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LYSIS OF SHORT RAMPS FOR DUAL-MODE AND PRT STATIONS

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16. Abstract

Analyses and computer programs are developed to determine how short it is possible to make the ramps leading into and out of off-line Personal Rapid Transit (PRT) stations. Simplified reference solutions are obtained and results are presented for state-of-the-art, improved, and advanced system parameters. Potential savings in the costs of stations are very large, due to the high construction cost of station ramps.

Both point-follower and vehicle-follower control systems are considered. For point-follower control systems, the acceleration ramp can usually be eliminated. The deceleration ramp can usually be greatly shortened; particularly if main guideway headway is sufficient for successive cars to enter a station. The speed of through cars is not affected.

For vehicle-follower control systems, small deviations in the speed of through cars allows both acceleration ramps and deceleration ramps to be appreciably shortened. The greater the velocity deviation, the shorter the ramps can be, limited only by the comfort, convenience and time-loss limits on the through cars.

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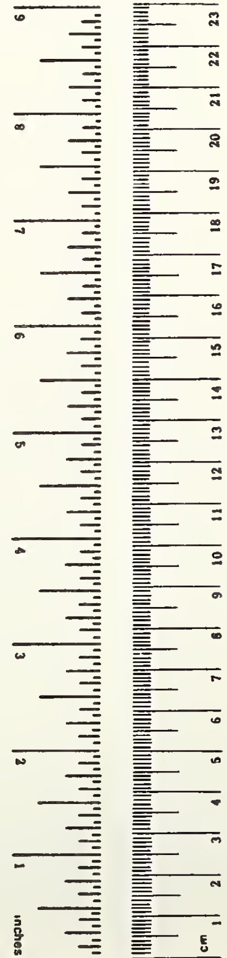
PREFACE

The work reported herein was performed by the Alden Self-Transit Systems Corporation and the Transportation Systems Center, U.S. Department of Transportation. TSC's primary participation was in the areas of the vehicle-follower computer program, the plotting routines, and the supplying of computer time on the Center's PDP-10; Alden's primary participation was the point-follower studies, the basic vehicle-follower equations and the analysis and design of the demonstration.

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

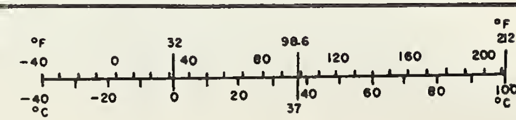


TABLE OF CONTENTS

TABLE OF CONTENTS (CONTINUED)

TABLE OF CONTENTS (CONTINUED)

LIST OF FIGURES

LIST OF FIGURES (CONTINUED)

LIST OF FIGURES (CONTINUED)

LIST OF TABLES

LIST OF TABLES (CONTINUED)

1. INTRODUCTION

This report is the result of continuing efforts to understand the safe-headway trade-offs for Personal Rapid Transit (PRT) and dual-mode systems. It adds a new dimension to the traditional interactions among control complexity, safety and acceleration. For both point-follower* and vehicle-follower* control systems it is possible greatly to reduce or, in some cases, completely to eliminate the ramps leading into and out of stations.

For point-follower control systems the acceleration ramp can generally be eliminated and the deceleration ramp can usually be greatly shortened; particularly if main-guideway headway is sufficient for successive cars to enter a station. The speed of the through cars is not affected.

For vehicle-follower control systems, small deviations in the speed of through cars allow both acceleration ramps and deceleration ramps to be appreciably shortened. The greater the velocity deviation, the shorter the ramps can be, limited only by the comfort and time-loss limits on the through cars.

The work described in this report was supported in part by the Transportation Systems Center, U.S. Department of Transportation, under contract number DOT-TSC-653.

1.1 CONCEPT

a. PRT Stations

The stations on PRT and dual-mode systems are "off-line," i.e., they are not located directly on the main guideway, as subway stations are. Off-line stations allow a through car to bypass stations at which it is not necessary to stop, allowing a non-stop trip from origin to destination. Trip time and inconvenience are reduced, and the perceived level of service is increased.

A car that is going to stop at an off-line station must

*These and other terms used in this report are defined in Section 1.3.

decelerate from guideway speed to station speed. The distance required for the speed change depends on the allowable deceleration and jerk characteristics of the vehicle. Curves of speed-change distance for typical decelerations and jerks are shown on Figure 1. For example, if deceleration is 0.1g and jerk is 0.1g/sec. the distance required to slow from 30 mph to 5 mph is 318 feet. The acceleration distances are the same as the deceleration distances.

b. Traditional Station

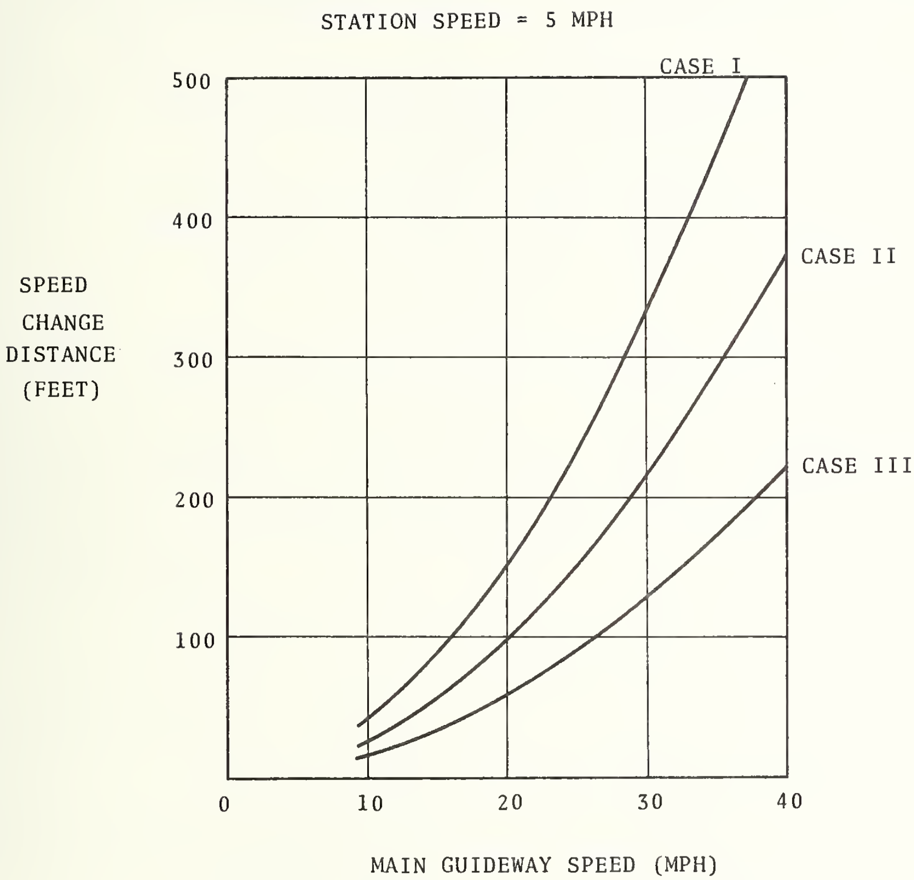
Traditional practice dictates that the speed changes between guideway and station take place on separate ramps. These ramps must be at least as long as the required acceleration and deceleration distances shown in Figure 1. In fact, additional lengths of ramp are required to connect the guideway and the ramp. They insure lateral clearance at the ends of the ramps. The additional length at the station entrance is called the breakaway distance, while that at the station exit is called the merge distance.

The schematic of a traditional station is shown in Figure 2A. A car would be completely clear of the main guideway before it starts to decelerate, and would have accelerated to full guideway speed before it enters the guideway. It is thus a minimul hazard to the cars on the guideway.

Long ramps simplify thinking about guideway safety, and there is no possible compromise in capacity. There are, however, considerations of cost. Due to compound curves, complex superelevation profiles and custom design, station ramps tend to be even more expensive than ordinary guideway--which is expensive enough. A typical elevated ramp might cost $1,000 per foot, exclusive of any cost for aesthetic considerations. A traditional bi-directional station on a 30-mph guideway might have 1000 feet of ramps, costing one million dollars. If station ramp length can be reduced even a little, sizable amounts of money can be saved.

c. Short Ramps

This report examines stations that allow part or all of the acceleration and deceleration to take place on the main guideway. The schematic of a "short-ramp" station is shown in Figure 2B.



