \frac{v^2}{2A_s} - \frac{v^2}{2A_e} \qquad (2\text{-}21)$$

The two new variables are A_m the maximum service acceleration rate and τ_d the station dwell time. These expressions for the minimum operational headway with on-line stations do not consider the effect of different control combinations or the effect of jerk limiting the acceleration and deceleration. This additional depth of analysis is not required for this situation since long headways result from this case of on-line stations.

2.2.1.2 Sensitivity Analysis — The minimum operational headway expressions presented in the previous section are investigated for a nominal control case representative of SGRT vehicles. The nominal parameter values were documented in the Classification and Definition of AGT Systems report[1]. One parameter at a time is varied (with the others held fixed) and the effect on minimum operational headway time is presented for each of the six combinations of vehicle control and headway protection. For the purpose of this sensitivity analysis the nominal control parameters are specified as:

$$
\begin{aligned}
v &= 25.0 \text{ m/s} \\
A_e &= 5.0 \text{ m/s}^2 \\
J_e &= 5.0 \text{ m/s}^3 \\
A_s &= 2.2 \text{ m/s}^2 \\
J_s &= 2.2 \text{ m/s}^3 \\
L &= 4.2 \text{ m} \\
\tau &= 0.5 \text{ s} \\
\tau_c &= 0.5 \text{ s} \\
K_s &= 1.3 \\
\Delta x &= 2.0 \text{ m} \\
\Delta v &= 3.0 \text{ m/s} \\
N_1 &= 3 \\
N_2 &= 1 \\
A_f &= 0.0 \text{ m/s}^2 \\
1/A_{LF} &= 0.0 \text{ s}^2/\text{m}
\end{aligned}
\tag{2-22}
$$

The nominal minimum operational headway times for the control combinations are:

Block Vehicle Follower and Block Headway Protection (BB)
$$h = 9.27s$$
Block Vehicle Follower and Continuous Headway Protection (BC)
$$h = 9.77s$$
Continuous Vehicle Follower and Block Headway Protection (CB)
$$h = 7.83s$$
Continuous Vehicle Follower and Continuous Headway Protection (CC)
$$h = 5.30s$$
Point Follower and Block Headway Protection (PB)
$$h = 8.83s$$
Point Follower and Continuous Headway Protection (PC)
$$h = 5.95s$$

The results of the velocity sensitivity analysis are shown in Figure 2-6. Notice that the vehicle control and headway protection combinations have been labeled using the abbreviations introduced above. The vehicle follower combinations tend to be slightly more sensitive to velocity than the point followers. The results of the emergency deceleration and emergency jerk sensitivity analysis are shown in Figure 2-7. Both quantities were varied together, keeping their ratio numerically equal to unity. In general, shorter headway control combinations are less sensitive to changes in the deceleration and jerk rates.

The results of the service deceleration and service jerk sensitivity analysis are shown in Figure 2-8. Both of these quantities are also varied simultaneously, keeping their ratio equal to unity. These parameters affect only the point follower combinations since they enter into minimum operational headway only with respect to the linespeed reduction focusing phenomenon of point follower control. When linespeed changes are made at very low acceleration levels, point follower control has headways very close to the headways for similar vehicle follower control combinations.

The results of the consist length sensitivity analysis are shown in Figure 2-9. Under the stated nominal conditions (at 25 m/s velocity, etc.), the corresponding minimum operational headway change was within a quarter of a second for the range of consist lengths studied. The results of the reaction delay sensitivity analysis are shown in Figure 2-10. The control combinations which nominally allow shorter headways have the lesser sensitivity to changes in the reaction delay time.

The results of the continuous headway violation detection delay sensitivity analysis are shown in Figure 2-11. As expected, only those control combinations having continuous headway protection show any sensitivity and the level of sensitivity is modest. The results of the safety factor sensitivity analysis are shown in Figure 2-12. All combinations are strongly sensitive to the safety factor. Combinations capable of the lower nominal headways are less sensitive however than those combinations resulting in the higher nominal headways.

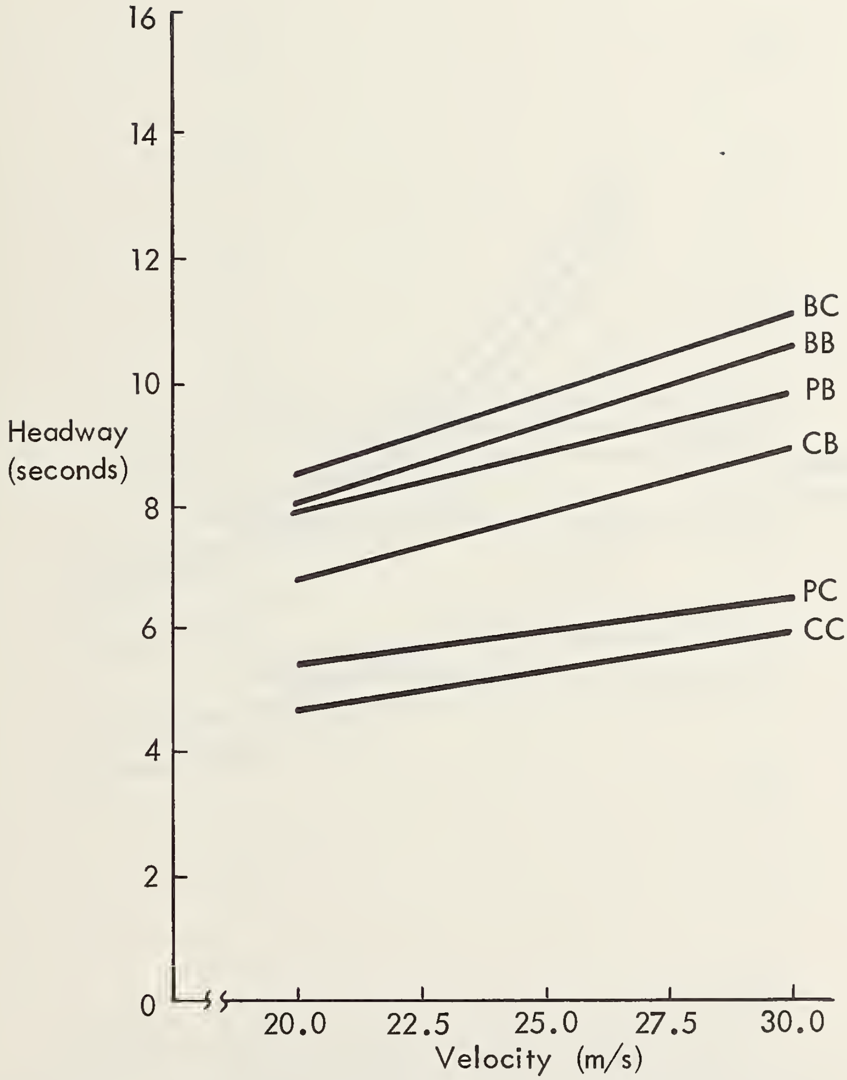


FIGURE 2-6. VELOCITY SENSITIVITY ANALYSIS

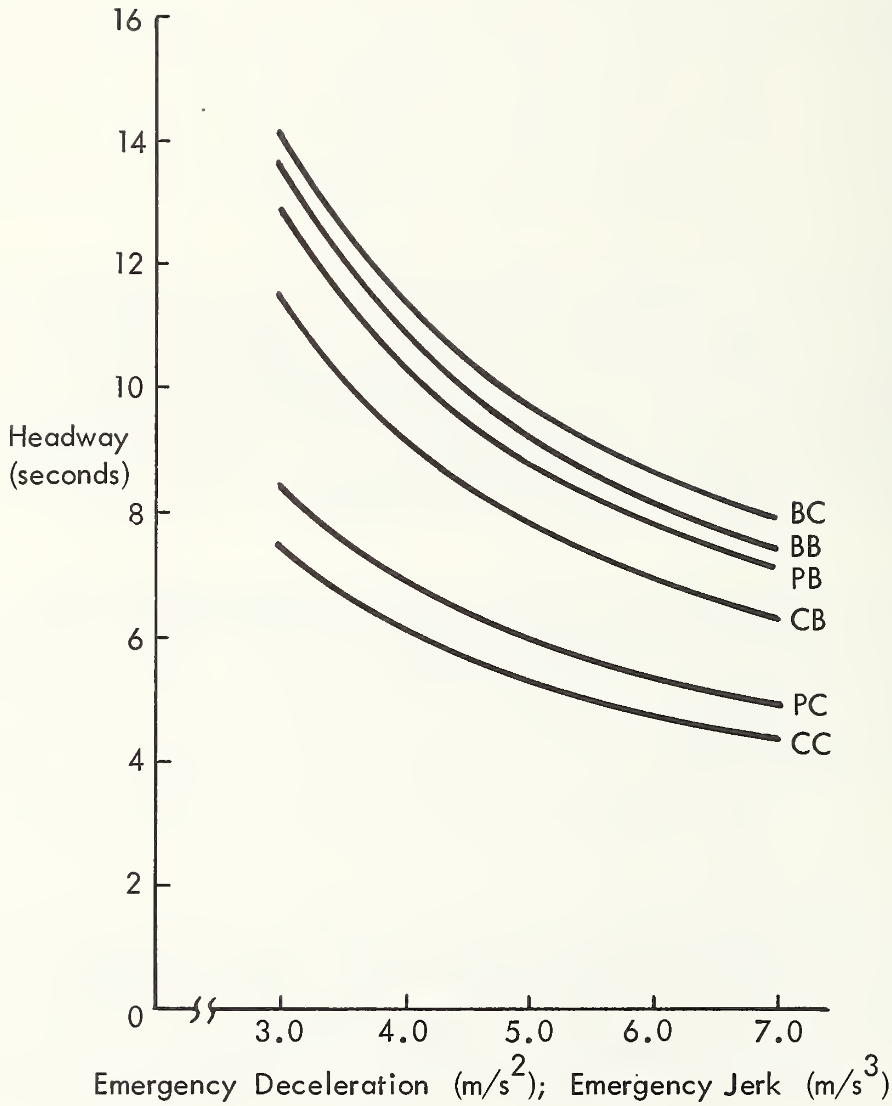


FIGURE 2-7. EMERGENCY DECELERATION AND JERK SENSITIVITY ANALYSIS

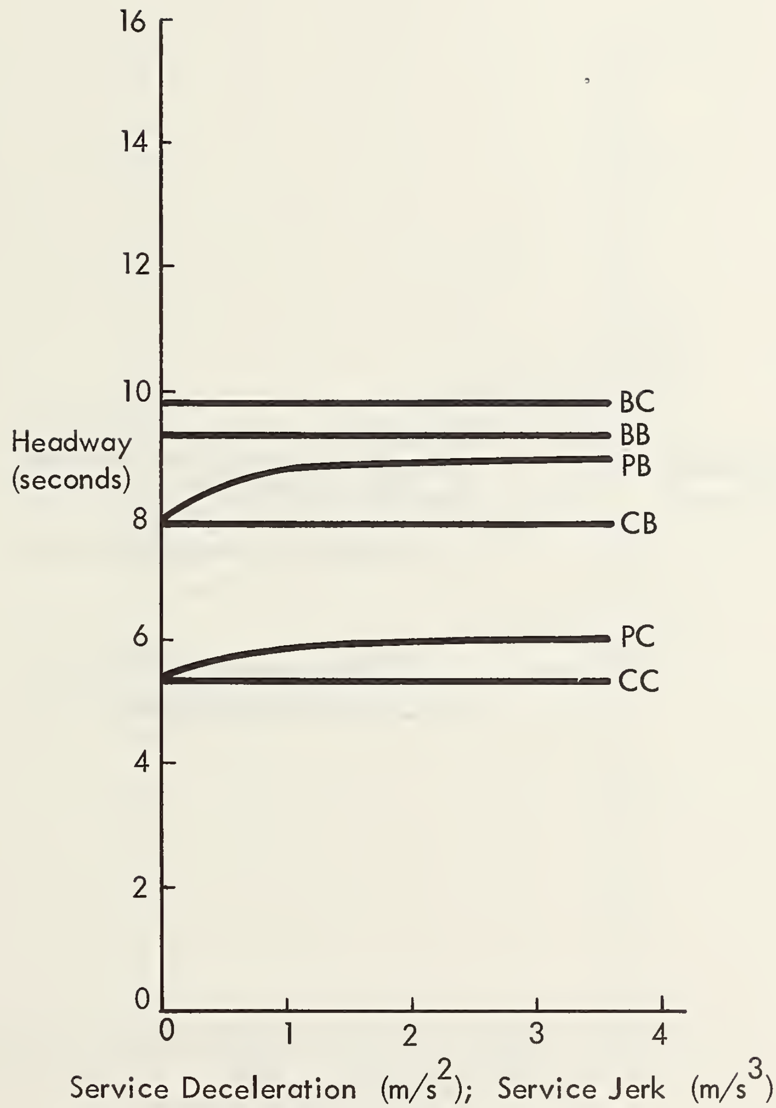


FIGURE 2-8. SERVICE DECELERATION AND JERK SENSITIVITY ANALYSIS

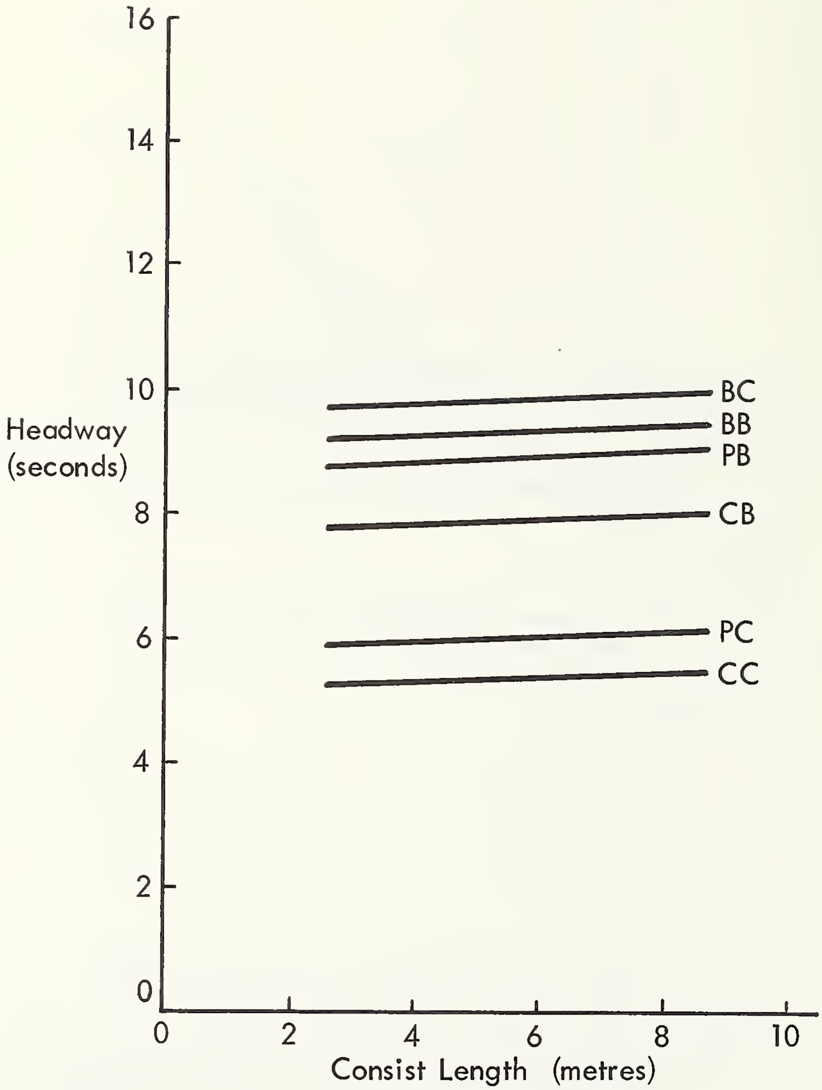


FIGURE 2-9. CONSIST LENGTH SENSITIVITY ANALYSIS

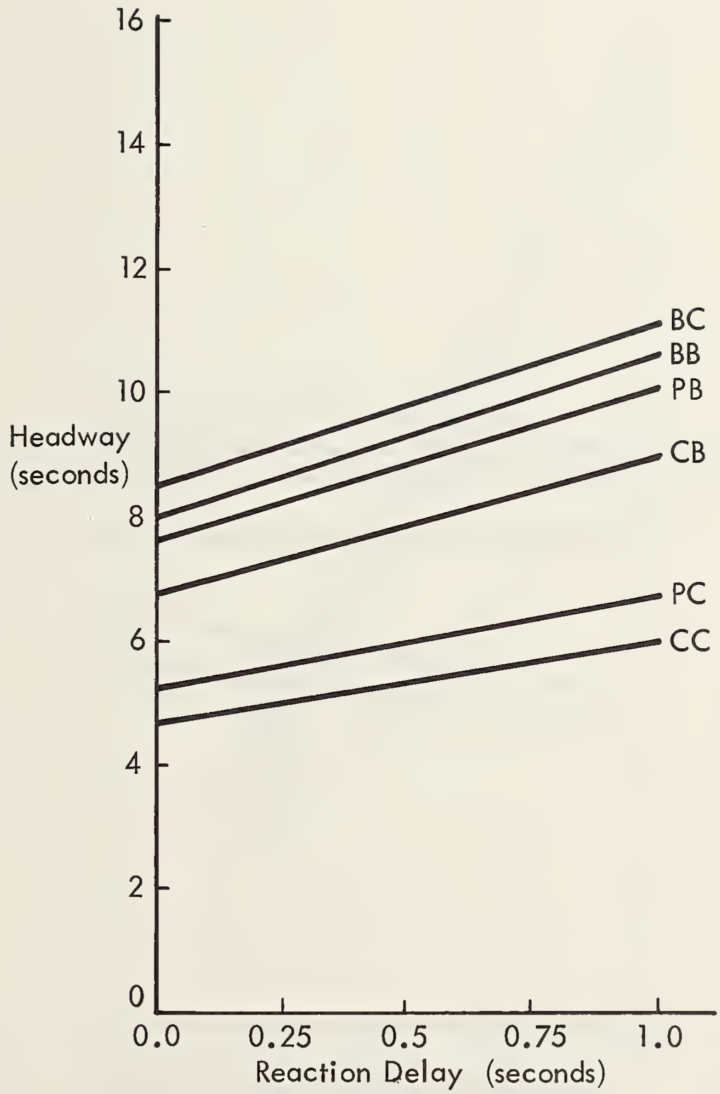


FIGURE 2-10. REACTION DELAY SENSITIVITY ANALYSIS

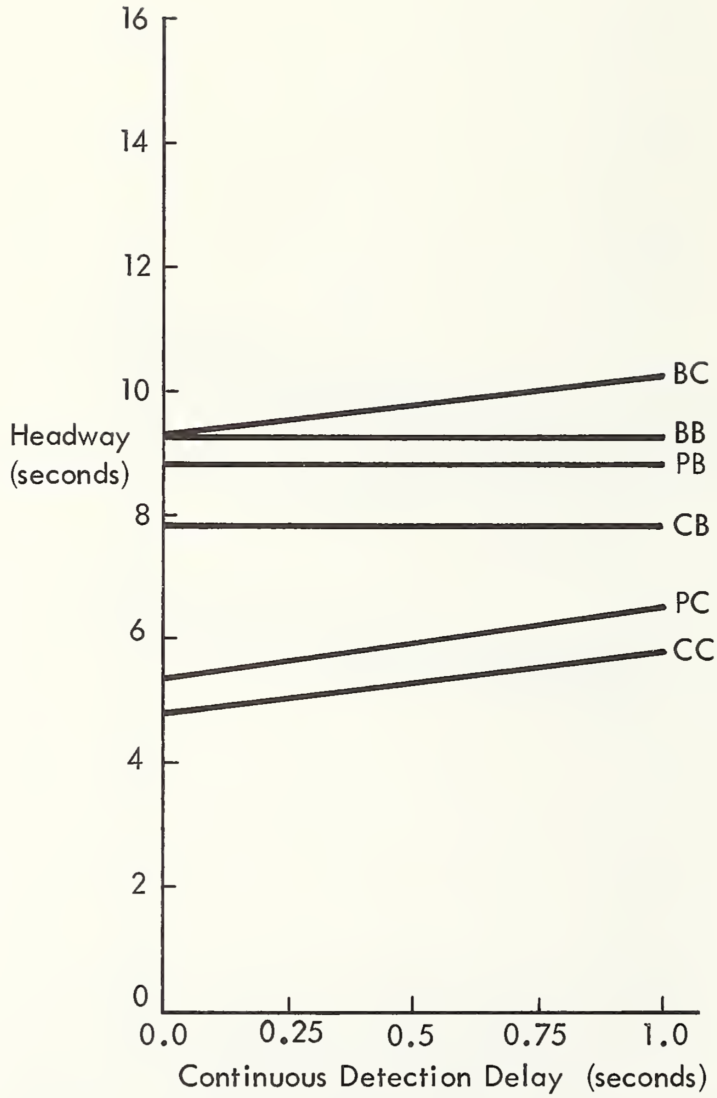


FIGURE 2-11. CONTINUOUS DECELERATION DELAY SENSITIVITY ANALYSIS

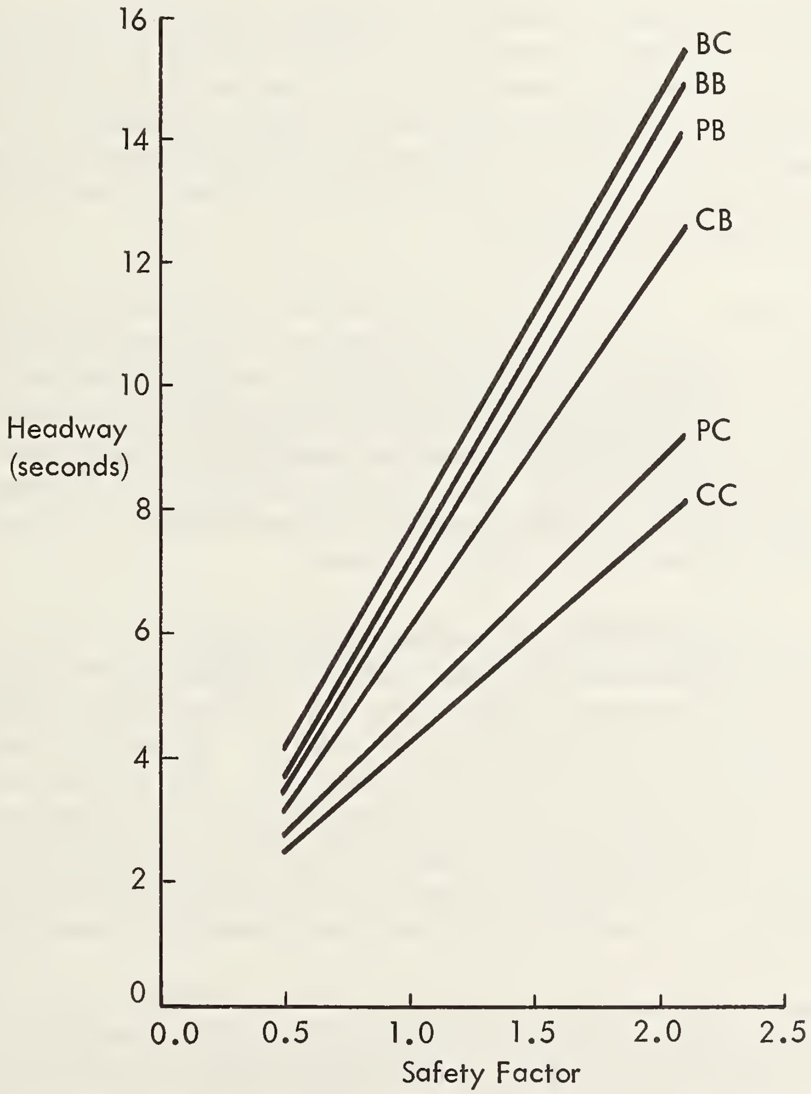


FIGURE 2-12. SAFETY FACTOR SENSITIVITY ANALYSIS

The results of the continuous position error sensitivity analysis are shown in Figure 2-13. Those control combinations with block vehicle follower control have no sensitivity while others have a low sensitivity. The results of the velocity reduction sensitivity analysis are shown in Figure 2-14. For reasons already stated, only the point follower control combinations show any sensitivity and it is of a moderate level. As the on-line velocity reduction goes to zero, the point follower and continuous vehicle followers give almost identical minimum operational headways

The results of the number of blocks for emergency stop sensitivity analysis are shown in Figure 2-15. All control combinations which use fixed guideway blocks for either vehicle control or headway protection have a strong sensitivity to this parameter. The sensitivity, however, decreases as the number of blocks increases, and the operational headways approach those of control combinations having continuous measurement only. In other words, as the number of blocks increases without bound, block measurement approaches continuous measurement.

The results of the number of blocks for smoothing contol sensitivity analysis are shown in Figure 2-16. Only those control combinations using fixed guideway blocks are affected. As shown, a significant decrease in headway for four of the combinations is possible by using no blocks for this purpose. This situation is possible but it involves either a step change from fractional linespeed to emergency braking or a step change from full linespeed to service braking. One block for smoothing on the other hand allows consecutive commands of full linespeed, fractional linespeed, service braking, and emergency braking as the aspect number decreases.

The results of the trailing vehicle acceleration at failure sensitivity analysis are shown in Figure 2-17. All control combinations have a moderate sensitivity to this parameter. The nominal case was a value of zero and, as described in Section 2.1.1, a nonzero value corresponds to a double failure situation. The results of the lead vehicle deceleration sensitivity analysis are shown in Figure 2-18. Notice that the reciprocal of the lead vehicle deceleration has been plotted since high to very high deceleration levels are generally encountered during failures. The effect on headway is moderate to strong. The worst case of infinite lead vehicle deceleration is the nominal case. Thus, designing for non "brickwall" stops allows lower operational headway times.

A few general conclusions on choosing control combinations may be drawn from these analyses. Block vehicle follower with continuous headway protection shows no gain in headway capability as compared to block vehicle follower with block headway protection. The block headway protection uses the same guideway blocks as those for the vehicle control while the continuous headway protection requires considerable additional equipment. Thus, this combination, BC, is found to have no advantages. With respect to minimum operational headway, the point follower control combinations show only a disadvantage as compared to their continuous vehicle follower counterparts. That is, CC, outperforms PC and CB outperforms PB for all headway comparisons. This situation is a result of the focusing distance phenomenon during line speed changes.

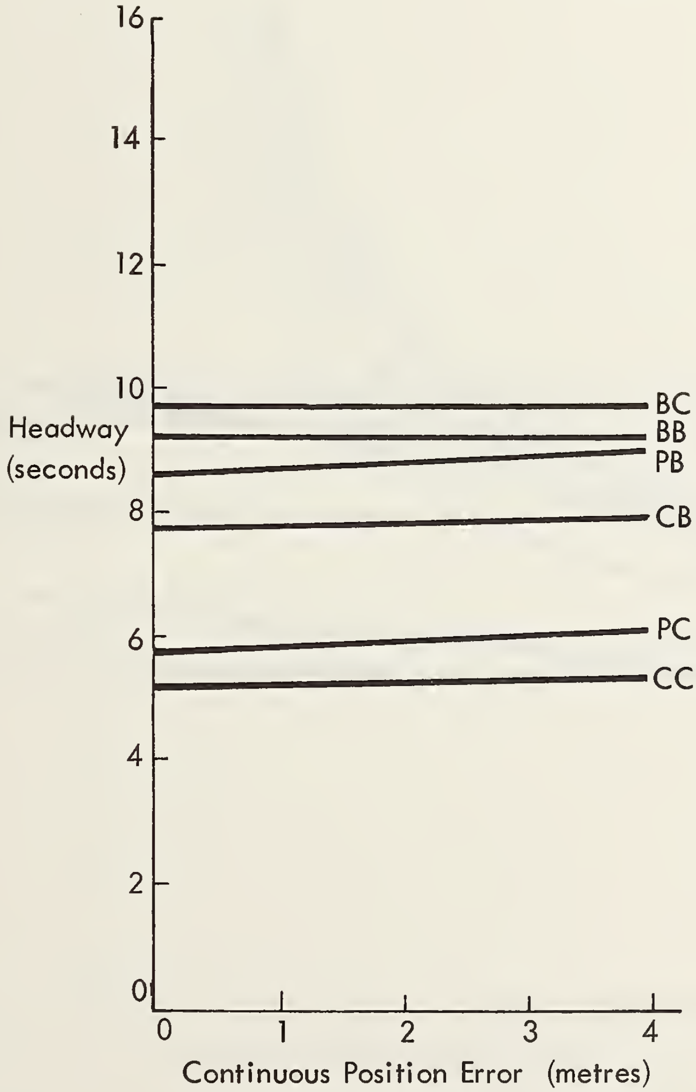


FIGURE 2-13. CONTINUOUS POSITION ERROR SENSITIVITY ANALYSIS

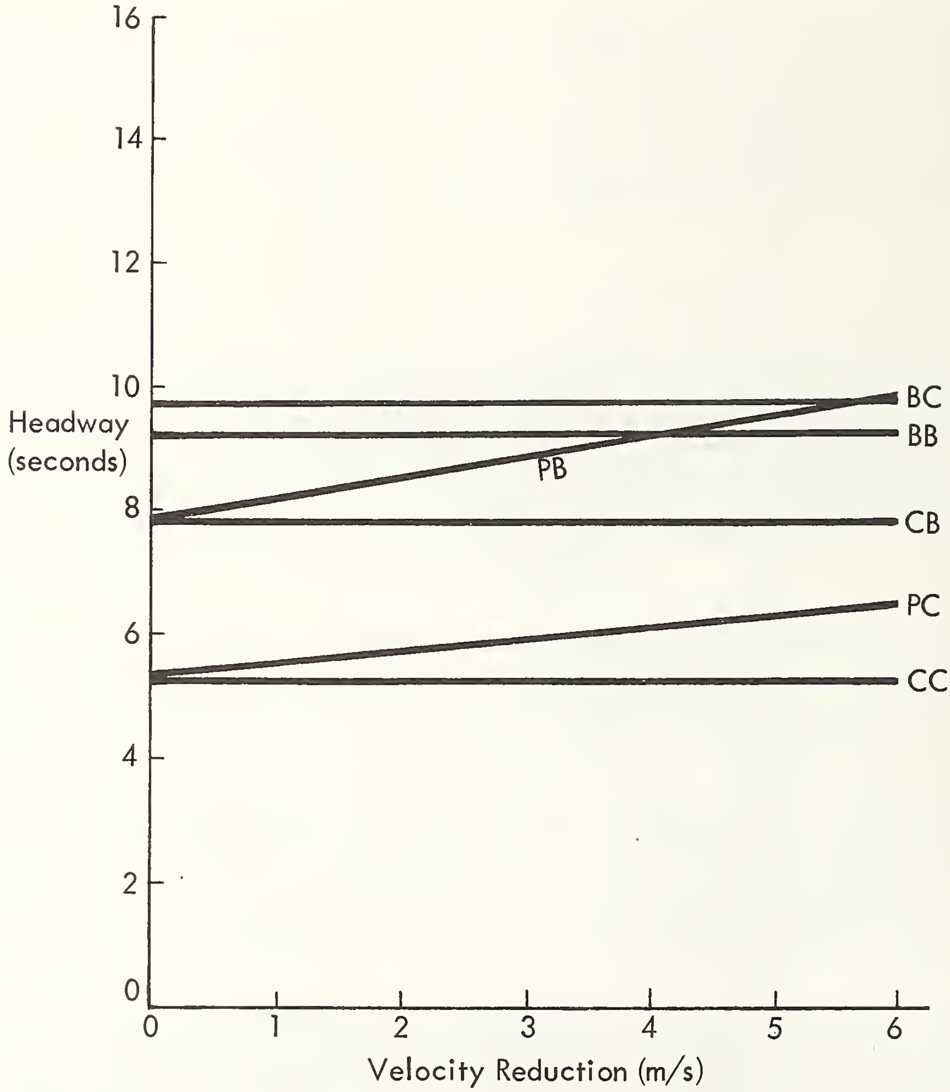


FIGURE 2-14. VELOCITY REDUCTION SENSITIVITY ANALYSIS

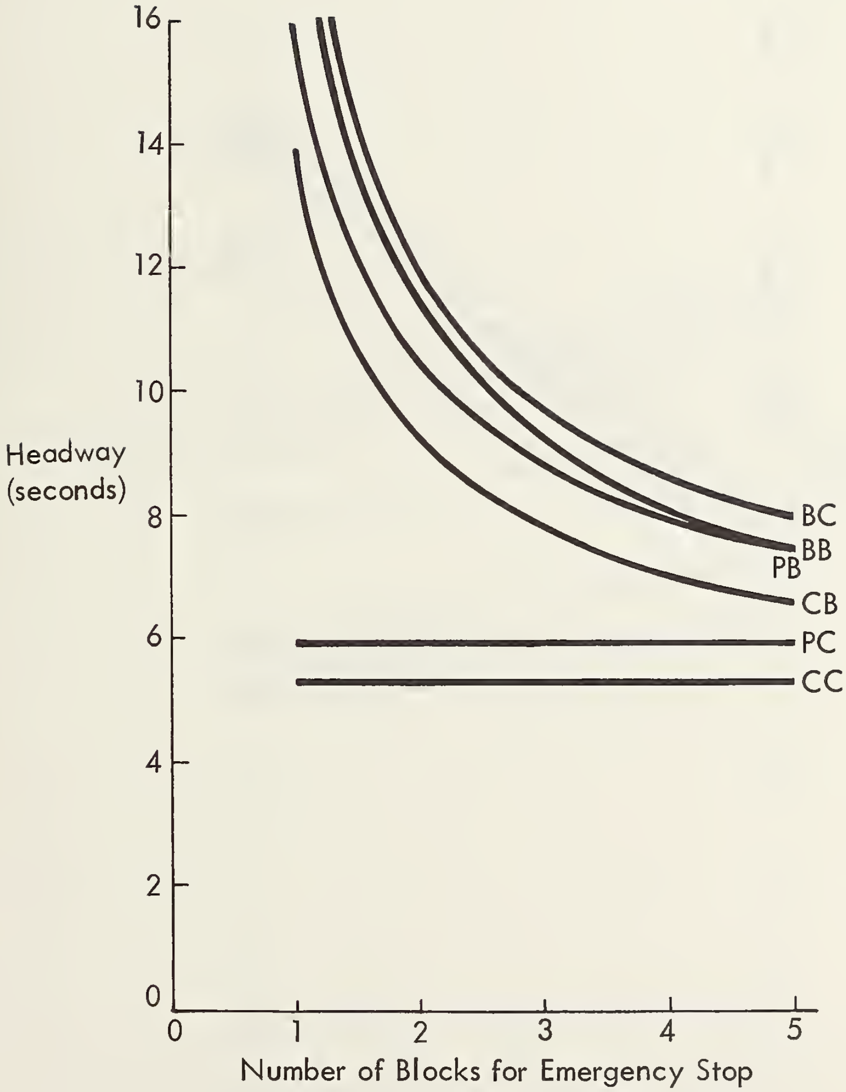


FIGURE 2-15. NUMBER OF BLOCKS FOR EMERGENCY STOP SENSITIVITY ANALYSIS

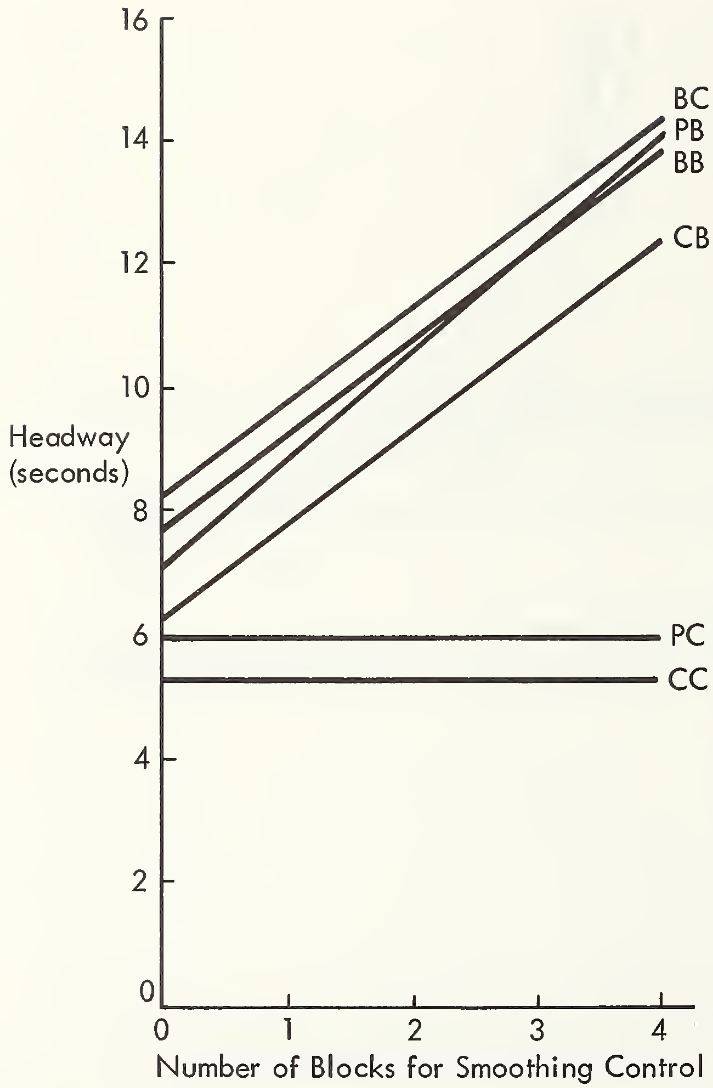


FIGURE 2-16. NUMBER OF BLOCKS FOR SMOOTHING CONTROL SENSITIVITY ANALYSIS

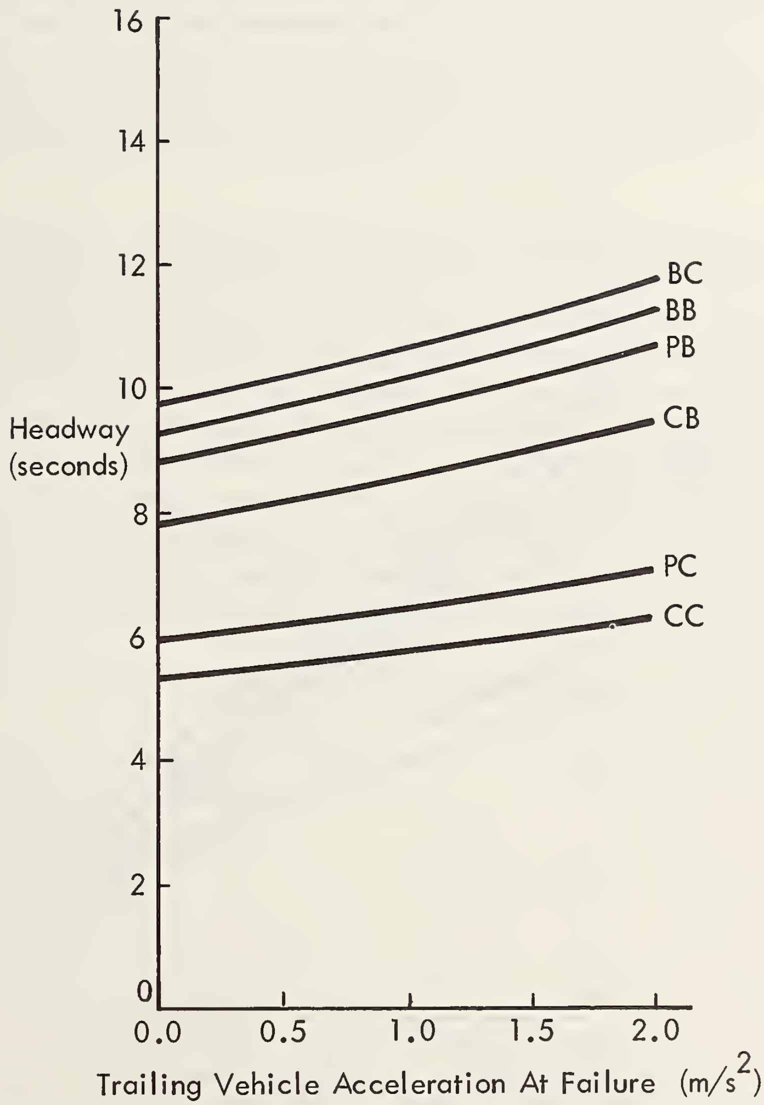


FIGURE 2-17. TRAILING VEHICLE ACCELERATION AT FAILURE SENSITIVITY ANALYSIS

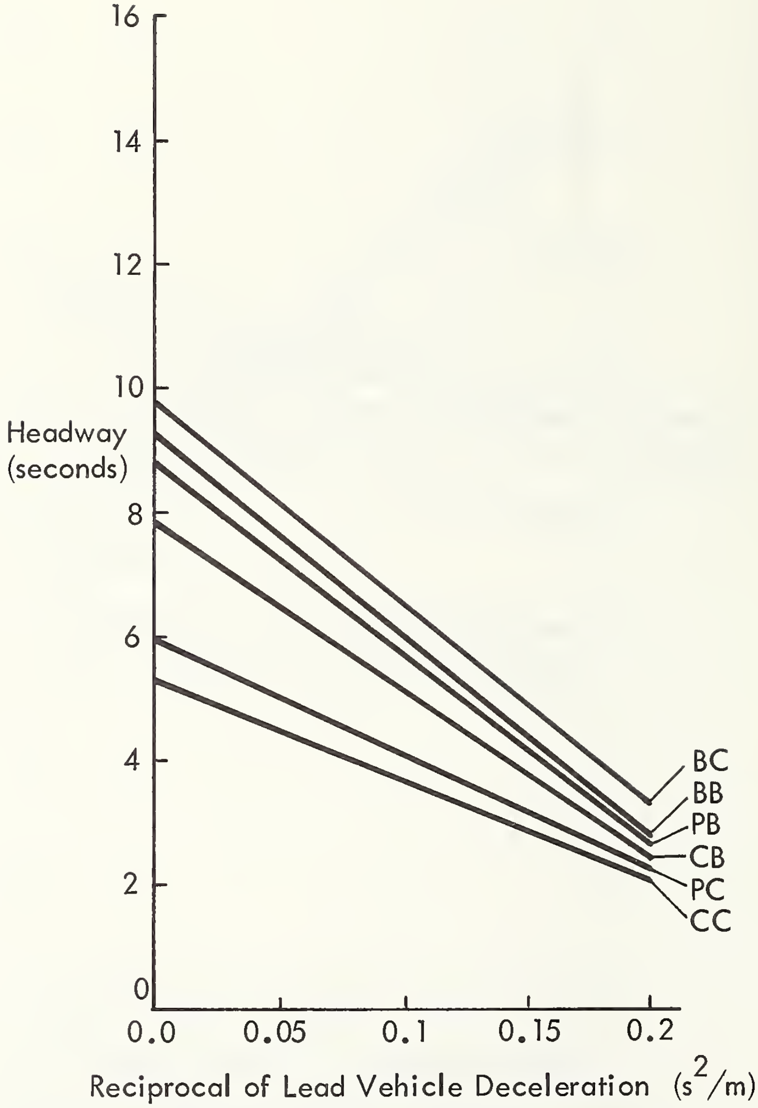


FIGURE 2-18. LEAD VEHICLE DECELERATION SENSITIVITY ANALYSIS

The results imply that any combination could be used at moderate to long headways, approximately greater than 20 seconds, and that under the nominal conditions stated on p. 2-21, no combination can achieve short and very short headways, approximately less than 4 seconds, without reducing the safety factor below unity and/or allowing for less than "brickwall" failures. Thus, when headways less than about 20 seconds are not required the traditional block vehicle follower with block headway protection (BB) is adequate and any other choice would offer capabilities greater than that utilized. For the short, less than 4 seconds, headway case continuous measurement, CC or PC, is called for. The region of performance between 4 seconds and 20 seconds, as the various sensitivity analyses show, is less clear in that the choice of control combination depends strongly on the ability to achieve parameter values, the relative cost of block equipment and continuous measurement equipment, etc.

2.2.1.3 Applications — The system level alternative operational control system performance evaluation is done in the context of SGRT vehicles. This class of vehicles was identified with the headway range 3 to 15 seconds in the Classification and Definition of AGT Systems[1] report. The results of the previous subsection show that the two combinations of control PC and CC should be used if headways approaching 3 seconds are desired. Other combinations do fall within the 15 second bound, however a design iteration after system level evaluation would then possibly be necessary. Thus, for this analysis, point follower vehicle control with continuous headway protection (PC) is employed with all primary operational control Types 1, 2, 3, and 4, and continuous vehicle follower with continuous headway protection (CC) is employed with primary Types 5 and 6. The primary operational control types are identified in Section 2.1.2.6.

The SGRT vehicle parameters which impact headway are as follows:

$$
\begin{aligned}
v &= 25.0 \text{ m/s} \\
A_e &= 5.0 \text{ m/s}^2 \\
J_e &= 5.0 \text{ m/s}^2 \\
\tau &= 0.2 \text{ s} \\
L &= 4.2 \text{ m} \\
\Delta x &= 2.0 \text{ m} \\
\Delta v &= 2.5 \text{ m/s} \\
A_s &= 2.2 \text{ m/s}^2 \\
J_s &= 2.2 \text{ m/s}^2 \\
K_s &= 1.3 \\
\tau_c &= 0.5 \text{ s} \\
A_f &= 0.0 \text{ m/s}^2 \\
\frac{1}{A_{LF}} &= 0.0 \text{ s}^2\text{/m}
\end{aligned}
\tag{2-23}
$$

A 5-percent error in velocity measurement is allowed for in the vehicle follower control and a 7-percent overshoot in linespeed velocity is allowed for in the case of point follower control. The error in velocity measurement for vehicle follower control can easily occur in the velocity control mode. The vehicle has open guideway ahead and receives a full linespeed command of 25 m/s. A 5-percent error in measurement however would result in the vehicle having a velocity of 26.25 m/s but controlling as if the velocity were 25 m/s. Thus, 25 m/s measured velocity must result in a safe spacing command for a true velocity of 26.25 m/s. This is necessary should the vehicle overtake another vehicle, a common occurrence. No velocity overshoot need be allowed for in vehicle follower control since the vehicle would measure the overshoot and thus its controller would appropriately adjust its headway time and distance.

The consideration of velocity overshoot for point follower control is necessary because a vehicle controlling on a point with linespeed velocity will overshoot the linespeed velocity. A 7-percent overshoot corresponds to a reasonable amount of control damping. Thus, a velocity of 26.75 m/s may momentarily occur and thus the slot distance at 25 m/s linespeed must be safe for that velocity. An error in velocity measurement will not be assumed. The reason is that the vehicle must always be making position measurements and thus can be designed to have zero mean error in velocity measurement.

The vehicle follower operational spacing is

$$S_o = 132.79\text{m} \tag{2-24}$$

for actual 26.25 m/s. This spacing must be generated by a controller which thinks it has a velocity of 25 m/s. A 5.3 second headway time at 25 m/s gives a spacing

$$S_o = 132.5\text{m} \tag{2-25}$$

which is the actual value used in DOCM simulations. The DOCM Equation 2-2 gives

$$D_m = 84.2\text{m} \tag{2-26}$$

Thus, the constants BK are

$$BK = \frac{S_o}{D_m} = 1.573 \tag{2-27}$$

The values chosen are

$$\begin{aligned} B &= 1.050 \\ K &= 1.498 \end{aligned} \tag{2-28}$$

This results in a headway protection at a safety factor less than the 1.3 of Equation 2-23. This is purposely done to give more leeway to the controller in controlling intervehicle spacing to ease the task of designing a controller for the first DOCM experiments.

The point follower operational spacing is

$$S_o = 150.31m \quad (2\text{-}29)$$

for momentary overspeed to 26.75 m/s. This spacing for a linespeed of 25 m/s gives a 6.0 second headway time. The variable B is required for setting the headway protection distance and is the same as for vehicle follower, i.e., B = 1.050. The variable K is not needed for point follower control except when queueing is required. For this case the value of Equation 2-28 is used.

For the system trade studies a count of actual or equivalent control blocks is used in arriving at an estimate of the control related costs. Guidelines for the determination of this control block count are presented in Appendix A.

2.2.2 Vehicle Control Analysis

The vehicle control algorithms implemented in the DOCM are described in general terms in Section 2.1.2.1. The feedback constants need to be chosen in Equations 2-4, 2-5, and 2-7. This section addresses the problem of choosing the coefficients. First, transfer functions are obtained for vehicles controlled by these algorithms, conditions necessary to ensure absolute and string stability are determined, and finally coefficients are chosen for DOCM simulations.

2.2.2.1 Transfer Functions — A block diagram of the Laplace transformed vehicle dynamics for the control case of Equation 2-4, corresponding to block vehicle follower vehicle control or to continuous vehicle follower vehicle control in the velocity control mode, is given in Figure 2-19.

The variables used in this and following block diagrams and their DOCM input names where applicable are:

- A_m - Service acceleration (ANSACC)
- A_d - Vehicle frontal area (IVFA)
- a_c - Commanded acceleration
- A_s - Service deceleration (ANSDEC)
- $a_1 \ldots a_6$ - Feedback coefficients (Elements of ANGAIN1, ANGAIN2, or ANGAIN3 depending on type of control)
- C_d - Aerodynamic drag coefficient (IVCD)
- C_r - Rolling friction coefficient (IVCR)
- C_s - Static friction coefficient (IVCS)
- $F_{b,p}$ - Force output of braking (b) or propulsion (p)
- $F_{b,\,p\,max}$ - Maximum force output of braking (b) or propulsion (p) (IVFB or IVFP)

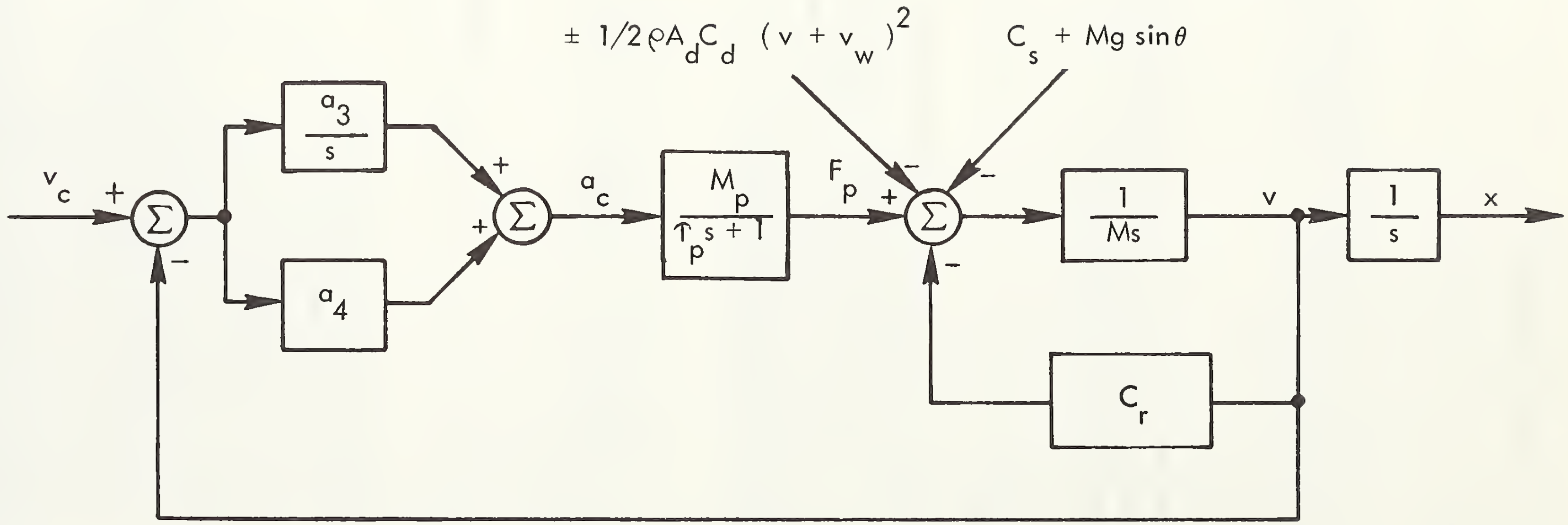


FIGURE 2-19. CONTINUOUS VEHICLE FOLLOWER IN VELOCITY CONTROL MODE AND BLOCK VEHICLE FOLLOWER VEHICLE DYNAMICS

g	-	Acceleration of gravity (ANGRAV)
J_s	-	Service jerk (ANSJRK)
M	-	Vehicle mass (IVMS)
$M_{b,p}$	-	Braking (b) or propulsion (p) proportionality coefficient ($\frac{M_{b,p}}{M}$ is IVBR and IVPR respectively)
P_{max}	-	Maximum propulsion power (IVPO)
s	-	Laplace transform variable
v	-	Vehicle velocity
v_c	-	Commanded velocity
v_p	-	Preceding vehicle velocity or control point velocity
v_w	-	Headwind velocity (LWVEL)
x	-	Vehicle position
x_o	-	Initial position
x_p	-	Preceding vehicle position or control point position
$\tau_{b,p}$	-	Braking (b) or propulsion (p) time constant (IVTB or IVTP)
θ	-	Grade angle
ρ	-	Density of air (ANDENA)
t	-	Time

Figure 2-19 is shown for the case $a_c \geq 0$ since propulsion coefficients are shown. When $a_c < 0$ all p subscripts change to b. Four forces are subtracted from the propulsive force F_p: a grade force, a static friction force, a rolling friction force, and an aerodynamic drag force. The sign on the aerodynamic drag force is positive when Sgn $(v + v_w)$ is positive and negative otherwise. Certain nonlinear constraints on variables are not shown. They are for $a_c \geq 0$

$$a_c = \mathrm{Min}\ (a_c, A_m)$$

$$F_p = \mathrm{Min}\ \left(F_p, F_{p\,max}, \frac{P_{max}}{v}\right) \tag{2-30}$$

$$\left|\frac{\Delta a_c}{\Delta t}\right| \leq J_s$$

and for $a_c < 0$

$$a_c = \mathrm{Max}\ (a_c, -A_s)$$

$$F_b = \mathrm{Max}\ (F_b, -F_{b\,max}) \tag{2-31}$$

$$\left| \frac{\Delta a_c}{\Delta t} \right| \leq J_s$$

Notice that F_b is a negative quantity but A_s and $F_{b\ max}$ are input as positive quantities. When the aerodynamic force is linearized and all constant forces ignored, the block diagram becomes that shown in Figure 2-20. The block diagram is for the linear portions of Equations 2-30 and 2-31 only. The new variables v', v_c', and x' are

$$\begin{aligned} v' &= v - v_c \\ v_c' &= v_c - v_c = 0 \\ x' &= x - v_c t - x_o \end{aligned} \tag{2-32}$$

These variables are deviation variables from the ideal vehicle response. The aerodynamic drag force is linearized as

$$\begin{aligned} \tfrac{1}{2}\rho A_d C_d (v + v_w)^2 &= \tfrac{1}{2}\rho A_d C_d (v_c + v_w)^2 + \rho A_d C_d (v_c + v_w) v' \\ &+ \tfrac{1}{2}\rho A_d C_d v'^2 \end{aligned} \tag{2-33}$$

The last term is very small and the first term is a constant force. Thus the second term is the linear portion of interest for Figure 2-20. It is convenient to define

$$C_d' = \rho A_d C_d \ (v_c + v_w) \ \mathrm{Sgn} \ (v + v_w) \tag{2-34}$$

A practical design transfer function is obtained by ignoring propulsion and braking system dynamics and by assuming accurate proportionality of output force to vehicle mass. That is

$$\begin{aligned} \tau_{b,p} &= 0 \\ \frac{M_{b,p}}{M} &= 1 \end{aligned} \tag{2-35}$$

Then the transfer function is

$$\frac{v'}{v_c'} = \frac{a_4 s + a_3}{s^2 + \left(a_4 + \dfrac{C_r + C_d'}{M_p}\right) s + a_3} \tag{2-36}$$

For reasonable input parameters

$$\frac{C_r + C_d'}{M_p} < .038 \tag{2-37}$$

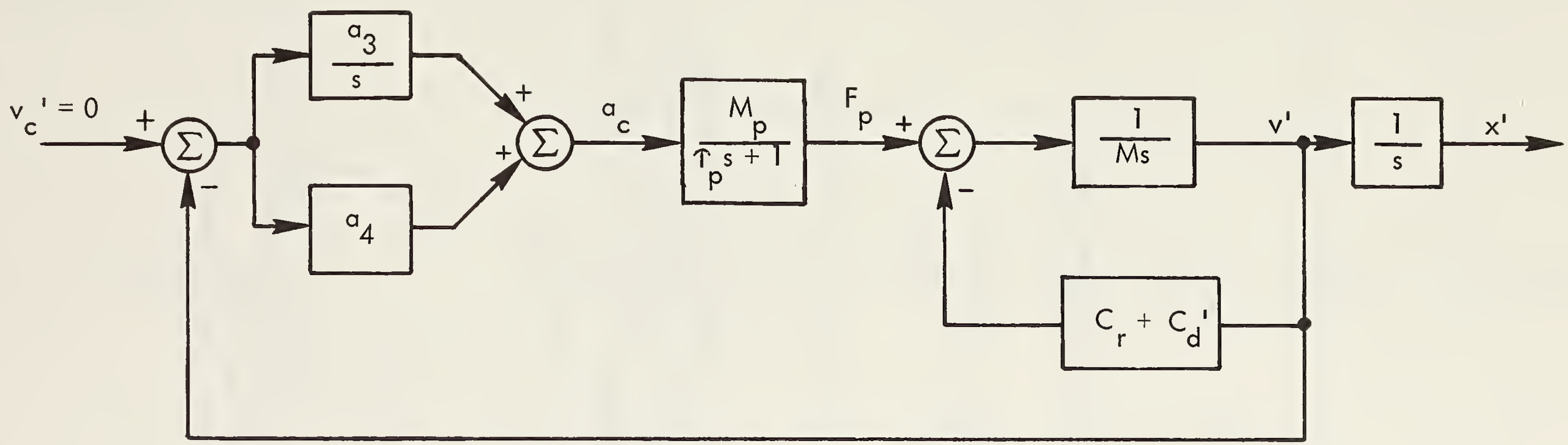


FIGURE 2-20. SIMPLIFIED VERSION OF FIGURE 2-19

and thus may be ignored, giving

$$\frac{v'}{v_c'} = \frac{a_4 s + a_3}{s^2 + a_4 s + a_3} \qquad (2\text{-}38)$$

a good numerical choice of parameters can be made from

$$\frac{v'}{v_c'} = \frac{3.2\omega_o s + \omega_o^2}{s^2 + 3.2\omega_o s + \omega_o^2} \qquad (2\text{-}39)$$

This leaves only the approximate break frequency ω_o to be chosen.

A block diagram of the Laplace transformed vehicle dynamics for the control case of Equation 2-5, corresponding to continuous vehicle follower vehicle control in the follower mode is given in Figure 2-21. Equations 2-30 and 2-31 also apply to this case. A linearized version of this block diagram in which all constant forces have been dropped and the variables

$$\begin{aligned} v' &= v - v_c \\ v_p' &= v_p - v_c \\ x' &= x - v_c t - x_o \\ x_p' &= x_p - v_c t - x_o - S_o' \end{aligned} \qquad (2\text{-}40)$$

introduced, is given in Figure 2-22. The variables v_p and x_p refer to the preceding vehicle. The aerodynamic drag has been linearized as in Equation 2-33 and 2-34, and the operational spacing S_o has been linearized to

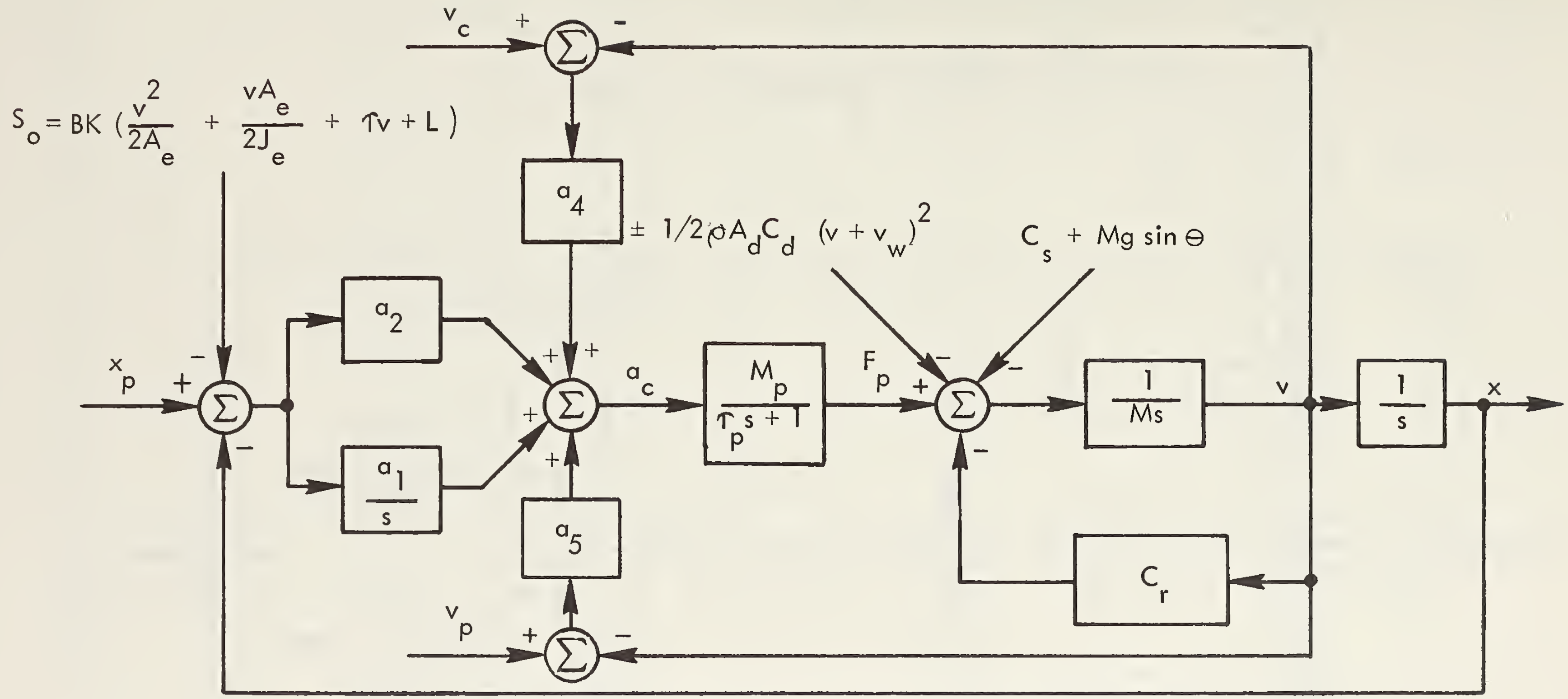


FIGURE 2-21. CONTINUOUS VEHICLE FOLLOWER VEHICLE DYNAMICS

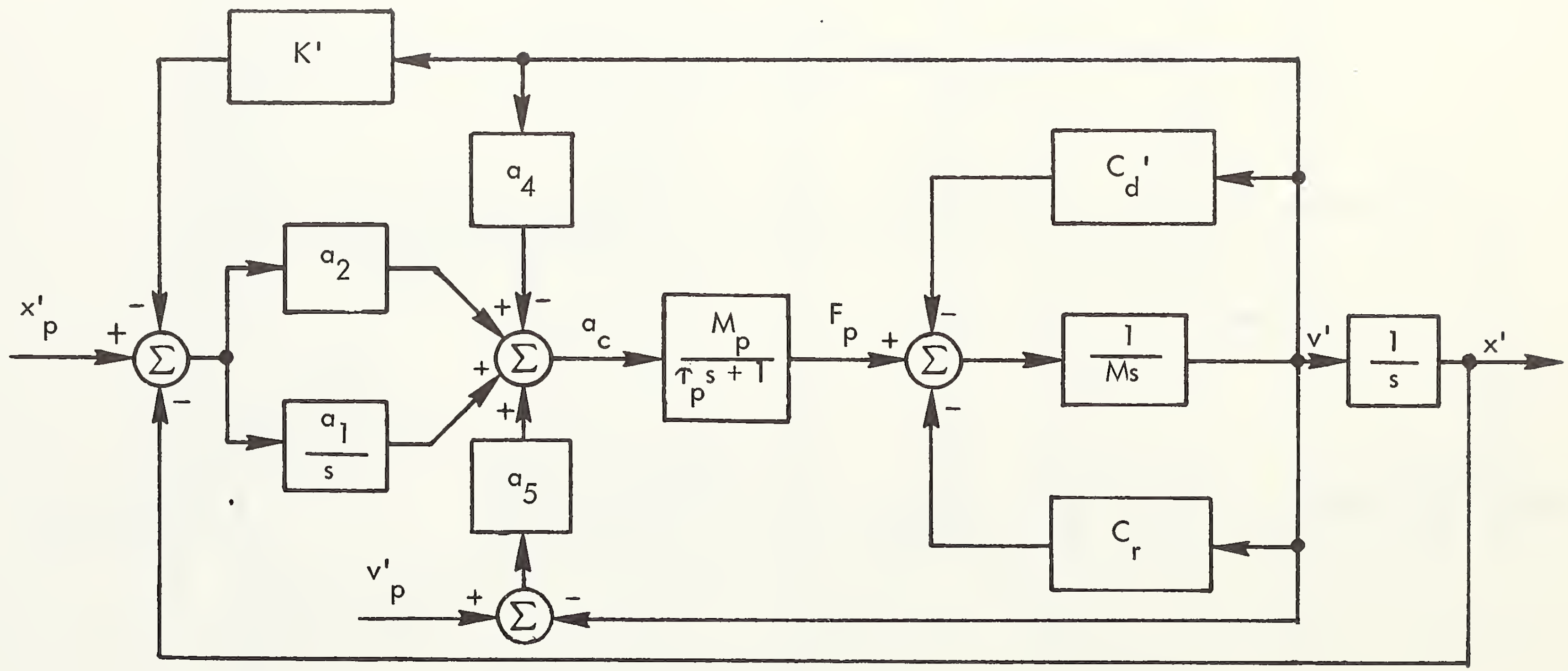


FIGURE 2-22. SIMPLIFIED VERSION OF FIGURE 2-21

$$S_o \simeq S_o' + K'v'$$

$$= BK\left(\frac{v_c^2}{2A_e} + \frac{v_c A_e}{2J_e} + \tau v_c + L\right) + BK\left(\frac{v_c}{A_e} + \frac{A_e}{2J_e} + \tau\right) v' \qquad (2\text{-}41)$$

A practical design transfer function is obtained by ignoring propulsion and braking system dynamics and by assuming accurate proportionality of output force to vehicle mass, i.e., Equation 2-35. The block diagram reduces to that of Figure 2-23. The parameter a_4' is

$$a_4' = a_4 + \frac{C_d' + C_r}{M_p} \qquad (2\text{-}42)$$

The transfer function is

$$\frac{x'}{x_p'} = \frac{a_5 s^2 + a_2 s + a_1}{s^3 + (a_5 + a_4' + a_2 K')\, s^2 + (a_2 + a_1 K')\, s + a_1} \qquad (2\text{-}43)$$

and if integral feedback is not used, i.e., $a_1 = 0$

$$\frac{x'}{x_p'} = \frac{a_5 s + a_2}{s^2 + (a_5 + a_4' + a_2 K')\, s + a_2} \qquad (2\text{-}44)$$

A standard choice similar to Equation 2-39 is not available for this case. In addition, the requirement of string stability to be considered in the next subsection places restrictions on the numerical choice of coefficients.

A block diagram of the Laplace transformed vehicle dynamics for the control case of Equation 2-7, corresponding to point follower vehicle control is given in Figure 2-24. The variables x_p and v_p are now the control point position and velocity respectively. The constraints of Equation 2-30 and 2-31 still apply. A linearized version of this block diagram in which all constant forces have been dropped is given in Figure 2-25. The linearization of the aerodynamic drag is

$$\tfrac{1}{2}\rho A_d C_d (v + v_w)^2 \simeq \tfrac{1}{2}\rho A_d C_d (v_p + v_w)^2 + \rho A_d C_d (v_p + v_w)(v - v_p)$$

$$C_d' = \rho A_d C_d (v_p + v_w)\ \mathrm{Sgn}\ (v + v_w) \qquad (2\text{-}45)$$

If Equation 2-35 is assumed, the practical design case of Figure 2-26 results. The transfer function is

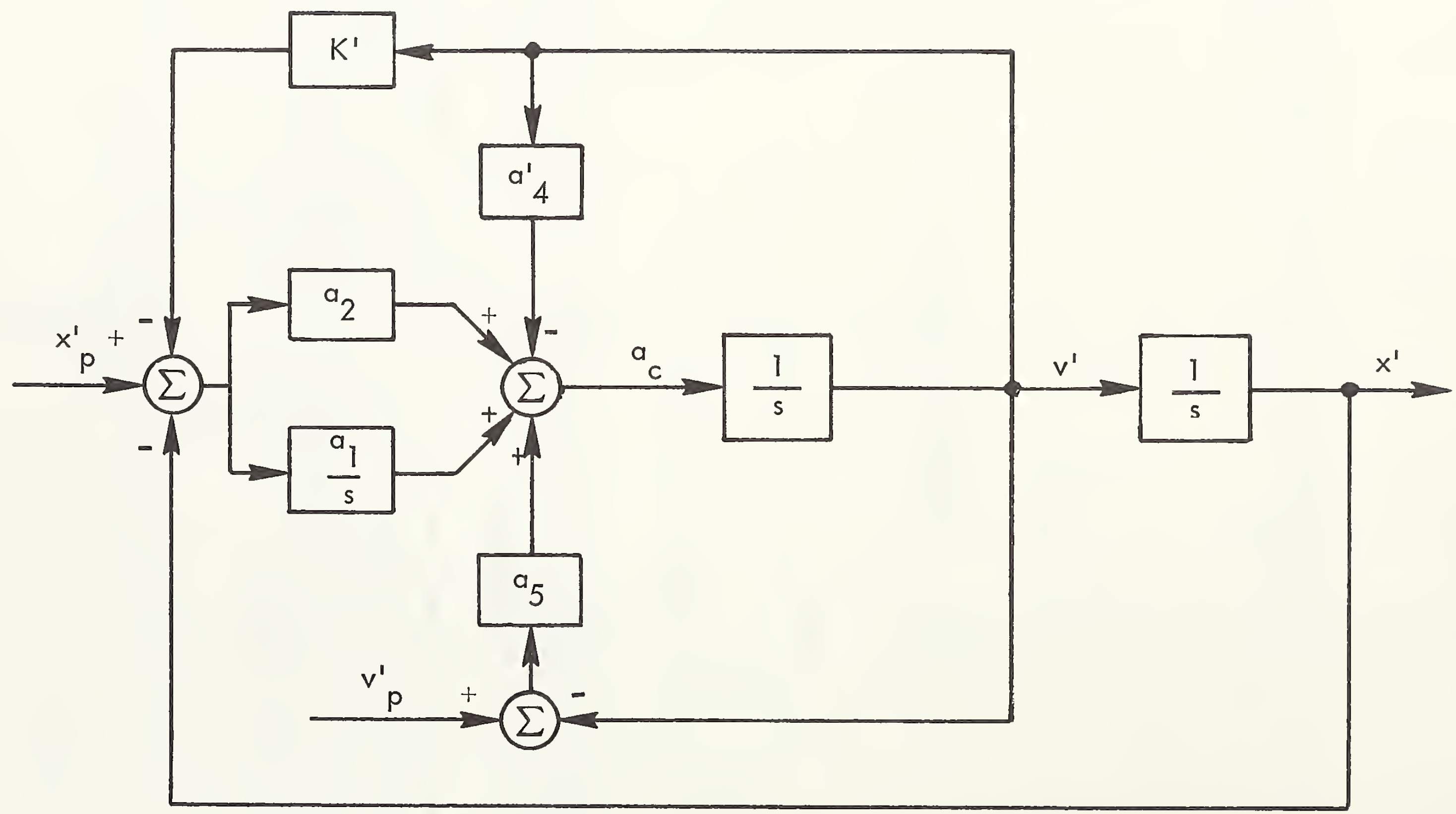


FIGURE 2-23. FURTHER SIMPLIFICATION OF FIGURE 2-21

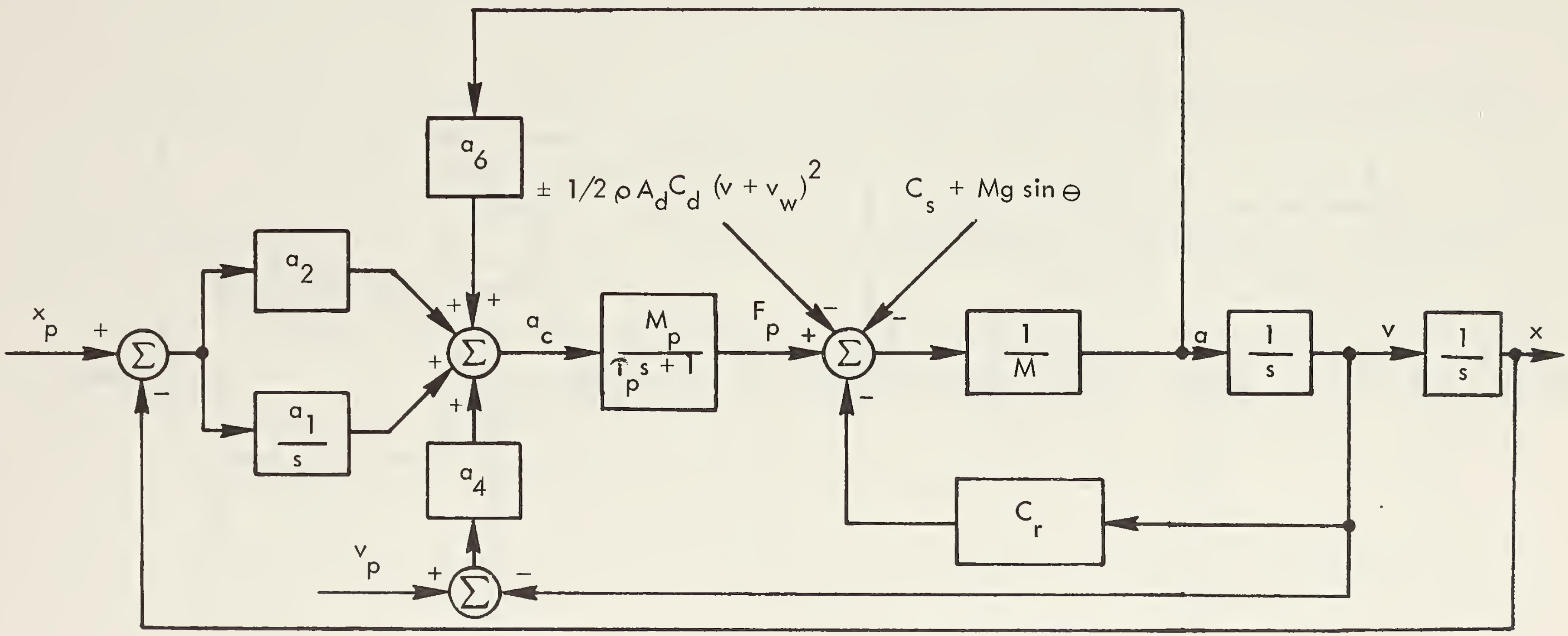


FIGURE 2-24. POINT FOLLOWER VEHICLE DYNAMICS

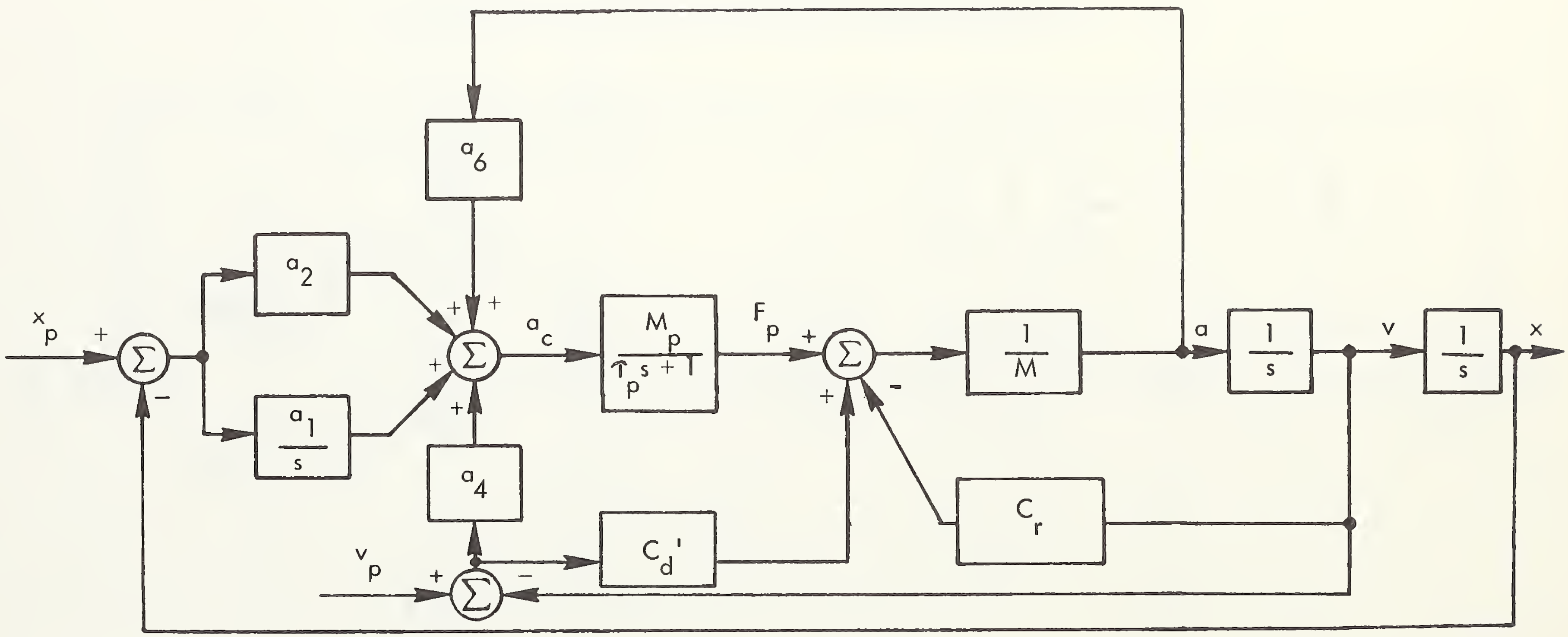


FIGURE 2-25. SIMPLIFIED VERSION OF FIGURE 2-24

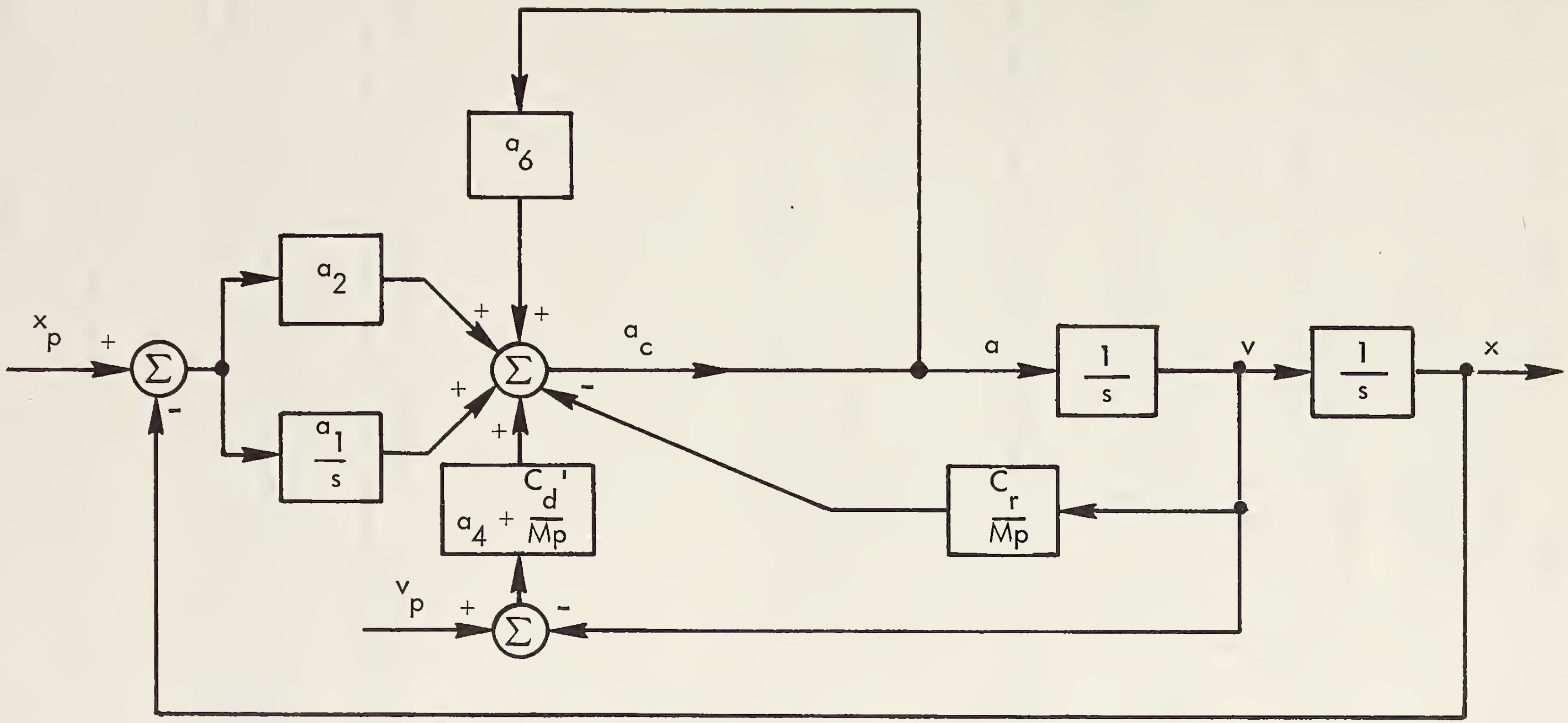


FIGURE 2-26. FURTHER SIMPLIFICATION OF FIGURE 2-24

$$\frac{x}{x_p} = \frac{\left(a_4 + \frac{C_d'}{M_p}\right) s^2 + a_2 s + a_1}{(1 - a_6)\, s^3 + \left(a_4 + \frac{C_d' + C_r}{M_p}\right) s^2 + a_2 s + a_1} \tag{2-46}$$

If integral feedback is not used the transfer function is

$$\frac{x}{x_p} = \frac{\left(a_4 + \frac{C_d'}{M_p}\right) s + a_2}{(1 - a_6)\, s^2 + \left(a_4 + \frac{C_d' + C_r}{M_p}\right) s + a_2} \tag{2-47}$$

The term $\frac{C_r}{M_p}$ is very small so these transfer functions are of a form which perform well when chosen according to

$$\frac{x}{x_p} = \frac{2.97\omega_o s^2 + 4.94\,\omega_o^2 s + \omega_o^3}{s^3 + 2.97\omega_o s^2 + 4.94\omega_o^2 s + \omega_o^3} \tag{2-48}$$

in the case of Equation 2-46 and

$$\frac{x}{x_p} = \frac{3.2\omega_o s + \omega_o^2}{s^2 + 3.2\omega_o s + \omega_o^2} \tag{2-49}$$

in the case of Equation 2-47.

2.2.2.2 Absolute and String Stability — Second and third order transfer functions were obtained in the previous section representing simplified forms of controlled vehicle dynamics. The feedback coefficients must be chosen to give good dynamic characteristics. An important and necessary characteristic is that the response be stable. That is, the response to a bounded input or disturbance must itself be bounded. For the case of vehicle follower vehicle control in follower mode, not only must the response be bounded, i.e., stable, the response should be decreasing, that is, string stable. Conditions for stability and string stability will be presented in this section.