	ACCELERATION (g's)	JERK (g's/sec)
CASE I	0.1	0.1
CASE II	0.15	0.3
CASE III	0.25	1.0

FIGURE 1 TYPICAL SPEED-CHANGE DISTANCES

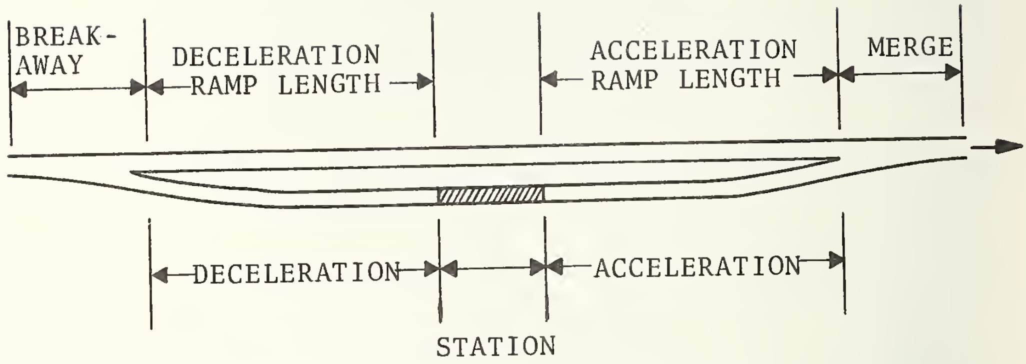


FIGURE 2A TRADITIONAL STATION

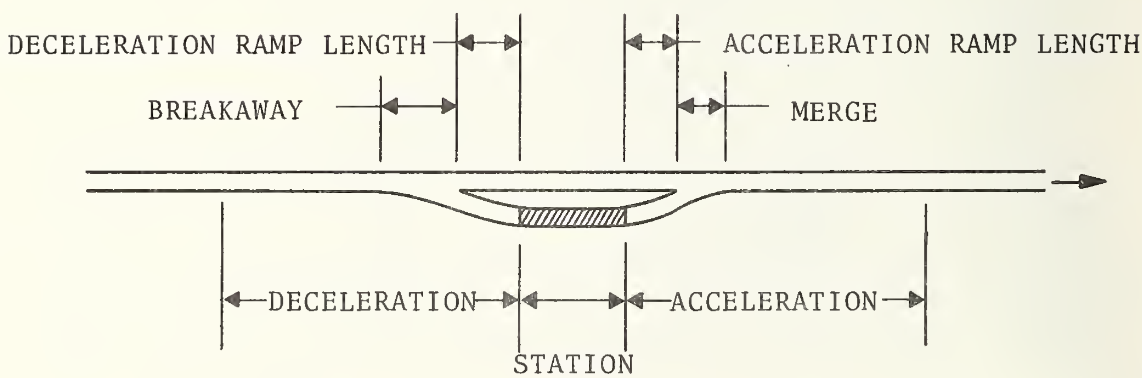


FIGURE 2B "SHORT RAMP" STATION

Note that, since speeds are lower on breakaway and merge, these distances may also be shorter than with the traditional station. Also note that, for a particular station, short ramps are not necessarily equal in length. Typically the acceleration ramp can be shorter than the deceleration ramp.

The amount of main quideway acceleration and deceleration depends on:

Main guideway headway
Station ramp headway
Control accuracy
Parameters of the headway protection system
Ramp costs.

This report discusses tools to analyze these interactions. Using these tools, the system designer can determine what is possible. What is desirable depends on the quantitative trade-offs among the parameters listed above and will vary with specific applications.

1.2 BACKGROUND

a. Prior Work

The headways required at constant speed, for unexpected-stop failures, have been analyzed by a number of investigators; see References 1, 2, 3 and 4, for example. The additional case of unexpected-stop failures during a deceleration was investigated in Reference 5. The effect of position and velocity measurement errors was separately investigated for constant speed in Reference 6.

b. HSAS Contract

In 1972, based on its previous work with headway-safety systems, Alden Self-Transit Systems received a contract (DOT-TSC-421) to design and demonstrate on its test track an independent Headway Separation Assurance Subsystem (HSAS). The Alden test track operates with a synchronous, point-follower control system, and the HSAS was primarily designed for this kind of system; the concept is also applicable, however, to non-synchronous control systems.

The HSAS is described in References 7, 8 and 9. A computer program was developed to aid in the design of the HSAS. It related safe headway to the parameters of the test track, such as speed and emergency deceleration capability, and to the parameters of the headway system itself, such as loop size and delay time. The program is described in Reference 10, and its application to the Alden test track is outlined in Reference 8.

c. Present Work

Early in 1973 a simplified analysis indicated that headway safety could be maintained even if much of the acceleration out of a station and much of the deceleration into a station are performed on the guideway rather than on separate ramps (see Section 2.2). It was also realized that the computer program discussed in Section 1.2b could be modified to consider the short-ramp case without any loss of flexibility. These arguments initiated, a few months later, the point-follower analysis of Section 2.

The analysis of ramp saving with vehicle-follower systems was initiated at the same time, recognizing the increasing importance of these systems--particularly the importance of a critical comparison with point-follower systems. The problem differed so fundamentally from the point-follower problem, however, that a completely new analysis and computer program had to be developed (see Section 3).

1.3 DEFINITIONS

In this section, some of the key words, phrases and concepts used in the report are defined.

Two types of control systems are considered: point-follower and vehicle-follower.

Vehicles under point-follower control are controlled to follow closely a fixed time-distance trajectory, i.e., they follow an imaginary target point. The motion of the point is termed the nominal trajectory or profile. The word slot is sometimes used in place of point. Not all moving points contain cars.

Each car that is traveling the same route follows the same trajectory. Thus, at every point on the guideway, the nominal speed of all passing cars is the same. The time separation between points or slots is normally constant and is called the system headway. A point-follower system with a constant time between slots is often called a synchronous system.

With a vehicle-follower system, the primary control is on velocity, rather than position. A car traveling on the guideway adjusts its speed to the lower of the following constraints:

> A civil speed, specified for every point in the guideway. It is similar to the profile speed for the point-follower, except that there is no specified time when the car must pass a point.
>
> A vehicle-follower law, which in its simplest form defines the relationship between the speed of a car and its distance from a preceding car.

The K factor is a useful measure of the separation between vehicles under vehicle-follower control. It also defines one of the vehicle-follower laws considered in this report. K factor is defined as the ratio of the space separting vehicles to the emergency stopping distance. It is basically a figure of merit. With a perfect control system, instantaneous failure detection, no braking delay, no safety margin, no possibility of an overspeed by the following car and a stonewall stop by the preceding car, cars would operate at a K factor of 1.

To the extent that the safety system and the control system are less than perfect, the operating K factor must be greater than one. Further, since the effect of real variations may be non-linear, a "safe" K factor will vary, depending on whether the car is on the guideway, a deceleration ramp or an acceleration ramp.

For overspeed and non-brickwall stops, the K factor is not a clear-cut measure of performance. Overspeed failures bear no physical relation to the definition of the K factor; and it may be highly misleading when judging overspeed safety. If the unexpected stop is at low deceleration (less than brickwall), K factors less than one may be perfectly possible. In spite of the restrictions, however, the K factor is a consistent way of quantifying relative separations in a physically meaningful manner.

Both the point-follower trajectory and the vehicle-follower civil speed follow a nominal profile. The nominal speed on the main guideway near the station is called main guideway speed. The speed in the station itself is called station speed, or platform speed. The speed changes between station and guideway speed are assumed to follow a trapezoidal acceleration/deceleration profile, limited by a maximum allowable jerk.

The portions of the guideway on which accelerations and decelerations between station speed and main guideway speed are performed, that are completely clear of the main guideway, are called the station ramps. Deceleration ramp length is the distance from the start of the ramp to the end of the deceleration region. Acceleration ramp length is the distance from the start of acceleration to the end of the ramp (see Figure 2).

A transition distance, called breakaway distance, is required to go from the main guideway to the start of the deceleration ramp. This distance depends on speed, allowable lateral jerk, allowable lateral acceleration, superelevation, and any geometric constraints. The distance required to go from the end of the acceleration ramp to the main guideway is called the merge distance.

Anywhere on the station ramp, or on the main guideway, two types of failure hazards may occur, an unexpected stop or an overspeed. Unexpected stops can occur with either point-follower or vehicle-follower systems. They are characterized by a constant failure deceleration to a complete stop. Uncontrolled overspeeds are a priori forbidden by the nature of vehicle-follower systems.

Given that a car has failed and that the error-sensing system is less than perfect, the failure will not be detected until a discovery time. After a further delay time, the failed car and adjacent cars start to perform an emergency stop.

The emergency stop of a non-failing car is a normal speed change, governed by emergency jerk and acceleration limits. Nominal emergency deceleration profiles may be modified by a brake tolerance which defines the percent deviation of jerk and acceleration. The distance between a car that has failed unexpectedly and the car that is brought to an emergency stop, after they have both stopped, is called the safety margin.

The point-follower analysis allows finite-control and failure-detection resolution. The car is assumed to operate in a position/velocity corridor whose width depends on the accuracy of the control system or the resolution of the failure-detection system. A car that is discovered outside of its corridor is considered unsafe.

The velocity and position corridors are related by assuming a sinusoidal deviation within the corridor, constrained by an allowable control acceleration. The position corridor is assumed to be bounded by either loops or check-in/check-out sensors. Position or velocity is periodically sensed. At standard sensing frequency, a check is made each time the car is due over either the center of contiguous loops or halfway between consecutive check-in/check-out sensors.

A failure-detection system based on velocity is termed velocity-error sensing, and one based on position is termed position-error sensing.

The vehicle-follower analysis makes use of the concept of a "ghost" car. The "ghost" car moves on the track either ahead of or behind a real car. Its position is tied to the position of the real car. Other cars respond to the ghost car as if it were a real car.

1.4 BASELINE PARAMETERS

Three sets of system parameters are assumed in the investigation.

Case I -- Parameters describe a "state-of-the-art" PRT, similar, for example, to the system in Morgantown.

Case II -- Parameters describe an "improved PRT," a system that is possible in the next few years, given moderate development effort.

Case III -- Parameters describe an "advanced PRT," a system that might be possible in several years, given intensive development in several key areas.

The parameters for the three cases are tabulated in Table 1. Maximum overspeed accelerations are set from 0.02 to 0.05 g's higher than the normal accelerations and it is assumed in all cases that the car is absolutely governed to not exceed 1.15, 1.10 or 1.05 times the nominal main guideway speed.

The three cases imply progressively higher-performance cars. The normal and emergency jerks and accelerations of Case III require that passengers are seated (perhaps even with seat belts). Case II passengers might be standing, but would require solid handholds. Case I passengers could probably be standing with minimal support.

TABLE 1 BASELINE PARAMETERS

	Case I State of the Art	Case II Improved	Case III Advanced
Vehicle Length (ft)	20	20	20
Main Guideway Speed (mph)	20, 30	20, 30	20, 30
Nominal Acceleration (g's)	0.1	0.15	0.25
Nominal Jerk (g's/sec)	0.1	0.3	1.0
Emergency Deceleration (g's)	0.25	0.3	0.6
Emergency Jerk (g's/sec)	0.5	0.6	1.2
Delay Time (seconds)	0.4	0.1 & 0.2	0.05 & 0.10
Station Speed (mph)	5	5	5
Unexpected Stop Failure (g's)	1.0	1.0	1.0
Overspeed Acceleration (g's)	0.12	0.18	0.30
<u>Maximum Possible Speed</u> Main Guideway Speed	1.15	1.1	1.05
Maximum Deviation Control Acceleration (g's)	.067	0.1	0.167
Break Tolerance (%)	10	5	2
Safety Margin (feet)	7	5	3

2. POINT-FOLLOWER ANALYSIS

This chapter examines the ramp length reductions possible with point-follower control systems. The sections contain a framework discussion, simplified reference solutions, a summary of the computer program, and results.

2.1 FRAMEWORK

a. Phenomena

Consider two adjacent cars traveling under point-follower control. They operate on the main guideway with one unit of headway.

1. Station Entrance

The nominal profiles of two such cars approaching a station are shown schematically in Figure 3. Distance is shown as a function of time. The slope of the curves is the speed.

A hazardous condition exists if the lead car (the heavy solid line) is slowing down from main guideway speed to enter the station. Were it to continue at main guideway speed it would follow the light solid line. The following car is traveling through on the main guideway (the dark dotted line). Were it to decelerate into the station, it would follow the light dotted line.

At some point in its trajectory, the preceding car enters the station ramp (shown schematically by the shaded part of the solid heavy line). It must at least do this before the heavy lines cross. The purpose of the analysis is to determine the relationship between safe headway, the system parameters, and the start of the ramp.

2. Station Exit

Consider now a car that is accelerating to main guideway speed, merging one headway time behind a through car. The path of the acceleration is shown by the heavy solid line of Figure 4. If the car had been coming down the main guideway, it would follow the light solid line.