For a second order transfer function with denominator equation

$$C_2 s^2 + C_1 s + C_0 = 0 \tag{2-50}$$

the Routh-Hurwitz stability criterion is

$$C_0 > 0$$
$$C_1 > 0$$
$$C_2 > 0 \qquad (2\text{-}51)$$

For a third order transfer function with denominator equation

$$C_3 s^3 + C_2 s^2 + C_1 s + C_0 = 0 \qquad (2\text{-}52)$$

the Routh-Hurwitz stability criterion is

$$C_0 > 0$$
$$C_1 > 0$$
$$C_2 > 0$$
$$C_3 > 0$$
$$C_2 C_1 \geq C_0 C_3 \qquad (2\text{-}53)$$

If these conditions are applied to the point follower transfer function of Equation 2-46 the conditions become.

$$1 - a_6 > 0$$
$$a_4 + \frac{C_d' + C_r}{M_p} > 0$$
$$a_2 > 0$$
$$a_1 > 0$$
$$a_2 \left(a_4 + \frac{C_d' + C_r}{M_p} \right) \geq a_1 - a_1 a_6 \qquad (2\text{-}54)$$

A transfer function between a preceding vehicle and a following vehicle is said to be string stable if the magnitude of the transfer function is less than or equal to unity at all frequencies[13,14], i.e., if

$$\left| \frac{x'_r}{x_p} (j\omega) \right| \leq 1 \qquad (2\text{-}55)$$

If this is applied to the transfer function of Equation 2-43 one obtains

$$\left| \frac{x'}{x_p'} (j\omega) \right| = \left| \frac{(a_1 - a_5\omega^2) + ja_2\omega}{(a_1 - (a_5 + a_4' + a_2K')\omega^2) + j\left((a_2 + a_1K')\omega - \omega^3\right)} \right|$$

$$= \left\{ \frac{(a_1 - a_5\omega^2)^2 + (a_2\omega)^2}{(a_1 - (a_5 + a_4' + a_2K')\omega^2)^2 + \left((a_2 + a_1K')\omega - \omega^3\right)^2} \right\}^{\frac{1}{2}} \quad (2\text{-}56)$$

Thus Equation 2-55 is satisified if the numerator is less than or equal to the denominator of the right hand side of Equation 2-56. This gives

$$\omega^4 + \omega^2 (a_2^2K'^2 + a_4'^2 + 2a_2a_5K' + 2a_4'a_5 + 2a_2a_4'K' - 2a_2 - 2a_1K') + (a_1^2K'^2 - 2a_1a_4') \geq 0 \quad (2\text{-}57)$$

It is easy to show that

$$\omega^4 + \omega^2C_2 + C_0 \geq 0 \quad (2\text{-}58)$$

if

$$C_0 \geq 0$$
$$C_2 \geq - 2\sqrt{C_0} \quad (2\text{-}59)$$

Thus, the condition for string stability becomes

$$a_1^2K'^2 - 2a_1a_4' \geq 0 \quad (2\text{-}60)$$

$$a_2^2K'^2 + a_4'^2 + 2a_2a_5K' + 2a_4'a_5 + 2a_2a_4'K' - 2a_2 - 2a_1K' \geq - 2\sqrt{a_1^2K'^2 - 2a_1a_4'}$$

When integral feedback is not used the transfer function is Equation 2-44 and the final condition for string stability is

$$a_2^2K'^2 + a_4'^2 + 2a_2a_5K' + 2a_4'a_5 + 2a_2a_4'K' - 2a_2 \geq 0 \quad (2\text{-}61)$$

which is simply Equation 2-60 with $a_1 = 0$.

2.2.2.3 Applications — For vehicle follower control in the velocity control mode the transfer function is Equation 2-38 and the suggested transfer function is Equation 2-39. The use of $\omega_o = 0.5$ has been found to be at least initially acceptable. Thus, ANGAN1 for the asynchronous control has been chosen as

$$\text{ANGAN1} = \begin{bmatrix} 0.0 \\ 0.0 \\ 0.25 \\ 1.60 \\ 0.0 \\ 0.0 \end{bmatrix} \tag{2-62}$$

In the vehicle following mode Equation 2-43 applies and no guidelines except those of string stability are available. A single set of controller gains is desired and were tested at v = 5, 15, and 25 m/s for string stability. The parameter K' from linearizing the intervehicle spacing equation is a function of commanded linespeed v_c,

$$K' = BK\left(\frac{v_c}{A_e} + \frac{A_e}{2J_e} + \tau\right) \tag{2-63}$$

Its numerial values at the three velocities are given in Table 2-5.

TABLE 2-5. K' VERSUS v_c

v_c (m/s)	K' (s)
5	2.67
15	5.82
25	8.97

The aerodynamic and rolling resistance term modifying a_4 as in Equation 2-42 has been evaluated for the conditions,

$$\begin{aligned} C_s &= 0.04 \times M \quad \text{N} \\ C_r &= 0.00375 \times M \quad \text{Ns/m} \\ M_p &= M \\ M &= 3948 \text{ kg (empty)}, \quad 5104 \text{ kg (loaded)} \\ \rho &= 1.205 \text{ kg/m}^3 \end{aligned}$$

$$
\begin{aligned}
A_d &= 4.54 \text{ m}^2 \\
C_d &= 0.65 \\
v_w &= \pm 13 \text{ m/s} \\
\theta &= \mp 1.72^\circ \quad (3\% \text{ grade})
\end{aligned} \qquad (2\text{-}64)
$$

and tabulated in Table 2-6.

TABLE 2-6. DRAG TERMS VERSUS v_c

v_c (m/s)	$\frac{C_d' + C_r}{M_p}$ (s^{-1})
5	0.020 0.007 0.004
15	0.029 0.014 0.005
25	0.038 0.021 0.012

The first value is for the case of maximum positive headwind and minimum empty vehicle mass, the second value is for zero headwind and loaded vehicle mass, and the third value is for maximum negative headwind and loaded vehicle mass. An exception is the third value for $v_c = 5$ m/s for which $v_w = 5$ m/s minimizes C_d'. These values are intended to span the reasonable range of values of these drag terms. The gain vector

$$
\text{ANGAN2} = \begin{bmatrix} 0.01 \\ 0.5 \\ 0.0 \\ 0.0 \\ 0.75 \\ 0.0 \end{bmatrix} \qquad (2\text{-}65)
$$

has been found to be string stable and to provide initially accepted vehicle dynamic behavior.

Bode plots of the transfer function of Equation 2-43 with these coefficients and the zero headwind case from Table 2-6 are given in Figure 2-27. As shown, at no

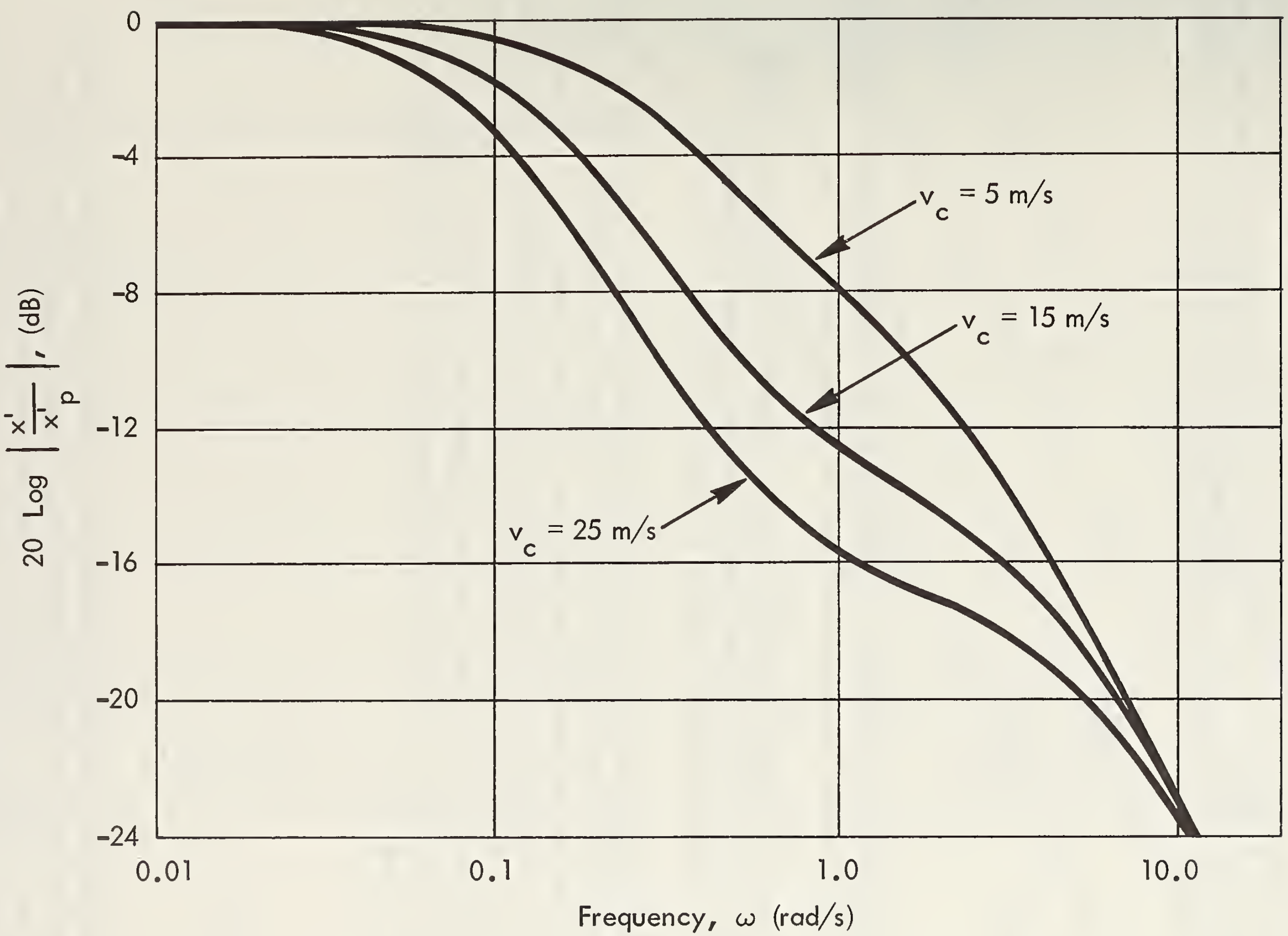


FIGURE 2-27. BODE PLOT OF VEHICLE FOLLOWER TRANSFER FUNCTIONS

frequency is the magnitude of the transfer function greater than 1. The effect of K' being a function of v_c and choosing constant controller gains is that the transfer function drops off more quickly with ω as v_c is increased. However, the high frequency response is similar.

For point follower control the transfer function is Equation 2-46 and the suggested transfer function is Equation 2-48. The case of ω_o = 0.25 and a_6 = 0.0 has been found to be initially acceptable. As documented in the DOCM User's Manual, the elements of ANGAN1 are the negative of the coefficients a_i. Thus the value

$$\text{ANGAN1} = \begin{bmatrix} -0.016 \\ -0.309 \\ 0.0 \\ -0.743 \\ 0.0 \\ 0.0 \end{bmatrix} \tag{2-66}$$

is used in the following simulations. The term $\frac{C_d'}{M_p}$ is here ignored compared to a_4 since it is small and the transfer function is well into the stable region.

Bode plots of the transfer function using the coefficients of Equation 2-48 are given in Figure 2-28. As seen, these transfer functions are not suitable for a vehicle follower type controller since they are not string stable.

The point follower controller in the DOCM changes from the control law of Equation 2-7 to another law when a vehicle has been assigned a new control point as when maneuvering at merges or attempting to dequeue. This new control law is the same as that of Equation 2-7 except that integral position error is not included and a second set of user input gains ANGAN2 are used. The vehicle dynamics has the transfer function of Equation 2-47 and Equation 2-49 gives the suggested transfer function parameter values. The case of ω_o = 0.5 and a_6 = 0.0 has been found to be initially acceptable. The gain vector used is thus

$$\text{ANGAN2} = \begin{bmatrix} 0.0 \\ -0.25 \\ 0.0 \\ -1.6 \\ 0.0 \\ 0.0 \end{bmatrix} \tag{2-67}$$

When the point follower controlled vehicles are forced to queue because of a vehicle failure, control reverts to a vehicle follower type control since the control points must be dropped when queueing. Thus a third vector of gains ANGAN3 must be input. These are initially taken as identical to the vehicle follower gains presented in Equation 2-65 except for a reversal of sign

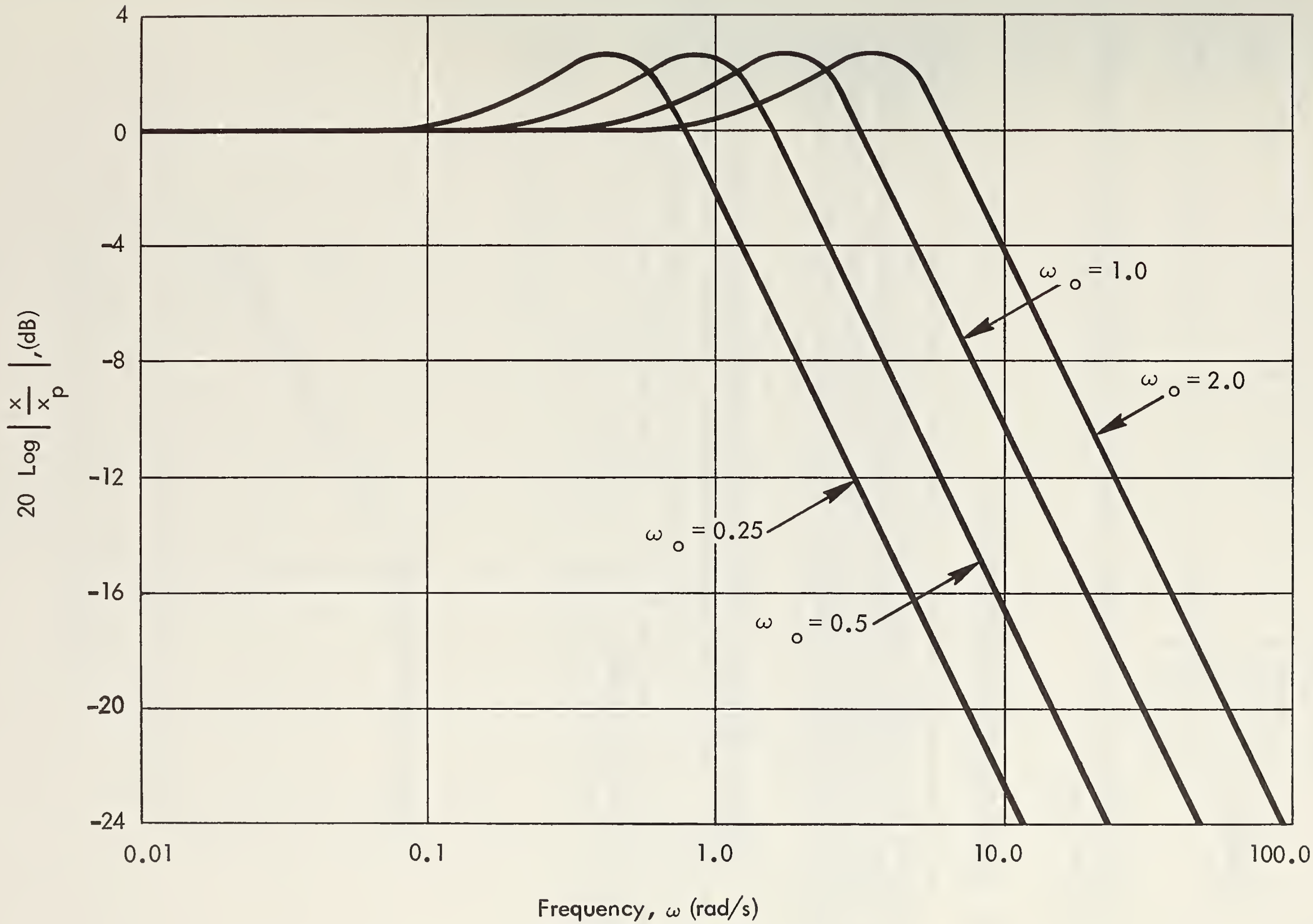


FIGURE 2-28. BODE PLOT OF POSSIBLE POINT FOLLOWER TRANSFER FUNCTIONS

$$\text{ANGAN3} = \begin{bmatrix} -0.01 \\ -0.5 \\ 0.0 \\ 0.0 \\ -0.75 \\ 0.0 \end{bmatrix} \tag{2-68}$$

This completes the selection of vehicle control for the initial DOCM simulations summarized in this report.

2.2.3 Single Vehicle Performance Analysis

Analytic expressions descriptive of single vehicle motion have been developed for use primarily in the vehicle analysis task of the Systems Trade Studies. These results as well as results on station deceleration requirements are summarized in this section and then applied to designing DOCM experiments of single vehicle dynamics. The results of the experiments are then compared to the ideal predicted by the analytic approach.

2.2.3.1 Analytic Expressions — An acceleration profile as shown in Figure 2-29 is established for a vehicle. The vehicle's acceleration is constant at its maximum level A_m until velocity v_1. At v_1 the maximum propulsion power P_{max} is all required for acceleration and overcoming drag and friction. The acceleration above v_1 is assumed to be linearly related to the velocity.

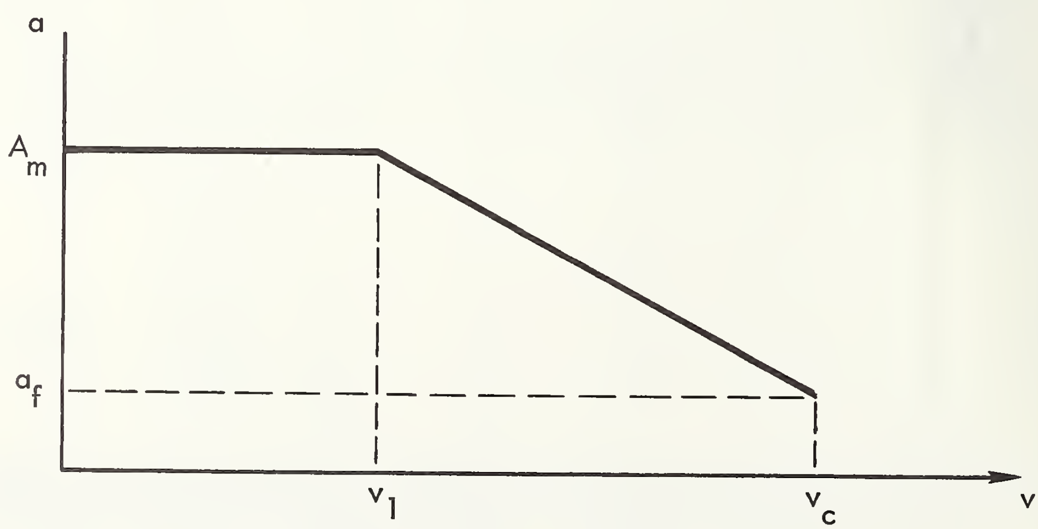


FIGURE 2-29. ACCELERATION PROFILE

The velocity v_c is the vehicle cruise velocity and the final acceleration capability at cruise velocity, a_f is again found from the power constraint equation. That equation is

$$P_{max} = Mav + C_1 v + C_2 v^2 + C_3 v^3 \tag{2-69}$$

where

$$C_1 = \tfrac{1}{2} \rho A_d C_d v_w^2 \, \mathrm{Sgn}\,(v + v_w) + C_s + Mg \sin\theta$$

$$C_2 = C_r + \rho A_d C_d v_w \, \mathrm{Sgn}\,(v + v_w)$$

$$C_3 = \tfrac{1}{2} \rho A_d C_d \, \mathrm{Sgn}\,(v + v_w) \tag{2-70}$$

are drag coefficients which account for aerodynamic drag, static and rolling friction, and grade retarding force. Note that C_s and C_r as used here and earlier are direct friction coefficients and not specific friction coefficients which must be multiplied by vehicle mass. The value of v_1 is found by solving Equation 2-69 with $a = A_m$ and the value a_f is found by solving Equation 2-69 with $v = v_c$. The profile is established by assuming a worst case condition. For SGRT vehicles the worst case conditions are those of Equation 2-64. The maximum propulsion power is chosen to be

$$P_{max} = 200{,}000 \text{ watts} \tag{2-71}$$

The acceleration profile of Figure 2-29 results in somewhat complex expressions for velocity, time, and position of a vehicle. Assuming that the profile has been established, the time, t, and distance, x, to accelerate from an initial velocity v_o to velocity v has three cases:

Case I

$$v_o \le v \le v_1$$

$$t = \frac{v - v_o}{A_m}$$

$$x = \frac{v^2 - v_o^2}{2A_m}$$

Case II

$$v_o \le v_1 \le v \le v_c$$

$$t = \frac{v_1 - v_o}{A_m} - \frac{1}{a} \ln \left(\frac{b - av}{b - av_1}\right)$$

$$x = \frac{v_1^2 - v_o^2}{2A_m} - \frac{v - v_1}{a} - \frac{b}{a^2} \ln\left(\frac{b - av}{b - av_1}\right)$$

Case III

$$v_1 \leq v_o \leq v \leq v_c$$

$$t = -\frac{1}{a} \ln\left(\frac{b - av}{b - av_o}\right)$$

$$x = -\frac{v - v_o}{a} - \frac{b}{a^2} \ln\left(\frac{b - av}{b - av_o}\right) \qquad (2\text{-}72)$$

where

$$a = \frac{A_m - a_f}{v_f - v_1}$$

$$b = \frac{A_m v_f - a_f v_1}{v_f - v_1} \qquad (2\text{-}73)$$

In decelerating from v to final velocity v_f a constant service deceleration of A_s is assumed. Thus for deceleration

$$t = \frac{v - v_f}{A_s}$$

$$x = \frac{v^2 - v_f^2}{2A_s} \qquad (2\text{-}74)$$

These equations for vehicle motion are presented in more detail in Section 5.3 and Appendix A of the report Analysis of SLT Systems Volume III[7].

The energy consumed by a vehicle accelerating along the profile of Figure 2-29 has also been calculated. The energy required to accelerate from v_o to velocity v also has three cases similar to the dynamics:

Case I

$$v_o \leq v \leq v_1$$

$$\text{Energy} = E_1 (v_o, v)$$

Case II.

$$v_o \leq v_1 \leq v \leq v_c$$

$$\text{Energy} = E_1 (v_o, v_1) + E_2 (v_1, v)$$

Case III

$$v_1 \leq v_o \leq v \leq v_c$$

$$\text{Energy} = E_2 (v_o, v) \tag{2-75}$$

Where

$$E_1 (p,q) \equiv \frac{1}{A_m} \left[\left(\frac{MA_m + C_1}{2} \right) (q^2 - p^2) + \frac{C_2}{3} (q^3 - p^3) + \frac{C_3}{4} (q^4 - p^4) \right]$$

$$\begin{aligned} E_2 (p,q) \equiv & - \frac{C_1}{a} (q - p) + \frac{M}{2} (q^2 - p^2) - \frac{C_3}{3a} (q^3 - p^3) \\ & - \left[\frac{C_1 b}{a^2} + \frac{C_2 b^2}{a^3} + \frac{C_3 b^3}{a^4} \right] \ln \left(\frac{b - aq}{b - ap} \right) \\ & - \frac{1}{2} \left[\frac{C_2}{a^3} + \frac{C_3 b}{a^4} \right] \left[(b - aq)^2 - (b - ap)^2 \right] \\ & - 2b \left[\frac{C_2}{a^2} + \frac{C_3 b}{a^3} \right] (q - p) \end{aligned} \tag{2-76}$$

where a and b are defined in Equation 2-73 and C_1, C_2, and C_3 are as in Equation 2-70.

The energy consumed by a vehicle at constant velocity v on a per metre basis is

$$\frac{\text{Energy}}{\text{metre}} = C_1 + C_2 v + C_3 v^2 \tag{2-77}$$

Energy in these equations is in units of joules or watt-seconds. These equations for vehicle energy are presented in more detail in Section 5.4 and Appendix B of the report Analysis of SLT Systems Volume III[7].

2.2.3.2 Single Vehicle Experiments — An acceleration profile similar to that of Figure 2-29 for SGRT vehicles is required. First C1, C2, and C3 of Equation 2-70 are evaluated for the worst design case of Equation 2-64 and 2-71 giving

$$\begin{aligned} C_1 &= 2005.16 \ \text{N} \\ C_2 &= 65.3589 \ \text{Ns/m} \\ C_3 &= 1.77765 \ \text{Ns}^2/\text{m}^2 \end{aligned} \tag{2-78}$$

Next, Equation 2-69 is solved for v_1 with $A_m = 2.2 \ m/s^2$, the maximum value of the service acceleration and deceleration. The result is

$$v_1 = 13.8176 \ \text{m/s} \tag{2-79}$$

Then a_f, the final acceleration capability at the cruise velocity of $v_c = 25$ m/s is round

$$\begin{aligned} v_c &= 25 \ \text{m/s} \\ a_f &= 0.63672 \ \text{m/s}^2 \end{aligned} \tag{2-80}$$

An increase of velocity to 27.5 m/s is included in the test profile. This higher velocity was not planned or designed for in establishing the minimum operational headway. However, it is desired to test the controller's ability to slightly alter cruise velocity. Thus a new acceleration profile is established for which

$$\begin{aligned} v_c &= 27.5 \ \text{m/s} \\ a_f &= 0.41651 \ \text{m/s}^2 \end{aligned} \tag{2-81}$$

The velocity v_1 is the name for both profiles. Using Equations 2-72, 2-73, and 2-74, a position, velocity, time profile is determined which starts at zero velocity, follows the acceleration profile specified by Equations 2-79 and 2-80 to $v_c = 25$ m/s, cruises at 25 m/s for about 11 seconds, then follows the second acceleration profile specified by Equations 2-79 and 2-81 to $v_c = 27.5$ m/s, holds that velocity for 10 seconds, brakes to 25 m/s, holds that velocity for about 5 seconds and finally brakes to a stop. The details are given in Table 2-7. This profile was used to define a velocity versus guideway position for several DOCM experiments with a single vehicle on a link. A linespeed of zero is not acceptable to the DOCM so $v = 0.5$ m/s was used at the beginning and end of the profile with no modification of time and position since the vehicle following the profile was started at zero velocity.

In the DOCM, velocity profiles can either be specified as constant velocity segments or constant acceleration segments. The constant acceleration segments were used since they fit the actual profile more accurately. For velocities above v_1, the acceleration of the desired profile is continuously changing and thus even step changes in acceleration do not perfectly fit the curve. However, the profile is specified every 2.5 m/s of velocity change for acceleration regions to reduce the discrepancy to a low level. Note also that the profiles would differ only between consecutive points of Table 2-7 and then only during vehicle acceleration.

TABLE 2-7. TEST PROFILE FOR VEHICLE FOLLOWER CONTROL

Position (m)	Velocity (m/s)	Time (s)
0.0	0.0	0.0
1.4	2.5	1.14
5.7	5.0	2.27
12.8	7.5	3.41
22.7	10.0	4.55
35.5	12.5	5.68
51.4	15.0	6.84
73.4	17.5	8.19
104.7	20.0	9.85
150.9	22.5	12.02
225.6	25.0	15.15
500.0	25.0	26.13
617.0	27.5	30.56
892.0	27.5	40.56
921.8	25.0	41.70
1047.0	25.0	46.71
1189.1	0.0	58.07

For point follower control, slots are defined on the link by specifying the headway slot time. The control point moves from the upstream to the downstream end of the slot, either at constant velocity or at constant acceleration in one slot headway time. Thus velocity points to describe a profile are given at slot boundaries only. This requires a modified profile from that of Table 2-7.

Point follower control must accept a fixed headway at all velocities. The chosen slot time of 6 seconds is not compatible with velocities below about 1 m/s. Thus v = 1 m/s is the lowest speed considered. Equations 2-72, 2-73, and 2-74 may be iteratively solved to establish velocity and position at 6 second intervals up to $v_c = 25$. One obtains the initial results of Table 2-8. The points

TABLE 2-8. INITIAL PROFILE CALCULATIONS FOR POINT FOLLOWER

Time (s)	Velocity (m/s)	Position (m)	Δx (m)
0.0	1.0	0.0	
6.0	14.195	45.6	45.6
12.0	22.915	160.6	115.0
14.7	25.0	225.4	64.8
18.0	25.0	308.0	82.6
22.4	27.5	424.9	116.9
24.0	27.5	468.9	44.0
25.1	25.0	498.7	29.8
30.0	25.0	621.2	122.5
36.0	11.8	731.6	110.4
40.9	1.0	763.0	31.4
42.0	1.0	764.1	1.1

not on an exact headway interval are the ideal end points of velocity change profiles. The actual profile specifiable in the DOCM must use only exact headway intervals of time. The following profile was used for point follower control and is a close equivalent to the profile of Table 2-7. It falls slightly below the performance level of the other profile in terms of minimizing velocity change times. The profile consists of one slot of constant velocity at $v_c = 1$ m/s followed by an acceleration to $v_c = 25$ m/s, a hold for one slot of that velocity, an acceleration to 27.5 m/s followed by a one slot hold of that velocity, a deceleration to $v_c = 25$ m/s followed by a one slot hold of that velocity, and finally a deceleration to $v_c = 1$ m/s and a one slot hold of that velocity. The details are given in Table 2-9. Velocity and position are at the upstream end of the slot and length is the length of the slot. As seen in slot 2 and 3, an acceleration profile close to the best profile is used and deceleration from $v_c = 25$ m/s is close to the best profile. The position and length of slots given correspond to constant levels of acceleration in each slot. In the case of point follower profiles, the vehicle was allowed to start the simulation at v = 1.0 m/s corresponding to initial linespeed.

TABLE 2-9. VELOCITY PROFILE FOR POINT FOLLOWER

Slot Number	Velocity (m/s)	Position (m)	Length (m)
1	1.0	0.0	6.0
2	1.0	6.0	45.0
3	14.0	51.0	108.0
4	22.0	159.0	141.0
5	25.0	300.0	150.0
6	25.0	450.0	157.5
7	27.5	607.5	165.0
8	27.5	772.5	157.5
9	25.0	930.0	150.0
10	25.0	1080.0	111.0
11	12.0	1191.0	39.0
12	1.0	1230.0	6.0
		1236.0	

Three experiments were performed for each case, i.e., three with vehicle follower control and three with point follower control. Since only a single vehicle was involved, the vehicle follower was in the velocity control mode. The experiments differed in the choice of guideway grade and headwind. The vehicle characteristics in these experiments are listed in Table 2-10. The parameters are as already given with the exception of A_m, A_s, J_s, $F_{b\ max}$ and $F_{p\ max}$. The parameter A_m and A_s in the DOCM are limits of commanded acceleration and braking respectively. Note, they are not limits on achieved vehicle acceleration and braking. The value 2.2 m/s^2 was meant as a limit on the achieved value. The total force required to attain 2.2 m/s^2 at v_1 for the case of a 3 percent grade and a 13 m/s headway is calculated to be

$$F_{p\ max} = 14,480 \text{ N} \tag{2-82}$$

which for a 5104 kilogram vehicle is a steady state propulsion command signal of

$$a_c = 2.84 \text{ m/s}^2 \tag{2-83}$$

Thus $F_{p\ max}$ has been set at this value and A_m has been set somewhat above the required a_c. The similar case for braking on the -3 percent grade with a -13 m/s headway at 0 m/s gives

$$F_{b\ max} = 12,830 \text{ N}$$

$$a_c = -2.51 \text{ m/s}^2 \tag{2-84}$$

TABLE 2-10. VEHICLE CHARACTERISTICS

A_d	=	$4.54\ m^2$
A_e	=	$5.0\ m/s^2$
A_m	=	$3.0\ m/s^2$
A_s	=	$3.0\ m/s^2$
A_{tol}	=	$3.1\ m/s^2$
C_d	=	0.65
C_r	=	19.14 NS/M
C_s	=	204.16 N
$F_{b\ max}$	=	12,830 N
$F_{p\ max}$	=	14,480 N
J_e	=	$5.0\ m/s^3$
J_s	=	$3.2\ m/s^3$
J_{tol}	=	$3.5\ m/s^3$
L	=	4.2 m
M	=	5104 kg
$\frac{M_{b,p}}{M}$	=	1.0
P_{max}	=	200,000 W
τ	=	0.2 s
τ_b	=	0.2 s
τ_p	=	0.2 s

The value for J_s was chosen as approximately 1.5 times the desired achievable acceleration level.

The characteristics and results of the experiments are summarized in Table 2-11. The RMS error results are for data points every 3 seconds. The integration time step of these experiments and all which follow was 0.05 seconds however. The vehicle follower was in the velocity control mode and thus did not have a true position error. The statistic reported for vehicle follower is based upon the time integral of velocity error. The probability of jerk violation is the number of vehicle integration steps of jerk above an input limit divided by the total number of vehicle integration steps. The tolerance limit used was $3.5 \ m/s^3$.

In general the controllers worked well during acceleration but not as well during deceleration. This was manifested as a delay in initial application of brakes and then in some cases moderately large errors in position at the end of the profile. This is possibly due to two causes. First, it may be necessary to consider the vehicle's jerk limit in setting up the profiles, especially in the portion where deceleration begins. Secondly, the integral feedback is intended to allow the vehicle control to cancel out the effect of constant forces under essentially steady state conditions. Steady state conditions were only briefly achieved during these experiments, and the integral control term became substantial toward the end of the acceleration portion of the profile. When a change to deceleration occurred in the profile, the integral term tended to produce a delay in responding to the change. Thus it is concluded that a decrease in the integral feedback may be desired or that integral feedback should be eliminated during changes of velocity.

2.2.3.3 Energy Comparisons and Conclusion — The results of Section 2.2.3.1 have been used to calculate the total propulsion energy for each of the six experiments summarized in Table 2-11. For all cases the acceleration profile information necessary for the calculation are A_m, v_1, v_c, a_f, v_o and v. A_m for the profile is $2.2 \ m/s^2$, v_1 is given in Equation 2-79, v_c and a_f correspond to Equations 2-80 and 2-81. The initial velocity for the profile portion of interest is v_o, and v is the final velocity for the profile portion of interest. The values of C_1, C_2, and C_3 are obtained from Equation 2-70 evaluated for the conditions applicable to the specific experiment. Since the vehicle follower velocity profile is exact the calculation of energy for the profile and energy per metre for cruise is straight forward. For the case of -13 m/s headwind the calculations must be done in two parts since the term $\mathrm{Sgn}\,(v + v_W)$ changes at $v = 13$ m/s, thus numerically changing the values of C_1, C_2, and C_3.

The calculation of energy for the point follower experiments is not completely straight forward because the velocity profile could not be so exactly specified. This case for a grade of -3 percent and headwind of -13 m/s is shown in detail.

The profile is divided into cruise portions and profile portions. The first and last slot give 12 metres of cruise at $v = 1$ m/s. The profile from 1 to 25 m/s and cruise at 25 m/s occurs in slots having a total length of 594 metres. The profile alone can be

TABLE 2-11. SUMMARY OF SINGLE VEHICLE LINK EXPERIMENTS

Run Identification	B(2009)	C(2013)	D(2017)	S(2577)	T(2582)	U(2586)
Control Type	Vehicle Follower	Vehicle Follower	Vehicle Follower	Point Follower	Point Follower	Point Follower
Grade (%)	3.0	0.0	-3.0	3.0	0.0	-3.0
Headwind (m/s)	13.0	0.0	-13.0	13.0	0.0	-13.0
Propulsion Work per Vehicle Second (W)	83,160	46,066	21,837	94,210	49,108	26,593
Brake Work per Vehicle Second (W)	15,018	20,845	30,735	14,726	20,495	37,762
RMS Position Error (m)	5.74	3.86	9.17	6.65	3.37	4.16
RMS Velocity Error (m/s)	0.58	0.45	1.06	0.97	0.65	0.71
Probability of Jerk Violation	0.0	0.0	0.6×10^{-3}	0.7×10^{-3}	3.4×10^{-3}	0.8×10^{-3}

done in 225.3 metres applying Equations 2-72 and 2-73. Thus, 368.7 metres is the total cruise distance at $v = 25$ m/s. Similarly the profile from 25 to 27.5 m/s and cruise at 27.5 m/s covers slots of total length 322.5 metres. The profile itself takes 116.9 metres leaving 205.6 metres of 27.5 m/s cruise.

Equation 2-70 when evaluated for Sgn = -1, corresponding to vehicle velocity less that 13 m/s gives

$$v \leq 13 \text{ m/s}$$

$$C_1 = -1596.84$$

$$C_2 = 65.3589$$

$$C_3 = -1.77765 \tag{2-85}$$

and for Sgn = 1

$$v \geq 13 \text{ m/s}$$

$$C_1 = -995.99$$

$$C_2 = -27.0789$$

$$C_3 = 1.77765 \tag{2-86}$$

The cruise and maneuver energy profile may then be evaluated for the several portions:

$$v_o = 1 \text{ m/s}$$

$$v = 1 \text{ m/s}$$

Maneuver energy = 0.0 Ws
Cruise energy = -1.533×10^3 Ws/m,

$$v_o = 1 \text{ m/s}$$

$$v = 13 \text{ m/s}$$

Maneuver energy = 3.837×10^5 Ws
Cruise energy = -1.048×10^3 Ws/m,

$$v_o = 13 \text{ m/s}$$

$$v = 25 \text{ m/s} \tag{2-87}$$

Maneuver energy = 1.020×10^6 Ws
Cruise energy = -5.619×10^2 Ws/m,

$$v_o = 25 \text{ m/s}$$

$$v = 27.5 \text{ m/s}$$

$$\text{Maneuver energy} = 2.798 \times 10^5 \text{ Ws}$$

$$\text{Cruise energy} = -3.963 \times 10^2 \text{ Ws/m.}$$

The total propulsion energy is then the sum of the maneuver energies and the products of cruise distance and cruise energy. In this case a negative cruise energy means zero propulsion energy since energy recovery capability is not assumed. The total propulsion energy is found to be 1.683×10^6 Ws.

The result of such calculations for the six experiments and the propulsion energies as calculated by the DOCM are tabulated in Table 2-12. Excellent agreement between simulated and calculated propulsion energy is obtained. The average difference is about 2.6 percent.

These six experiments confirm that the analytic expressions of Section 2.2.3.1 are very useful for representing realistic single vehicle dynamic performance and for calculating the required propulsion energy. It is expected, however, that the specific control laws used to follow the profiles could be further refined. All the analytic expressions have been programmed on a desk-top calculator with magnetic card storage and are extensively used in the vehicle analysis task.

2.2.4 Multiple Vehicle Link Performance Analysis

In this section several different DOCM experiments involving more than one vehicle on a single guideway link are reported. In addition a subsection is devoted to an additional analytic headway result and an analytic investigation of station deceleration ramp requirements for off-line stations.

2.2.4.1 Additional Analytic Results — The acceleration profile first introduced in Section 2.2.3.1 has an impact on the operational headway expressions for on-line station situations presented at the end of Section 2.2.1.1. These expressions assume that the service acceleration remains constant at A_m until the final velocity v is attained. However, the more detailed analysis including propulsion power limits showed that A_m could be maintained only up to the velocity v_1. An analysis involving two cases of acceleration, i.e., one at constant A_m and a second at linearly decreasing acceleration, could be imposed upon the Bergmann approach. A simplified approach has been taken to determine a reasonable upper bound on minimum headway[9]. The upper bound is the maximum headway of all the cases implied by the complex dynamic behavior. The result is

$$S_o = \frac{v^2}{2A_e} + \frac{v^2}{2A_s} + vt_{accel} - S_a + \tau v + \tau_d v + L \qquad (2\text{-}88)$$

where t_{accel} is the time to accelerate from zero to v and S_a is the distance traveled while accelerating. These are calculated using Equation 2-72. It is easily confirmed that when A_m is the acceleration for the entire profile, the expression agrees with the first and most conservative case of Equation 2-20.

TABLE 2-12. CALCULATED VERSUS SIMULATED PROPULSION ENERGY

Run Identification	B(2009)	C(2013)	D(2017)	S(2577)	T(2582)	U(2586)
Control Type	Vehicle Follower	Vehicle Follower	Vehicle Follower	Point Follower	Point Follower	Point Follower
Grade (%)	3.0	0.0	-3.0	3.0	0.0	-3.0
Headwind (m/s)	13.0	0.0	-13.0	13.0	0.0	-13.0
Propulsion Work (Ws)	6.687×10^6	3.707×10^6	1.758×10^6	6.736×10^6	3.585×10^6	1.702×10^6
Calculated Propulsion Work (Ws)	6.707×10^6	3.726×10^6	1.685×10^6	6.224×10^6	3.526×10^6	1.683×10^6

If all vehicle deceleration for entering an off-line station is done off of the mainline guideway, the deceleration ramp must have length

$$S_d = L + \frac{v^2}{2A_s} \tag{2-89}$$

where v is the guideway velocity at the diverge point. The consist length must be included because the train must completely clear the mainline guideway before deceleration is begun. An analysis has been made to determine the length of the deceleration ramp if a portion of the deceleration is done on the mainline guideway[10]. The result is

$$S_d = L + \frac{v^2}{2A_s} - v\left(h_m - h_n + \sqrt{\frac{2v\,(h_n - h_m)}{A_s}}\right) \tag{2-90}$$

where h_m is the minimum operational headway time and h_n is the nominal operational headway time. Thus, if vehicles are always operated at a headway time that is greater than the minimum operational headway time associated with the implemented vehicle control and headway protection combination, some reduction in station deceleration ramp length is possible. This situation is not likely to occur on every portion of a network, however, it may be applied to certain sections of relatively low demand. The result also opens an interesting possibility of providing control of greater sophistication than required by headway in order that some deceleration may be done online and thus reduce station guideway cost.

2.2.4.2 String Stability Experiments — In Section 2.2.2.2 the condition necessary to ensure string stability was presented. This condition was considered in the choice of controller gains as reported in Section 2.2.2.3. The results of experiments to check for string stability are reported in this section.