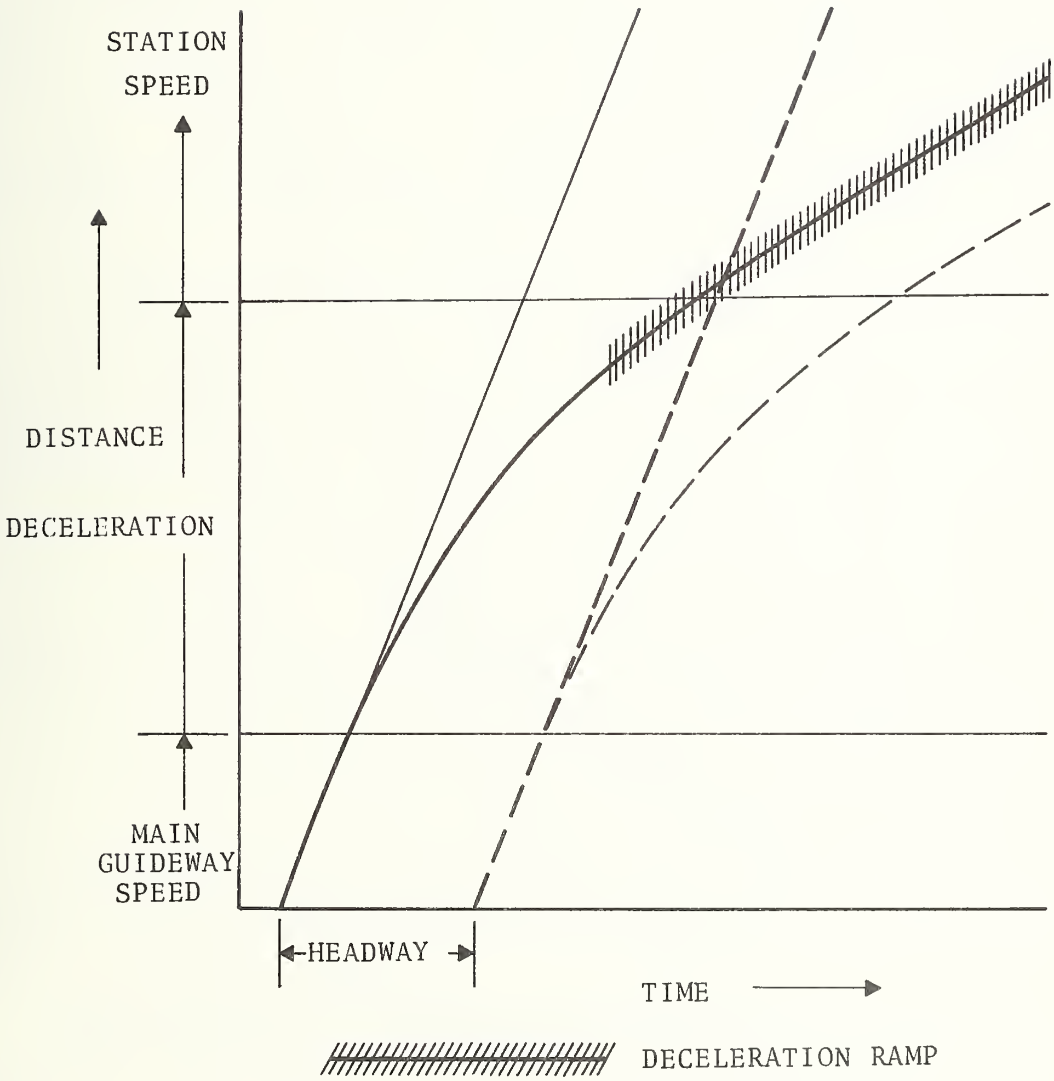


FIGURE 3 NOMINAL PROFILES AT STATION ENTRANCE

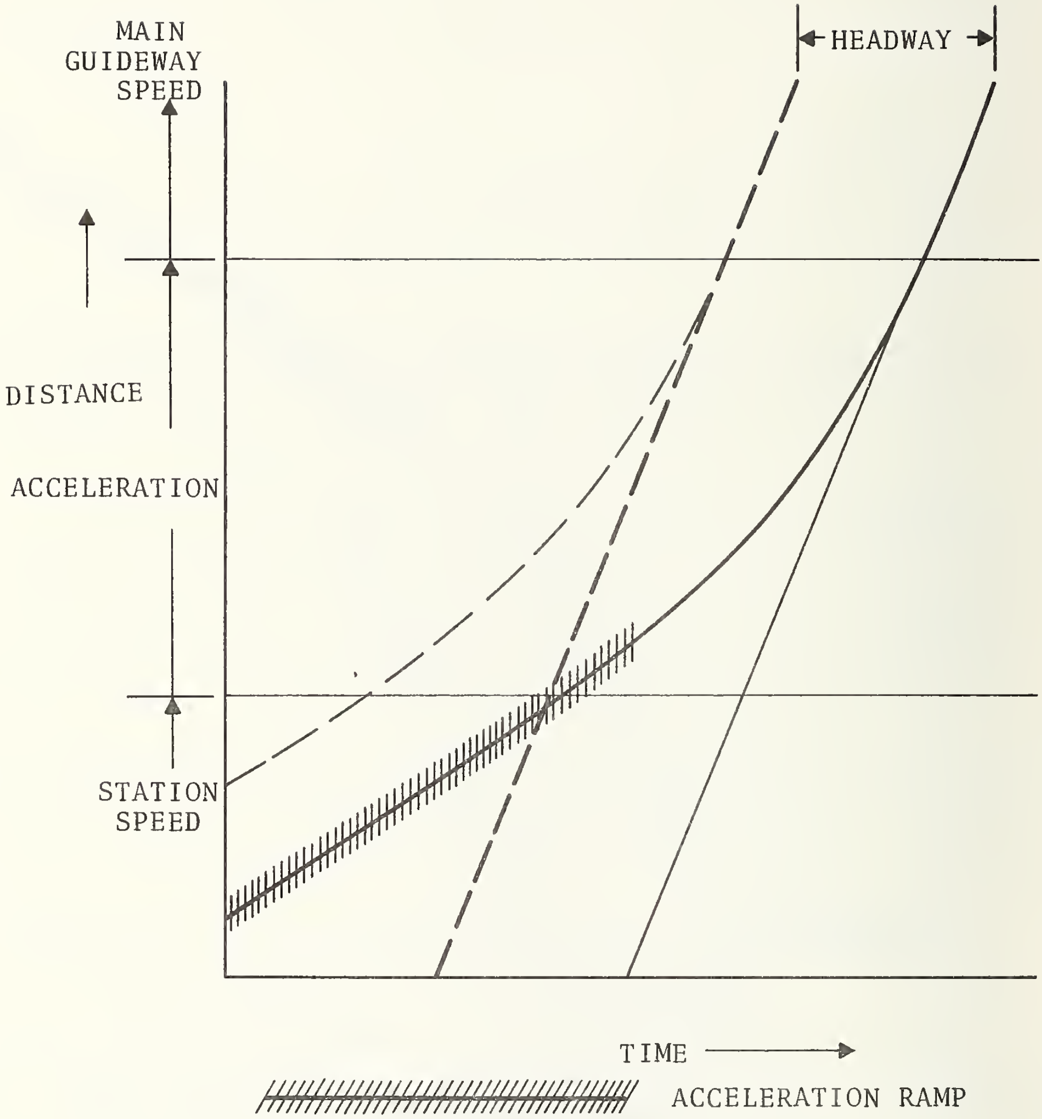


FIGURE 4 NOMINAL PROFILES AT STATION EXIT

The trajectory of the through car is shown by the heavy dotted line. Were the through car to have come out of the station, it would follow the light dotted line. The hazardous condition is that of the accelerating car following the through car. The opposite condition is shown by the light lines and is clearly less critical.

The end of the station ramp is shown schematically by the shaded solid line. Its safe location will, as in the case of the deceleration ramp, depend on system headway and the parameters of the system. From Figure 4 it is clear, however, that the ramp must extend past the intersection of the heavy lines, or else cars will collide in normal operations.

b.Deviations From Nominal Profile

The heavy lines in Figures 3 and 4 schematically represent the cars' nominal profiles. All of the cars will, in the course of normal operation, deviate from these profiles due to control tolerences, wind gusts, grade, etc. It is assumed that this deviation is within a position corridor. The half-width of the corridor is assumed to be proportional to the speed, such that

$$dx = CV \qquad (1)$$

where dx is the maximum distance deviation from a nominal trajectory (or half-width of the corridor) in feet,
V is nominal speed in feet per second, and
C is the corridor constant in seconds.

A position corridor is shown schematically in Figure 5. The nominal profile (the dark solid line) is a deceleration-speed change. Corridor width decreases in proportion to speed or the slope of the nominal profile.

It is now assumed that normal control deviations are approximated by a sinusoidal oscillation within the corridor. One such path is shown by the light solid line in Figure 5. This sinusoidal deviation is assumed to be limited by a maximum-deviation control acceleration, dA. Assuming a quasi-steady velocity and applying the standard harmonic relationships, we obtain the following

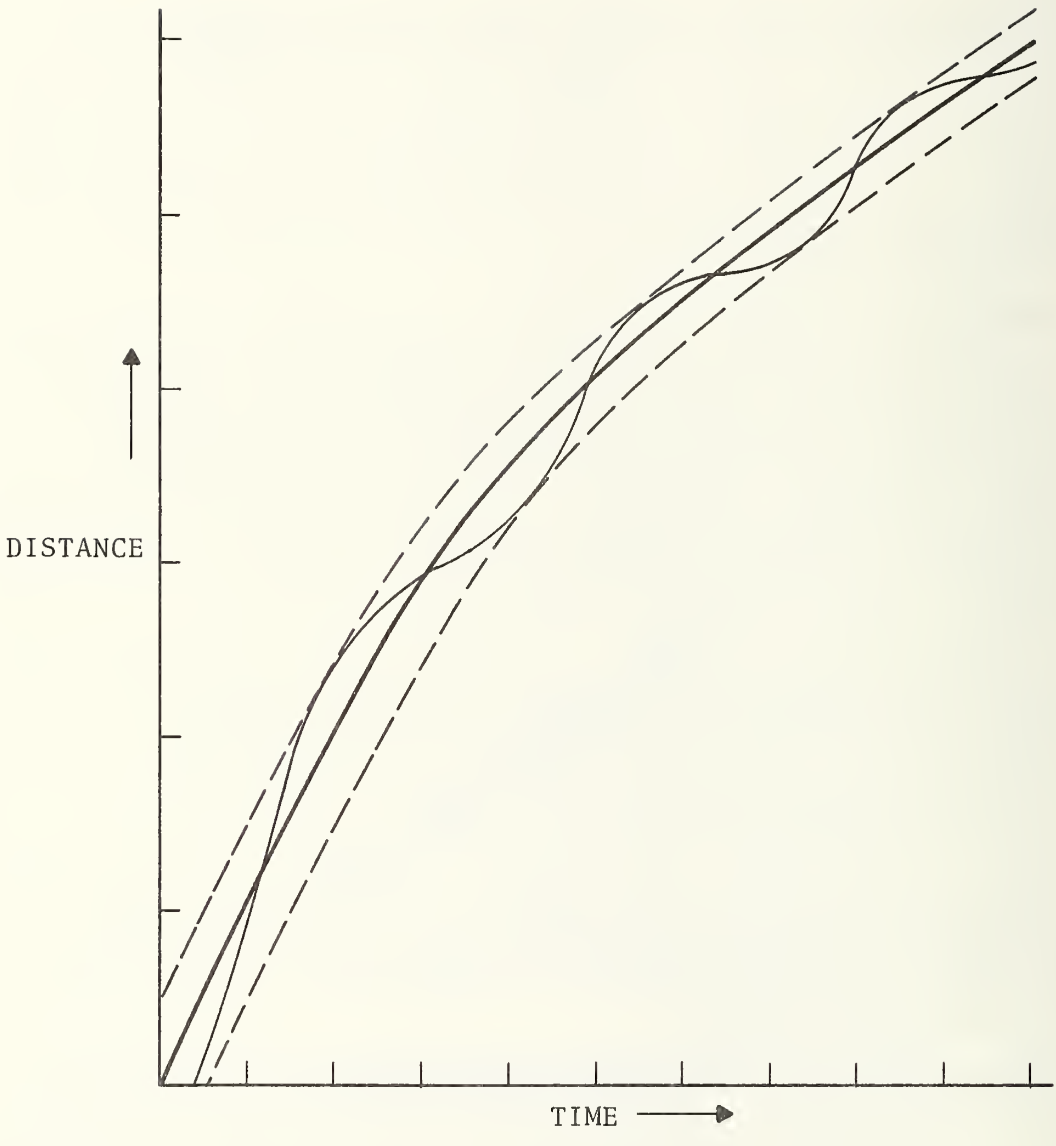


FIGURE 5 SCHEMATIC OF POSITION DEVIATION

expression for the maximum deviation velocity:

$$dV_m = \sqrt{dA_{cm}\ dx_m}\ , \tag{2}$$

where dV_m is maximum deviation velocity, in feet per second, and

dA_m is the maximum deviation control acceleration, in feet per second squared.

Combining Equations (1)and(2) yields the following expression:

$$dV_m = \sqrt{dA_{cm}\ CV}\ . \tag{3}$$

The expressions for the acceleration, velocity and position deviations are given by:

$$dA_c = dA_{cm} \sin \omega t, \tag{4}$$

$$dV = dV_m \cos \omega t, \tag{5}$$

$$dX = dX_m \sin \omega t, \tag{6}$$

where $\omega = \sqrt{dA_{cm}/dX_m}$ is the frequency of the sinusoidal deviation,

dA_c is the acceleration deviation, in feet per second squared,

dV is the velocity deviation, in feet per second, and

dX is the position deviation, in feet.

Normalized forms of Equations (4), (5), and (6) are plotted in Figure 6 as a function of the phase angle, ωt. Relative variations in position, velocity and acceleration are illustrated.

Plots of maximum velocity deviation and maximum position deviation for representative values of the corridor constant C are shown on Figure 7, for a 0.1g control acceleration.

c. Hazards

The position/velocity corridor defines the normal control deviation. It is now assumed that if the car is discovered beyond