The conditions for these, and all subsequent experiments, are zero headwind and zero grade. This places less severe requirements on the vehicle propulsion and braking and thus parameters have been varied from those listed in Table 2-10. The new set of vehicle characteristics are given in Table 2-13. The total force required to attain 2.2 m/s^2 at v_1 for the case of a 0 percent grade and a 0 m/s headwind is calculated to be

$$F_{p\ max} = 12{,}040\ N \tag{2-91}$$

which for a 5104 kg vehicle is a steady state propulsion command signal of

$$a_c = 2.36\ m/s^2 \tag{2-92}$$

F_p max has been set to this value and A_m is slightly above this value. The similar case for braking at 0 m/s gives

TABLE 2-13. VEHICLE CHARACTERISTICS

A_d	=	$4.54\ m^2$
A_e	=	$5.0\ m/s^2$
A_m	=	$2.4\ m/s^2$
A_s	=	$2.2\ m/s^2$
A_{tol}	=	$2.6\ m/s^2$
C_d	=	0.65
C_r	=	19.14 Ns/m
C_s	=	204.16 N
$F_{b\ max}$	=	11,025 N
$F_{p\ max}$	=	12,040 N
J_e	=	$5.0\ m/s^3$
J_s	=	$3.2\ m/s^3$
J_{tol}	=	$3.5\ m/s^3$
L	=	4.2 m
M	=	5104 kg uniform
	=	3948— 5104 kg nonuniform
$\frac{M_{b,p}}{M}$	=	1.0
P_{max}	=	200,000 W uniform
	=	160,000—200,000 W nonuniform
τ	=	0.2 s
τ_b	=	0.2 s
τ_p	=	0.2 s

$$F_{b\,max} = 11{,}025 \text{ N}$$

$$a_c = -2.16 \text{ m/s}^2 \tag{2-93}$$

thus establishing F_b max and A_s. A_{tol} is set at 2.6 m/s^2, slightly above A_m and A_s. When uniform vehicles are used in an experiment the mass and maximum power output correspond to an SGRT vehicle with its full load of 17 passengers (@ 68 kg per person). When nonuniform vehicles are specified for an experiment the mass of each injected vehicle is chosen from a uniform distribution ranging from empty vehicle at 3948 kilograms to fully loaded vehicle at 5104 kilograms. In a similar manner the maximum propulsion power is chosen from a uniform distribution with full rated power at one end and 20 percent degraded power at the other end. Since both of these random processes occur simultaneously, the power per unit mass of nonuniform vehicles may be either above or below the case of uniform vehicles.

Four string stability experiments were performed. The linespeed velocities were 25, 15 and 5 m/s corresponding to the velocities for which the transfer function was plotted in Figure 2-27. Uniform vehicles were used except for a fourth experiment at 15 m/s using nonuniform vehicles. It was assumed that these velocities were all for a system designed for a nominal 25 m/s linespeed. Thus, B and K did not change. These parameters and the headway equation established the headways of 3.90 seconds at 15 m/s and 3.21 seconds at 5 m/s. Eight vehicles were involved in all four experiments. The first vehicle was open loop controlled to have a true vehicle acceleration equal to a square wave of amptitude $\pm$ 1.0 m/s^2 and of frequency one cycle every 6 seconds or 1.05 rad/s. The Fourier series for this function contains the multiples 1, 3, 5, ... of this frequency. The second through eighth vehicles were closed loop controlled in the vehicle follower mode. The results of the four experiments are summarized in Table 2-14. The results are presented as ranges on velocity and acceleration for each vehicle. The velocity about which the range is centered is either 25, 15, or 5 m/s and for acceleration the range is centered on 0 m/s^2. Vehicle number 1 results are the analytically known values based upon the open loop acceleration. For the other vehicles the results were determined from a 100 second simulation in which data was available every second. Results were taken only after a vehicle had been in the simulation for more than 6 seconds to allow for some damping of initial transients. This method of taking data was not entirely successful in removing transient effects from the velocity results for 25 and 15 m/s experiments. Acceleration however is seen to be continually decreasing with increasing vehicle ID number. The vehicles are concluded to show good string stability in these experiments.

2.2.4.3 Link Flow Experiments — Several experiments were performed in which a single link was simulated at various levels of utilization. Three types of control were simulated, synchronous point follower, quasi-synchronous point follower, and asynchronous vehicle follower.

The vehicle parameters are those of Table 2-13 for the nonuniform vehicles. The vehicle control and headway protection is based upon estimated vehicle state information.

TABLE 2-14. SUMMARY OF STRING STABILITY EXPERIMENTS

Run Identification		AA(1534)	H(2037)	S(5018)	AA(1535)
Velocity (m/s)		25.0	15.0	15.0	5.0
Vehicle Generation		Uniform	Uniform	Nonuniform	Uniform
Velocity Range (m/s)	Vehicle 1	3.000	3.000	3.000	3.000
	Vehicle 2	0.438	0.693	0.692	1.008
	Vehicle 3	0.124	0.156	0.157	0.532
	Vehicle 4	0.095	0.086	0.093	0.288
	Vehicle 5	0.114	0.071	0.078	0.142
	Vehicle 6	0.136	0.094	0.102	0.086
	Vehicle 7	0.150	0.115	0.123	0.049
	Vehicle 8	0.155	0.128	0.137	0.035
Acceleration Range (m/s^2)	Vehicle 1	2.000	2.000	2.000	2.000
	Vehicle 2	0.427	0.630	0.630	1.009
	Vehicle 3	0.104	0.182	0.182	0.553
	Vehicle 4	0.046	0.056	0.057	0.259
	Vehicle 5	0.016	0.016	0.016	0.105
	Vehicle 6	0.010	0.011	0.011	0.052
	Vehicle 7	0.008	0.008	0.009	0.026
	Vehicle 8	0.006	0.008	0.009	0.013

As currently available, the DOCM uses only simple extrapolation to calculate estimated state from measurements. The measurements may be made either at time intervals or as vehicles pass wayside fixed position equipment. The DOCM User's Manual[4] fully describes the options available. The measurements for all the preceding experiments have been perfect measurement without noise taken at every integeration time step. For the link flow experiments and those that follow, additional realism has been introduced into the measurement by adding random noise to each measured value. Ideal measurements of vehicle position and velocity are taken every integration time step and then noise from a normal distribution of zero mean is added to each measurement. The standard deviation of the position measurement noise is taken as 0.5 metre and the standard deviation of the velocity measurement noise is taken as 0.25 m/s.

For the point follower link flow experiments, the link consists of 7 slots each of which is 150 metres long giving a nominal travel time of 42 seconds. For the vehicle follower link flow experiments, the link is 1000 metres long giving a nominal travel time of 40 seconds. Vehicles are injected into the link beginning at time zero and link flow statistics are gathered over the time interval from 80 to 880 seconds. Thus, the link is in full service during the entire statistical interval. For point follower simulations, the injected vehicles are generated by the DOCM input processor using a user input probability of slot occupancy. For vehicle follower simulations, the DOCM input processor also produces the injected vehicles but other user input variables are required. The user supplies the minimum headway time (5.3 seconds for these vehicle follower experiments), the average headway time, and a non-zero probability of a vehicle being at the minimum headway.

The results of the synchronous point follower experiments are given in Table 2-15. A quasi-synchronous point follower experiment at 100 percent of capacity V (4209) was also made. The experimental results are identical to the synchronous experiment M (3971) in all details. Thus for normal link flow there is no difference, as simulated in the DOCM, between synchronous and quasi-synchronous point follower. The ideal percent of capacity corresponds to the user input variable and the actual percent of capacity is based upon the link input rate during the statistical period. The results show that there is no effect on normal vehicle link flow characteristics when the utilization is changed. This is a characteristic expected of point follower vehicle control because the vehicles are oblivious of each other during normal flow conditions.

The results of the asynchronous vehicle follower experiments are given in Table 2-16. Significant changes in the probability of jerk violations and the propulsion and brake work are seen to result from changing the link utilization. The trends are all in the expected direction. The change in propulsion work, however, is small, representing only a 2.9 percent difference between the two extremes tested. Substantial change in brake work occured, however brake work is at all times less than 5.2 percent of propulsion work. The conclusion is that the vehicle interactions during vehicle follower link flow result in some increased dynamic changes and use of energy. However, for a well designed controller, this effect is very small.

TABLE 2-15. SUMMARY OF SYNCHRONOUS POINT FOLLOWER LINK FLOW EXPERIMENTS

Run Identification	M(3971)	N(3972)	O(3975)	P(3978)
Control Type	Point Follower	Point Follower	Point Follower	Point Follower
Ideal Percent of Capacity	100	80	60	40
Actual Percent of Capacity	100	84.96	61.65	41.98
Probability of Jerk Violation	0.0024	0.0023	0.0023	0.0023
Propulsion Work per Vehicle Second (W)	44,926	44,918	44,931	44,954
Brake Work per Vehicle Second (W)	19	23	20	19
Average Travel Time (seconds)	42.01	42.01	42.01	42.01
Minimum Travel Time (seconds)	41.99	41.99	42.00	42.00
Maximum Travel Time (seconds)	42.02	42.02	42.02	42.02

TABLE 2-16. SUMMARY OF ASYNCHRONOUS VEHICLE FOLLOWER LINK FLOW EXPERIMENTS

Run Identification	K(3609)	Z(5357)	A(5358)	B(5359)
Control Type	Vehicle Follower	Vehicle Follower	Vehicle Follower	Vehicle Follower
Ideal Percent of Capacity	100	80	60	40
Actual Percent of Capacity	100	78.39	57.89	41.47
Probability of Jerk Violation	0.0125	0.0077	0.0051	0.0031
Propulsion Work per Vehicle Second (W)	46,167	45,615	45,031	44,846
Brake Work per Vehicle Second (W)	2,388	1,349	602	367
Average Travel Time (seconds)	40.34	40.09	40.09	40.09
Minimum Travel Time (seconds)	40.23	39.55	39.66	39.73
Maximum Travel Time (seconds)	40.39	40.31	40.23	40.20

The point follower controlled vehicles used slightly less propulsion energy for all but the lowest link flow rate then did the vehicle follower controlled vehicles. The predictability of link travel time with point follower control is much better than for vehicle follower control because vehicle follower control does not directly enforce a desired position versus time. However, the range in variation of link travel times with vehicle follower control is less than one second.

2.2.4.4 Headway Protection Experiments — Several experiments were performed to test the headway protection feature. As previously stated, for the continuous headway protection being used in these experiments, an emergency stop is commanded when measured head-to-head vehicle distance is less than the spacing calculated according to Equations 2-2 and 2-3. A true state headway violation may exist prior to this because of measurement errors and noise.

In the headway protection experiments, ten nonuniform vehicles with characteristics, as given in Table 2-13 were simulated at 25 m/s and minimum operational headways. Measurement noise as described in Section 2.2.4.3 was present. The lead vehicle was open loop decelerated at 20 m/s^2 starting at about time 42 seconds. Vehicles 2 through 10 continued under closed loop control until the end of the simulation at time 100 seconds. The results are summarized in Table 2-17. Experiment U (5343) had asynchronous vehicle follower, V (5347) had synchronous point follower, and an unreported experiment I (2041) had quasi-synchronous point follower control. The quasi-synchronous experiment had the identical results as the synchronous point follower experiment. For the experiments just listed, once the vehicle entered an emergency condition it was not allowed to revert back to normal control. For reported experiments W (5350) and J (2048), the stop time after an emergency stop, a user input variable ANESTP, was set to zero. Thus one integration time step after the vehicle stopped, control reverted back to normal closed loop procedures. The quantities reported in Table 2-17 are the head-to-head vehicle distance at the end of the simulation and the time between the first reported headway violation and the time the vehicle is first stopped. Considerable differences exist among the four experiments. For the vehicle follower case U (5343), the second vehicle stopped with the most intervehicle space because it had little time to reduce its speed under closed-loop control and registered a headway violation at a relatively high velocity, reflected in a longer time from violation to stop. All other vehicles remained in closed loop control until a velocity of approximately 1.5 m/s was reached at which point the safe headway criteria was violated. For the point follower case V (5347), all vehicles responded in similar fashion. They continued to follow their control point at linespeed and then found themselves in a headway violation condition while at linespeed. Thus a much longer time is reported as required to emergency stop but a larger separation at stop was achieved. For the two experiments in which control reverted to closed-loop at the end of the emergency stop the vehicles closed some of the intervehicle gaps. For example in W (5350), all vehicles inched forward until all had about the same spacing. Note that this inching forward process involved several starts, headway violations and emergency stops for each vehicle. For the point follower case, J (2048), the vehicle must try to catch a passing control point and considerably more control calculations are necessary as compared to vehicle follower control. Such attempts were made by the first four vehicles and as seen in the results, they did close their spacing. The number two vehicle in the experiment J (2048)

TABLE 2-17. SUMMARY OF HEADWAY PROTECTION EXPERIMENTS

Run Identification		U(5343)	W(5350)	V(5347)	J(2048)
Control Type		Vehicle Follower	Continued Vehicle Follower	Point Follower	Continued Point Follower
Head-to-Head Distance (m)	Vehicle 2	12.44	6.48	21.33	4.20
	Vehicle 3	6.07	6.10	23.14	4.85
	Vehicle 4	6.98	6.48	21.27	9.03
	Vehicle 5	5.24	6.59	20.85	14.70
	Vehicle 6	6.92	5.86	21.50	75.41
	Vehicle 7	5.40	5.76	22.20	22.20
	Vehicle 8	6.48	6.64	22.85	22.85
	Vehicle 9	6.56	6.83	19.17	19.17
	Vehicle 10	6.24	6.50	18.28	18.28
Initial Violation to Stop (s)	Vehicle 2	2.30	2.30	5.10	5.10
	Vehicle 3	0.50	0.55	5.10	5.10
	Vehicle 4	0.65	0.55	5.10	5.10
	Vehicle 5	0.60	0.65	5.15	5.15
	Vehicle 6	0.60	0.55	5.10	5.10
	Vehicle 7	0.50	0.55	5.10	5.10
	Vehicle 8	0.60	0.60	5.10	5.10
	Vehicle 9	0.60	0.65	5.20	5.20
	Vehicle 10	0.55	0.60	5.20	5.20

finally had a collision with vehicle number one at a velocity of 0.2 m/s. This occurred because of four consecutive measurements which underestimated safe spacing and thus a headway violation was not responded to until it was too late.

These experiments show that the headway protection algorithm works well but that special procedures need to be enacted after an emergency stop. Returning to normal closed loop control, at least with the identical control laws suitable for normal link flow conditions, does not work well.

2.2.4.5 System Start-Up Experiments — A method of starting a system link after the removal or repair of a failed vehicle was tested for the three control combinations being considered. The case of synchronous and quasi-synchronous point follower were identical in experimental results. The point follower experiments started with ten vehicles having initial conditions for position and velocity equal to the end conditions of experiment V (5347) of the previous section. The vehicle follower experiments started from the end conditions of experiment U (5343) of the previous section. There are no numerical results that are particularly descriptive of the results of the experiments. A short verbal description is given of the various experiments.

Experiment K (2051) consisted of ten vehicles under vehicle follower control. All vehicles were returned to closed loop control at the beginning of the simulation. Vehicles 7, 9, and 10 made initial attempts to move and immediately experienced headway violations. They braked and entered 5 seconds of stop associated with the emergency mode. All other vehicles moved out successfully, vehicle number 1 in velocity control mode and the others in vehicle follower mode. Vehicle 1 reached a peak velocity of about 35.3 m/s before returning to 25 m/s linespeed because its control included a term proportional to the time integral of velocity error. Such integral feedback is not useful for a situation such as this. Another alternative would be to issue a gradually increasing linespeed command rather than the full 25 m/s linespeed given in this experiment. Vehicles 7, 9, and 10 successfully moved out after the arbitrary 5 second duration of their emergency stop mode ended.

Experiment L (2061) used a similar strategy of returning vehicles to closed loop control at one time for the case of synchronous point follower. Various vehicles were declared by the simulation to have lost their slot and placed in an emergency mode. After a 5 second delay vehicles returned to closed loop control and initiated dequeueing maneuvers or were reclassified as queued depending upon the condition of immediately preceding vehicles. Sometimes more than one vehicle was assigned to the same slot. This clearly was not a good start up procedure for point follower control. Experiment M (2066) for quasi-synchronous point follower gave identical results.

Experiment AA (3729) was a repeat of experiment K (2051) for vehicle follower control with an important modification. All vehicles were open loop commanded an acceleration of -2 m/s^2 at the start of the experiment. The vehicles were returned to closed loop control one at a time beginning with vehicle number 1. Two seconds were allowed between each return to closed loop control. No vehicle received an emergency command after being returned to closed loop control. All vehicles performed well under this procedure. Integral of velocity error feedback was still used along with a constant 25 m/s linespeed command so vehicle overspeed occurred similar to that in experiment K (2051).

Experiment AA (3732) applied a count off procedure similar to that in AA (3729) to the control case of synchronous point follower. Vehicles were returned to closed loop control one every headway time of 6 seconds. This procedure would have worked well if all vehicles had stopped one headway distance apart. When a vehicle was returned from open loop control one of two things happened. If the vehicle was located within a tolerance distance of the control point associated with its current location it was returned to normal point follower control. This happened even though its velocity was zero instead of being close to linespeed. Since the velocity would remain low during the first several seconds, slot tolerance would always be lost and the vehicle issued an emergency command to stop. After the emergency stop delay period the vehicle returned to closed loop control and initiated dequeueing procedures. The other series of events which could happen when a vehicle was returned from open loop control was that the vehicle immediately was recognized as not having slot tolerance, an emergency command was issued, but from zero velocity. After the emergency stop delay period the vehicle was returned to closed loop control and initiated dequeueing procedures.

Both cases led to the initiation of dequeueing procedures. The difference was only in the time taken to start the procedures. Vehicles which had initial slot tolerance took longer. This lost time had the bad effect that two vehicles could then start dequeueing at about the same time and there could be instances of two vehicles assigned to the same slot. This of course would eventually lead to a headway violation, emergency braking, and delay.

No further experiment modifications were tried. The procedure recommended at this time is to time the initial return from open loop control to be at least one headway later than the preceding vehicle and to choose the time so that the vehicle does not see initial slot tolerance and is forced to initiate dequeue procedures immediately.

2.2.5 Merge Performance Analysis

In this section several DOCM experiments involving a guideway merge element and a guideway intersection element (two diverges and two merges) are reported. In addition a subsection is devoted to an analytic investigation of slot advance and retard maneuver distance and time requirements. This is used as an aid in choosing realistic merge geometries.

2.2.5.1 Analytic Results — An analysis has been made to determine the time and distance required to accomplish slot advance and slot retard maneuvers[11]. The average acceleration for increasing velocity is taken as A and the average deceleration for decreasing velocity A_s is assumed to be

$$A_s = K_s A \tag{2-94}$$

The nominal linespeed is v and the change of velocity used during the maneuver is Δv taken as positive for both increase and decrease of velocity. The number of slots advanced or retarded is n, positive for advance and negative for retard. The slot headway time is h_s. The change in relative position for a maneuver is

$$\Delta x = n h_s v \qquad n = 0, \pm 1, \pm 2, \ldots \tag{2-95}$$

however this change in position occurs while the vehicle is moving. Thus, there is a maneuver distance required to accomplish this Δx change in position. If a trapezoidal velocity profile is assumed (i.e., step changes in acceleration) the maneuver distance and time for slot advances are

$$x = \Delta x \left(1 + \frac{v}{\Delta v}\right) + \frac{v \Delta v}{2A} \left(\frac{K_s + 1}{K_s}\right)$$

$$t = \frac{x - \Delta x}{v} \tag{2-96}$$

This maneuver distance may be minimized with respect to Δv, giving the minimum results

$$x_{min} = \Delta x + v \sqrt{\frac{2 \Delta x}{A} \left(\frac{K_s + 1}{K_s}\right)}$$

$$t_{min} = \sqrt{\frac{2 \Delta x}{A} \left(\frac{K_s + 1}{K_s}\right)}$$

$$\Delta v_{opt} = \sqrt{\frac{2AK_s \Delta x}{K_s + 1}} \tag{2-97}$$

For the case of slot retard, Equation 2-96 and 2-97 become

$$x = \Delta x \left(1 - \frac{v}{\Delta v}\right) + \frac{v \Delta v}{2A} \left(\frac{K_s + 1}{K_s}\right)$$

$$t = \frac{x - \Delta x}{v}$$

$$x_{min} = \Delta x + v \sqrt{- \frac{2 \Delta x}{A} \left(\frac{K_s + 1}{K_s}\right)}$$

$$t_{min} = \sqrt{- \frac{2 \Delta x}{A} \left(\frac{K_s + 1}{K_s} \right)}$$

$$\Delta v_{opt} = \sqrt{- \frac{2AK_s \Delta x}{K_s + 1}} \qquad (2-98)$$

These results may be applied to the vehicle characteristics representative of SGRT being investigated. The minimum operational headway of 6 seconds for point follower did not allow for any planned increase in commanded velocity above 25 m/s, only for a modest dynamic overshoot in achieving 25 m/s. However, in establishing the acceleration profile it was determined that values of

$$a_f = 0.637 \text{ m/s}^2$$

$$a_f = 0.417 \text{ m/s}^2 \qquad (2-99)$$

corresponded to cruise velocities of 25 m/s and 27.5 m/s respectively. Slot advances were investigated for the average of these acceleration rates. Thus parameters are

$$A = 0.527 \text{ m/s}^2$$

$$K_s = 4.15$$

$$\Delta v = 2.5 \text{ m/s} \qquad (2-100)$$

The Ks gives an As = 2.2 m/s^2 for service deceleration. For slot retard a Δv = 25 m/s was used since the vehicle can be allowed to stop during the maneuver. The profile acceleration from zero to 25 m/s takes a distance of 225.5 metres. This is the distance for a constant acceleration rate of 1.39 m/s^2. Thus

$$A = 1.39 \text{ m/s}^2$$

$$K_s = 1.58$$

$$\Delta v = 25 \text{ m/s} \qquad (2-101)$$

are the parameters which were used. The results are given in Table 2-18. It is seen that an extremely long maneuver distance and time is required to advance even one slot. The optional Δv which minimized maneuver distance for this case is 11.3 m/s and even then the distance is 812 metres. (Such a Δv is far beyond safe limits for the chosen headway and does not correspond to the value of acceleration available). Thus it may be concluded that a slot advance for quasi-synchronous control under the conditions being investigated is infeasible. For slot retards of -1 and -2 the optimal Δv is less than the allowed 25 m/s, however for other retards the vehicle comes to a stop. Notice that the required distance

TABLE 2-18. SLOT MANEUVER REQUIREMENTS

Number of Slots	3	2	1	-1	-2	-3	-4	-5
Relative Position Change (m)	450	300	150	-150	-300	-450	-600	-750
Maneuver Distance (m)	5023	3373	1723	319	364	367	367	367
Maneuver Time (s)	182.9	122.9	62.9	18.8	26.5	32.7	38.7	38.7
v Utilized (m/s)	2.5	2.5	2.5	16.0	22.6	25.0	25.0	25.0

is never more than the total distance required to decelerate to a stop and accelerate back to linespeed.

Based upon the requirement of 367 metres to decelerate to a stop and accelerate back to linespeed, the geometry of an asynchronous merge element has been chosen as shown in Figure 2-30. Input links 1 and 2 are identical. For FIFO merge, decision points D_1 and D_2 are used. When priority is to be given to link 1, the decision point is D_1' instead of D_1, and when priority is to be given to link 2, the decision point is D_2' instead of D_2.

The geometry of an asynchronous intersection element for simulation is shown in Figure 2-31 and is based upon the merge geometry of Figure 2-30. D_{18}, for example, is the decision point for the path number 3 consisting of links 1, 4, and 8. The distance between D_{18} and D_{17} and between D_{27} and D_{28} is 100 metres. Thus it may be confirmed that all decision points are 600 metres upstream of the merge point M. However, a vehicle receiving its merge assignment at D_{18} or D_{27} may not begin to maneuver until after it has diverged and is on link 4 or 6 respectively. Thus the length available for maneuver is 600 metres for two paths and 500 metres for the other two paths. The link lengths were chosen to at least partially reflect true geometric constraints and also to illustrate the ability to independently locate points for each path.

The geometry of a quasi-synchronous point follower merge element has been chosen as illustrated in Figure 2-32, where each dash depicts a slot. D_1 and D_2 are the decision points and Q_1 and Q_2 are the downstream end of the queueing region should queueing be necessary. The Chu merge algorithm bases the merge maneuver given at D_1 and D_2 on the occupancy of the blocks in the analysis region. This region for this merge consists of the three blocks upstream of D_1 and D_2 and the first block downstream. The merge assignment is given as soon as the vehicle enters the block downstream of D_1 and D_2. Thus that block is available both for analysis and for maneuver. The vehicle maneuver occurs in the three blocks downstream of D_1 and D_2. The three blocks each of length 150 metres were chosen to allow at least a three block slip.

The geometry of a quasi-synchronous intersection element is chosen as illustrated in Figure 2-33. In a manner similar to the asynchronous intersection, the decision points on each path are located an equal distance (in this case, number of slots) upstream of the merge. Should queueing become necessary, the vehicles would queue upstream of the diverge points. The option of queueing on the four maneuver ramps is also available. Maneuvering may not start until after the diverge so three slots are available for maneuver on the two short paths and four slots on the two longer paths. Since the previous analysis has shown that slot advance is not realistic for this system, no forward area blocks are used in these quasi-synchronous guideway elements.

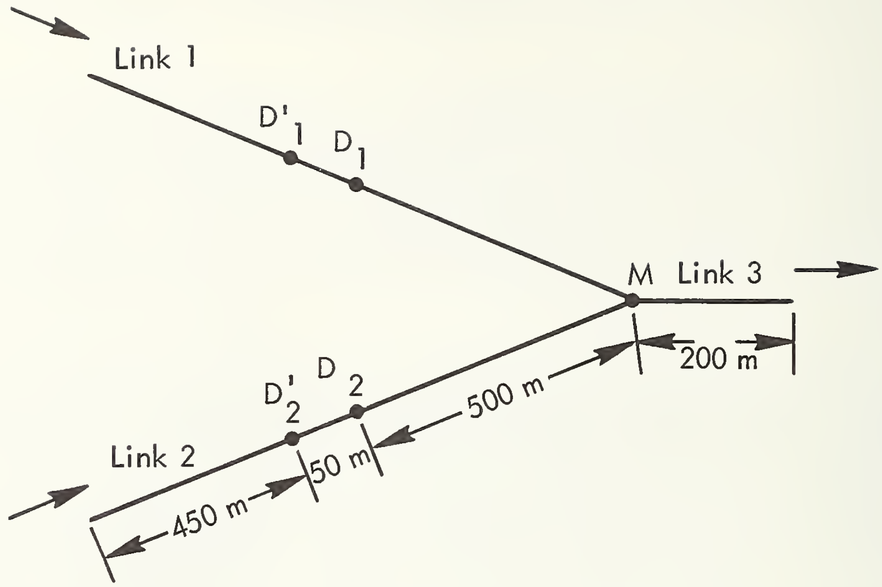
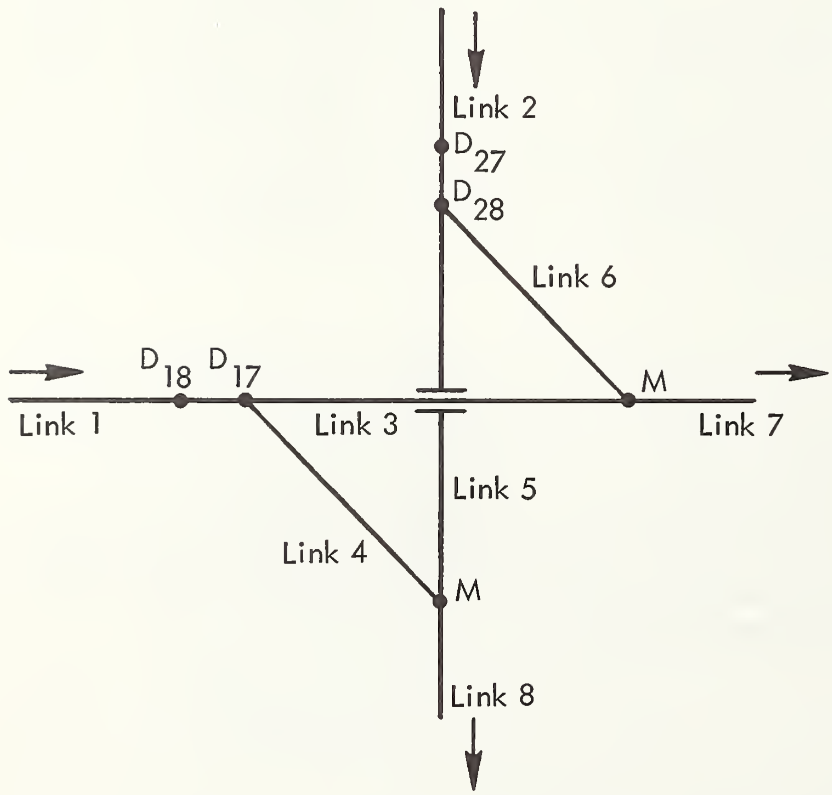


FIGURE 2-30. ASYNCHRONOUS MERGE GEOMETRY



Link 1	-	400 metres
Link 2	-	400 metres
Link 3	-	600 metres
Link 4	-	500 metres
Link 5	-	600 metres
Link 6	-	500 metres
Link 7	-	200 metres
Link 8	-	200 metres

FIGURE 2-31. ASYNCHRONOUS INTERSECTION GEOMETRY

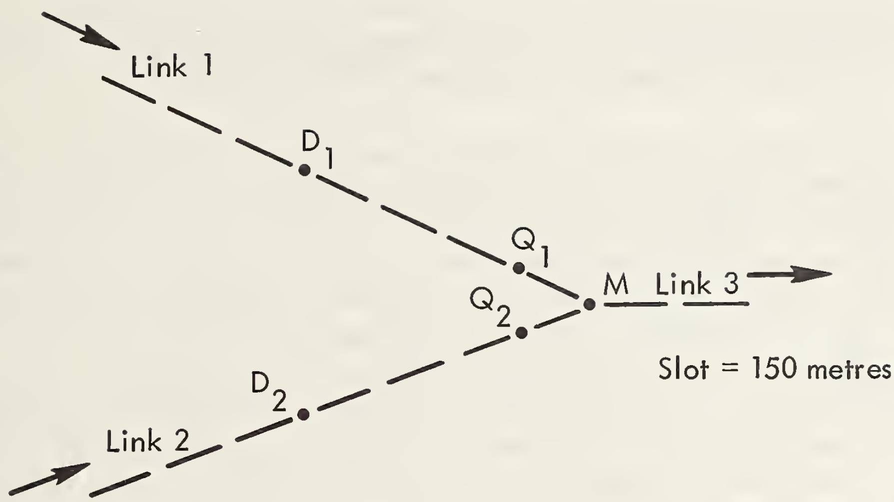


FIGURE 2-32. QUASI-SYNCHRONOUS MERGE GEOMETRY

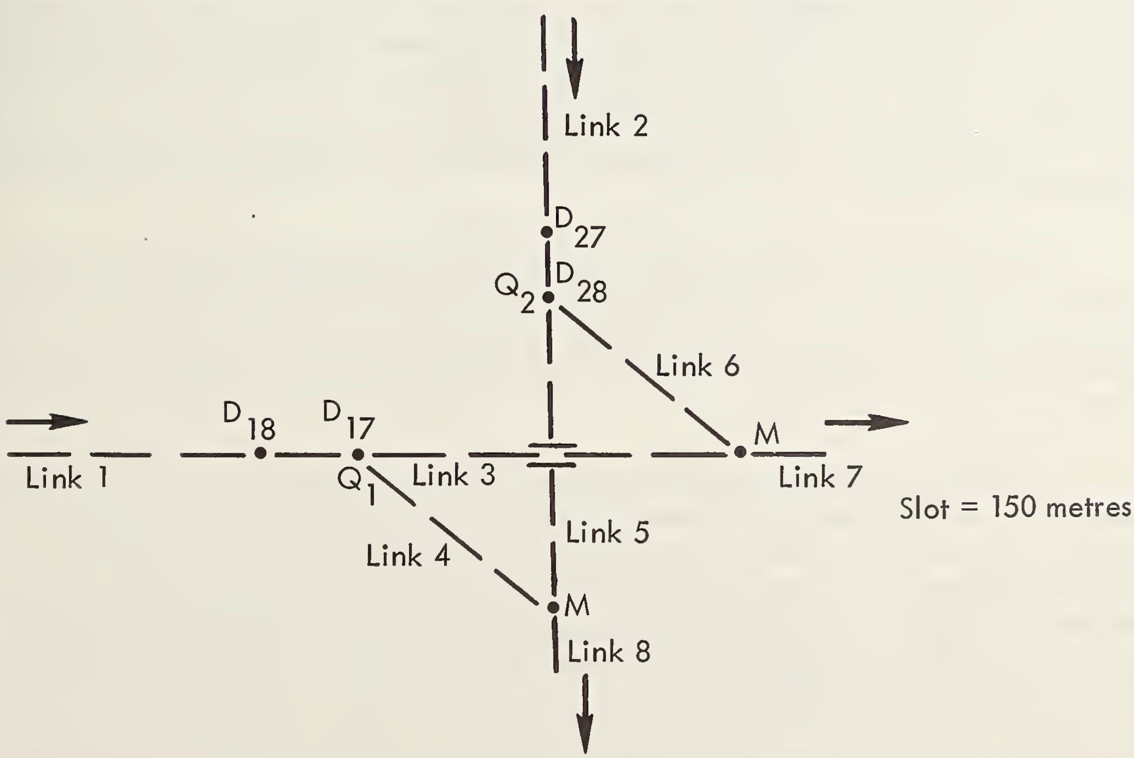


FIGURE 2-33. QUASI-SYNCHRONOUS INTERSECTION GEOMETRY

2.2.5.2 Merge Flow Experiments — The geometries of both asynchronous and quasi-synchronous merge elements for DOCM simulation were presented in the previous section. The results of merge flow experiments are presented in this section.

The vehicles injected into the simulations had the nonuniform vehicle characteristics as described in Table 2-13. The user must supply vehicle injection rate parameters for each input link. Experiments were performed at four different input flow conditions. The high density, even flow experiments had each input at 45 percent of capacity and thus the merge output was at 90 percent of linespeed capacity. For the high density, uneven flow experiments the merge output remained at 90 percent of capacity but the inputs were different, being at 60 and 30 percent. These ideal flow rates were cut in half for experiments at low flow densities. The ideal and actual flow conditions for the asynchronous experiments at 5.3 seconds headway are summarized in Table 2-19. The ideal and actual flow conditions for the quasi-synchronous experiments at 6.0 seconds headway are summarized in Table 2-20. These flow statistics, as well as the other experimental results which follow, are for an 800 second interval of time beginning 80 seconds after the start of the simulation. The 80 second initial period was allowed to load the network element and allow at least one vehicle to have been ejected from the simulation after traveling the full simulated length of guideway.

Ten merge flow experiments for asynchronous control were performed. The specific conditions and results are summarized in Table 2-21. Comparing experiments D (3185) and H (3208) which gave 50 metre priority to one path for the case of even demand shows a slight lowering of the priority path's travel time but also an increase in the travel time on the other path. The weighted average travel time, obtained by weighting the individual path average travel times by the path flows, increases for the priority merge. Another experiment, I (3216), not included in this summary, gave priority to path 2 in the even flow case. The path 1 and path 2 statistics essentially switched as compared to experiment H (3208) as expected, and the weighted average travel time was also greater than for experiment D (3185).

Experiments F (3199), G (3204), and N (5092) were performed for the uneven flow situation at high density. The priority merge cases resulted in lower average travel time for the path with priority and increased travel time for the path without priority as compared to the FIFO merge case. However, the FIFO merge resulted again in the lowest weighted average travel time.

Completely analagous experiments and results are reported for low flow density. The overall results on propulsion energy show only minor differences attributable to merge strategy and those differences are not of any obvious pattern. There is however, an obvious difference in the amount of brake work required as the flow densities change. Uneven flow results in less brake work than does even flow. The apparent reason is that for uneven flow, a larger portion of the vehicles require little or no maneuvering than for the case of even flows.

The quasi-synchronous merge flow experiments were made using the input flows as already summarized in Table 2-20. The proper combination of merge element geometry,

TABLE 2-19. ASYNCHRONOUS MERGE INJECTION RATES

Density		High	High	Low	Low
Uniformity		Even	Uneven	Even	Uneven
Ideal Percent of Capacity	Path 1	45.0	60.0	22.5	30.0
	Path 2	45.0	30.0	22.5	15.0
Actual Percent of Capacity	Path 1	43.3	55.7	19.4	27.7
	Path 2	43.0	24.6	19.0	10.9

TABLE 2-20. QUASI-SYNCHRONOUS MERGE INJECTION RATES

Density		High	High	Low	Low
Uniformity		Even	Uneven	Even	Uneven
Ideal Percent of Capacity	Path 1	45.0	60.0	22.5	30.0
	Path 2	45.0	30.0	22.5	15.0
Actual Percent of Capacity	Path 1	43.2	62.4	25.0	34.8
	Path 2	37.6	26.5	23.3	12.9

TABLE 2-21. SUMMARY OF ASYNCHRONOUS MERGE FLOW EXPERIMENTS

Run Identification		D(3185)	H(3208)	F(3199)	G(3204)	N(5092)	O(5094)	P(5100)	Q(5101)	R(5104)	S(5114)
Density		High	High	High	High	High	Low	Low	Low	Low	Low
Uniformity		Even	Even	Uneven	Uneven	Uneven	Even	Even	Uneven	Uneven	Uneven
Merge Strategy		FIFO	Priority Path 1	FIFO	Priority Path 1	Priority Path 2	FIFO	Priority Path 1	FIFO	Priority Path 1	Priority Path 2
Probability of Jerk Violotion		0.0112	0.0117	0.0095	0.0099	0.0096	0.0048	0.0051	0.0041	0.0038	0.0044
Propulsion Work per Vehicle Second (W)		47031	47125	46629	46530	46597	45908	45721	45529	45655	45562
Brake Work per Vehicle Second (W)		7067	7560	5294	5510	5457	2494	2402	1722	1910	1796
Poth 1 Trovel Time (seconds)	Avg.	50.91	50.21	49.67	49.31	50.12	48.64	48.35	48.45	48.25	48.61
	Min.	48.01	48.01	47.70	47.71	47.43	47.76	47.78	47.89	47.91	47.90
	Mox.	58.74	58.16	55.53	53.88	57.88	53.02	51.25	52.83	51.21	54.81
Path 2 Trovel Time (seconds)	Avg.	50.59	51.80	50.65	52.01	50.10	48.59	49.01	48.57	49.32	48.35
	Min.	48.06	48.08	48.06	48.06	48.06	48.06	48.06	48.05	48.07	48.04
	Mox.	57.71	61.04	56.58	57.66	54.23	52.74	54.49	52.35	54.69	52.39
Weighted Average Travel Time (seconds)		50.75	51.00	49.97	50.14	50.11	48.62	48.68	48.48	48.55	48.54
Moximum Range of Trovel Time (seconds)		10.73	13.03	8.88	9.95	10.45	5.26	6.71	4.94	6.78	6.91

feedback control law, and possibly vehicle performance parameters to provide good merge element performance for the high density of input flow case was difficult to find. No combination was found which produced no vehicle injection rejections. That is, a situation involving headway violations, emergency stopping, queueing, and eventually a backing up of vehicles to the extent that some vehicles had to be refused entry into the upstream end of the simulated merge element occured in all experiments performed for the high density with even flows input case.

The results of these experiments which were not complete successes are reported in the form of the time sequence of events which lead up to and include the undesirable merge behavior. The first group of experiments used the merge geometry of Figure 2-32, and the control already developed in a previous section. The results for experiment J (3220) at high density and even flows are given in Table 2-22. The problem occurred on path number two when vehicles in consecutive slots were commanded a -1, -2, and -3 slot maneuver. The safe headway distance between the vehicle executing the -3 slip and the vehicle executing the -2 slip was violated 5.9 seconds after the trailing vehicle began its maneuver. This resulted in an emergency stop and forced queueing for other vehicles. Vehicle 62 started dequeue procedures 5 seconds after stopping but the high flow densities caused an increasing queue to form and finally the first vehicle was rejected from the simulation about 61 seconds after the initial trouble. The results for a similar situation, except that the flows were uneven and priority was given to the path with heaviest flow, are reported in Table 2-23. The maneuver situation which resulted in problems was that of two consecutive vehicles receiving a slot slip command of -2 slots. The second vehicle to receive the -2 slot slip command had a headway violation 6.8 seconds after the command to slip. The resulting queueing again caused an eventual vehicle injection rejection. The same experiment was also run for the case of priority given to the path with the lighter flow. The results are given in Table 2-24. Notice that the slot maneuver assignments are different but that the situation again results in a -2 slot slip being commanded to consecutive vehicles.

The control law used during maneuvers under quasi-synchronous control is that of Equation 2-7 without the integral position error feedback and uses gain vector ANGAN2. If the second element of ANGAN2 is made smaller in absolute magnitude than that of Equation 2-67, the vehicle will respond less quickly to a slot slip command. Thus experiments were made with a new gain vector

$$\text{ANGAN2} = \begin{bmatrix} 0.0 \\ -0.167 \\ 0.0 \\ -1.6 \\ 0.0 \\ 0.0 \end{bmatrix} \qquad (2\text{-}102)$$

The results of an experiment using the high density even flow demand are reported in Table 2-25. The previous problem of experiment J (3220) is avoided. That is, consecutive vehicles can execute a -2 slot maneuver without a headway violation. This successful portion is reported in Table 2-25. However, as the experiment continued,

TABLE 2-22. SUMMARY OF QUASI-SYNCHRONOUS MERGE RUN J(3220)

Vehicle I.D.	56	57	58	59	60	61	62	63	64	65	66			76
Path	1	1	2	1	2	1	2	2	1	1	2			1
Time at Decision Point (s)	432	438	438	444	444	450	450		468	480				
Slot Maneuver Assignment	0	0	-1	-1	-2	-2	-3		-3	-3				
Emergency Time (s)							455.9	463.4						
Forced Queue (s)								456.1			468.1			
Loss of Slot (s)														
First Injection Rejection (s)														516

TABLE 2-23. SUMMARY OF QUASI-SYNCHRONOUS MERGE RUN T (5118)

Vehicle I.D.	32	33	34	35	36	37	38	39	40	41	42	43		51
Path	1	2	1	2	1	2	1	1	1	2	1	2		1
Time at Decision Point (s)	228	228	246	246	252	252	258	264	270	276		288		
Slot Maneuver Assignment	0	-1	0	-1	-1	-2	-2	-2	-2	0		-3		
Emergency Time (s)								270.8	272.4		282.9			
Forced Queue (s)									270.9		270.9			
Loss of Slot (s)														
First Injection Rejection (s)														342

TABLE 2-24. SUMMARY OF QUASI-SYNCHRONOUS MERGE RUN L(3234)

Vehicle I.D.	32	33	34	35	36	37	38	39	40	41	42	43		51
Path	1	2	1	2	1	2	1	1	1	2	1	2		1
Time at Decision Point (s)	228	228	246	246	252	252	258	264		276		288		
Slot Maneuver Assignment	-1	0	-1	0	-2	-1	-2	-2		-3		-3		
Emergency Time (s)							264.7	266.3			278.8	293.7		
Forced Queue (s)								264.9	264.9		264.9			
Loss of Slot (s)														
First Injection Rejection (s)														342

TABLE 2-25 (1 OF 2). SUMMARY OF QUASI-SYNCHRONOUS MERGE RUN T(1322)

Vehicle I.D.	56	57	58	59	60	61	62	63	64	65	66	67	68	69
Path	1	1	2	1	2	1	2	2	1	1	2	1	2	1
Time at Decision Point (s)	432	438	438	444	444	450	450	462	468	480	486	492	492	504
Slot Maneuver Assignment	0	0	-1	-1	-2	-2	-3	-2	-2	-1	-1	-1	-2	-1
Emergency Time (s)														
Forced Queue (s)														
Loss of Slot (s)														
First Injection Rejection (s)														

TABLE 2-25 (2 OF 2). CONTINUED SUMMARY OF QUASI-SYNCHRONOUS MERGE RUN T(1322)

Vehicle I.D.	70	71	72	73	74	75	76	77	78	79				89
Path	2	1	2	1	1	2	1	1	2	1				1
Time at Decision Point (s)	504	510	510	516	522	522								
Slot Maneuver Assignment	-2	-2	-3	-3	-3	-4								
Emergency Time (s)					530.0	523.9								
Forced Queue (s)						522.0	530.2	530.2	522.1	534.1				
Loss of Slot (s)														
First Injection Rejection (s)														612

slot slip requirements became even more severe. Vehicle number 75 was commanded to perform a -4 slot slip. This exceeded the maneuver limit for the merge element of Figure 2-32 since the decision points are only 3 full slots downstream of the upstream end of the simulation. The vehicle was commanded to queue but very soon experienced a headway violation with a preceding vehicle slipping -3 slots. A few seconds later another headway violation occurred on the other input path involving two vehicles executing -3 slot maneuvers. A different choice of ANGAN2 may solve the headway violation problem but the -4 slot maneuver situation requires a different merge element design. Another experiment, J (3902), was made with an ANGAN2 with slightly increased feedback on position as compared to the experiment T (1322) just reported. The gain vector used is

$$\text{ANGAN2} = \begin{bmatrix} 0.0 \\ -0.2 \\ 0.0 \\ -1.6 \\ 0.0 \\ 0.0 \end{bmatrix} \qquad (2\text{-}103)$$

The results are summarized in Table 2-26. The problem situation is completely similar to that of the previous experiment except that the headway violation for vehicle number 74 occurred 1.2 seconds sooner.

The geometry of the quasi-synchronous merge element was modified to that shown in Figure 2-34 to allow for a -4 slot maneuver command without necessitating a queue situation. An experiment was run with this merge geometry and ANGAN2 as given in Equation 2-102. The results are summarized in Table 2-27. The -4 slot maneuver did not initiate a queue command but the two consecutive -3 slot maneuvers did cause a headway violation. The position feedback gain in ANGAN2 was reduced even more giving

$$\text{ANGAN2} = \begin{bmatrix} 0.0 \\ -0.111 \\ 0.0 \\ -1.6 \\ 0.0 \\ 0.0 \end{bmatrix} \qquad (2\text{-}104)$$

The effect of this change on the headway violation problem was not determined because the experiment using this gain, AA (3135), experienced another type of failure. The experiment is summarized in Table 2-28. Vehicle number 7 was commanded a -2 slot maneuver at time 60 seconds and thus was due to pass through the merge at time 90 seconds. When this happened the vehicle was not within the user prescribed distance of 25 metres of its control point and thus received an emergency command. Slot tolerance is set as linespeed times a user input fraction of slot time. Tolerance is not checked after

TABLE 2-26. SUMMARY OF QUASI-SYNCHRONOUS MERGE RUN J(3902)

Vehicle I.D.	70	71	72	73	74	75	76	77	78	79				89
Path	2	1	2	1	1	2	1	1	2	1				1
Time at Decision Point (s)	504	510	510	516	522	522								
Slot Maneuver Assignment	-2	-2	-3	-3	-3	-4								
Emergency Time (s)					528.8	523.7								
Forced Queue (s)						522.0	528.9	528.9	522.1	534.1				
Loss of Slot (s)														
First Injection Rejection (s)														612

TABLE 2-27. SUMMARY OF QUASI-SYNCHRONOUS MERGE RUN AA(3131)

Vehicle I.D.	70	71	72	73	74	75	76	77	78	79				89
Path	2	1	2	1	1	2	1	1	2	1				1
Time at Decision Point (s)	510	516	516	522	528	528			546					
Slot Maneuver Assignment	-2	-2	-3	-3	-3	-4			-3					
Emergency Time (s)					534.2		541.1			548.4				
Forced Queue (s)							534.4	534.4		534.4				
Loss of Slot (s)														
First Injection Rejection (s)														612

TABLE 2-28. SUMMARY OF QUASI-SYNCHRONOUS MERGE RUN AA(3135)

Vehicle I.D.	1	2	3	4	5	6	7	8	9	10	11	12		27
Path	1	2	1	2	2	1	2	1	2	1	2	1		2
Time at Decision Point (s)	36	36	48	48	54	60	60	78	78	84	90	96		
Slot Maneuver Assignment	0	-1	0	-1	-1	-1	-2	0	-1	-1	-1	-1		
Emergency Time (s)							90.1	96.6	100.9					
Forced Queue (s)										101.1	101.1	101.1		
Loss of Slot (s)							90.1							
First Injection Rejection (s)														168

the vehicle passes the decision point but it must be checked again at the end of the maneuver region which for this simulation was at the point of merge. The merge was blocked and all following vehicles either emergency stopped or queued.

Experiments using the merge geometry of Figure 2-34, the gain of Equation 2-102, and the high density uneven flow demand were made for both cases of priority. The results were completely successful in that no queueing or headway violations occurred. These experiments will be summarized shortly. Similiar experiments were performed with a gain vector as given in Equation 2-104. The case of priority given to path 1 is summarized in Table 2-29. A slot maneuver of -2 again resulted in a loss of slot emergency as the vehicle passed through the merge point. The case of priority given to path 2 is summarized in Table 2-30. The -2 slot maneuver was again commanded and loss of slot failure occurred at the merge point.

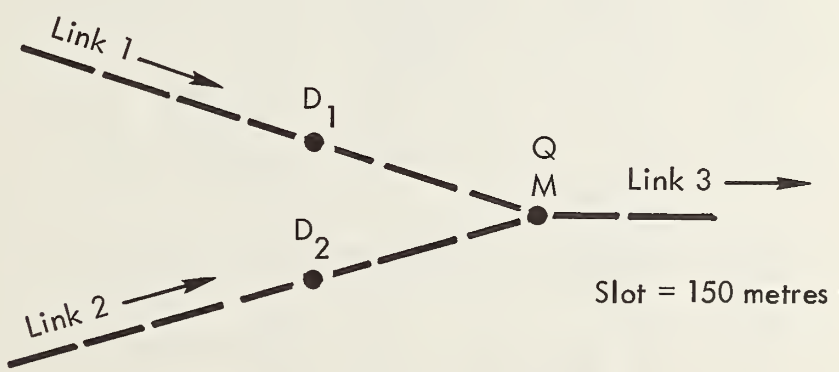


FIGURE 2-34. REVISED QUASI-SYNCHRONOUS MERGE GEOMETRY

Six merge experiments using the revised quasi-synchronous merge element of Figure 2-34 and the revised gain of Equation 2-102 were run for the four vehicle injections summarized in Table 2-20. Only the vehicle injection case of high demand with even flow gave merge maneuver problems as previously reported. A summary of performance statistics for the other five experiments is made in Table 2-31. The nominal travel time for this merge element is 54 seconds. The weighted average travel time appears to be very insensitive to the choice of which path is to have priority, even for the case of uneven path flows. The even flow case at both densities of flow is seen in general to require more and larger maneuvers. The unsuccessful experiment reported in Table 2-27 required at least a -4 slot maneuver while the successful experiments for uneven flows

TABLE 2-29. SUMMARY OF QUASI-SYNCHRONOUS MERGE RUN AA(3137)

Vehicle I.D.	7	8	9	10	11	12	13	14	15	16				
Path	1	2	1	2	1	1	2	1	1	2				
Time at Decision Point (s)	60	66	72	72	84	96	96	102	114					
Slot Maneuver Assignment	-1	-1	-1	-2	-1	0	-1	-1	0					
Emergency Time (s)				102.1	108.0	113.9	118.0	122.4	128.7	134.8				
Forced Queue (s)								118.8	118.8	118.2				
Loss of Slot (s)				102.1										
First Injection Rejection (s)														

TABLE 2-30. SUMMARY OF QUASI-SYNCHRONOUS MERGE RUN AA(3138)

Vehicle I.D.	7	8	9	10	11	12	13	14	15	16				25
Path	1	2	1	2	1	1	2	1	1	2				1
Time at Decision Point (s)	60	66	72	72	84	96	96	102	114	120				
Slot Maneuver Assignment	-1	-1	-2	-1	-1	-1	0	-1	0	0				
Emergency Time (s)			102.1		108.0	117.9	113.9	122.6	128.6					
Forced Queue (s)														
Loss of Slot (s)			102.1											
First Injection Rejection (s)														156

TABLE 2-31. SUMMARY OF QUASI-SYNCHRONOUS MERGE FLOW EXPERIMENTS

Run Identification		AA(3132)	AA(3133)	AA(4360)	AA(4363)	AA(4365)
Density		High	High	Low	Low	Low
Uniformity		Uneven	Uneven	Even	Uneven	Uneven
Merge Strategy		Priority Path 1	Priority Path 2	Priority Path 1	Priority Path 1	Priority Path 2
Probability of Jerk Violation		0.0079	0.0076	0.0040	0.0041	0.0041
Propulsion Work per Vehicle Second (W)		50776	50761	46990	47212	47258
Brake Work per Vehicle Second (W)		11989	11983	4365	4334	4385
Path 1 Travel Time (seconds)	Avg.	57.82	59.28	54.56	54.57	55.65
	Min.	54.02	54.02	54.02	54.02	54.02
	Max.	66.12	72.11	66.10	60.11	60.11
Path 2 Travel Time (seconds)	Avg.	60.58	57.22	56.96	57.82	54.79
	Min.	54.02	54.02	54.02	54.03	54.02
	Max.	72.11	66.12	72.11	60.09	60.09
Weighted Average Travel Time (seconds)		58.64	58.67	55.72	55.45	55.42
Maximum Range of Travel Time (seconds)		18.09	18.09	18.09	6.09	6.09

at high density required only -3 slot maneuvers. Also at low densities, the even flow case required -3 slot maneuvers and the uneven case only -1 slot maneuvers. The even case also has a higher average travel time.

2.2.5.3 Intersection Flow Experiments - Two illustrative intersection experiments were run. One for asychnchronous control and one for quasi-synchronous control. The intersection geometry for the asynchronous experiment was given in Figure 2-31. The nominal travel time on path 1 consisting of links 1, 3, 7 and on path 2 consisting of links 2, 5, 8 was 48 seconds. The travel time on path 3 consisting of links 1, 4, 8 and on path 4 consisting of links 2, 6, 7 was 44 seconds. The intersection geometry for the quasi-synchronous experiment was given in Figure 2-33. Based upon experience with the merge experiments, this intersection geometry is not expected to be able to handle high density flow but should handle low density flow with 45 percent slot occupancy on the input and output links. The nominal travel time on paths 1 and 2 is 54 seconds and 48 seconds on paths 3 and 4. The ideal and actual vehicle injection rates are summarized in Table 2-32.

The results of the two experiments are summarized in Table 2-33. The weighted average travel time for the asynchronous intersection should be compared with a nominal travel time for the actual vehicle distribution of 45.98 seconds. The similar measure for the quasi-synchronous intersection should be compared with a nominal travel time of 51.19 seconds. For the case of these two fairly comparable intersections, the quasi-synchronous control case results in slightly greater excess travel time and a slight increase in energy consumption.

2.2.5.4 Merge Performance Conclusions - In Section 2.2.5.2 it was concluded that FIFO merge strategy for asynchronous control is better than priority merge for all four of the vehicle injection conditions, in terms of weighted average travel time and also in terms of minimizing the range of travel times. Also from the experimental results for quasi-synchronous control, no advantage was noted in giving priority to the heavier input path. Thus, for normal merge situations it is concluded that FIFO merge for both asynchronous and quasi-synchronous is preferred, and a random choice in breaking a possible tie is as good as trying to choose a priority path. The decision points are placed at a common travel time before the merge point. Such a placement may not be possible under certain conditions, for example at stations. Thus for these situations a merge policy other than FIFO may be necessary.

The lack of one successful experiment with quasi-synchronous precludes a full comparison between asynchronous and quasi-synchronous control in merges. However, a comparison can be made based upon the five available quasi-synchronous experiments and their asynchronous counterparts. The case of FIFO merge is used for asynchronous and the best numerical result is picked from quasi-synchronous whenever a choice is possible. The results are summarized in Table 2-34. For the reported experiments, asynchronous control is consistently seen to give superior performance in terms of energy and excess travel time. In addition, the asynchronous experiments are at 5.3 second headways while the quasi-synchronous experiments are at 6.0 second headways, a 13.2 percent capacity difference.

TABLE 2-32. INTERSECTION INJECTION RATES

Intersection Merge Control		Asynchronous	Quasi-Synchronous
Ideal Percent of Capacity	Link 1	45.0	45.0
	Link 2	45.0	45.0
Actual Percent of Capacity	Link 1	46.3	44.4
	Link 2	40.0	39.1
Ideal Percent of Flow	Path 1	50.0	50.0
	Path 2	50.0	50.0
Actual Percent of Flow	Path 1	58.0	50.8
	Path 2	43.1	55.8

TABLE 2-33. SUMMARY OF INTERSECTION EXPERIMENTS

Run Identification		AA(1618)	AA(1217)
Intersection Merge Control		Asynchronous	Quasi-Synchronous
Probability of Jerk Violation		0.0055	0.0037
Propulsion Work per Vehicle Second (W)		45969	46585
Brake Work per Vehicle Second (W)		2374	3199
Path 1 Travel Time (seconds)	Average	48.63	54.24
	Minimum	47.75	54.03
	Maximum	52.92	60.08
Path 2 Travel Time (seconds)	Average	48.76	54.41
	Minimum	48.08	54.03
	Maximum	52.79	60.09
Path 3 Travel Time (seconds)	Average	44.61	50.07
	Mimimum	44.05	48.03
	Maximum	48.76	54.14
Path 4 Travel Time (seconds)	Average	44.58	49.70
	Minimum	43.84	48.03
	Maximum	47.63	54.14
Weighted Average Travel Time (seconds)		46.70	52.25
Maximum Range of Travel Time (seconds)		5.17	6.11

TABLE 2-34. COMPARISON OF ASYNCHRONOUS AND QUASI-SYNCHRONOUS CONTROL FOR MERGE EXPERIMENTS

Control Type		Asynchronous	Quasi-Synchronous	Asynchronous	Quasi-Synchronous	Asynchronous	Quasi-Synchronous	Asynchronous	Quasi-Synchronous
Density		High	High	High	High	Low	Low	Low	Low
Uniformity		Even	Even	Uneven	Uneven	Even	Even	Uneven	Uneven
Probability of Jerk Violation		0.0112	--	0.0095	0.0076	0.0048	0.0040	0.0041	0.0041
Propulsion Work per Vehicle Second (W)		47031	--	46629	50761	45908	46990	45529	47212
Brake Work per Vehicle Second (W)		7067	--	5294	11983	2494	4365	1722	4334
Path 1 Excess Travel Time (seconds)	Avg.	2.91	--	1.67	3.82	0.64	0.56	0.45	1.65
	Max.	10.74	--	7.53	12.12	5.02	12.10	4.83	6.11
Path 2 Excess Travel Time (seconds)	Avg.	2.59	--	2.65	6.58	0.59	2.96	0.57	0.79
	Max.	9.71	--	8.58	18.11	4.74	18.11	4.35	6.09
Weighted Average Excess Travel Time (seconds)		2.75	--	1.97	4.64	0.62	1.72	0.48	1.42
Maximum Range of Travel Time (seconds)		10.73	--	8.88	18.09	5.26	18.09	4.94	6.09

A further look will now be taken of the difficulty in obtaining complete success with the quasi-synchronous control. The headway time of 6 seconds was calculated in Section 2.2.1.3 based upon the vehicle paramters of Equation 2-23. The simulated vehicle was held close to these parameters with the exception of the safety factor applied to the "brick-wall" stopping distance. The simulated safety factor of 1.05 was chosen to be less than the 1.30 used in the headway calculations to ease the problem of controller design. One parameter which entered the headway calculation however is being badly violated in the quasi-synchronous merge. That parameter is change in linespeed, Δv. Even though line-speed does not change at the merge, a command to slip a slot causes an effective change of linespeed. For the maneuvers of -3 and -4 slots the vehicle either stops or comes very close to stopping. Thus Δv is equal to linespeed. The minimum operational headway distance for the case of

$$\begin{aligned} v &= 26.75 \text{ m/s} \\ \Delta v &= 26.5 \text{ m/s} \\ K_s &= 1.3 \end{aligned} \tag{2-105}$$

is

$$S_o = 190.4 \text{ m} \tag{2-106}$$

This implies a headway time of 7.6 seconds based upon a nominal linespeed of 25 m/s. The simulated value of K_s was 1.05. For this value the operational headway distance is

$$S_o = 147.1 \text{ m} \tag{2-107}$$

or a headway time of 5.9 seconds. These results imply that control at 6.0 second headways for the merge is possible but allows almost no margin to ease the task of controller design. Thus based upon these findings, the problems encountered are expected. Possible changes would include changing headway, increasing the maneuver distance, and further modification of the feedback gains. In any event, the design of a quasi-synchronous merge to provide performance close to that of an asynchronous merge is a considerable task.

2.3 SUBSYSTEM CONTROL OBSERVATIONS

The results of the minimum operational headway analysis imply that block vehicle follower control with block headway protection is adequate for systems with headways greater than about 20 seconds. The results also show that under the nominal conditions stated on p. 2-21, no control combination is capable of headways less than about 4 seconds without reducing the safety factor below unity and/or allowing for less that "brickwall" failures of the preceding vehicle. For similar vehicle and control equipment capabilities, point follower control requires somewhat longer headways than vehicle follower control because of the focusing distance phenomenon during line speed changes. This effect proved to be a serious problem in achieving a completely successful merge control situation for quasi-synchronous control.

The single vehicle experiments on a link confirmed that the vehicles can be controlled by either point follower or vehicle follower control methods to closely follow a performance profile chosen to match the power plant limitations of the vehicle. Thus the analytic expressions developed to predict dynamic performance and energy usage were determined to be very accurate and are recommended for use in further analyses. Headway protection was adequate in the experiments performed to check this feature. A simple and efficient technique was tested for start up of a link after a failure for vehicle follower control, but no completely successful procedure was found for the case of point follower control.

Link flow experiments showed that point follower control uses slightly less energy in the steady state and has slightly better predictability of link flow travel times as compared to vehicle follow control. Merge flow experiments showed the opposite situation. That is, vehicle follower control in general results in less energy consumption and less variation in merge element travel times. A simple FIFO merge algorithm gives the minimum merge travel time for all the input flow situations tested for vehicle follower asynchronous merge. A priority algorithm can be used to decrease the average travel time on the priority path, but the nonpriority path shows a significant increase in travel time which results in an overall increase in merge travel time. The Chu* algorithm for quasi-synchronous merging proved to be effective, however as already noted, the detailed choice of merge synchronous merging than for asynchronous merging.

*Bibliography entries 10 and 11.

3.0 ALTERNATIVE OPERATIONAL CONTROL SYSTEM PERFORMANCE EVALUATION

The alternative operational control system evaluation is different from the preceding operational control subsystem analysis in that control strategy combinations are now to be evaluated in the context of an entire system. This second level of analysis consists of three evaluation studies. The first study, the alternative strategy evaluation, considers the system performance effects of alternative operational control strategies in the context of a single system deployment. The deployment used is a high-speed SGRT system with a grid network of moderate size and complexity. The second study, the alternative mechanization evaluation, compares the software and hardware mechanizations of the alternative control strategies in the context of the same baseline system deployment. The third and last study, the entrainment capability evaluation, evaluates the dynamic system performance effects of operational entrainment capabilities using the same baseline system deployment.

3.1 ALTERNATIVE STRATEGY EVALUATION

The objective of the alternative strategy evaluation is to evaluate three alternative operational control strategy combinations in the context of a single baseline system deployment. As proposed in the AGT System Analysis Requirements and Plan Volume I — Requirements [12], the three control combinations consist of asynchronous longitudinal control with non-deterministic dispatch, synchronous longitudinal control with deterministic dispatch, and quasi-synchronous control with quasi-deterministic dispatch. The vehicle control and headway protection pair and merge strategy for use in each control combination was chosen based upon the subsystem analysis of the previous sections. Before the alternative strategies can be evaluated, a baseline system must be chosen. The system used is based upon the GRT 2 representative system deployment but requires several modifications.

3.1.1 System Deployment Reconfiguration

No single system of the representative system deployments covered in the System Trade-Off Analysis Requirements and Plan Volume I — Requirements satisfies the criteria to serve as a baseline system for the alternative operational control system performance evaluation. The criteria are that: the system should have sufficient operational switching to fully exercise the operational control capabilities, the system should use relatively small vehicles and off-line stations to allow the short headways necessary to present a realistic test case, and finally, the system's demand and network description must have been completed prior to the operational control evaluation study.

It was decided to reconfigure GRT 2 to be suitable for the alternative operational control system performance evaluation. The demand developed for GRT 2 is documented in the Representative Application Areas for AGT report[2]. Specifically, the a.m. peak period demand from 6:30 to 8:30 a.m. was used in this alternative operational control system performance evaluation. This consists of the peak hour plus a half hour before and after the peak hour. The preceding half hour allows for system start up and the following half hour may be used to observe any dissipation of queues. In general, statistics were collected over the peak hour from 7 to 8 a.m. The nominal GRT 2 system has on-line stations and uses an IGRT vehicle. This is changed to off-line stations and SGRT vehicles of 17 passenger capacity as analyzed in the previous subsystem analyses.

The station locations and basic network developed for GRT 2 was used with the addition of several crossovers. The crossovers allow greater flexibility of vehicle path selection and alter the GRT 2 network which is basically a line-haul network to have more grid network characteristics. The network is illustrated in Figure 3-1. The numbered boxes correspond to off-line stations. The numbered circles are network nodes. A copy of the network file is given in Table 3-1. Four data items are given for each network link, in order they are: upstream node number, station/guideway identifier, downstream node number, and link length. The identifier is 1 if a station is associated with the link, and 0 otherwise.

The station configuration used throughout the analysis is shown in Figure 3-2. The station input ramp has capacity 3, the input queue has capacity 20, each of four docks has capacity 3, each of four output queues has capacity 20, and the output ramp has capacity 3. Also included in the station but only partially illustrated because its full connectivity is difficult to illustrate is a storage area of capacity 20. The storage is connected so that vehicles may come from the input ramp or from any of the docks and also so that vehicles may leave storage to go to the input queue or to any of the output queues. The high capacities were necessary to allow proper operation of the synchronous and quasi-synchronous simulation which will be discussed later. Less capacity is possible in some cases, in particular for the asynchronous simulation, but a detailed station design was not performed.

The deboard time was set to a constant 8 seconds plus 1 second per deboarding passenger. The board time was given the same parametric representation as the deboard time. The service policy specified for all simulations was multi-party demand responsive with the fleet size chosen by the input processor based upon the peak level of demand and a user input estimated vehicle load factor. Vehicle diversion from the guideway to board trips waiting at intermediate stations which were not the vehicle destination was enabled.

For demand responsive service, empty vehicle management policies must be specified. Empty vehicles were obtained by using the earliest available option which first looks on input ramps of the station, then looks in local station storage, and then for the earliest expected arrival allowing a 250 second maximum delay. Once a vehicle emptied it was dispersed, first, according to the current need option and secondly, to local storage.

A guideway velocity of 25 m/s was specified on all guideway links. Travel times were specified within the station to be 5.7 seconds on the input ramp, 3 seconds on the input queue, 3 seconds on the output queue, 6.1 seconds on the output ramp, and 13

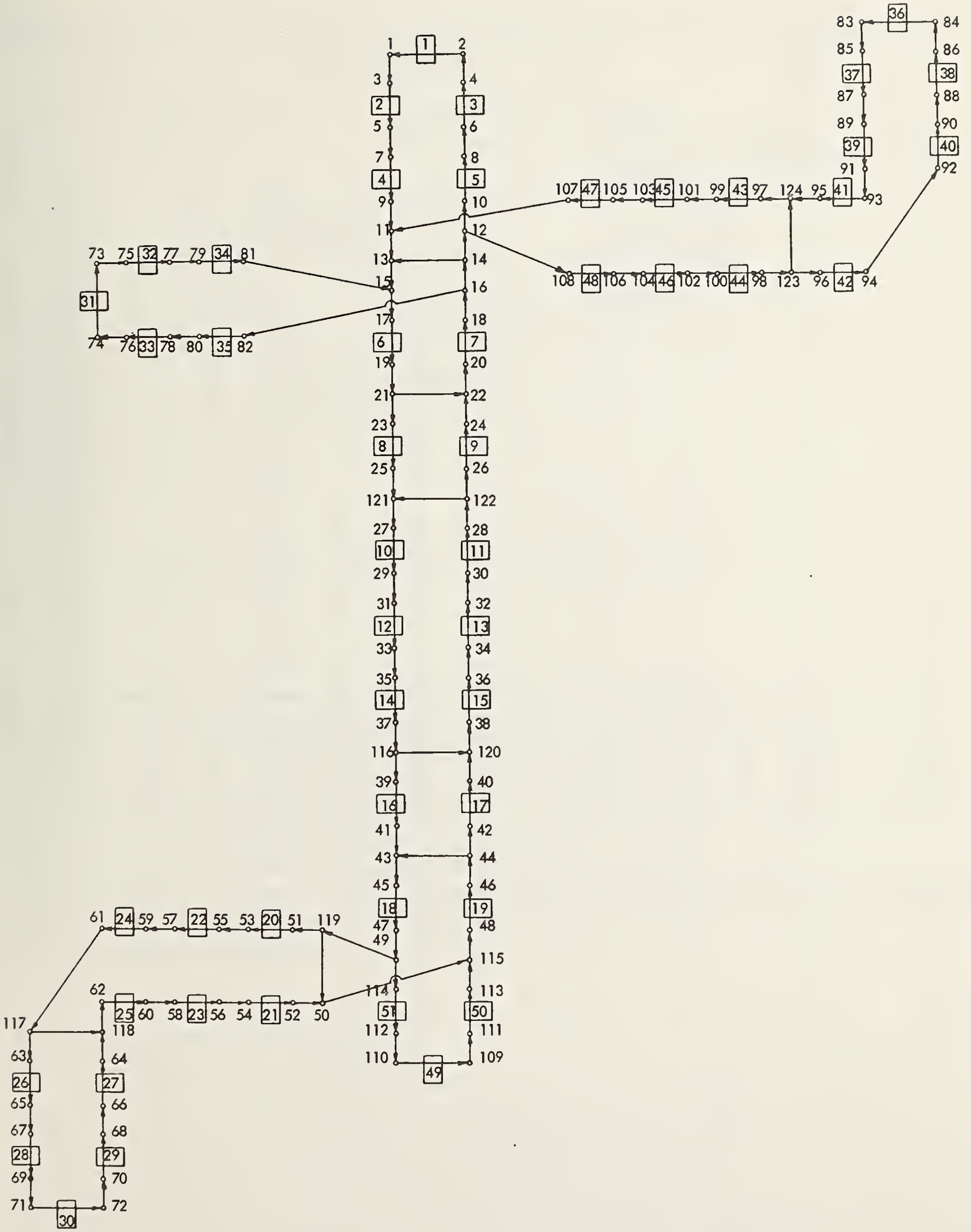


FIGURE 3-1. NETWORK FOR ALTERNATIVE OPERATIONAL CONTROL SYSTEM PERFORMANCE EVALUATION

TABLE 3-1. NETWORK FILE

AGT.IANDD.NETWORK(EOCSE)'

2	1	1	250	1	0	3	4362	4	0	2	4362	3	1	5	250
6	1	4	250	5	0	7	3355	8	0	6	3355	7	1	9	250
10	1	8	250	9	0	11	969	12	0	10	969	11	0	13	719
14	0	12	719	13	0	15	250	16	0	14	250	15	0	17	250
18	0	16	250	17	1	19	250	20	1	18	250	19	0	21	250
22	0	20	250	21	0	23	1375	24	0	22	1375	23	1	25	250
26	1	24	250	25	0	121	631	28	0	122	250	27	1	29	250
30	1	28	250	29	0	31	949	32	0	30	949	31	1	33	250
34	1	32	250	33	0	35	529	36	0	34	529	35	1	37	250
38	1	36	250	37	0	116	250	40	0	120	822	39	1	41	250
42	1	40	250	41	0	43	649	44	0	42	649	43	0	45	250
46	0	44	250	45	1	47	250	48	1	46	250	47	0	49	250
50	0	115	250	49	0	119	250	52	0	50	1709	51	1	53	250
54	1	52	250	53	0	55	1115	56	0	54	1115	55	1	57	250
58	1	56	250	57	0	59	1115	60	0	58	1115	59	1	61	250
62	1	60	250	61	0	117	250	64	0	118	879	63	1	65	250
66	1	64	250	65	0	67	2292	68	0	66	2292	67	1	69	250
70	1	68	250	69	0	71	1971	72	0	70	1971	71	1	72	250
74	1	73	250	73	0	75	2645	76	0	74	2645	75	1	77	250
78	1	76	250	77	0	79	2668	80	0	78	2668	79	1	81	250
82	1	80	250	81	0	15	4190	16	0	82	4190	115	0	48	250
84	1	83	250	83	0	85	3154	86	0	84	3154	85	1	87	250
88	1	86	250	87	0	89	1874	90	0	88	1874	89	1	91	250
92	1	90	250	91	0	93	1763	94	0	92	1763	93	1	95	250
96	1	94	250	95	0	124	1649	98	0	123	250	97	1	99	250
100	1	98	250	99	0	101	352	102	0	100	352	101	1	103	250
104	1	102	250	103	0	105	899	106	0	104	899	105	1	107	250
108	1	106	250	107	0	11	1868	12	0	108	1868	122	0	121	250
110	1	109	250	109	0	111	1454	112	0	110	1454	111	1	113	250
114	1	112	250	113	0	115	279	49	0	114	279	117	0	63	879
118	0	62	250	117	0	118	250	119	0	51	1709	119	0	50	250
44	0	43	250	116	0	39	822	120	0	38	250	122	0	26	631
121	0	27	250	21	0	22	250	14	0	13	250	123	0	96	1649
124	0	97	250	123	0	124	250	116	0	120	250				

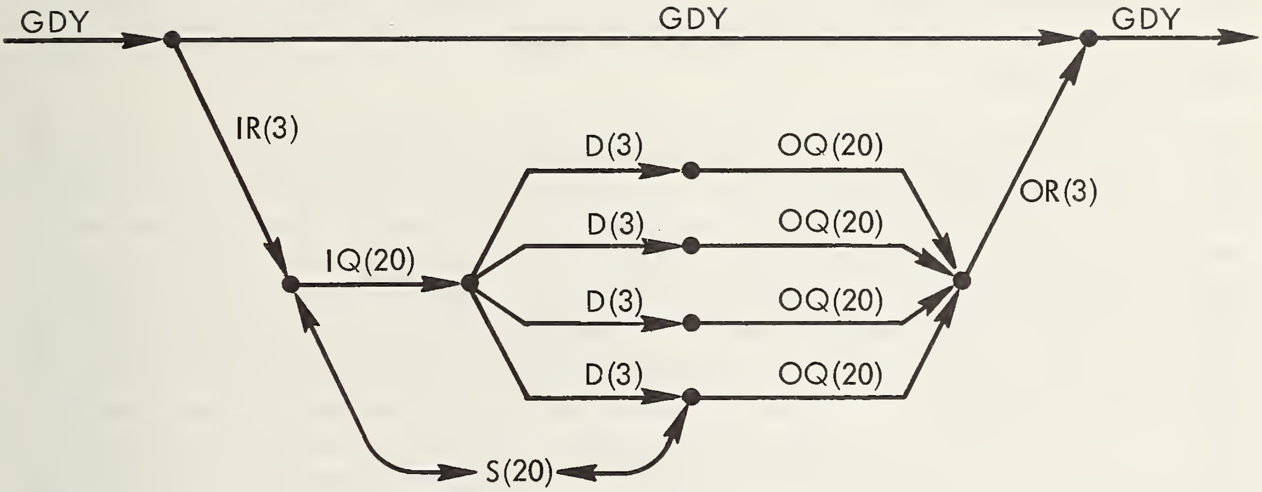


FIGURE 3-2. OFF-LINE STATION CONFIGURATION

seconds to and from storage. The input and output ramp travel times were chosen to be the time lost in decelerating to a stop and accelerating back to linespeed respectively. As given in Table 2-7, the time and distance necessary for the SGRT vehicle to accelerate to cruise velocity following the acceleration profile defined by Equations 2-79 and 2-80 is 15.15 seconds and 225.6 metres. This is 6.1 seconds longer than the time to cruise the same distance. The extra deceleration travel time of 5.7 seconds is found in a similar manner. This method allows the entire distance between stations to be represented as normal guideway. However, since all operational control alternatives are to be evaluated within the context of one network and station configuration, the exact details of either are not of extreme importance.

3.1.2 Asynchronous Control Evaluation

The operational control combination of asynchronous longitudinal control and non-deterministic dispatch strategy is evaluated in this section. SGRT vehicles are associated with 3 to 15 second headways. To approach the lower end of this range, a combination of continuous vehicle follower vehicle control and moving block headway protection is assumed. As determined by the subsystem parametric analysis of minimum operational headway and DOCM simulations, a headway of 5.3 seconds is feasible for the vehicle of assumed characteristics. This headway was specified on all guideway links. Since FIFO merge was determined by the subsystem analysis to be generally preferred to priority, it was specified for all system merges. The cruise velocity was set to a mean of 25 m/s on all guideway links with a standard deviation of 0.5 m/s. The variable block vehicle position regulation scheme was specified along with a vehicle length of 5 metres, thus allowing vehicles to queue with a nose to nose spacing of 5 metres as an approximation to the actual continuous vehicle control with moving block headway protection combination.

3.1.2.1 Estimated Load Factor Sensitivity Evaluation - As already stated, the input processor of the DESM was allowed to pick the vehicle fleet size and determine the initial placement of vehicles. The fleet size was based upon the peak hour demand level and a user input estimated vehicle load factor. A series of experiments was performed to determine a reasonable value for this factor. The results are summarized in Table 3-2. The fleet size is seen to be linearly related to the reciprocal of the estimated load factor. All the measures listed either increase or decrease monotonically as the load factor varied, with the single exception of average trip travel speed which peaked for a load factor of 0.40. This is related to a situation of significantly increasing queues for a load factor less than 0.45. The general result however is that system performance in terms of passenger service measures improves as the fleet size is increased. The fleet size which would be used in actual practice is thus a trade-off between system cost and performance. An estimated load factor value of 0.45 was chosen as giving reasonable system performance and was applied in all of the analyses.

Several of the reported statistics need elaboration. The number of passengers served is the number of passengers allowed to begin the board event during the statistical interval. The average maximum passenger delay demand to dispatch is the average over the hour of the individual longest delays in dispatching which occurred in each 3 minute statistical interval. Thus this statistic is based upon only twenty passengers. The low value of average passenger delay indicates good service, but a few passengers do experience long delays in dispatching. This points out an inability of the demand responsive service algorithm to guarantee an empty vehicle arrival within a given time as is possible with scheduled service using fixed routes. The average delay for station merge is the average of the time between being ready to launch and actually launching. It is a measure of time to find a synchronous slot, a quasi-synchronous window, or time delay in station entrainment. The average number of passengers waiting per station is the average over all samples of the total number of passengers waiting divided by the number of stations in the system. The maximum number of passengers waiting is the maximum over all samples of the sum of passengers waiting in all stations. The maximum number of vehicles in a queue is the maximum over all samples of the maximum number of vehicles in any one queue on a single guideway link. The average number of queued vehicles is the average over all samples of the current number of queued vehicles. The percent guideway utilization is the quotient of the number of vehicles entering a link and the number of headway times (the maximum possible number of vehicles) during the hour long period. The specific link is that between nodes number 15 and 17 of Figure 3-1. This link was chosen because it is one of the most heavily utilized links in the network.

3.1.2.2. Demand Sensitivity Evaluation — The purpose of a demand sensitivity evaluation in the context of the alternative operational control system performance evaluation is to observe the ability of a given operational control combination to handle increased demand situations requiring an increase in the fleet size. The demand level was increased to 150 and 200 percent of the nominal demand. The input processor was again used to calculate the fleet size assuming the same estimated vehicle load factor of 0.45.

TABLE 3-2. ESTIMATED LOAD FACTOR SENSITIVITY EVALUATION FOR ASYNCHRONOUS CONTROL

Run Identification	AA(2270)	AA(2273)	AA(2247)	AA(2278)	AA(2282)	
Control Type	Asyn	Asyn	Asyn	Asyn	Asyn	
Estimated Load Factor	0.35	0.40	0.45	0.50	0.55	
Demand (%)	100	100	100	100	100	
Number Of Vehicles	286	251	223	200	182	
Number Of Passengers Arriving	9,686	9,686	9,686	9,686	9,686	
Number Of Passengers Served	9,644	9,632	9,528	9,400	9,296	
Average Trip Time Demand To Completion (s)	460.2	480.7	486.9	504.9	516.6	
Average Trip Travel Speed (m/s)	19.72	19.74	19.61	19.55	19.28	
Average Number Passengers Per Revenue Vehicle	5.58	6.00	6.27	6.67	7.18	
Average Proportion Vehicles In Revenue Service	0.644	0.677	0.725	0.745	0.761	
Average Passenger Distance Per Vehicle Distance	3.920	4.354	4.807	5.185	5.746	
Average Passenger Delay Demand To Dispatch (s)	79.4	104.1	109.2	132.3	140.6	
Average Maximum Passenger Delay Demand To Dispatch (s)	386.7	571.7	732.0	977.1	1,299.7	
Average Delay For Station Merge (s)	0.0	0.0	0.0	0.0	0.0	
Average Number Of Passengers Waiting Per Station	3.30	4.56	5.20	7.20	8.27	
Maximum Number Of Passengers Waiting	324	440	510	582	606	
Maximum Vehicles In A Queue	7	6	5	5	5	
Average Number Queued Vehicles	4.00	3.03	1.89	1.63	1.24	
Percent Guideway Utilization	69.49	64.04	58.89	52.71	48.29	

The results of the demand sensitivity evaluation for the control case of asynchronous longitudinal control and non-deterministic dispatch are summarized in Table 3-3. The demand was generated using a deterministic demand generation procedure exterior to the DESM input processor and is thus free of random effects attributable to the random number seed. However, fractional trips for any origin destination pair are ignored. Thus the number of passengers arriving are not precisely in agreement with the 150 and 200 percent ideal increases. (Note, there are 2,550 legitimate origin-destination pairs to which trips may be assigned.) The fleet size was increased by exactly 150 and 200 percent. Thus the passenger arrivals per fleet vehicle is 1.8 percent greater than the nominal for the 150 percent demand case and is 2.5 percent greater than the nominal for the 200 percent demand case. This difference could be expected to produce a very small change in performance.

The maximum and average amount of queueing is seen to dramatically increase with demand. However system performance is seen to remain approximately constant because of increased levels of link utilization. An especially interesting result is that the average passenger delay and average maximum passenger delay statistics improve for the 150 percent demand case. The reason for this result is not known and requires more extensive study. A possible explanation is that the 17 passenger capacity vehicle is more suited for the 150 percent of demand case, and possibly a larger fleet of smaller vehicles but same total fleet capacity would better serve the 100 percent nominal demand case.

As already mentioned in Section 3.1.1, the station design was chosen to allow proper system operation in the case of synchronous control. Asynchronous studies had already been made for a different station layout when the adverse effect on synchronous control was first discovered. The station originally used for asynchronous simulations is shown in Figure 3-3. As shown, two parallel input queue, dock, and output queue paths were specified. The queue capacities are drastically less than the station of Figure 3-2. The storage link of twenty vehicle capacity is connected in a similar manner as before with the illustration not showing the full details of the connectivity. The asynchronous control results obtained using the station of Figure 3-3 are presented in Table 3-4 for 100, 110, 150, and 200 percent of nominal demand. The change in station configuration was the only difference from the system reported in Table 3-3. There are relatively minor differences in detailed results and the trends are all the same. The case of 110 percent of demand shows the same trend toward improved system performance in terms of passenger dispatch delays as shown by the 150 percent of demand.