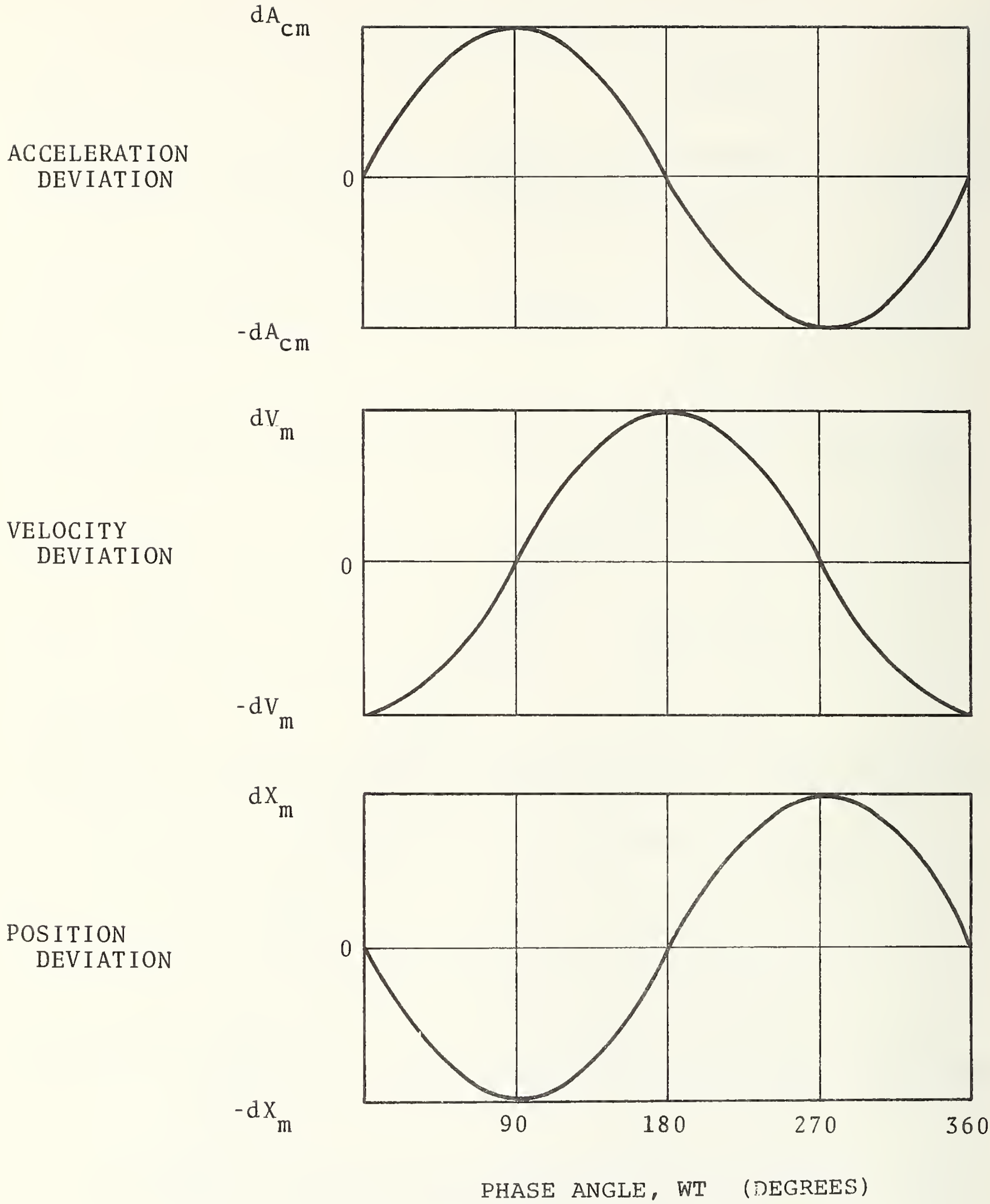


FIGURE 6 ACCELERATION, VELOCITY, AND POSITION DEVIATIONS VERSUS PHASE ANGLE

CONTROL ACCELERATION = 3.22 FT/SEC^2

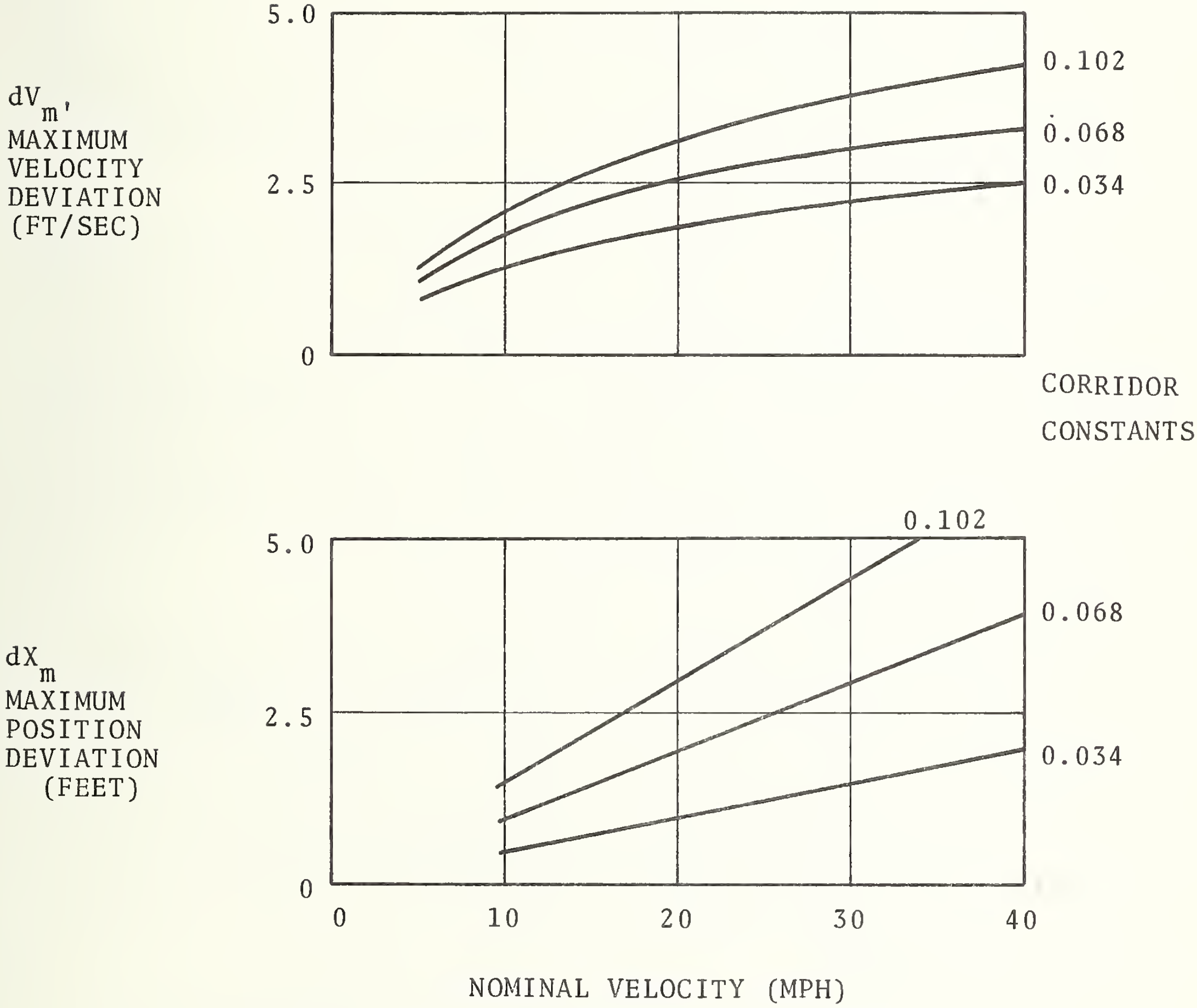


FIGURE 7 MAXIMUM DEVIATIONS OF VELOCITY AND POSITION

the corridor, an emergency is indicated, and immediate action must be taken.

The "worst" initial condition within the corridor will depend on the type of failure and on whether velocity or position error is being sensed. There is a corresponding worst initial position for the adjacent car.

1. Unexpected Stop

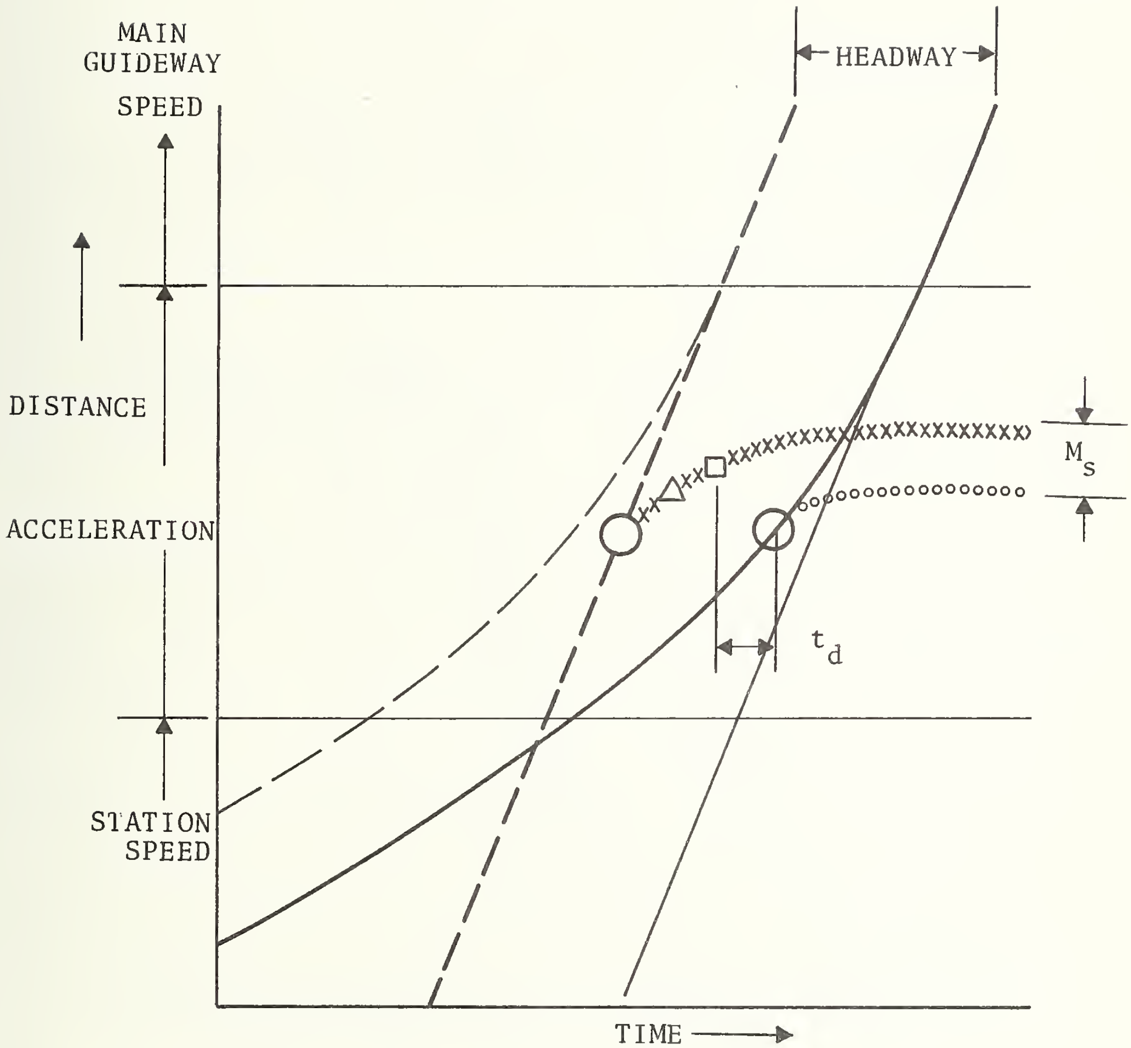
The unexpected-stop hazard is caused by the failure of a preceding car, assumed to take place at a constant g deceleration. (One g is assumed for the baseline cases in Table 1.)

A schematic representation of an unexpected stop on a station-exit acceleration ramp is shown by the "x" line in Figure 8. A circle is shown at the start of the unexpected stop to indicate that it might start anywhere within the car's position/velocity corridor. (Similarly, the unexpected stop of a preceding car entering a station might occur anywhere along the solid line of Figure 9. This case is not illustrated, but would be analogous to the one illustrated in Figure 8.)

2. Overspeed

The overspeed hazard is posed by a following car. We have assumed in the analysis that the car accelerates at constant g's to a "maximum possible" speed and remains at that speed until it is brought to an emergency stop. While other overspeed profiles are clearly possible this model satisfies realistic overspeed sequences. The baseline vlaues of overspeed, acceleration and maximum possible speed used for the results of Section II-D have been listed in Table 1.