3.1.2.3 Failure Response Evaluation - The response of the asynchronous controlled system to a link failure is presented in this section. Throughout the availability analysis of the representative system deployments a link failure time of 600 seconds has been used. This same time duration of failure was used in this evaluation. A simulation of the nominal system case of asynchronous control was made with the only difference being that the network link between nodes number 15 and 17 was failed for 600 seconds commencing at 7 a.m., that is, at the beginning of the peak hour over which statistics were gathered. The failure consisted of allowing no vehicles to exit the particular link. As seen from the

TABLE 3-3. DEMAND SENSITIVITY EVALUATION FOR ASYNCHRONOUS CONTROL

Run Identification	AA(2247)	AA(2252)	AA(2255)			
Control Type	Asyn	Asyn	Asyn			
Estimated Load Factor	0.45	0.45	0.45			
Demand (%)	100	150	200			
Number Of Vehicles	223	335	447			
Number Of Passengers Arriving	9,686	14,812	19,896			
Number Of Passengers Served	9,528	14,686	19,166			
Average Trip Time Demand To Completion (s)	486.9	498.0	611.7			
Average Trip Travel Speed (m/s)	19.61	18.44	14.89			
Average Number Passengers Per Revenue Vehicle	6.27	6.87	8.05			
Average Proportion Vehicles In Revenue Service	0.725	0.728	0.769			
Average Passenger Distance Per Vehicle Distance	4.807	5.108	6.046			
Average Passenger Delay Demand To Dispatch (s)	109.2	88.5	123.3			
Average Maximum Passenger Delay Demand To Dispatch (s)	732.0	485.7	757.6			
Average Delay For Station Merge (s)	0.0	0.0	0.0			
Average Number Of Passengers Waiting Per Station	5.20	5.72	12.51			
Maximum Number Of Passengers Waiting	510	564	970			
Maximum Vehicles In A Queue	5	21	66			
Average Number Queued Vehicles	1.89	19.52	85.99			
Percent Guideway Utilization	58.89	87.74	98.64			

TABLE 3-4. DEMAND SENSITIVITY EVALUATION FOR ASYNCHRONOUS CONTROL USING ALTERNATE STATION

Run Identification	AA(5165)	G(4727)	AA(5170)	AA(5172)		
Control Type	Asyn	Asyn	Asyn	Asyn		
Estimated Load Factor	0.45	0.45	0.45	0.45		
Demand (%)	100	110	150	200		
Number Of Vehicles	223	245	335	447		
Number Of Passengers Arriving	9,686	10,748	14,812	19,896		
Number Of Passengers Served	9,532	10,682	14,704	19,182		
Average Trip Time Demand To Completion (s)	486.1	480.7	496.7	612.5		
Average Trip Travel Speed (m/s)	19.55	19.37	18.29	14.88		
Average Number Passengers Per Revenue Vehicle	6.23	6.64	6.94	7.84		
Average Proportion Vehicles In Revenue Service	0.727	0.709	0.726	0.768		
Average Passenger Distance Per Vehicle Distance	4.743	4.917	5.138	5.910		
Average Passenger Delay Demand To Dispatch (s)	114.1	95.2	84.9	142.0		
Average Maximum Passenger Delay Demand To Dispatch (s)	849.5	502.7	401.9	833.3		
Average Delay For Station Merge (s)	0.0	0.0	0.0	0.0		
Average Number Of Passengers Waiting Per Station	5.65	4.58	5.42	14.53		
Maximum Number Of Passengers Waiting	526	442	558	1,216		
Maximum Vehicles In A Queue	5	6	15	52		
Average Number Queued Vehicles	2.24	3.42	17.41	90.96		
Percent Guideway Utilization	58.30	67.72	88.78	98.20		

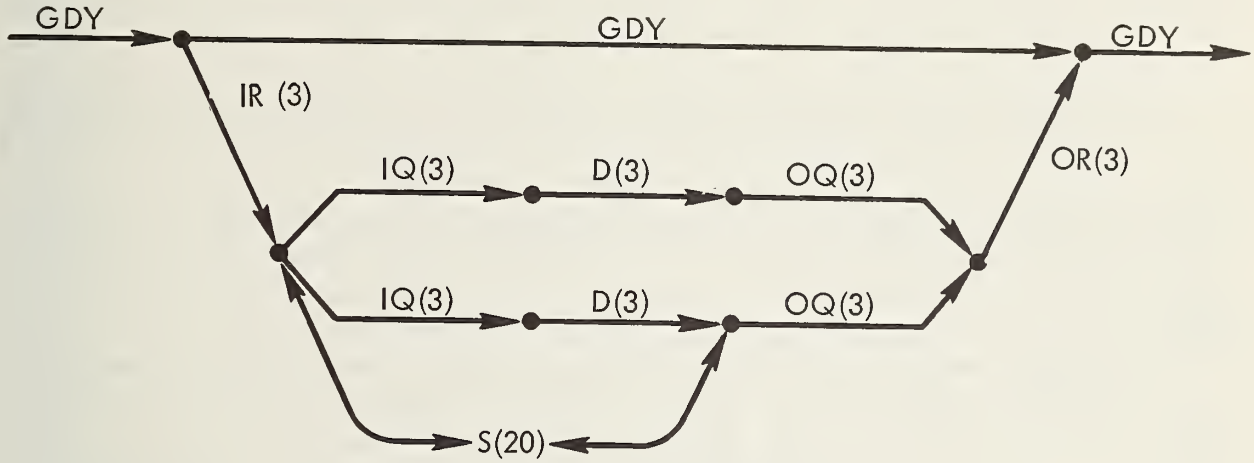


FIGURE 3-3. ALTERNATE STATION CONFIGURATION

network illustration of Figure 3-1, the failed link is just downstream of the merges of three branches of incoming vehicle flow and was chosen because a blockage of this link would have a direct effect on several other links.

The results of both the nominal case and the case with a failure are summarized in Table 3-5. The statistics show a decrease in the level of service but no drastic effects. Notice that the average number of queued vehicles is about half the number reported for the 150 percent of nominal demand simulation and thus is not excessive.

3.1.3 Synchronous Control Evaluation

The operational control combination of synchronous longitudinal control and deterministic dispatch strategy is evaluated in this section. The same SGRT vehicle of 17 passenger capacity as used in the asynchronous control evaluation was used. The subsystem analysis showed that a 6 second headway is feasible for vehicles of the given characteristics so this was set as the headway time. The fixed block vehicle position regulation scheme must be specified with synchronous control. Thus in the event of a queueing situation, the vehicles queue one headway distance apart. The cruise velocity was set to exactly 25 m/s on all guideway links. Initial simulations were made using the station configuration of Figure 3-3. The results indicated a considerable amount of guideway queuing, a condition not expected for synchronous control. The cause of the queueing was determined to be a situation involving first station number 6,

TABLE 3-5. FAILURE RESPONSE EVALUATION FOR ASYNCHRONOUS CONTROL

Run Identification	AA(2247)	AA(1817)				
Control Type	Asyn	Asyn				
Estimated Load Factor	0.45	0.45				
Demand (%)	100	100				
Failure	No	Yes				
Number Of Vehicles	223	223				
Number Of Passengers Arriving	9,686	9,686				
Number Of Passengers Served	9,528	9,516				
Average Trip Time Demand To Completion (s)	486.9	553.1				
Average Trip Travel Speed (m/s)	19.61	18.47				
Average Number Passengers Per Revenue Vehicle	6.27	6.62				
Average Proportion Vehicles In Revenue Service	0.725	0.722				
Average Passenger Distance Per Vehicle Distance	4.807	5.049				
Average Passenger Delay Demand To Dispatch (s)	109.2	148.8				
Average Maximum Passenger Delay Demand To Dispatch (s)	732.0	822.8				
Average Delay For Station Merge (s)	0.0	0.0				
Average Number Of Passengers Waiting Per Station	5.20	7.27				
Maximum Number Of Passengers Waiting	510	748				
Maximum Vehicles In A Queue	5	24				
Average Number Queued Vehicles	1.89	9.77				
Percent Guideway Utilization	58.89	53.29				

and then spreading to other stations close to station 6 in which vehicles exited the guideway for the station and then experienced long delays in reentering the guideway. When all links within a station are at specified maximum capacity, a vehicle commanded to enter the station will queue on the guideway upstream of the station diverge point. If this situation occurs under the asynchronous or quasi-synchronous control option, the vehicle simply continues along the network and exits to another station at the first opportunity. Passengers who desired exit at the bypassed station are then assigned an extra travel time penalty which for this investigation was set at 300 seconds. Bypassing a station under synchronous control would immediately result in schedule disruptions because of deterministic dispatch. Thus for synchronous control only, the vehicle queues outside the station with the hope that station entry can be gained before the arrival of another vehicle. The capacity of stations was increased in several steps until the station illustrated in Figure 3-2 was obtained and found to eliminate any guideway queueing. This general station configuration has greater capacity than needed at all but a few stations during the a.m. peak period. Further station design was not performed.

3.1.3.1 Demand Sensitivity Evaluation - The results of system simulations at 100, 150 and 200 percent of nominal a.m. peak demand are summarized in Table 3-6. The fleet size is seen to be about 2.7 percent larger than the fleet size for the asynchronous case. This is because of an increase in the average trip distance attributable to the specification of fixed guideway blocks as required for synchronous and quasi-synchronous control. All guideway links are rounded off to integer lengths of 150 metres, corresponding to one slot length. The total length of guideway for the synchronous and quasi-synchronous control case is 115.2 kilometres and is 112.3 kilometres for the case of asynchronous control. This increase in guideway distance is a random effect and is not systematically related to the control choice.

The results show that system performance significantly degraded as demand increased. Notice that queuing occurred for the 200 percent of nominal demand simulation. This was investigated and determined to be the same situation as mentioned earlier. One station became full of vehicles about half way through the statistical hour and caused vehicles to queue on the guideway upstream of the station. Thus, the system was not operating in a true synchronous manner over the entire network for this one case, and performance results may be slightly different had the operation been purely synchronous.

As already mentioned, all of the experiments in the alternative operational control system performance evaluation were made using multi-party demand responsive service with diversions allowed to board trips at stations which are along the vehicle path but at which it would not have normally stopped. This option was used because a 17 passenger vehicle is somewhat large for pure multi-party demand responsive service. It was determined that this policy of diverting to intermediate stations causes inefficeint dispatching for both deterministic and quasi-deterministic dispatch policies. The reason is that the slot or merge reservation window assigned to a synchronous or quasi-synchronous vehicle at its time of launch is chosen to accommodate its initially planned station to station trip. However, if the vehicle diverts from its initially planned trip, it must be assigned a new slot or merge reservation window before it can return to the guideway.

TABLE 3-6. DEMAND SENSITIVITY AND DIVERSION SENSITIVITY EVALUATIONS FOR SYNCHRONOUS CONTROL

Run Identification	AA(2811)	AA(3742)	AA(1129)	AA(5898)		
Control Type	Syn	Syn	Syn	Syn		
Estimated Load Factor	0.45	0.45	0.45	0.45		
Demand (%)	100	150	200	100		
				No Diverge		
Number Of Vehicles	229	344	459	229		
Number Of Passengers Arriving	9,686	14,812	19,896	9,686		
Number Of Passengers Served	9,438	12,854	15,522	9,150		
Average Trip Time Demand To Completion (s)	555.6	666.9	827.0	573.0		
Average Trip Travel Speed (m/s)	16.73	13.66	11.04	18.52		
Average Number Passengers Per Revenue Vehicle	7.29	8.33	9.35	7.11		
Average Proportion Vehicles In Revenue Service	0.767	0.834	0.875	0.652		
Average Passenger Distance Per Vehicle Distance	5.387	6.574	7.511	4.558		
Average Passenger Delay Demand To Dispatch (s)	127.2	239.8	344.3	175.5		
Average Maximum Passenger Delay Demand To Dispatch (s)	830.8	1,596.1	2,246.8	1,044.5		
Average Delay For Station Merge (s)	11.16	16.84	18.16	8.46		
Average Number Of Passengers Waiting Per Station	4.74	18.14	40.81	9.20		
Maximum Number Of Passengers Waiting	426	2,012	4,480	706		
Maximum Vehicles In A Queue	0	0	16	0		
Average Number Queued Vehicles	0	0	10.3	0		
Percent Guideway Utilization	61.67	66.00	71.17	74.17		

The dispatch algorithm currently implemented is inefficient in this situation for two reasons. The first reason is that the unused portion of the reserved trip is not made available for the dispatching of other vehicles at the time of a diversion from the initially planned trip. The second reason for dispatch inefficiency is that obvious future diversions are ignored at the time of initial dispatch and a non-stop trip from origin to final destination is reserved. The first change, that of releasing unused reservation space, should be a relatively easy modification of the current algorithm, the second change, that of looking ahead for obvious diversions and scheduling a trip only as far as the first diversion, is a modification whose details are nonobvious.

An experiment was made in which diversions were not allowed. The results are also presented in Table 3-6 and should be compared with the previous results for 100 percent of nominal demand. The average delay for station merge decreased, indicating that the dispatch algorithm could find a trip slot more quickly. Also, average trip travel speed increased and percent guideway utilization significantly increased. However, average trip time increased because of a significant increase in average passenger delay between demand origination and dispatch. The conclusion is that the vehicles traveled with less difficulty through the network but that passengers were forced to wait longer in boarding a vehicle and from the passenger viewpoint the service was degraded. Based upon this result the use of vehicle diversions is justified.

3.1.3.2 Failure Response Evaluation - The response of the synchronously controlled system to a link failure is presented in this section. The failure is identical to the failure used in Section 3.1.2.3. Briefly, the exit of the guideway link between nodes number 15 and 17 is disabled for 600 seconds at the beginning of the one peak hour over which statistics are gathered. The summary results of the failure experiment and the nominal no failure case are presented in Table 3-7.

A significant amount of queueing did occur. It should be remembered that the maximum number of vehicles in a queue statistic is for any one link. In the case of this network with fixed block control, the largest possible queue on any link is 29 vehicles. Performance as measured for the hour was significantly but not drastically degraded. An interesting result is that a small increase occurred in the number of passengers allowed entry to vehicles. This was not expected and is probably a function of the fortuitous timing of random events.

3.1.4 Quasi-Synchronous Control Evaluation

The operational control combination of quasi-synchronous longitudinal control and quasi-deterministic dispatch strategy is evaluated in this section. The same 17 passenger SGRT vehicle as used in the previous evaluation is used. A 6 second headway was used with quasi-synchronous control during the subsystem analysis. The quasi-synchronous merge experiments were not completely successful at this headway. Specifically, a -4 slot maneuver caused a headway violation. Reconsideration of minimum operational headway showed that 6 seconds is very close to the minimum theoretical headway at a safety factor of 1.05 if a full stop is allowed in making a slot maneuver.

TABLE 3-7. FAILURE RESPONSE EVALUATION FOR SYNCHRONOUS CONTROL

Run Identification	AA(2811)	AA(3498)				
Control Type	Syn	Syn				
Estimated Load Factor	0.45	0.45				
Demand (%)	100	100				
Failure	No	Yes				
Number Of Vehicles	229	229				
Number Of Passengers Arriving	9,686	9,686				
Number Of Passengers Served	9,438	9,454				
Average Trip Time Demand To Completion (s)	555.6	631.6				
Average Trip Travel Speed (m/s)	16.73	15.61				
Average Number Passengers Per Revenue Vehicle	7.29	7.69				
Average Proportion Vehicles In Revenue Service	0.767	0.770				
Average Passenger Distance Per Vehicle Distance	5.387	5.833				
Average Passenger Delay Demand To Dispatch (s)	127.2	167.7				
Average Maximum Passenger Delay Demand To Dispatch (s)	830.8	835.3				
Average Delay For Station Merge (s)	11.16	11.93				
Average Number Of Passengers Waiting Per Station	4.74	6.92				
Maximum Number Of Passengers Waiting	426	748				
Maximum Vehicles In A Queue	0	28				
Average Number Queued Vehicles	0	16.33				
Percent Guideway Utilization	61.67	59.83				

However, since a -3 slot maneuver was successfully made in the subsystem merge experiments at a 6 second headway, those conditions were taken as inputs to the quasi-synchronous system level experiments. Thus the headway is specified as 6 seconds, the maximum slot maneuver is 3 slots, and no slot advance is allowed. Fixed block vehicle position regulation is specified and the cruise velocity is 25 m/s everywhere on the guideway. The same slight increase in guideway length described with respect to the synchronous evaluation again occurred.

3.1.4.1 Quasi-Deterministic Dispatch Parameter Evaluation - The two dispatch options specified in the two previous evaluations, that is, deterministic and non-deterministic, require no user input parameters. The option to be evaluated at this time, quasi-deterministic dispatch, requires two user input parameters. One parameter specifies the time length of the merge assignment window, and the other parameter is the threshold fraction to which the window may be filled with vehicles at the time of dispatch. For example, if the headway time is 6 seconds, the merge window is 24 seconds, and the threshold value is 0.75, only 3 vehicles could be assigned to any merge window even though the window is four headway times long.

The effect of varying both of these parameters has been investigated, and the results summarized in Table 3-8. Merge window lengths of 6, 12, 24, and 48 seconds and threshold values of 1.00, 0.75, and 0.50 were investigated. Since integer numbers of vehicles must be assigned, some combinations of these values are not possible. In general it is observed that a threshold value different from 1.00 has a severe effect on system performance, however it does drastically reduce the amount of on guideway queueing. The effect of a threshold of 0.75 is approximately the same as changing the system headway time to 8 seconds, and a threshold of 0.50 is approximately the same as a headway time of 12 seconds. All of the merge window widths with a threshold value of 1.00 have approximately equal performance. The case of a 24 second window with a threshold of 1.00, however, did minimize the average trip time and passenger delay times and for this reason was chosen to be the nominal parameter values for further quasi-synchronous evaluations.

3.1.4.2 Demand Sensitivity Evaluation - The results of system simulations at 100, 150, and 200 percent of the nominal a.m. peak demand are summarized in Table 3-9. The fleet sizes are identical to those used for the synchronous evaluation because the same network and thus trip distance modifications occurred. There is a significant but not catastrophic degradation of system performance as the demand increases.

3.1.4.3 Failure Response Evaluation - The response of the quasi-synchronously controlled system to the same link failure situation as used for the previous two failure response evaluations was determined. The performance is summarized in Table 3-10 along with the nominal no failure performance. Performance degraded but not drastically. Again the maximum number of vehicles in a queue is for any one link and cannot exceed 29 vehicles for this network.

TABLE 3-8 (1 of 2). QUASI-DETERMINISTIC DISPATCH PARAMETER EVALUATION

Run Identification	AA(4775)	AA(4788)	AA(4799)	AA(5732)	AA(4812)	AA(4815)
Control Type	Quasi-Syn	Quasi-Syn	Quasi-Syn	Quasi-Syn	Quasi-Syn	Quasi-Syn
Estimated Load Factor	0.45	0.45	0.45	0.45	0.45	0.45
Demand (%)	100	100	100	100	100	100
Merge Window (s)/Threshold	6/1.00	12/1.00	12/0.50	24/1.00	24/0.75	24/0.50
Number Of Vehicles	229	229	229	229	229	229
Number Of Passengers Arriving	9,686	9,686	9,686	9,686	9,686	9,686
Number Of Passengers Served	9,400	9,420	6,828	9,586	8,906	6,382
Average Trip Time Demand To Completion (s)	572.3	574.2	830.3	551.3	615.4	858.6
Average Trip Travel Speed (m/s)	16.83	16.69	10.86	17.68	15.37	10.68
Average Number Passengers Per Revenue Vehicle	7.21	7.17	8.19	6.96	7.69	7.67
Average Proportion Vehicles In Revenue Service	0.755	0.767	0.876	0.730	0.810	0.872
Average Passenger Distance Per Vehicle Distance	5.397	5.435	7.532	5.254	5.978	7.418
Average Passenger Delay Demand To Dispatch (s)	140.0	148.4	363.2	134.3	195.8	432.2
Average Maximum Passenger Delay Demand To Dispatch (s)	758.4	891.2	1,891.0	687.6	1,139.9	1,912.8
Average Delay For Station Merge (s)	9.01	8.96	29.37	6.91	13.83	30.60
Average Number Of Passengers Waiting Per Station	5.73	5.87	25.4	5.51	9.70	31.14
Maximum Number Of Passengers Waiting	564	520	2,974	620	942	3,414
Maximum Vehicles In A Queue	7	8	0	9	2	1
Average Number Queued Vehicles	0.38	0.87	0	0.60	0.04	0.00
Percent Guideway Utilization	61.17	61.50	30.50	62.00	48.67	28.00

TABLE 3-8 (2 of 2). QUASI-DETERMINISTIC DISPATCH PARAMETER EVALUATION

Run Identification	AA(4818)	AA(4823)	AA(4829)			
Control Type	Quasi-Syn	Quasi-Syn	Quasi-Syn			
Estimated Load Factor	0.45	0.45	0.45			
Demand (%)	100	100	100			
Merge Window(s)/Threshold	48/1.00	48/0.75	48/0.50			
Number Of Vehicles	229	229	229			
Number Of Passengers Arriving	9,686	9,686	9,686			
Number Of Passengers Served	9,354	8,522	6,436			
Average Trip Time Demand To Completion (s)	588.6	678.6	858.4			
Average Trip Travel Speed (m/s)	16.24	13.96	10.77			
Average Number Passengers Per Revenue Vehicle	7.36	7.92	8.11			
Average Proportion Vehicles In Revenue Service	0.766	0.822	0.857			
Average Passenger Distance Per Vehicle Distance	5.478	6.398	7.499			
Average Passenger Delay Demand To Dispatch (s)	141.5	248.8	384.3			
Average Maximum Passenger Delay Demand To Dispatch (s)	743.5	1,247.9	1,823.3			
Average Delay For Station Merge (s)	8.12	17.85	32.94			
Average Number Of Passengers Waiting Per Station	6.06	12.81	29.96			
Maximum Number Of Passengers Waiting	506	1,332	3,332			
Maximum Vehicles In A Queue	9	3	2			
Average Number Queued Vehicles	0.51	0.06	0.01			
Percent Guideway Utilization	60.83	45.00	30.50			

TABLE 3-9. DEMAND SENSITIVITY EVALUATION FOR QUASI-SYNCHRONOUS CONTROL

Run Identification	AA(5732)	AA(1136)	AA(1140)			
Control Type	Quasi-Syn	Quasi-Syn	Quasi-Syn			
Estimated Load Factor	0.45	0.45	0.45			
Demand (%)	100	150	200			
Merge Window(s)/Threshold	24/1.00	24/1.00	24/1.00			
Number Of Vehicles	229	344	459			
Number Of Passengers Arriving	9,686	14,812	19,896			
Number Of Passengers Served	9,586	13,330	16,450			
Average Trip Time Demand To Completion (s)	551.3	643.8	797.2			
Average Trip Travel Speed (m/s)	17.68	14.07	11.13			
Average Number Passengers Per Revenue Vehicle	6.96	8.54	9.64			
Average Proportion Vehicles In Revenue Service	0.730	0.797	0.849			
Average Passenger Distance Per Vehicle Distance	5.254	6.591	7.421			
Average Passenger Delay Demand To Dispatch (s)	134.3	184.9	268.0			
Average Maximum Passenger Delay Demand To Dispatch (s)	687.6	1,493.0	1,797.1			
Average Delay For Station Merge (s)	6.91	11.57	12.26			
Average Number Of Passengers Waiting Per Station	5.51	13.69	29.59			
Maximum Number Of Passengers Waiting	620	1,606	3,558			
Maximum Vehicles In A Queue	9	9	28			
Average Number Queued Vehicles	0.60	7.65	25.82			
Percent Guideway Utilization	62.00	68.50	79.67			

TABLE 3-10. FAILURE RESPONSE EVALUATION FOR QUASI-SYNCHRONOUS CONTROL

Run Identification	AA(5732)	AA(1898)				
Control Type	Quasi-Syn	Quasi-Syn				
Estimated Load Factor	0.45	0.45				
Demand (%)	100	100				
Failure	No	Yes				
Number Of Vehicles	229	229				
Number Of Passengers Arriving	9,686	9,686				
Number Of Passengers Served	9,586	9,494				
Average Trip Time Demand To Completion (s)	551.3	662.7				
Average Trip Travel Speed (m/s)	17.68	15.29				
Average Number Passengers Per Revenue Vehicle	6.96	7.86				
Average Proportion Vehicles In Revenue Service	0.730	0.765				
Average Passenger Distance Per Vehicle Distance	5.254	5.852				
Average Passenger Delay Demand To Dispatch (s)	134.3	188.3				
Average Maximum Passenger Delay Demand To Dispatch (s)	687.6	922.0				
Average Delay For Station Merge (s)	6.91	7.77				
Average Number Of Passengers Waiting Per Station	5.51	8.12				
Maximum Number Of Passengers Waiting	620	838				
Maximum Vehicles In A Queue	9	28				
Average Number Queued Vehicles	0.60	18.77				
Percent Guideway Utilization	62.00	57.17				

3.1.5 Comparative Control Evaluation

The results presented in the preceding sections on system performance for each of the three control combinations are compared in this section. The headway used in each of the previous evaluations was based upon subsystem studies documented in this report. However, since the asynchronous control combination was evaluated at 5.3 second headway while all the other control combinations were evaluated at 6.0 second headways, it was decided to see what difference in performance would result if the asynchronous control was also simulated at 6.0 second headway. Also, to eliminate any effect of the rounding of synchronous and quasi-synchronous guideway links to whole units of 150 metres, the network file used for this new asynchronous simulation was altered to agree with the synchronous network. The results of simulations at 100, 150, and 200 percent of nominal demand are presented in Table 3-11. If these results are compared to the original results summarized in Table 3-3, system performance is seen to vary only slightly at 100 and 150 percent of nominal demand and to vary more drastically at 200 percent of nominal demand. Several measures of performance, such as average passenger delay, decreased for the modified deployment, probably due to the minor increase in fleet size attributable to the increased network length. Thus two effects are seen, slight performance improvement at nominal demand due to increased fleet size and a significant decrease in performance as the demand passes approximately 150 percent of nominal demand. Notice also that the amount of queuing approximately doubled, due primarily to the change in headway.

The average trip time from initial demand to trip completion for the three control combinations is illustrated in Figure 3-4. The curve drawn for asynchronous control corresponds to the simulations of Section 3.1.2 using the appropriate headway. The performance level using the same headway as for the synchronous and quasi-synchronous is indicated by the vertical dashed lines. The performance level achieved for the failure situation, evaluated only for the nominal demand level, are the appropriately labeled single points. For normal operations, asynchronous control performed best and synchronous control performed worst but only slightly worse than quasi-synchronous control. For the failure situation, asynchronous control still performed best but now quasi-synchronous performed worse than synchronous. If demand and fleet size had continued to increase all three appear to approach approximately equal performance when equal headways are observed.

The results for average trip travel speed are given in Figure 3-5. These results are completely similar in ranking as the results for average trip travel time except that this measure is a reciprocal situation and a higher speed is more desirable.

The results for average passenger delay time from initial demand to dispatch are given in Figure 3-6. The asynchronous control combination performed best and the synchronous control combination performed worst, except at nominal demand where the synchronous control combination performed somewhat better than the quasi-synchronous control combination. When a failure was considered at the nominal demand level, the average passenger delays increased but the ranking was not altered. The modified asynchronous simulations still outperformed the quasi-synchronous and synchronous control combinations. As already mentioned, the slight increase in fleet allowed improved performance at nominal demand level. The interesting phenomenon of decreased delay for

TABLE 3-11. DEMAND SENSITIVITY EVALUATION FOR ASYNCHRONOUS CONTROL AT 6.0 SECOND HEADWAY AND MODIFIED NETWORK

Run Identification	AA(6290)	AA(6292)	AA(6296)			
Control Type	Asyn	Asyn	Asyn			
Estimated Load Factor	0.45	0.45	0.45			
Demand (%)	100	150	200			
Number Of Vehicles	229	344	459			
Number Of Passengers Arriving	9,686	14,812	19,896			
Number Of Passengers Served	9,612	14,682	18,300			
Average Trip Time Demand To Completion (s)	491.6	533.1	736.8			
Average Trip Travel Speed (m/s)	19.19	16.86	12.69			
Average Number Passengers Per Revenue Vehicle	6.47	7.29	8.79			
Average Proportion Vehicles In Revenue Service	0.716	0.734	0.785			
Average Passenger Distance Per Vehicle Distance	4.730	5.419	6.580			
Average Passenger Delay Demand To Dispatch (s)	96.3	86.1	166.0			
Average Maximum Passenger Delay Demand To Dispatch (s)	581.7	436.5	899.9			
Average Delay For Station Merge (s)	0.0	0.0	0.0			
Average Number Of Passengers Waiting Per Station	4.22	5.52	19.60			
Maximum Number Of Passengers Waiting	408	408	1,768			
Maximum Vehicles In A Queue	9	35	83			
Average Number Queued Vehicles	4.98	42.96	138.31			
Percent Guideway Utilization	74.00	96.33	100.00			

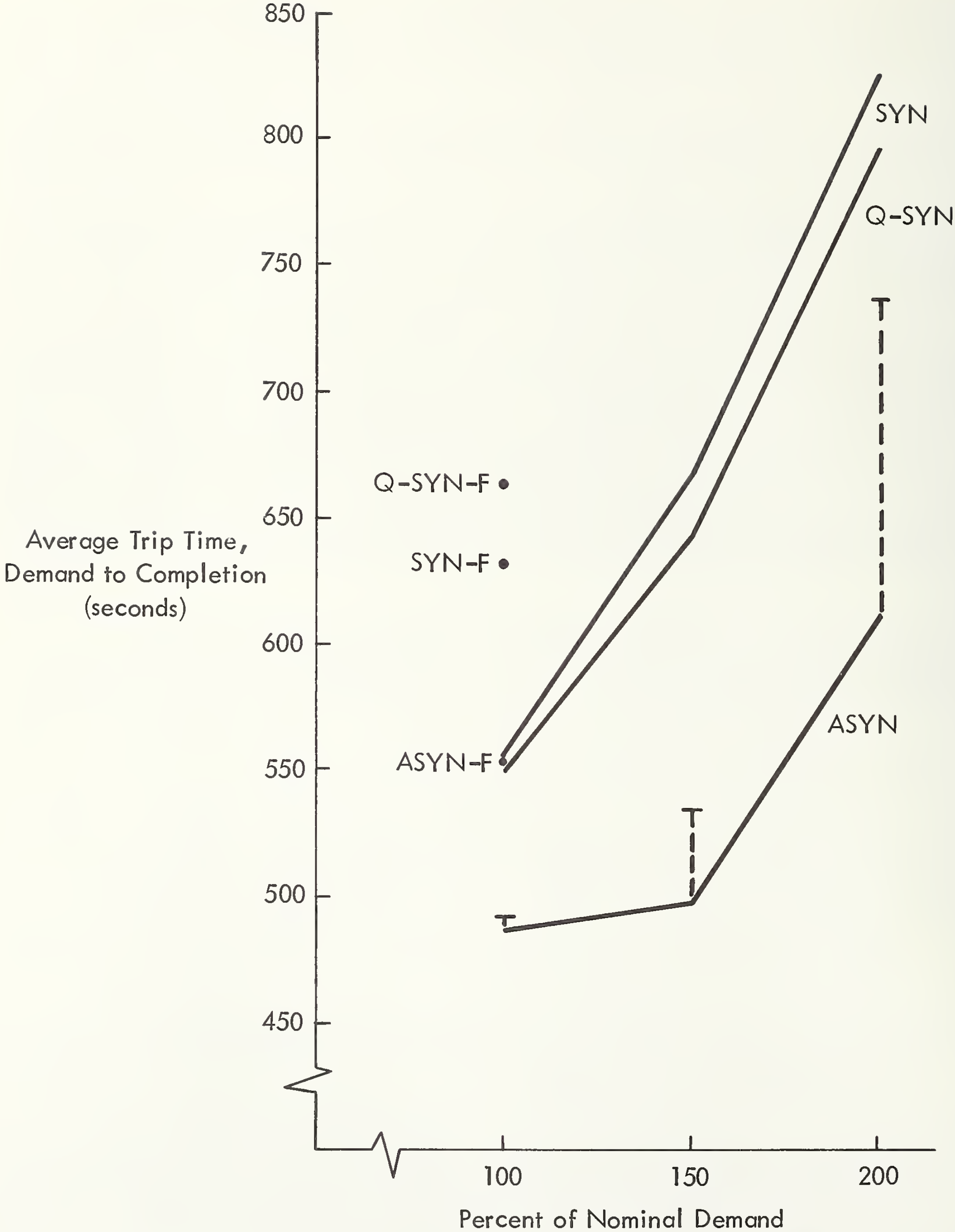


FIGURE 3-4. AVERAGE TRIP TIME FOR CONTROL COMBINATIONS

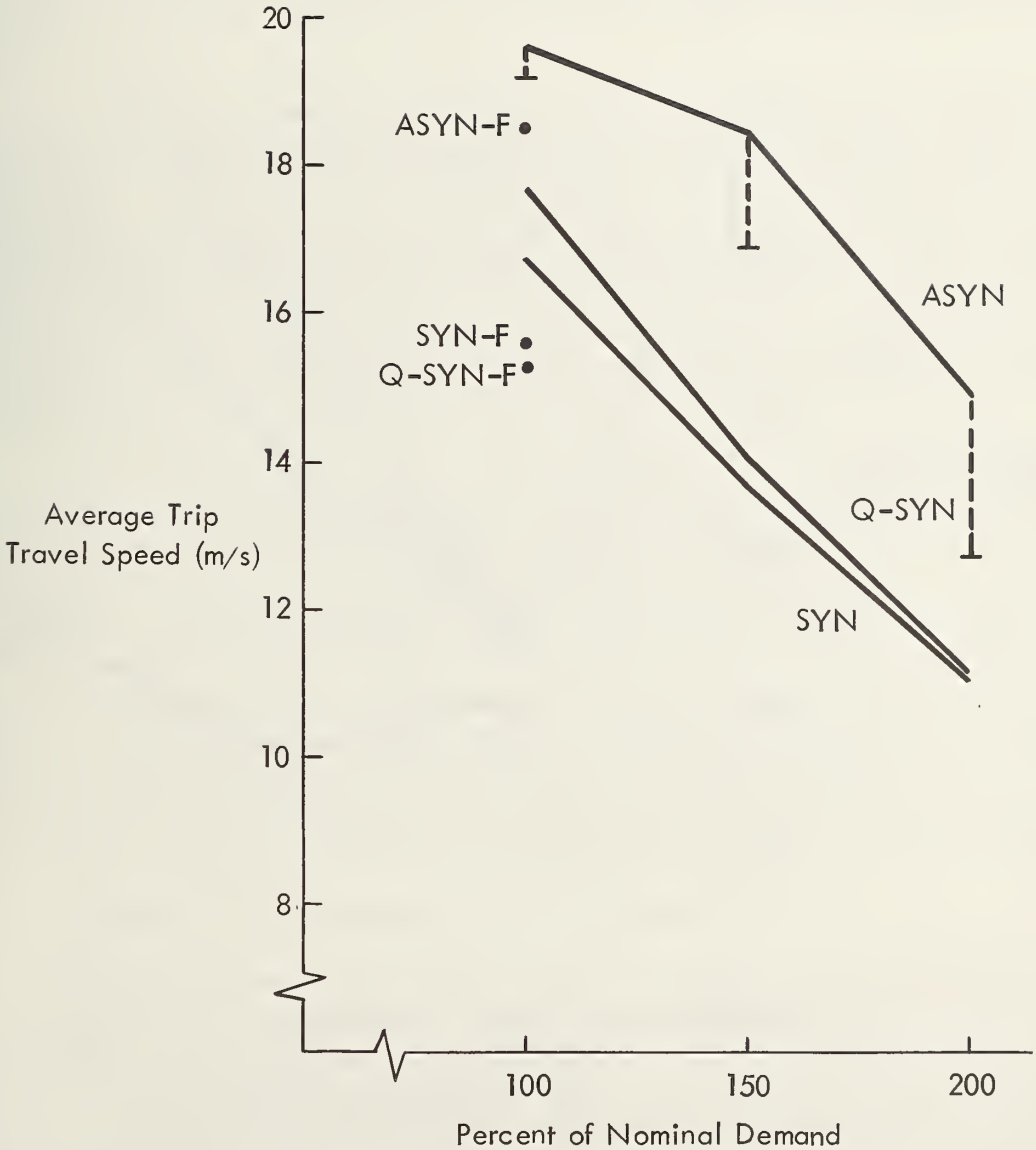


FIGURE 3-5. AVERAGE TRIP TRAVEL SPEED FOR CONTROL COMBINATIONS

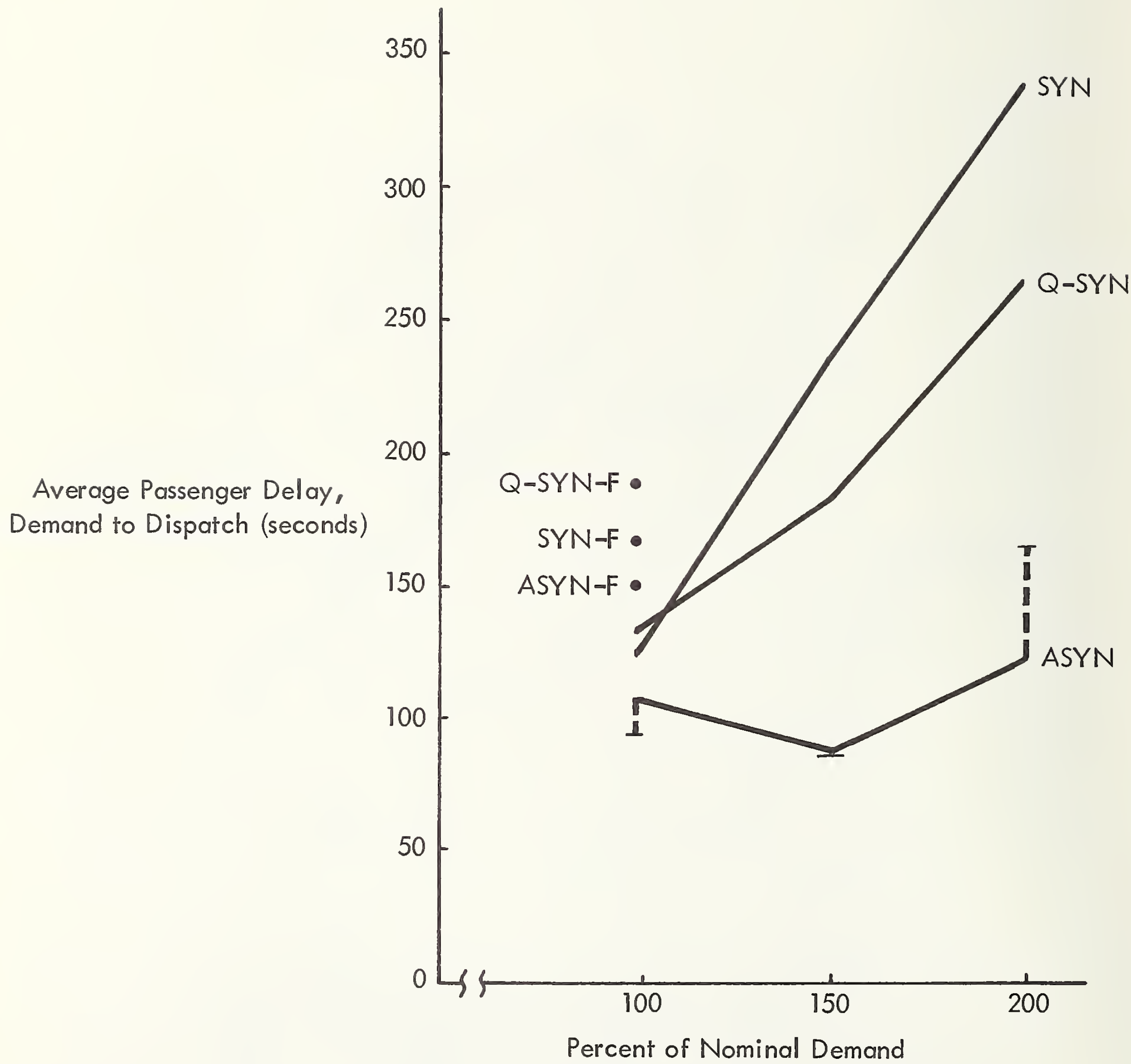


FIGURE 3-6. AVERAGE PASSENGER DELAY FOR CONTROL COMBINATIONS

150 percent of nominal demand is still observed but to a lesser degree.

The comparison of the average number of passengers waiting per station for the three control combinations is made in Figure 3-7. At 150 and 200 percent of nominal demand, asynchronous control leaves the fewest passengers waiting and synchronous control leaves the most passengers waiting. At nominal demand the rankings change but the average results vary by less than one passenger per station. The failure situation increased the number waiting but the nominal demand ranking order is preserved. The altered asynchronous showed improved performance at nominal demand and poorer performance at high demand.

The difference between the number of passengers arriving and passengers served, normalized by the number of passengers arriving is illustrated in Figure 3-8 for the three control combinations. All three control combinations performed well at nominal demand but for increased demand levels, synchronous and quasi-synchronous control showed drastic degradation while asynchronous control remained essentially constant. The failure situation, interestingly, showed little change from the nonfailure situation. Synchronous improved slightly while asynchronous and quasi-synchronous became slightly worse. The altered asynchronous case showed the similar situation of improving at low demand and degrading at high demand but generally outperforming the other two control combinations.

Upon the bases of the experiments just summarized for a 17-capacity SGRT vehicle and for the network illustrated in Figure 3-1, it is concluded that asynchronous longitudinal control with non-deterministic dispatch outperforms both synchronous longitudinal control with deterministic dispatch and quasi-synchronous longitudinal control with quasi-deterministic dispatch. The quasi-synchronous control combination appears to be slightly preferred to the synchronous control combination. Approximately one-third to two-thirds of the performance advantage of the asynchronous control combination at 200 percent of nominal demand is attributable to the shorter headway attainable with asynchronous control. At 150 and 100 percent of nominal demand the headway advantage is seen to be very small, and synchronous and quasi-synchronous control probably gave slightly optimistic performance values because of the small fleet size advantage allowed due to the slight network oversizing.

3.2 ALTERNATIVE MECHANIZATION EVALUATION

The hardware and software mechanizations of the three alternative operational control combinations are evaluated in this section. The evaluation is in terms of the higher level component and computation requirement definition made for each of the operational control strategies in Section 2.1.3. In the context of that requirement definition the continuous vehicle control and moving block headway protection strategies used in all three of the control strategy combinations evaluated at the system level fall into the category of medium headway.