The schematic view of the trajectory of a through car that overspeeds at a station entrance is shown in Figure 9. Again, the circle is shown at the start of the overspeed to indicate that the failure may start from anywhere within the deviation corridor. An overspeed can occur anywhere along the dotted line of Figure 9 (a following through-car), or along the solid line of Figure 8 (a following accelerating car). The sequence of events is the same.



xxxxxxxxxxx UNEXPECTED STOP

ooooooooooo EMERGENCY STOP

□ DISCOVERY TIME

△ "JUST CATCH" TIME

t_d DELAY TIME

M_s SAFETY MARGIN

FIGURE 8 UNEXPECTED-STOP FAILURE AT STATION EXIT

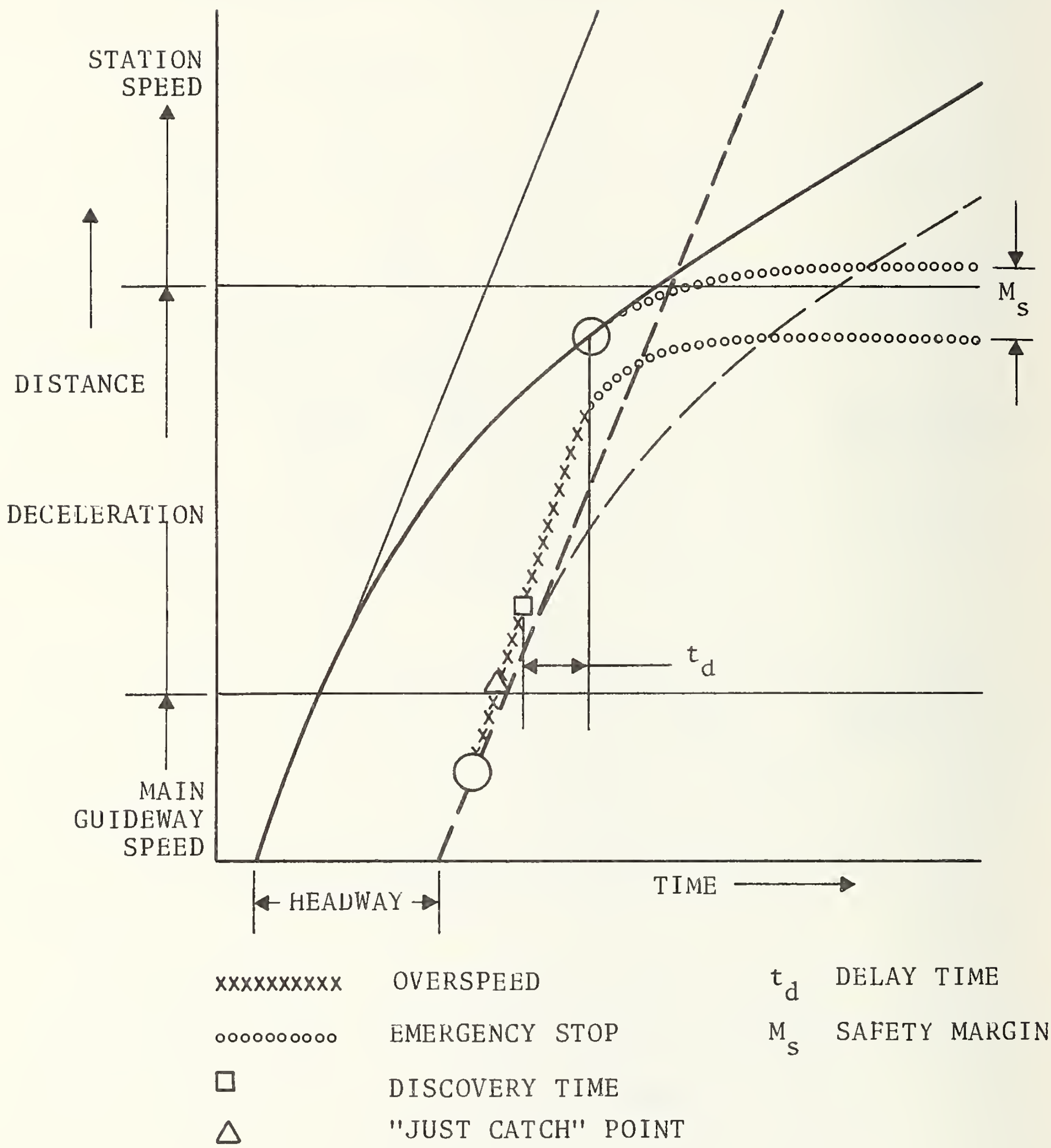


FIGURE 9 OVERSPEED FAILURE AT STATION ENTRANCE

d. Discovery of a Failed Car

A failing car will ultimately reach a point where its velocity or distance deviation is equal to the corridor width. This point is called the "just-catch" point. If a position or velocity error is measured at this point, the car will be considered safe. This point is thus a limiting condition for the analysis. Were the car beyond the corridor, it would immediately be considered unsafe. Were it just short of the maximum deviation values, it could have failed even earlier and still be considered safe. The "just-catch" point thus represents a "worst case." In other words, if a car "just catches" the deviation corridor at a measurement point, it will be the maximum possible distance outside of the corridor at the next measurement point. "Just-catch" points are shown in Figures 8 and 9 by triangles.

The position and velocity of the cars are assumed to be measured at fixed sample-time intervals. One sample-time interval after the "just-catch" point, the car will be discovered out of position. This is called the discovery time. The sample-time interval may vary - it is, however, within the analysis, assumed to be a constant. Discovery times are shown schematically in Figures 8 and 9 by squares. The squares and triangles are separated from each other by the sample-time intervals.

It is now convenient to consider the concept of standard sample-time interval. This interval is directly related to the corridor width and is consistent with available sensing techniques, such as check-in/check-out sensors or contiguous loops. Standard sample-time interval is the time required to move either from the center of one contiguous loop to the center of the next loop, or the time to move from one check-in/check-out sensor to the next.

The standard sample-time interval assumes that a car's position is checked each time the car is nominally due over the center of a loop. If it is within the loop, it is safe. If not, it is beyond the corridor and there is an emergency. The maximum deviation is half the loop's length. Thus, the standard sample-time interval, or the time to move from the center of one loop to the center of the next contiguous loop, is given by

$$S = 2C, \tag{7}$$

where S is the standard sample time interval, in seconds.

This model is precisely equivalent to a series of check-in/check-out sensors. A car traveling along the nominal profile will pass a sensor after each standard sample-time interval. The car's position is sensed when it is nominally halfway between the sensors. If it has checked in at the first sensor, and not checked out at the next, it is safe.

The standard sample-time interval of Equation 7 fixes the relationship between sample time and corridor width -- one that follows from a typical implementation of position-error sensors. The standard interval is also consistent with combined position- and velocity-error measurement. For example, velocity might be measured on board and broadcast to contiguous loops when the car is due over the center of those loops. Position and velocity would be measured simultaneously.

e. Emergency Stop

The analysis assumes that at the discovery time a sequence is started to bring the cars to an emergency stop. The elements of the sequence are: time to recognize that an emergency exists, possible time to modify the reaction if the system is in a degraded mode of operation, time to transmit a stop signal to the cars (send command, power off, etc.) and time to start to apply brakes. Delay time is shown by the symbol t_d in Figure 8 and 9.

It is assumed that the reaction to the emergency is to bring both cars to an emergency stop. In general, it will not be known what causes the emergency, and stopping both cars is the only all-inclusive reaction.

The emergency stop is assumed to follow a specified profile along the guideway, i.e., geometric deceleration. A trapezoidal deceleration history is assumed, governed by allowable emergency jerk and deceleration. Emergency-stop profiles are shown by the circles in Figures 8 and 9.

After both the failed car and the adjacent car have come to an emergency stop, they will, in the worst case, be separated by the safety margin, as shown in Figures 8 and 9.

f. Ramp Location

1. Station Entrance

Assume that the lead car in an overspeed emergency just enters the station ramp at the conclusion of its emergency stop. The headway required to maintain the specified safety margin between the lend car and an overspeeding following car, that has also come to an emergency stop, is a dividing-line condition. It defines the required headway for the length of that ramp (or, vice-versa, the ramp length for that headway). It is the result of an overspeed failure at a fixed point on the guideway. If that failure had taken place earlier (assuming that the headway is the same as the dividing-line condition) the safety margin would be greater than specified. If the failure had taken place later, the safety margin would be less than specified, but the preceding car would be on the ramp and laterally separated from the following car.

The reasoning process for an unexpected-stop failure of the preceding car is the same. The safe ramp length that goes with a given headway is defined by assuming that the lead car after a failure has entered the ramp and just cleared the guideway, and that the following car stops one safety-margin distance behind it.

The above discussion assumes that a preceding car that is slowing down to enter a station must make the turn onto the ramp even if it fails and that a car that is not entering the station must not switch, even if it overspeeds. These conditions can met by many PRT switching systems.

2. Station Exit

In Figure 8, the required ramp length for an unexpected stop of the preceding car is defined by the point at which the following car comes to rest after an emergency stop. The second car must not have entered the guideway at this point. Critical values of headway, safety margin and failure point are associated with this ramp length. If the ramp were shorter, or if the unexpected stop of the through car were to start sooner, the safety margin would be violated. If the ramp were longer and the failure took place a little later, there would be a larger-than-specified safety margin at the conclusion of the emergency.