The asynchronous control combination evaluated in a previous section consists of: continuous vehicle follower vehicle control for medium headway, moving block headway protection for medium headway, first-in/first-out merge strategy for an asynchronous system, and non-deterministic dispatch strategy. If the equipment requirements of these

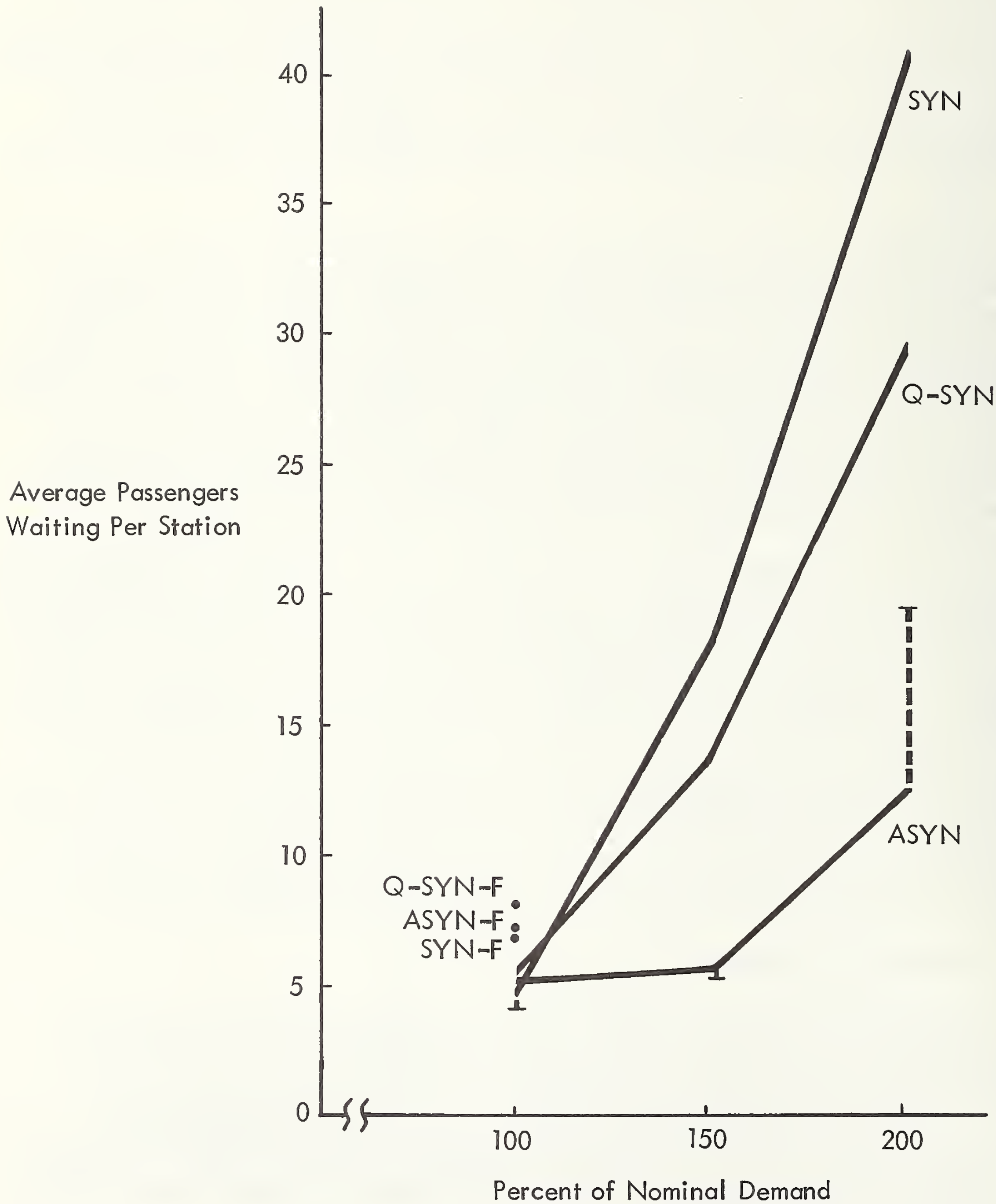


FIGURE 3-7. AVERAGE PASSENGER WAITING PER STATION FOR CONTROL COMBINATIONS

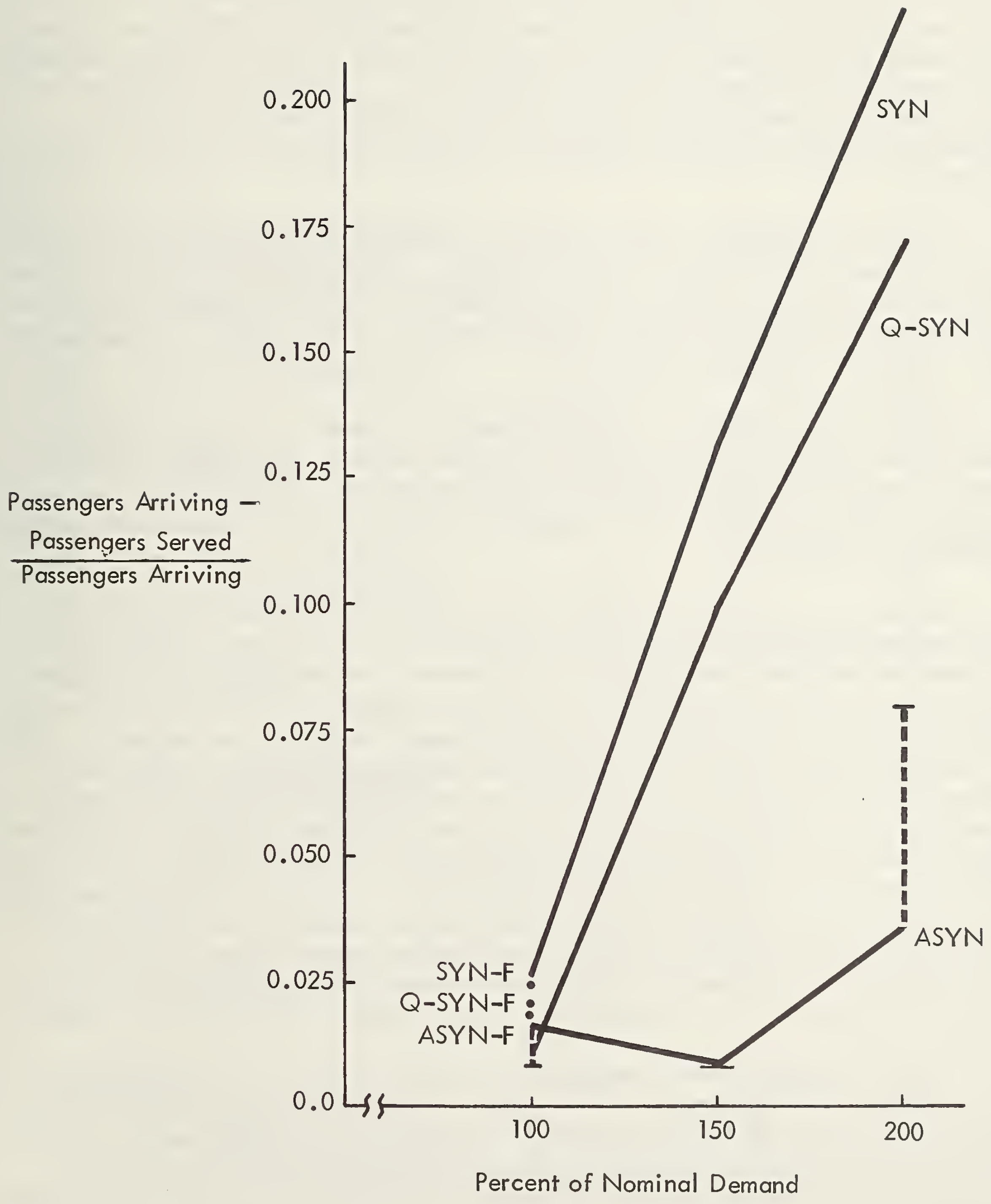


FIGURE 3-8. DIFFERENCE OF ARRIVING AND SERVED PASSENGERS FOR CONTROL COMBINATIONS

strategies as identified in Table 2-4 are collapsed across strategies and the computation requirements are summed, the result is the requirements identified in the first column of Table 3-12. The rationale for this approach is that equipment identified more than once may be used jointly by the strategies involved while computation capability may not be shared, and in a roughly additive fashion requires increased amounts of software and computation hardware. As already pointed out in Section 2.1.3, the high, medium and low levels of computation are qualitative only and are not strictly comparable between strategies. However, this method does give a reasonable qualitative ranking of strategy combinations.

The quasi-synchronous control combination evaluated in a previous section consists of: point follower vehicle control for medium headway, moving block headway protection for medium headway, first-in/first-out merge strategy for a quasi-synchronous system, and quasi-deterministic dispatch strategy. The requirements for this strategy combination are given in the second column of Table 3-12.

Finally, the synchronous control combination evaluated in a previous section consists of: point follower vehicle control for medium headway, moving block headway protection for medium headway, scheduled merge strategy for a synchronous system, and deterministic dispatch strategy. The requirements for this combination are given in the third column of Table 3-12.

Comparing the results for the three combinations it is seen that, at least as far as this higher level definition is concerned, the vehicle mounted, guideway mounted, and station mounted equipment and computation requirements are equivalent. The equipment is, in general, not being used in the same way but is required by the three overall combinations of strategies. The localized and central control requirements are somewhat different. The quasi-synchronous control combination requires a substantially higher level of localized control computation because of the need to calculate slot maneuvers at merge and intersections. The central control computation varies in that the synchronous control combination is identified as requiring the most computation, and the asynchronous control combination is identified as requiring the least computation. The data linking structure for the synchronous and quasi-synchronous control combinations is more complex in that central control is linked both to individual stations and localized control directly, while the asynchronous control combination appears to be structured so that central control is linked to local control, which in turn is linked to individual stations and portions of guideway.

The fairly common vehicle requirements fit well with the cost analysis details as given in Section 8.0 of the Analysis of SLT Systems Volume III [13], where vehicle cost was not differentiated upon the basis of control. It is suggested that the high requirements of localized control for the quasi-synchronous control combination be accounted for by attributing a cost of station control and communication amount (CSTCC) to every network merge as well as to every station. For the other two combinations the amount CSTCC should be applied only to stations. The single cost amount (CCEQ) for the cost of computer and control equipment at the central location could be modified using a multiplicative factor based upon the central control computation requirement. The cost of wayside communication and control as related to the cost of an equivalent control block appears

TABLE 3-12. ALTERNATIVE MECHANIZATION EVALUATION

	ASYN	Q-SYN	SYN
Vehicle Mounted			
Guideway Data Receiving Equipment	X	X	X
Vehicle Data Sending Equipment	X	X	X
Direct Intervehicle Distance Measurement			
Benchmark Detector	X	X	X
Velocity Measurement	X	X	X
Other State Variable Measurement	X	X	X
Computation	2M+2L	2M+2L	2M+2L
Propulsion Actuator	X	X	X
Braking Actuator	X	X	X
Guideway Mounted			
Vehicle Data Receiving Equipment	X	X	X
Guideway Data Sending Equipment	X	X	X
Benchmarks	X	X	X
Presence Detectors	X	X	X
Interblock Data Links			
Station Mounted			
Vehicle Data Receiving Equipment	X	X	X
Dispatch Data Sending Equipment	X	X	X
Presence Detectors	X	X	X
Localized Control			
Computation	M+2L	H+M+L	M+L
Signal Generation	X	X	X
Data Link With Station	X		
Central Control			
Computation	L	M+L	H+L
Data Link With Station		X	X
Data Link With Localized Control	X	X	X

Legend

ASYN - Asynchronous Control Combination
H - High Level of Computation Required
L - Low Level of Computation Required
M - Medium Level of Computation Required
Q-SYN - Quasi-Synchronous Control Combination
SYN - Synchronous Control Combination
X - Required

to be reasonable based upon the result obtained in Appendix B where the greater number of equivalent control blocks identified for the synchronous and quasi-synchronous control combinations corresponds to the increased complexity of the data linking structure.

3.3 ENTRAINMENT CAPABILITY EVALUATION

The DESM has two entrainment options, one which allows entrainments (and detrainments) on the guideway and one which entrains vehicles in stations after the board event is completed. The detailed dynamics of these events is not modeled. Entrainment on the guideway may be specified only for demand responsive service with asynchronous longitudinal control. Entrainment occurs at a network merge whenever two vehicles arrive at the merge point with a time separation of less than or equal to one headway. Entrainment can occur within a station if demand responsive service is specified and two vehicles have a common destination. The user may specify the maximum train consist and also the maximum time a vehicle will wait within a station to allow entrainment.

These entrainment options were investigated singly and in combination, allowing 15 seconds maximum delay time in stations to accomplish an entrainment and allowing train consists up to three vehicles. The system and other control options were identical to the nominal asynchronous control combination reported in Section 3.1.2.

3.3.1 Entrainment Evaluation at Nominal Demand

The entrainment options of entraining within stations, entraining on the guideway, and entraining both within stations and on the guideway were evaluated for the case of 100 percent of nominal a.m. peak demand. The peak hour statistics along with the statistics for the case of no entrainment are summarized in Table 3-13. The statistic for average number of queued vehicles is not reported here because a flaw in the gathering of queued vehicle statistics for the case of entrainment was discovered which was unresolved at the time of these simulations. Additional statistics consisting of counts of vehicles leaving stations and entering and leaving guideway links are given in Table 3-14. These are counts over all stations and guideway links for the peak one hour period. Notice that the sum of the number of entrained vehicles on guideway links and the number of detrained vehicles on guideway links is equal to the number of vehicles entering guideway links. The count of vehicles entering guideway links is consistently greater than the count of vehicles leaving guidway links. This occurs for the peak hour situation because at the beginning of the hour a significant fraction of the vehicle fleet is still in station storage, while at the end of the hour all but a small number of these vehicles have been called into service, and essentially none have had the opportunity to be returned to station storage. Notice that for this case, station entrainment resulted in no entrainments and thus no performance difference from the nominal case. Also, when both station and guideway entrainment are enabled the resulting entrainment activity is greater than the sum of separate station and guideway entrainment. This is partially due to the fact that the diverge to pick up passengers at intermediate stations option is enabled. However, an entrained vehicle will not diverge unless guideway entrainment is enabled, thus

TABLE 3-13. ENTRAINMENT EVALUATION AT NOMINAL DEMAND

Run Identification	AA(2247)	AA(2263)	AA(2266)	AA(2268)		
Control Type	Asyn	Asyn	Asyn	Asyn		
Estimated Load Factor	0.45	0.45	0.45	0.45		
Demand (%)	100	100	100	100		
Entrainment	None	STN	GDY	STN-GDY		
Number Of Vehicles	223	223	223	223		
Number Of Passengers Arriving	9,686	9,686	9,686	9,686		
Number Of Passengers Served	9,528	9,528	9,596	9,582		
Average Trip Time Demand To Completion (s)	486.9	486.9	478.8	487.5		
Average Trip Travel Speed (m/s)	19.61	19.61	19.64	19.58		
Average Number Passengers Per Revenue Vehicle	6.27	6.27	6.31	6.34		
Average Proportion Vehicles In Revenue Service	0.725	0.725	0.724	0.718		
Average Passenger Distance Per Vehicle Distance	4.807	4.807	4.777	4.800		
Average Passenger Delay Demand To Dispatch (s)	109.2	109.2	101.5	110.2		
Average Maximum Passenger Delay Demand To Dispatch (s)	732.0	732.0	545.2	633.2		
Average Delay For Station Merge (s)	0.0	0.0	0.0	2.95		
Average Number Of Passengers Waiting Per Station	5.20	5.20	4.48	5.02		
Maximum Number Of Passengers Waiting	510	510	454	472		
Maximum Vehicles In A Queue	5	5	3	5		
Average Number Queued Vehicles						
Percent Guideway Utilization	58.89	58.89	60.07	60.66		

TABLE 3-14. ENTRAINMENT EVENT COUNTS AT NOMINAL DEMAND

Run Identification	AA (2247)	AA (2263)	AA (2266)	AA (2268)
Demand (%)	100	100	100	100
Entrainment	NONE	STN	GDY	STN-GDY
Number of Vehicles Leaving Stations	3,756	3,756	3,794	3,752
Number of Entrained Vehicles Leaving Stations	0	0	28	42
Number of Vehicles Entering Guideway Links	16,834	16,834	17,025	16,799
Number of Vehicles Leaving Guideway Links	16,794	16,794	17,008	16,766
Number of Entrained Vehicles on Guideway Links	0	0	234	398
Number of Detrained Vehicles on Guideway Links	16,834	16,834	16,791	16,401

allowing only one of the vehicles to leave the guideway.

3.3.2 Entrainment Evaluation at Increased Demand

The same entrainment options evaluated at nominal demand were simulated at increased demands corresponding to 150 and 200 percent of nominal demand. The simulations at 150 percent of nominal demand ran normally but the simulations at 200 percent of nominal demand encountered a program abnormality about half way through the two hour simulated period which caused excessive use of computer time. This abnormality was not resolved in time to allow simulation of the 200 percent of nominal demand case.

The summary results of the simulations at 150 percent of nominal demand are given in Tables 3-15 and 3-16. For this case only one instance of an entrainment within the station occurred. However, a significant number of vehicles were entrained as they left the station and entered the guideway for the guideway entrainment option,and even more were entrained when both station and guideway entrainment were enabled. When guideway entrainment is enabled, the vehicles within the station do not need to have a common destination since they may detrain on the guideway after traveling a portion of their trip in an entrained condition.

3.3.3 Comparative Entrainment Evaluation

The results for the entrainment study are evaluated in terms of the five measures of system performance used in Section 3.1.5 for the control combination evaluation. The average trip time results are presented in Figure 3-9. Guideway entrainment alone improves performance at both demand levels while combined station and guideway entrainment cause a slight decrease in performance at nominal demand and a substantial improvement at increased demand. The results for average trip travel speed are given in Figure 3-10. The results are similar to the previous measure but in the reciprocal sense and the combined station and guideway entrainment does not show as dramatic an improvement at increased demand.

The results for the average passenger delay time are given in Figure 3-11. These results show that station entrainment alone has very little effect while guideway entrainment alone improves performance at both demand levels. Combined station and guideway entrainment causes a small loss of performance at nominal demand but a dramatic gain in performance at higher demand. The results for the average number of passengers waiting per station are given in Figure 3-12. Again, guideway entrainment shows performance improvement at both demand levels and combined station and guideway entrainment shows some improvement at nominal demand but substantial improvement at increased demand. Finally, the results for the difference between the number of arriving passengers and the number of served passengers are given in Figure 3-13. Station entrainment alone caused a small loss of performance at increased demands while the other two options gave improvement at both demand levels.

TABLE 3-15. ENTRAINMENT EVALUATION AT INCREASED DEMAND

Run Identification	AA(2252)	AA(2284)	AA(2285)	AA(2288)		
Control Type	Asyn	Asyn	Asyn	Asyn		
Estimated Load Factor	0.45	0.45	0.45	0.45		
Demand (%)	150	150	150	150		
Entrainment	None	STN	GDY	STN-GDY		
Number Of Vehicles	335	335	335	335		
Number Of Passengers Arriving	14,812	14,812	14,812	14,812		
Number Of Passengers Served	14,686	14,668	14,722	14,724		
Average Trip Time Demand To Completion (s)	498.0	497.5	492.2	481.3		
Average Trip Travel Speed (m/s)	18.44	18.46	18.78	18.66		
Average Number Passengers Per Revenue Vehicle	6.87	6.86	6.90	6.80		
Average Proportion Vehicles In Revenue Service	0.728	0.728	0.727	0.726		
Average Passenger Distance Per Vehicle Distance	5.108	5.091	5.141	5.028		
Average Passenger Delay Demand To Dispatch (s)	88.5	89.2	84.3	79.2		
Average Maximum Passenger Delay Demand To Dispatch (s)	485.7	500.4	620.3	463.4		
Average Delay For Station Merge (s)	0.0	2.45	0.0	9.38		
Average Number Of Passengers Waiting Per Station	5.72	5.83	5.20	4.97		
Maximum Number Of Passengers Waiting	564	564	510	398		
Maximum Vehicles In A Queue	21	21	8	10		
Average Number Queued Vehicles						
Percent Guideway Utilization	87.74	87.60	93.04	93.63		

TABLE 3-16. ENTRAINMENT EVENT COUNTS AT INCREASED DEMAND

Run Identification	AA (2252)	AA (2284)	AA (2285)	AA (2288)
Demand (%)	150	150	150	150
Entrainment	NONE	STN	GDY	STN-GDY
Number of Vehicles Leaving Stations	5,251	5,225	5,340	5,382
Number of Entrained Vehicles Leaving Stations	0	2	68	111
Number of Vehicles Entering Guideway Links	23,660	23,705	24,427	24,063
Number of Vehicles Leaving Guideway Links	23,612	23,651	23,360	24,024
Number of Entrained Vehicles on Guideway Links	0	2	611	943
Number of Detrained Vehicles on Guideway Links	23,660	23,703	23,816	23,120

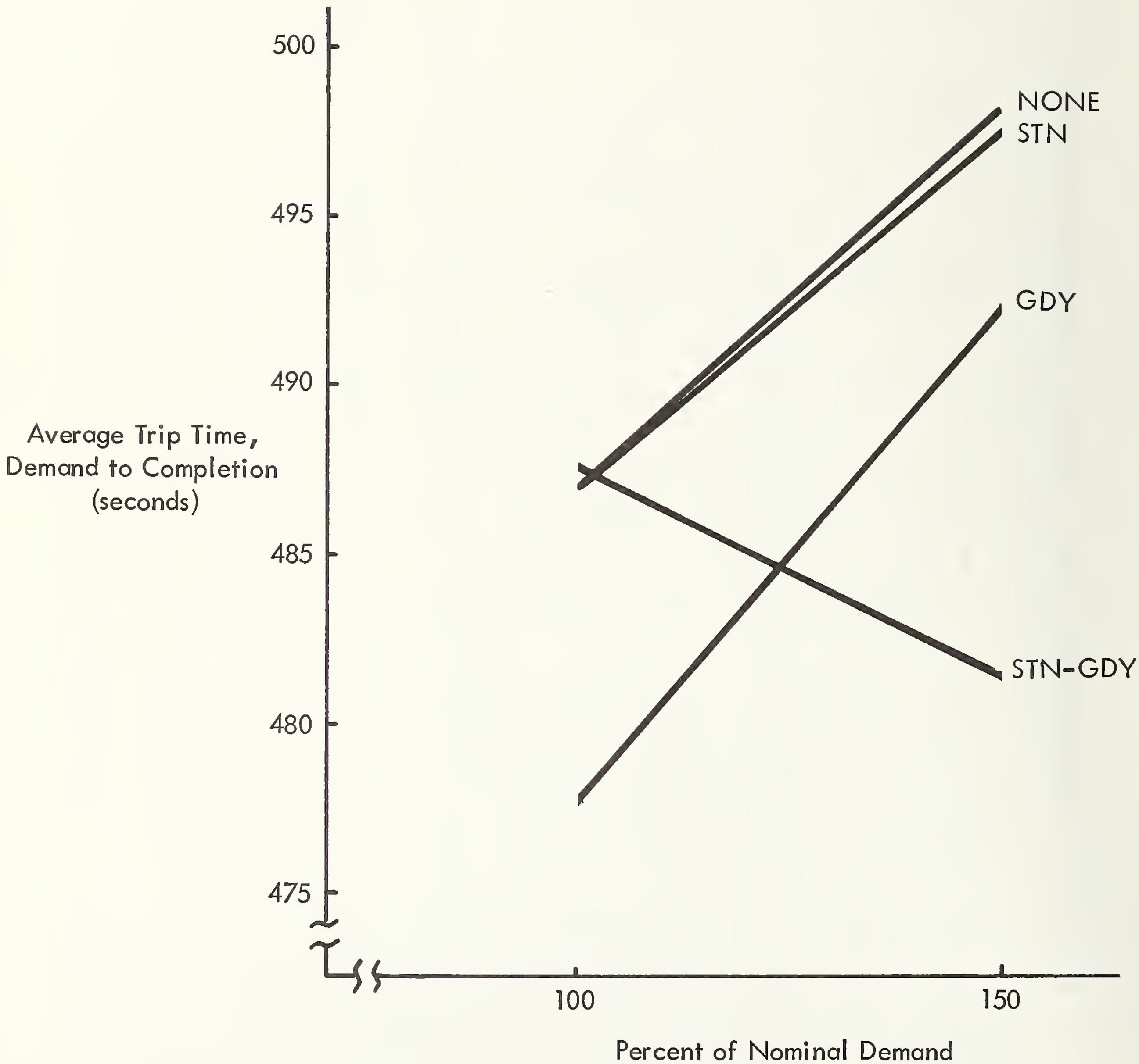


FIGURE 3-9. AVERAGE TRIP TIME FOR ENTRAINMENT OPTIONS

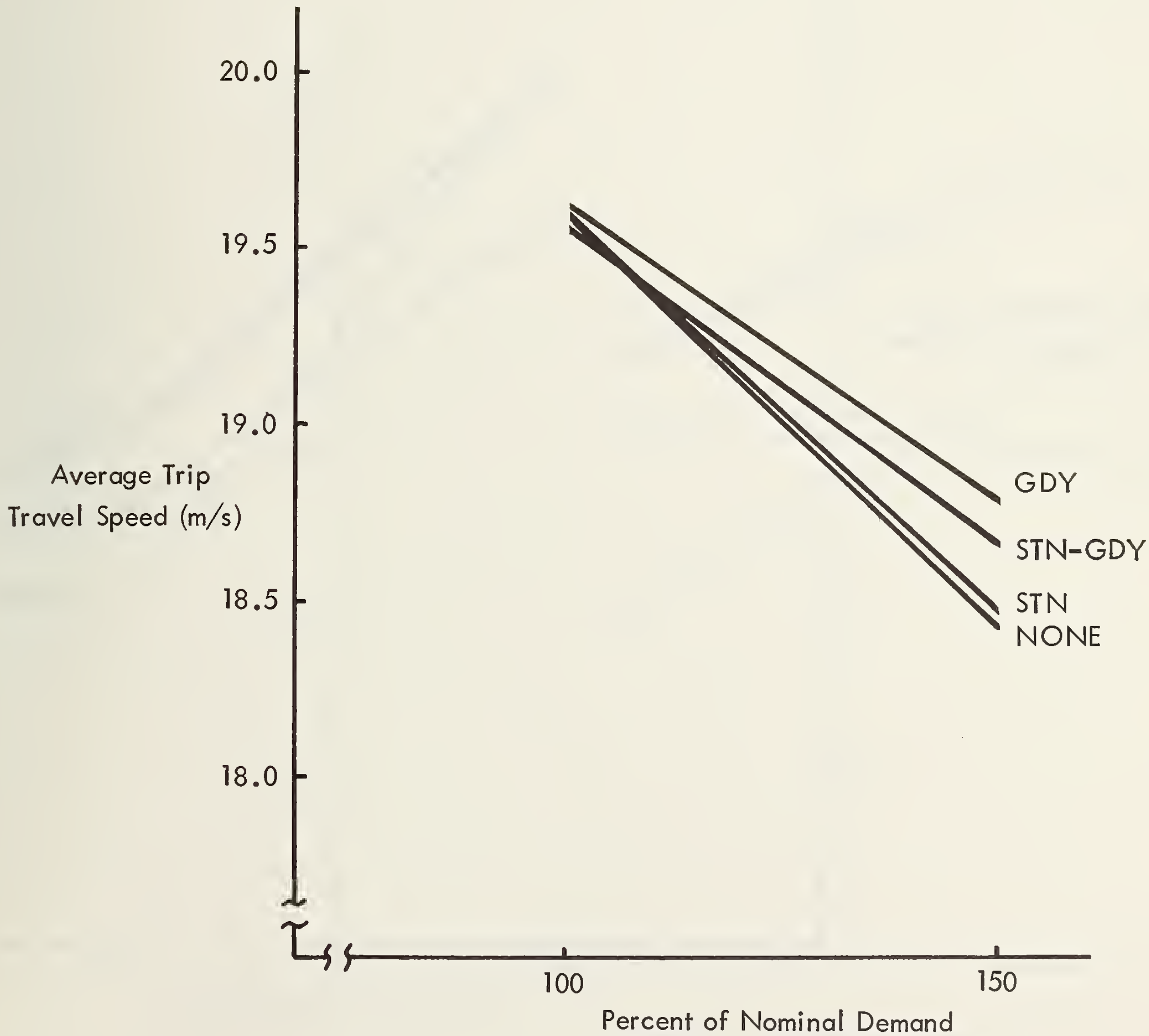


FIGURE 3-10. AVERAGE TRIP TRAVEL SPEED FOR ENTRAINMENT OPTIONS

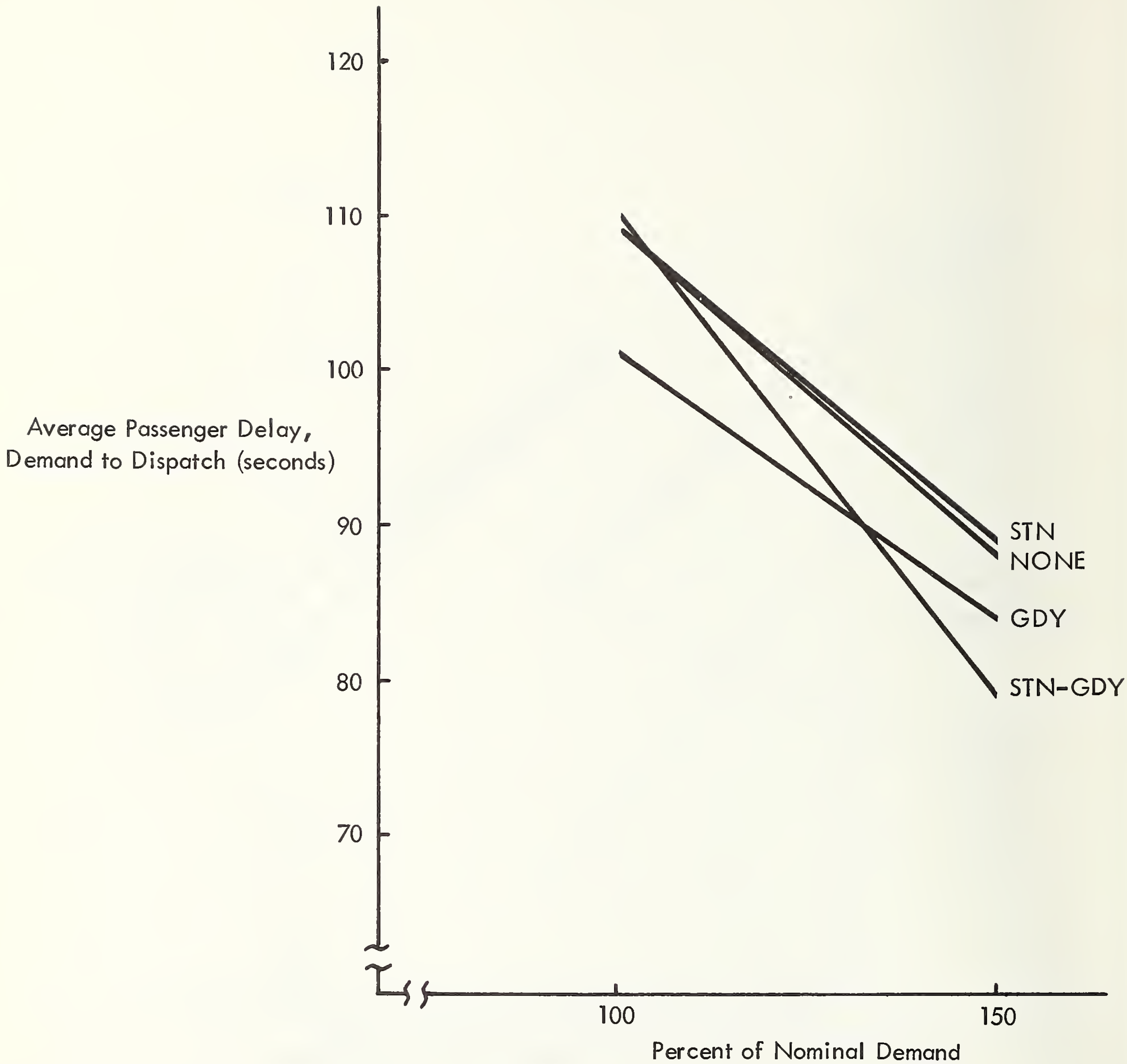


FIGURE 3-11. AVERAGE PASSENGER DELAY FOR ENTRAINMENT OPTIONS

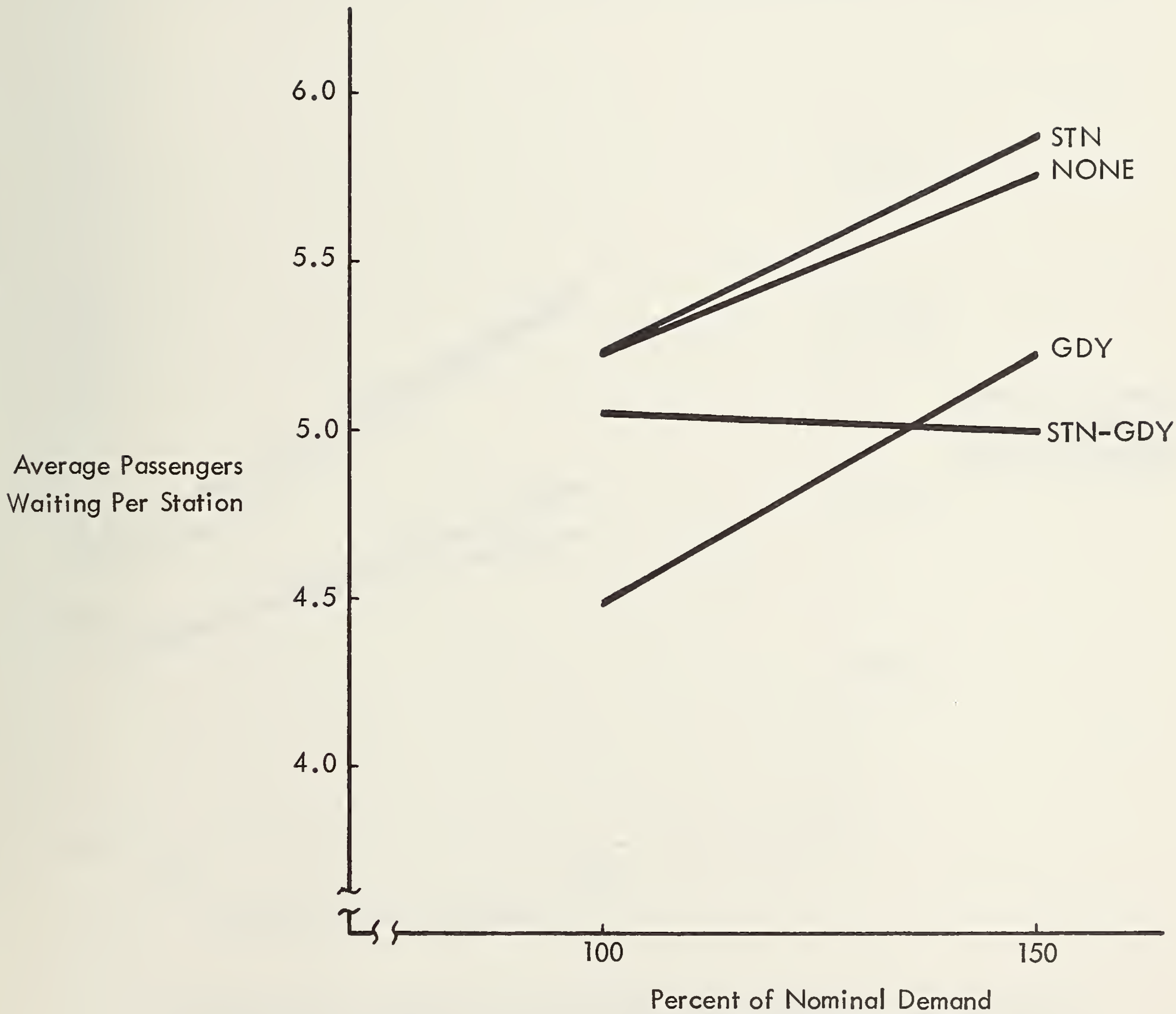


FIGURE 3-12. AVERAGE PASSENGERS WAITING FOR ENTRAINMENT OPTIONS

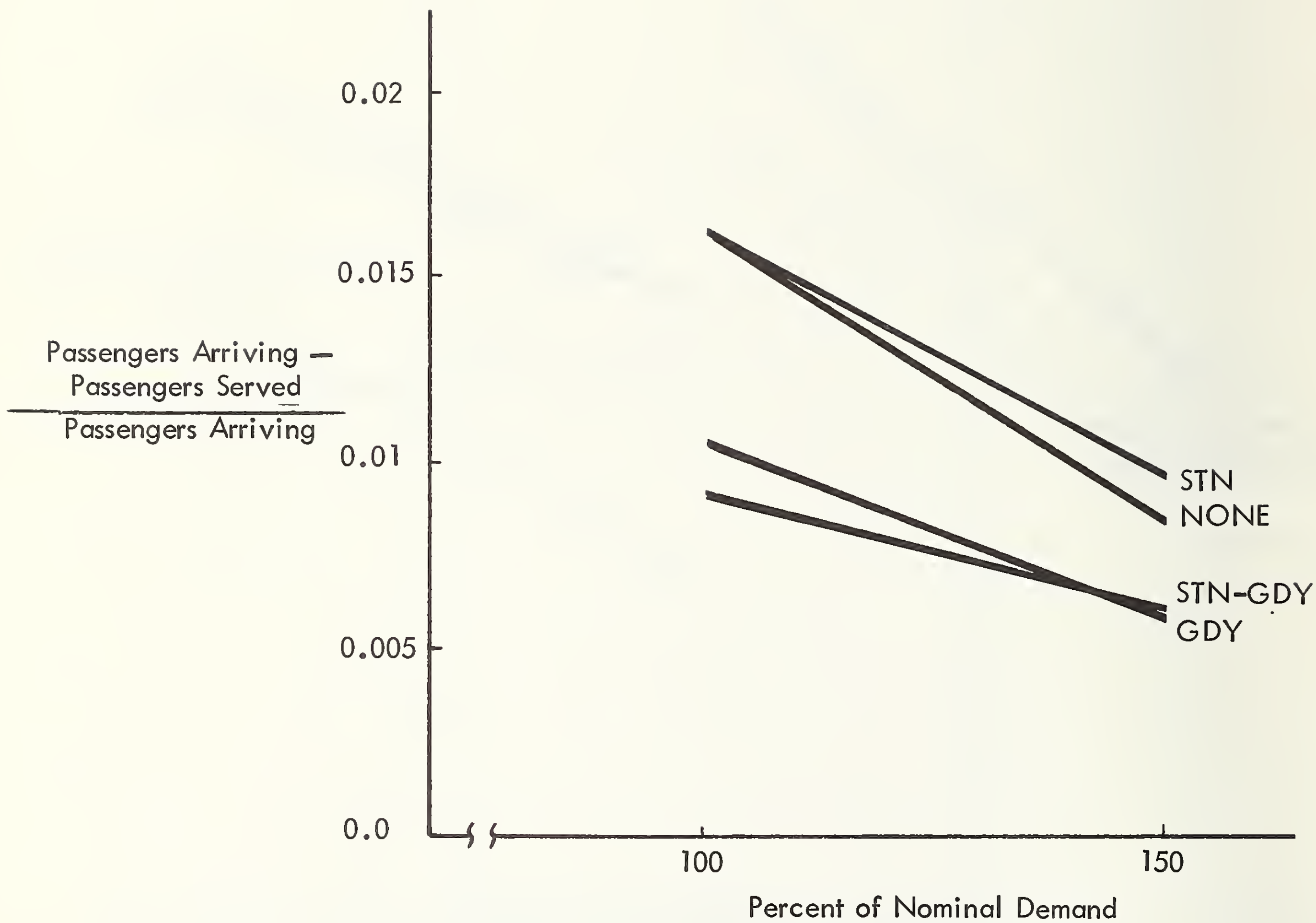


FIGURE 3-13. DIFFERENCE OF ARRIVING AND SERVED PASSENGERS FOR ENTRAINMENT OPTIONS

Since only one maximum wait time to entrain within the station was considered, these results are far from being an exhaustive study of entrainment. However, with this noted restriction, in general, entrainment within a station appears to only be a useful feature if it is combined with guideway entrainment. When so combined, performance usually improves but is a function of demand level and maximum entrainment wait time. In all cases, guideway entrainment by itself is observed to improve system performance.

4.0 CONCLUSIONS

4.1 SUBSYSTEM LEVEL CONCLUSIONS

The minimum operational headway analysis showed that the vehicle control and headway protection combination consisting of continuous moving block headway protection and fixed block vehicle follower vehicle control offers no advantage over the simpler combination using fixed blocks for both functions. In all cases, point follower control was found to require longer headway separation than vehicle follower control because of the focusing distance phenomenon during line speed changes. Under the nominal conditions stated in p. 2-21, no combination of vehicle control and headway protection was found to offer headway separations less than about 4 seconds without requiring a safety factor less than unity and/or not considering "brickwall" failures.

Subsystem experiments with single vehicles on a link confirmed that analytic expressions descriptive of vehicle motion give velocity profiles which may be followed by the vehicle controller with good accuracy. Also, analytic expressions for vehicle propulsion energy were found to be in excellent agreement with energy usage as found from the experiments.

The vehicle follower feedback gains were chosen to analytically give string stability at 25, 15, and 5 metres per second using only one numerical value of the coefficients. Experiments with a string of vehicles at minimum headway spacing showed that the control is indeed string stable.

Link flow experiments using both point follower and vehicle follower vehicle control showed that point follower control produces energy consumption and travel times which are independent of the link utilization. In general, the point follower control uses less brake energy and less propulsion energy except at the lowest link utilization. The link travel time is also slightly more predictable with point follower control as compared against vehicle follower control.

Headway protection was experimentally confirmed for both point follower and vehicle follower control. For the vehicle follower case, substantial braking of following vehicles occurs under normal control before the headway violation triggers emergency braking. The point follower case follows the control point without braking up to the time of headway violation. Link start up procedures were also experimentally tested. A simple and efficient procedure was tested for vehicle follower control, but a good procedure was not tested for point follower control.

Merge flow experiments showed that a priority merge strategy is effective in reducing travel time on the priority path, however, the travel time increases on the other path. A FIFO merge strategy results in the minimum flow weighted average travel time and thus was concluded to be the preferred strategy, except possibly in special situations. A comparison of merging under asynchronous control and under quasi-synchronous control showed superior performance for asynchronous control for both energy usage and minimizing excess travel time. A quasi-synchronous merge experiment at even high flow rates was not successfully performed. The correct combination of headway, control parameters and merge geometry was not found after several experiments. The results of two intersection experiments were completely similar to the merge flow results.

4.2 SYSTEM LEVEL CONCLUSIONS

Based upon the measures: average trip time, average trip travel speed, average passenger delay, average number of passengers waiting, and the difference of arriving and served passengers, the control combinations of asynchronous longitudinal control with non-deterministic dispatch was found to give better system level performance than the other two control combinations evaluated at the system level. The other two combinations are quasi-synchronous longitudinal control with quasi-deterministic dispatch and synchronous longitudinal control with deterministic dispatch. The asynchronous control case gave superior performance at 100, 150, and 200 percent of nominal demand except for the measures average number of passengers waiting and the difference of arriving and served passengers for the nominal demand case. Those measures were approximately the same for all three control combinations. The quasi-synchronous case outperformed the synchronous control case at increased demand,and at nominal demand the two reversed their ranking for some of the measures.

Based upon the subsystem analysis, the asynchronous control case was given a headway advantage at the system level. Experiments were also performed for which the headway advantage was removed. Asynchronous control still gave superior performance but to a lessened degree, especially for the case of 200 percent of nominal demand.

A calculation of the control related system cost of the three control combinations resulted in asynchronous control being the lower and in quasi-synchronous control being the higher.

A system level aggregation of the hardware, computation and software requirements identified at the subsystem level showed that the vehicle mounted, guideway mounted, and station mounted hardware, computation and software requirements are similar for the three control cases studied. The case of quasi-synchronous control was identified as requiring higher amounts of localized control computation, and the amount of central control computation is the least for asynchronous control and the most for synchronous control. The data link structure for asynchronous control was identifed as being hierarchical while the structure for synchronous and quasi-synchronous was identified as a structure of more direct communication between parts.

The comparative entrainment evaluation showed a clear performance improvement when dynamic guideway entrainment of vehicles at merges was enabled. Entrainment within stations results in a performance improvement only when combined with dynamic guideway entrainment to allow vehicles to divert from trains on the guideway. Even then, the result is a function of the demand level, indicating that the wait time to allow an entrainment within the station is an important parameter.

4.3 RECOMMENDATIONS

During the experimental work reported in the previous sections, a few shortcomings of algorithms in both the DOCM and DESM were noted. They are as follows:

Quasi-synchronous and synchronous point follower control in the DOCM continually checks if a vehicle is within a tolerance bound for following its control point. If it is not within tolerance, it is declared to have lost its slot and put into an emergency stop. The tolerance test is currently based only on position. During link start-up tests this caused some difficulty since some vehicles, even though stopped, were close enough to their control point to be considered within tolerance. A test to also check for velocity tolerance would eliminate this problem and may be useful under other circumstances. It should be noted that when dequeueing and attempting to catch a slot, tolerance tests are made on both position and velocity to determine if slot tolerance has been regained.

The difficulty encountered in the quasi-synchronous merge experiments using the DOCM was one of determining a proper combination of control, headway, and merge geometry and was not due to any deficiency in the DOCM. However, it did point out an additional control feature which would be desirable to have incorporated in the DOCM. The feature would be to set a lower bound on the vehicle velocity which could be used during quasi-synchronous maneuvers. This would allow the analyst to disallow the possibility of a vehicle making a full stop to accomplish a slot slip, and would correspond better with the allowance for linespeed change considered in establishing the minimum operating headway.

During synchronous and quasi-synchronous control experiments at the system level a desirable modification of the dispatching algorithm was noted. Using either quasi-deterministic or deterministic dispatch, a vehicle in demand responsive service plans its trip from origin to final destination at the time of its launch. If the vehicle is allowed to divert to serve passengers along its travel path, a portion of its originally planned trip is unused. At this time, that unused portion remains in the merge reservation table and unnecessarily hinders vehicle launches being attempted throughout the system. A desirable modification of the dispatch algorithm would clear any unused trip from the merge reservation table at the time a vehicle diverts from its originally planned trip. A more sophisticated approach would determine which vehicles would be diverting under the divert option at their launch time and would plan a trip only as far as the station into which the vehicle would divert.

During the experimental work reported in the previous sections, a number of areas were identifed which warrant more detailed study. The areas are as follows:

Vehicle control should be studied in more detail. Specifically, the control was designed based upon a linear model even though the simulation model is non-linear. Consideration needs to be given of the effect of the non-linearities on control. Integral feedback was used in the experiments. The advantages and disadvantages of integral feedback need to be experimentally determined under steady linespeed and varying linespeed situations.

Quasi-synchronous merging needs additional study to determine good combinations of control parameters, merge geometry, and minimum operational headway.

Link start up procedures for point follower control combinations would benefit from additional study.

At the system level of analysis, the observed phenomenon of improving performance as demand initially increased for asynchronous control needs additional study. The anticipated situation is that vehicle capacity changes, keeping the same fleet capacity, will have a significant effect on performance.

A more detailed study of entrainment to allow a parametric investigation of demand level, fleet size, allowable wait time to accomplish station entrainment, and maximum train size, should be done.

5.0 LIST OF REFERENCES

1. R. Lee, F. S. A. Alberts, and G. Sullo, Classification and Definition of AGT Systems, System Operation Studies for Automated Guideway Transit Systems, GM Transportation Systems Division, EP-77002, January 1977.

2. R. Cowan, L. Bonderson, and F. Alberts, Representative Application Areas for AGT, System Operation Studies for Automated Guideway Transit Systems, GM Transportation Systems Division, EP-77054, July 1977.

3. E. J. Hinman and G. L. Pitts, "Speed and Headway Considerations for the New Urban Demonstration," APL/JHU TIR 001, February 1973.

4. J. F. Duke and R. Blanchard, Detailed Operational Control Model User's Manual, System Operation Studies for Automated Guideway Transit Systems, GM Transportation Systems Division, EP-78053A, June 1978.

5. J. F. Duke, Detailed Operational Control Model Technical Specification, System Operation Studies for Automated Guideway Transit Systems, GM Transportation Systems Division, EP-77034, March 1977.

6. J. F. Duke, Discrete Event Simulation Model Technical Specification, System Operation Studies for Automated Guideway Transit Systems, GM Transportation Systems Division, EP-77083, September 1977.

7. R. A. Lee, J. Boldig, M. J. Rizzuto, G. C. Sullo, Analysis of SLT Systems Volume III - Analysis Techniques and Data Sources, System Operation Studies for Automated Guideway Transit Systems, GM Transportation Systems Division, EP-78059A, July 1978.

8. D. R. Bergmann, "Generalized Expressions for the Minimum Time Interval Between Consecutive Arrivals at An Idealized Railway Station," Transportation Research, Volume 6, 1972, pp. 327-341.

9. J. H. Waller, "An Upper Bound on Minimum Headway," GM Transportation Systems Division Inter-Organization Memo, 1979.

10. M. J. Rizzuto, "Vehicle Deceleration Lanes at Off-Line Stations -- Update," GM Transportation Systems Division Inter-Organization Memo, SOS-I-780702, May 1978.

11. J. G. Bender, "Slot Maneuver Distance Requirement," GM Transportation Systems Division Inter-Organization Memo, 1979.

12. J. G. Bender, R. A. Lee, and R. N. Oglesby, AGT System Analysis Requirements and Plan Volume I - Requirements, System Operation Studies for Automated Guideway Transit Systems, GM Transportation Systems Division, EP-77019C, January 1978 Update.

13. R. Herman, E.W. Montroll, R.B. Potts, and R.W. Rothery, "Traffic Dynamics: Analysis of Stability in Car Following," Operations Research, Vol. 7, 1959, pp. 86-106.

14. R.L. Cosgriff, J.J. English, and W.B. Roeca, "An Automatic System for Longitudinal Control of Individual Vehicles," Highway Research Record. Vol. 122, 1966, pp. 7-18.

15. F. S. A. Alberts and A. E. Tenderson, Data Collection Trip Reports, System Operation Studies for Automated Guideway Transit Systems, GM Transportation Systems Division, EP-77059, July 1977.

6.0 BIBLIOGRAPHY

1. J. H. Auer, Jr., "A Rail-Transit People-Mover Headway Comparison," Presented at the 28th IEEE Vehicular Technology Conference, Denver, Colorado, March 22-24, 1978.

2. J.G. Bender and R.E. Fenton, "On the Flow Capacity of Automated Highways," Transportation Science, Vol. 4, No. 1, February 1970.

3. J. G. Bender, R. E. Fenton, and K. W. Olson, "An Experimental Study of Vehicle Automatic Longitudinal Control," IEEE Transactions on Vehicular Technology, Volume VT-20, No. 4, November 1971.

4. S. J. Brown, Jr., "Adaptive Merging Under Car-Follower Control," APL/JHU CP 038/TPR 029, October 1974.

5. S. J. Brown, Jr., "Characteristics of a Linear Regulation Control Law for Vehicles in an Automatic Transit System," APL/JHU CP 009/TPR 020, January 1972.

6. S. J. Brown, Jr., "Point-Follower Automatic Vehicle Control: A Generic Analysis," APL/JHU CP 057/TPR 025, May 1977.

7. R. J. Caudill and W. L. Garrard, "Vehicle Follower Longitudinal Control for Automated Guideway Transit Vehicles," Report No. UMTA-MN-11-0002-77-1, February 1977.

8. R. J. Caudill and J. N. Youngblood, "Intersection Merge Control in Automated Transportation Systems," Transportation Research, Volume 10, 1976, pp. 17-24.

9. H. Y. Chiu, G. B. Stupp, Jr., and S. J. Brown, Jr., Vehicle-Follower Controls for Short Headway AGT Systems - Functional Analysis and Conceptual Designs," APL/JHU CP 051/TPR 035, December 1976.

10. K. -C. Chu, "Decentralized Control of High-Speed Vehicular Strings," Transportation Science, Volume 8, No. 4, November 1974, pp. 361-384.

11. K. -C. Chu, "Optimal Decentralized Regulation for a String of Coupled Systems," IEEE Transactions on Automatic Control, Volume AC-19, June 1974, pp. 243-246.

12. J. L. Dais and H. L. York, "Platoon - Operated Stations for Quasi-Synchronous Personal Rapid Transit Networks," Transportation Research, Volume 8, 1974, pp. 63-70.

13. R. R. Evans and K. Cowes, "Headway Separation Assurance Subsystem (HSAS)," Alden Self-Transit Systems Corp., Report No. UMTA-MA-06-0031-75-4.

14. R. E. Fenton and P. M. Chu, "On Vehicle Automatic Longitudinal Control," Transportation Science, Volume 11, No. 1, February 1977, pp. 73-91.

15. R. E. Fenton and J. Glimm, "A Headway Safety Policy for Automated Highway Operations," Presented at the 28th IEEE Vehicular Technology Conference, Denver, Colorado, March 22-24, 1978.

16. "Final Report on the Design of a Generic Control System for Deterministically Controlled Ground Transportation Systems, Volume 1 - Summary and Specifications," TRW Systems Group, for Office of High Speed Ground Transportation, U. S. DOT Report FRA RT-72-36, February 1972.

17. "Final Report on the Design of a Generic Control System for Deterministically Controlled Ground Transportation Systems, Volume II - Supporting Engineering," TRW Systems Group, for Office of High Speed Ground Transportation, U. S. DOT Report FRA RT-72-37, February 1972.

18. W. L. Garrard, G. R. Hand, and R. Raemer, "Suboptimal Feedback Control of a String of Vehicles Moving in a Single Guideway," Transportation Research, Volume 6, 1972, pp. 197-210.

19. W. L. Garrard and A. L. Kornhauser, "Design of Optimal Feedback Systems for Longitudinal Control of Automated Transit Vehicles," Transportation Research, Volume 7, 1973, pp. 125-144.

20. E. J. Hinman, "Command and Control Studies for Personal Rapid Transit, Program Status, 1973," APL/JHU CP 031/TPR 027, December 1973.

21. E. J. Hinman and G. L. Pitts, "Practical Headway Limitations for Personalized Automated - Transit Systems," Proceedings IEE, Volume 122, No. 7, July 1975, pp. 755-758.

22. E. J. Hinman and G. L. Pitts, "Speed and Headway Considerations for the New Urban Demonstration," APL/JHU TIR 001, February 1973.

23. R. D. Kangas, "Alternative Dual Mode Network Control Strategies," Report No. DOT-TSC-OST-72-10, March 1972.

24. D. L. Kershner, R. C. Rand, and W. J. Roesler, "Network Model Studies for Automated Guideway Transit: Advanced Group Rapid Transit Models," APL/JHU CP 044/TPR 033, February 1976.

25. D. L. Kershner and W. J. Roesler, "Network Model Studies for Personal Rapid Transit," APL/JHU CP 040A/TPR 031A, June 1975.

26. P. M. Kirk, "Automated Personal Transit Control Systems," Presented at the Intersociety Conference on Transportation, Denver, Colorado, September 23-27, 1973.

27. A. L. Kornhauser and P. McEvaddy, "A Quantitative Analysis of Synchronous vs. Quasi-Synchronous Network Operations of Automated Transit Systems," Transportation Research, Volume 9, 1975, pp. 241-248.

28. A. L. Kornhauser, L. M. Sweet, and R. J. Caudill, "Concepts of Longitudinal Control and Vehicle Management for Automated Highway Systems," Transportation Program, Princeton University.

29. F. J. McGinley, "A Survey of Quasi-Synchronous PRT Interchange Control Algorithms," Transportation Planning and Technology, Volume 3, February 1977, pp. 233-245.

30. "Morgantown Personal Rapid Transit Longitudinal Control System Design Summary," Boeing Aerospace Company, Report No. UMTA-MA-06-0048-75-4, December 1975.

31. G. L. Pitts, "Augmented Block Guidance for Short-Headway Transportation Systems," Report No. UMTA-MD-06-0008-72-1, September 1972.

32. A. S. Priver, "Survey of PRT Vehicle Management Algorithms," Report No. UMTA-MA-06-0031-74-13, September 1974.

33. A. J. Pue, "A State-Constrained Approach to Vehicle-Follower Control for Short-Headway AGT Systems," APL/JHU CP 058/TPR 038, August 1977.

34. B. Pulk and R. Hynes, "Unified Approach to Vehicle Follower Longitudinal Control System Design," Presented at the 28th IEEE Vehicular Technology Conference, Denver, Colorado, March 22-24, 1978.

35. W. J. Roesler, M. C. Waddell, B. M. Ford, and E. A. Davis, "Operating Strategies for Demand-Actuated ACGU Systems, Volume II Evaluation and Comparison," APL/JHU CP 004/TPR 019 Volume II, March 1972.

36. W. J. Roesler, M. B. Williams, B. M. Ford, and M. C. Waddell, "Comparisons of Synchronous and Asynchronous PRT Vehicle Management and Some Alternative Routing Algorithms," APL/JHU, Presented at the 1973 International Conference on Personal Rapid Transit, Minneapolis, Minnesota, May 2-4, 1973.

37. R. M. Storwick, "Stability of the Collision-Proof and Related Braking Laws," Presented at the 28th IEEE Vehicular Technology Conference, Denver, Colorado, March 22-24, 1978.

38. "Study of Synchronous Longitudinal Guidance as Applied to Intercity Automated Highway Networks," TRW Systems Group, for Office of High Speed Ground Transportation, U. S. DOT Report 06818-W666-RO-00, September 1969.

39. G. M. Takasaki, and R. E. Fenton, "On the Identification of Vehicle Longitudinal Dynamics," IEEE Transactions on Automatic Control, Volume AC-22, August 1977, pp. 610-615.

40. D. E. Whitney and M. Tomizuka, "Normal and Emergency Control of a String of Vehicles by Fixed Reference Sampled-Data Control," IEEE Transaction on Vehicular Technology, Volume VT-21, No. 4, November 1972, pp. 128-138.

41. R. E. Whitten, "Analysis of Position Error Headway Protection," Alden Self-Transit Systems Corp., Report No. UMTA-MA-06-0031-75-3, July 1975.

42. D. F. Wilkie, "A Moving Cell Control Scheme for Automated Transportation Systems," Transportation Science, Volume 4, November 1970, pp.347-364.

43. A. M. Yen, "Vehicle Operating Strategies for Small Automated Guideway Transit Network," Report No. UMTA-VA-06-0025-77-1, August 1977.

44. H. L. York, "The Simulation of a PRT System Operating Under Quasi-Synchronous Control," Dept. of Aerospace Engineering and Mechanics, University of Minnesota.

7.0 GLOSSARY

Asynchronous

Operation of vehicles under velocity control or in the vehicle-follower mode with speed changes allowed to prevent potential merge conflicts.

Automated Guideway Transit (AGT)

Computer-controlled transit system operating in demand or scheduled service on a fixed, exclusive guideway.

Automated Rail Transit (ART)

A class of AGT systems which provides multiple-stop service, carries at least 100 passengers in its minimum train consists, operates at speeds equal to or greater than 55 km/h, and generally runs at headways of more than 1 minute.

Availability-Factor Relationships

The sensitivity of the vehicle and passenger availability measures to changes in parameters which affect either system reliability or failure management strategy.

Average Queue Transit Time (TQ)

Average time required to move through a platform boarding queue during a period of congestion such as the peak hour. For a particular station the value is calculated as the difference between the average wait time and one-half the average route headway.

Capital Cost (base year)

The initial cost of deploying a system expressed in base year (1977) dollars. Capital cost is the sum of guideway construction cost, passenger station construction and equipment cost, AGT vehicle cost, central control construction and equipment cost, maintenance facility construction and equipment cost, power distribution system installation cost, and feeder system costs including vehicles, maintenance facilities, and control facilities.

Catalogued Procedure

A pre-coded set of Job Control Language (JCL) statements that is assigned a name, placed in a data set, and may be retrieved and executed by one JCL statement.

Central Business District (CBD)

The downtown retail trade area of a city. As defined by the Census Bureau, the CBD is an area of very high land valuation characterized by a high concentration of retail business offices, theaters, hotels, and service businesses, and by a high traffic flow.

Central City (CC) of an SMSA

The largest city in an SMSA. One or two additional cities may be secondary Central Cities in the SMSA.

Central City (CC) of an Urbanized Area (UA)

A city of at least 50,000 persons within closely settled incorporated and unincorporated areas that meet the criteria for urbanized ring (fringe) areas. A few UA's contain twin cities with a combined population of at least 50,000.

Central City Ring (CCR)

The portion of a Central City not included in the CBD.

Checkpoint File

A file created at a user-specified time by the Model Processor and containing all data necessary to restart the MP from that time.

Closed-Loop Control

Advancement of vehicles under generated control based upon the estimated system state.

Control Block

A specific section of guideway corresponding to a single control segment of a fixed block vehicle regulation and/or headway protection system.

Cruise Speed

The constant velocity at which a vehicle travels after acceleration and prior to braking. This velocity is usually less than the maximum design speed, but can be equal to it.

Crush Load Capacity

The maximum total capacity which a vehicle is designed to accommodate. This limitation is defined by either a vehicle weight limitation or a passenger comfort criterion.

Demand Activated Service Policy

A service policy in which routes, which may include intermediate station stops, are generated in real time on the basis of passenger demand, i.e., point-to-point routing with demand stop.

Demand Responsive Service Policy

A service policy in which non-stop routes are generated in real time on the basis of passenger demand, i.e., point-to-point routing with no intermediate stops.

Demand Stop Service Policy

A service policy in which vehicles travel on predetermined routes but stop at stations along the route only in response to specific passenger demand.

Demand Type

A system deployment parameter which specifies the demand environment on which a detailed demand model will be specified. Three metropolitan area demands and four activity center demand types are identified:

1. Metropolitan area - high CBD, high reverse commutation
2. Metropolitan area - high CBD, low reverse commutation
3. Metropolitan area - low CBD, low reverse commutation

1. Activity Center Line-Haul
2. Activity Center Circulation
3. Activity Center in High Demand CBD
4. Activity Center in Low Demand CBD

Design Load per Vehicle

The nominal passenger capacity of each vehicle.

Deterministic

A strategy by which all merge conflicts are resolved before launch, and barring failures, each vehicle is assured of traversing the network in a predetermined time.

Dial-A-Ride Service

Transit service operated by generating vehicle paths in continual response to demand.

Downtown People Mover (DPM)

An AGT system deployed in a CBD environment.

Empty Vehicle Management (EVM)

A set of strategies which govern the disposition of active, empty vehicles not assigned to a fixed route nor enroute to service a passenger demand. Alternative strategies include:

Circulation

Vehicles are circulated on the network until needed to satisfy a demand. The distribution of circulating vehicles may be based on historical demand or on current demand patterns.

Station storage - historical

Vehicles are routed to stations for storage based on historical demand data.

Station storage - real time

Vehicles are either stored in the station when they become empty or are routed to other stations and stored based on current demand patterns.

Event Model

A representation of an entity (a subsystem or process) in terms of discrete states of the entity and the time required to change from one state to another for use in a discrete event simulation.

Fixed Block

A longitudinal control or headway protection mechanization wherein blocks are hardwired to the guideway and each block transmits velocity or braking commands to the vehicle based on the occupancy of preceding blocks. For longitudinal control, the commands may be altered by central or local control. For headway protection the blocks transmit either braking or velocity limit commands to vehicles which establish upper bounds for any other commands.

Fixed Route Service

Transit service operated on predetermined paths.

Flow Capacity (ρ_c)

A measure of system capacity in terms of passenger spaces per second past a point; the ratio of traveling unit capacity to average route headway.

Fully Connected Grid (FG)

A grid network in which vehicles proceed directly from one station to any other station without retracing any one- or two-directional portion of the guideway.

Global Variables

Variables stored in a common area and known by one name to all segments included in the program.

Grid

Any guideway on which vehicles are presented with a choice of paths during normal operation.

Grid Transit (GT)

A transit system deployed in any demand environment which uses an FG or PG network and has more extensive operational switching capability than an MSLT. Generally shorter headways result than in MSLT. This category includes PRT systems and many systems which are often referred to as Group Rapid Transit (GRT).

Guideway Interface

The vehicle components which contact the guideway for support. Usually the interface is wheels but in some cases it is an air or magnetic levitation force.

Headway

A frequency of service measure: the mean time between vehicles passing a point along a route of known configuration.

Headway Equation

An analytic function which expresses the relationship between minimum headway and system parameters such as traveling unit (vehicle or train) length, cruise speed, acceleration, communication delay, and expected position error.

Intermediate Vehicle Group Rapid Transit (IGRT)

A class of AGT systems which provides multiple-stop service and carries from 25 to 69 passengers in its minimum train consist. Low speed IGRT systems have a maximum operating speed of 13 to 54 km/h and tend to run at 15 to 60 s headways. High speed IGRT systems operate at speeds greater than 54 km/h and at headways which usually fall between 15 and 90 s.

Intersection

An X-type merge with 2 input links, 2 output links, 4 ramp links, 4 through paths, and either 2 or 4 queuing areas.

Large Vehicle Group Rapid Transit (LGRT)

A class of AGT systems which provides multiple-stop service, has a minimum train consist capacity of 70 to 109 passengers, operates at a maximum speed of 13 to 54 km/h, and usually runs at headways of 30 to 90 s.

Lateral Control Interface

Vehicle and guideway components that interface to control the vehicle's lateral movement.

Loop

A guideway on which motion is unidirectional during normal operation (except possibly at short station segments or at ends of runs) and which is defined by a closed path.

Loop of Closed Geometry (S)

A simple loop as defined above which encircles no area.

Macro

A standard code segment that is generated in-line at compile time by specification of single statement.

Maximum Operating Speed

The maximum speed at which a vehicle can travel. This limit is imposed by vehicle and propulsion system design constraints.

Merge Strategy

A strategy for resolving merge conflicts. Three strategies are considered·

1. FIFO (first-in, first-out)
2. Prescheduled
3. Priority

Metro Shuttle Loop Transit (MSLT)

A transit system deployed in a metropolitan environment and having high speed capability but no or limited operational switching capability. The network may be of any type. If it is a grid network, however, the switching is of limited capability. This category includes most guideway transit systems currently deployed in metropolitan areas.

Minimum Traveling Unit

The minimum number of vehicles with which a train can operate. For some systems the minimum traveling unit is a single vehicle.

Minimum Traveling Unit Capacity

The nominal capacity (not crush capacity) of a single vehicle times the number of vehicles in a minimum train consist.

Moving Block

A headway protection mechanization wherein an emergency protection zone which moves along with the vehicle is established around each vehicle. Emergency braking commands are issued to the traveling vehicle whenever its emergency protection zone infringes upon that of a leading vehicle.

Multiple Loop (ML)

Any network consisting of two or more loops and requiring that passengers transfer from a vehicle constrained to one loop to a vehicle constrained to another loop if they wish to travel between two points not served by a single loop.

Network Element

Either a link, merge, or an intersection modeled in the DOCM.

Network Type

A system deployment parameter which specifies network configuration. Seven network types are identified:

1. Shuttles (S)
2. Loop of closed geometry (L)
3. Open loop, one-way (L1)
4. Open loop, two-way (L2)
5. Multiple loop (ML)
6. Partially connected grid (PG)
7. Fully connected grid (FG)

Nominal Capacity

Vehicle capacity including seated and standing passengers as specified by the manufacturer according to a passenger comfort criterion. The average area allotted to each standee is generally at least 2.5 square feet.

Non-deterministic

A strategy by which potential conflicts at merges are not considered before launch but are resolved locally in the vicinity of each merge.

Off-Vehicle Feeder Travel Time for Access

The mean time per person enroute to a specific AGT station for delay or non-vehicle travel (including any walking to feeder route or waiting for feeder bus, transferring between vehicles, parking a car, or walking all the way), while going from zone centroids to a specific station.

Off-Vehicle Feeder Travel Time for Egress

The mean time per person enroute from a specific AGT station for delay or non-vehicle travel (including waiting at stations for bus, walking from route to destination, transferring between vehicles, or walking all the way), while going from a specific station to zone centroids.

On-Vehicle Feeder Time for Access

The mean time per person enroute to a specific AGT station spent aboard a feeder vehicle (including feeder bus or private auto), while going from zone centroids to a specific station.

On-Vehicle Feeder Travel Time for Egress

The mean time per person enroute from a specific AGT station spent aboard a feeder vehicle (including the feeder bus or private auto), while going from a specific station to zone centroids.

Open-Loop Control

Advancement of vehicles by user-specified control independent of system state.

Open Loop, One-Way (L1)

A single loop encircling an area and providing one-way circulation.

Open Loop, Two-Way (L2)

Two loops deployed side-by-side encircling an area and providing two-way circulation.

PARAFOR

A superset of FORTRAN utilizing PL/1 macros to add structured programming facilities to standard FORTRAN.

Partially Connected Grid (PG)

A grid network which does not qualify as a Fully Connected Grid (FG).

Partitioned Data Set

A type of file organization in which independent groups of sequentially organized records, called members, are on direct-access storage.

Path

A sequence of guideway links used by a vehicle to travel between two points on a network.

Personal Rapid Transit (PRT)

A class of PRT systems which provides non-stop point-to-point service, has a minimum traveling unit capacity of 3 to 6 passengers, and runs at very short headways, usually 3 s or less. Low speed PRT has a maximum operating speed of 13 to 54 km/h, while high speed PRT has a maximum operating speed exceeding 54 km/h.

Platoon Movement

Simultaneous advancement of a row of vehicles or trains.

Practical Minimum Headway

The minimum headway at which vehicles can operate under normal conditions.

Prescheduled Pathing

A vehicle pathing strategy in which the primary path from origin to destination is predetermined and specified for all station pairs.

Precision Stopping Tolerance

The tolerance within which a vehicle can stop at a given point.

Quasi-deterministic

A strategy by which merge conflicts are not resolved prior to launch, but information about the future state of the network is used to launch vehicles at times that provide a high probability of efficient merging.

Quasi-synchronous

Operation of vehicles under point-follower control but with change of control points allowed to resolve potential merge conflicts by advancing or slipping one or more slots.

Reliability Block Diagram

A diagram that illustrates what equipment or combinations of equipment are required for successful system operation.

Representative System

A collection of values for the following system characteristics and strategies

1. Vehicle characteristics
2. Guideway characteristics
3. System management strategies
4. Reliability characteristics
5. Cost characteristics

The range of values are chosen to be interrelated in such a way as to represent a general class of state-of-the-art systems for the purpose of conducting system analyses within the SOS program.

Representative System Deployment

A specific combination of a representative system, demand type, and network configuration defined for the purpose of conducting system analyses within the SOS program.

Response Time

A frequency of service measure· the mean time between a request for and the arrival of a dial-a-ride service vehicle.

Ripple Movement

Advancement of vehicles and trains one at a time for a row of stationary vehicles/trains.

Route

A designated set of destinations, usually defined by stations, to which a vehicle must travel. The path, or links, to be traversed between any two destinations is not specified.

Routing Strategy

A strategy which identifies routes for vehicles/trains. Two alternatives are fixed routing and real time select routing. Real time routing is used only with demand responsive service and demand activated service, while fixed routing is employed for demand stop and fixed route service policies.

Rural and Scattered Urban (R&SU)

The remaining rural and urban portions of counties not included as part of the urbanized ring of the UA, but still within the boundaries of the SMSA. Thus, with the exception of the New York and Los Angeles SMSA's, the SMSA consists of two components— the UA and the Rural and Scattered Urban. Both New York and Los Angeles Urbanized Areas (UA's) extend into counties outside the boundaries of the SMSA.

Scheduled, Real Time Pathing

A vehicle pathing strategy in which the primary path from origin to destination is selected from among specified alternatives just prior to departure from the origin station on the basis of current traffic conditions on the network.

Sector

An area serviceable by one vehicle in subscription service during a prescribed time interval for a specific demand density.

Service Type

Either non-stop (personal transit) or multiple-stop (group transit) service.

Shuttles (S)

A guideway on which bi-directional motion occurs during normal operation and which is defined by a single curve connecting two distinct end points. Also, any network consisting of two or more simple shuttles, either following the same path or different paths.

Shuttle Loop Transit (SLT)

A low speed AGT system deployment in an activity center demand environment having any non-grid type of network. Thus, SLT system deployments require no operational switching but may require passenger transfers.

Small Vehicle Group Rapid Transit (SGRT)

A class of AGT systems which provides multiple-party service, has a capacity of 7 to 24 passengers in its minimum train consist, and usually operates at headways between 3 and 15 s. Low speed SGRT has a maximum operating speed of 16 to 54 km/h, and high speed SGRT a maximum of over 54 km/h.

Standard Metropolitan Statistical Area (SMSA)

A county or group of counties containing at least one city (or twin cities) with a population of 50,000 or more, plus adjacent counties which are metropolitan in character and integrated economically and socially within the central city.

Switching Mechanism

The mechanism, located either on the vehicle or the guideway, by which vehicles/ trains are switched.

Synchronous

Operation of vehicles under point-follower control with no changes allowed in control points during a given guideway trip.

Theoretical Minimum Headway

The minimum headway at which two vehicles can travel, assuming there are no merges or on-line stations.

Total Value Capital Cost

The sum of all capital costs except interest expense over the life cycle period expressed in base year dollars.

Urbanized Area (UA)

An area containing a central city (or twin cities) of 50,000 or more population, plus the surrounding closely settled incorporated and unincorporated areas which meet certain criteria of population size and density (urbanized ring). UA's differ from SMSA's in that UA's exclude the rural portions of counties composing the SMSA's, as well as places that were separated by rural territory from the densely populated fringe around the central city. The components of the UA's include the central city, as defined above, and the urbanized rings, as defined below.

Urbanized Ring (UR)

Various areas contiguous to a central city or cities, which together constitute its urbanized ring, or "urban fringe," as termed by the Census Bureau.

Variable Cost (base year)

The annual cost of operating and maintaining a system expressed in base year (1977) dollars. Variable costs include maintenance costs, energy costs, and administrative costs for both the AGT and feeder systems.

Vehicle Capacity

When used in correlations of vehicle dimensions and cost to capacity, nominal vehicle capacity is assumed. However, the system simulations interpret vehicle capacity as the maximum number of passengers which can occupy a vehicle at one time.

APPENDIX A
GUIDELINES FOR DETERMINING A COUNT OF CONTROL BLOCKS

The costing for wayside communication and control is performed on a "per block" basis, with more blocks being associated with shorter headway systems and systems of increased complexity. However, the vehicle control and headway protection algorithms defined and analyzed in the operational control subsystem analysis often do not use a physical control block. Thus a methodology is required for counting blocks when blocks are actually used and for counting pseudo-blocks when physical blocks are not used. The following methodology gives a block count representative of a blocking situation of modest sophistication when actual blocks exist, and since the block count on guideway links is based upon headway, it essentially extrapolates a true block situation into the case of pseudo-blocks. Additional blocks will be assumed for the proper control of merges, diverges, and stations.

Merge - Three blocks will be assumed per link upstream of the merge point and one block will be assumed downstream as shown in Figure A-1 for a total of seven blocks per merge. These blocks are in addition to blocks to be specified later which depend on link length.

Diverge - One block per link downstream of a diverge point will be assumed as shown in Figure A-2 for a total of two blocks per diverge.

Station - Stations which have a total consist capacity, summing over all station links, of less than or equal to three will have three blocks assumed for the purpose of implementing a deceleration profile and one block assumed for the purpose of specifying an acceleration profile. Thus, a typical on-line station has four blocks as shown in Figure A-3. A typical off-line station combines the requirements for merge and diverge resulting in 12 blocks per station as shown in Figure A-4.

As stations become more complex and/or have capacities which exceed three consists, additional cost of control is incurred. However, no duplication of the control function of acceleration and deceleration is required. Also, storage areas and the station links connecting the storage area to other station functions are considered to be special cases requiring a minimum of costly control. For these reasons, additional blocks will be assigned to stations in the following way. One block will be assumed for each storage or storage connecting link, and one block will be assumed for each unit of consist capacity greater than three. This consist capacity should not include the capacity of the storage and storage connecting links. As an example, consider how the station illustrated in Figure 3-4 varies from the base off-line station for which 12 blocks are assigned. The non-storage capacity is greater than three and adds 21 blocks. The storage and four storage connecting links add five more blocks for a total of 38 blocks.

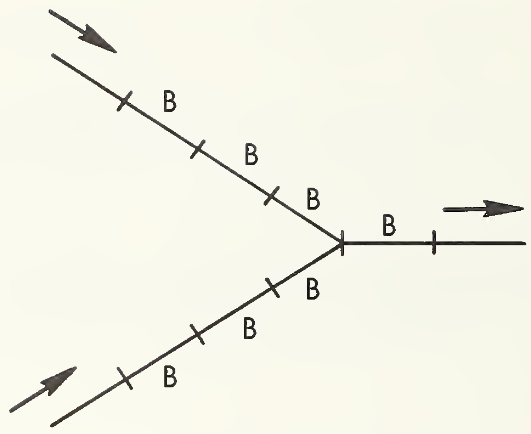


FIGURE A-1. ADDITIONAL MERGE BLOCKS

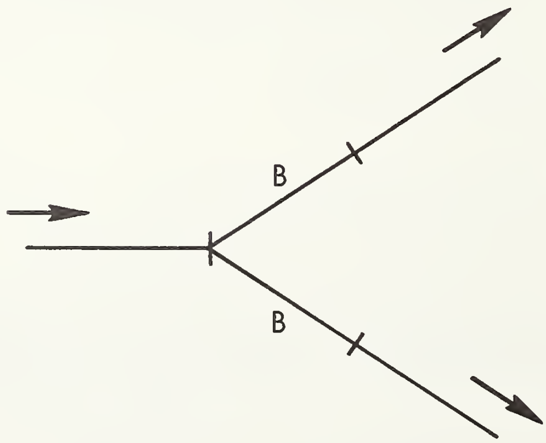


FIGURE A-2. ADDITIONAL DIVERGE BLOCKS

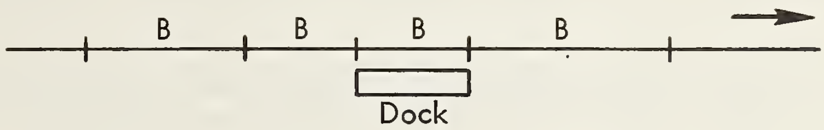


FIGURE A-3. TYPICAL ON-LINE STATION

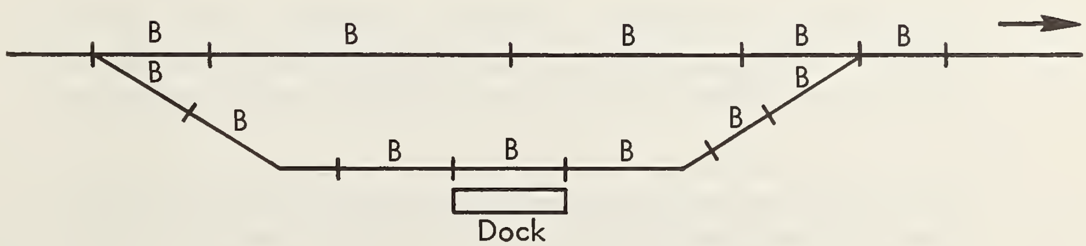


FIGURE A-4. TYPICAL OFF-LINE STATION

In performing DESM simulations, the most complex station required anywhere in the network is often defined as the general station for the simulation. It is advised that several groups of stations be identified based upon the actual consist utilization of the stations. The number of control blocks per station should then be separately calculated for each of the groups.

Guideway Links - The guideway links at which stations are defined are not considered since they are included in the block count assignment to stations. The other guideway links at which stations are not defined should be assigned blocks according to the formula

$$\text{Blocks} = \text{Integer}\left(\frac{3\,(D - D_A - D_D)}{Vh} + 1\right) \tag{A-1}$$

Where:

D = Link length

D_A = Any vehicle acceleration distance associated with an on-line station at the upstream end of the link

D_D = Any vehicle deceleration distance assocated with an on-line station at the downstream end of the link

V = Link cruise velocity

h = Link headway time

The value of h to be used is often not the link headway time entered for the DESM simulation and its specific value is at the discretion of the analyst. The following are some suggested values corresponding to different control options:

1. For synchronous and quasi-synchronous controlled systems use the slot headway time assuming that the specified slot time is approximately the maximum value which provides acceptable system performance.

2. For asynchronous systems with scheduled service use the route headway time during the peak demand period reduced by a factor of 0.75. If more than one route uses the same link, the link headway time is related to the route headways h_i by

$$h = \frac{1}{\Sigma \frac{1}{h_i}} \tag{A-2}$$

The factor 0.75 should again be applied. This factor allows for a margin of safety and gives some ability to accommodate an increase in vehicle flow.

3. For asynchronous systems with demand responsive service the route headways are unavailable. An average headway value applicable to the entire system may be calculated from a measure appearing in the performance summary report of the DESM. The headway is calculated as

$$h = \frac{3600\ (\text{Number of guideway links} - \text{Number of stations})}{\text{Maximum number of vehicles leaving links per hour}} \qquad \text{(A-3)}$$

The factor 0.75 should also be applied to the headway.

These suggested headway values may appear to be more stringent for synchronous and quasi-synchronous controlled systems. This is intended since this type of control requires that the slot headway time be attainable everywhere while asynchronous systems can be more flexibly controlled to provide short headways at congested areas while requiring relatively longer headway on the portions of guideway having less vehicle flow.

APPENDIX B
ALTERNATIVE OPERATIONAL CONTROL COSTS

The guidelines for performing a control block count presented in Appendix A will be applied to the three systems evaluated in the alternative operational control system performance evaluation. The costs identified for control of complex grid-like networks are:

$8,662 per block (CWCC)
$51,000 per station control (CSTCC)
$5,405,000 per central control (CCEQ)

The finding of the alternative mechanization evaluation will be used to somewhat alter these cost factors. The quasi-synchronous control combination was found to have a high localized control computation requirement. This will be reflected in the cost evaluations which follow by assuming a station control cost at every merge as well as at every station for this combination of control. The three control combinations were found to vary in the level of central control computation. For the asynchronous control combination, which required a low level, the central control cost will be multiplied by 2/3. For the synchronous control combination, which required a high level, the central control cost will be multiplied by 3/2. Finally, for the quasi-synchronous control combination, identified as requiring a medium level of central control computation, the central control cost will not be modified.

Aynchronous Control Combination - The headway is determined from Equation A-3 to be

$$h = \frac{3,600\ (135 - 51)}{18,620} \times 0.75 = 12.18 \text{ seconds}$$

where 18,620 is the maximum number of vehicles leaving links per hour as reported in the performance summary report for the 100 percent of nominal demand simulation. Using Equation A-1, blocks are assigned to each non-station link of the network file of Table 3-1. The result is 1,026 blocks.

The large capacity station of Figure 3-2 was the nominal station for all the system level simulations for reasons already noted. However, its large capacity was seldom fully utilized. In particular for the asynchronous control case, the station illustrated in Figure 3-3 is of more realistic capacity and yielded approximately the same system performance. For lack of any further station design considerations it will be assumed to be the common base station. For the synchronous and quasi-synchronous control cases this station will be assumed to be modified for a few of the stations. This station of Figure 3-3 was evaluated for blocks in Appendix A and found to use 38.

The 11 merges and diverges account for 99 blocks. The total block count is then

$$1{,}026 + 51 \times 38 + 99 = 3{,}063$$

The control related cost is thus:

$$3{,}063 \times \$8{,}662 + 51 \times \$51{,}000 + 2/3 \times \$5{,}405{,}000$$

$$= \$32.7 \times 10^6$$

Synchronous Control Combination - The headway time is the slot time of 6.0 seconds. Using Equation A-1, 2,046 blocks are assigned to the non-station guideway links.

The DESM model processor's intermediate sampling report was checked for station vehicle occupancy at the end of the a.m. peak hour. Two stations, number 6 and 7, were found to have 33 and 38 vehicles respectively on the station output queue links. Taking the value 38, this is 32 vehicles more than allowed for in the station of Figure 3-3. To allow for this situation and a possible similar situation at two other stations during the p.m. peak period, the total count of station blocks will be increased by 4 x 32 blocks.

The 11 merges and diverges account for 99 blocks. The total block count is then

$$2{,}046 + 51 \times 38 + 4 \times 32 + 99 = 4{,}211$$

The control related cost is thus:

$$4{,}211 \times \$8{,}662 + 51 \times \$51{,}000 + 3/2 \times \$5{,}405{,}000$$

$$= \$47.2 \times 10^6$$

Quasi-Synchronous Control Combination - The headway time is again 6.0 seconds. Equation A-1, thus assigns 2,046 blocks to the non-station guideway links.

The intermediate sampling report at the end of the peak a.m. hour showed only stations 6 and 7 with excessive vehicle occupancy. They had 23 and 26 vehicles respectively on the output queue links. Taking the value 26, this is 20 vehicles more than allowed for in the station of Figure 3-3. These two stations are increased to four to allow for other stations loading during the p.m. peak period. The station block count will be increased by 4 x 20 blocks.

The 11 merges and diverges account for 99 blocks and the merges are also assigned a station cost to account for the high level of local control computation associated with the quasi-synchronous control combination. The total block count is

$$2{,}046 + 51 \times 38 + 4 \times 20 = 4{,}163$$

The control related cost is thus:

$$4{,}163 \times \$8{,}662 + 51 \times \$51{,}000 + 11 \times \$51{,}000$$

$$+ \$5{,}405{,}000 = \$44.6 \times 10^6$$

APPENDIX C

REPORT OF NEW TECHNOLOGY

This study provided the analysis results of the performance, cost, and operating characteristics of the functions of vehicle control, headway protection, longitudinal control, merge strategy, and dispatch strategy. The study was performed at both the system and subsystem levels. An understanding of various control function options of the AGT systems in terms of performance, cost, and operating characteristics was obtained through the study. This understanding led to the guideline for choosing between control alternatives.

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