While unexpected stops have proven to be more critical at the station exit than overspeeding, similar reasoning leads to a ramp length associated with the overspeed of the accelerating car.

2.2 SIMPLIFIED REFERENCE CASES

Two reference cases, one for the station entrance and one for the station exit, provide valuable insights into possible ramp savings.

a. Station Entrance

A simplified analysis of the station entrance provided the first assurance that sizable ramp savings might be possible, and led directly to the present study. The case is illustrated in Figure 10, and its argument goes as follows.

Assume that a lead car is entering a station along the heavy solid line, and that a following car is continuing down the main guideway following the heavy dotted line. Assume, in addition, that it is safe for both cars to enter the station at system headway; the first along the heavy solid line and the second along the light dotted line. Traditional practice would dictate that the lead car leave the guideway at point A. A little reflection will reveal, however, that the lead car might as well stay on the main guideway until B. At that time, the following car has not yet started to slow down, and so far as safety is concerned, it does not make any difference whether the following car is going to continue on down the guideway or turn off. If it is safe for both to decelerate into the station, it is also safe for both to stay on the main guideway. Thus, the ramp does not have to start, at least until point B. The ramp that is saved is the distance that the lead car has traveled in one headway time, or the distance from B to C. The length of the ramp is the deceleration distance, minus

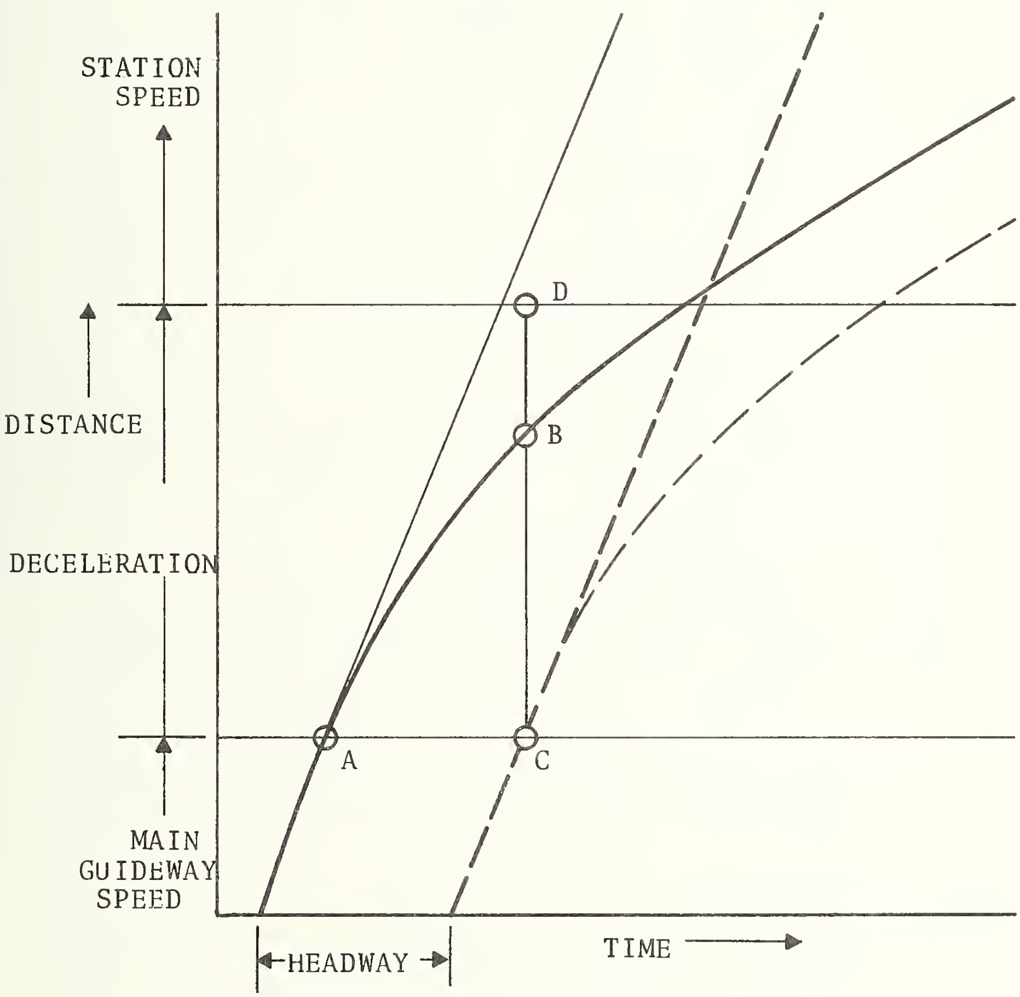


FIGURE 10 SIMPLIFIED MODEL FOR STATION ENTRANCE

MAIN GUIDEWAY SPEED = 20MPH
STATION SPEED = 5MPH

(ADJACENT CARS CAN SAFELY DECELERATE INTO STATION)

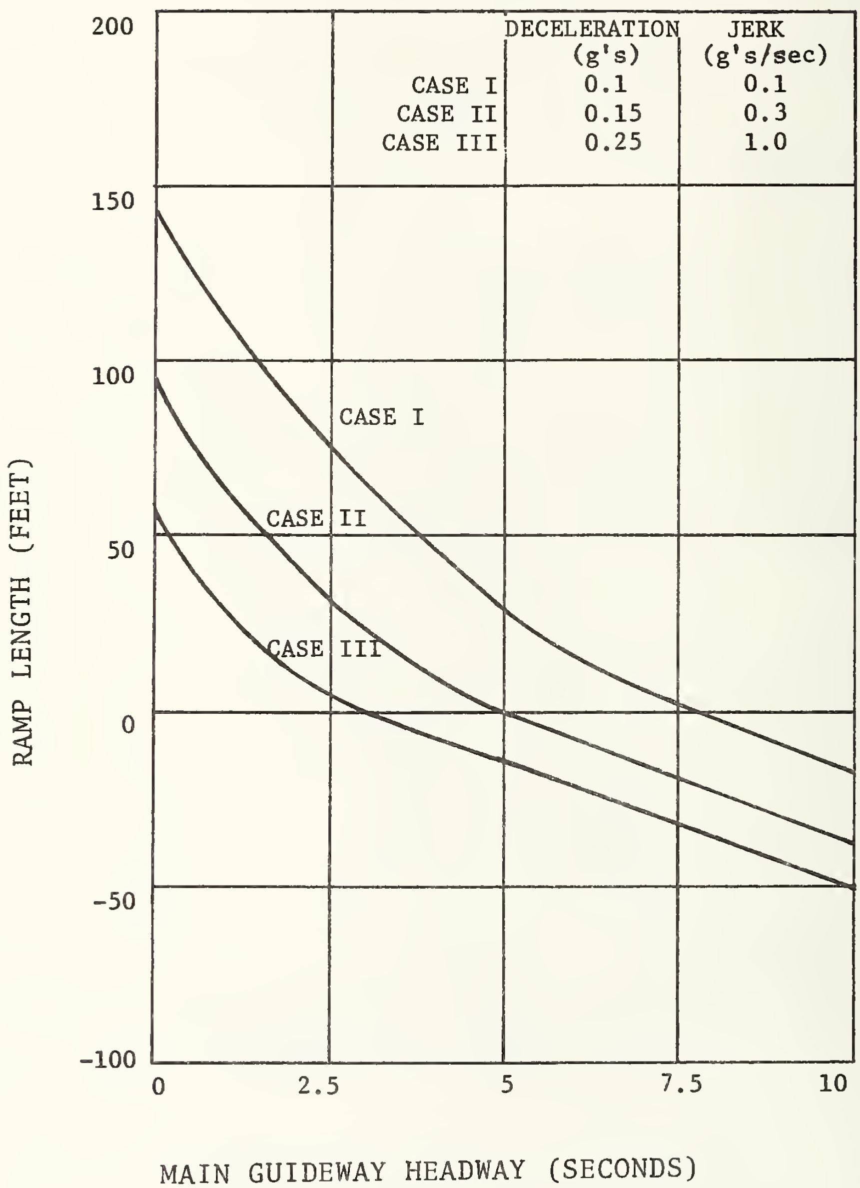


FIGURE 11 DECELERATION RAMP LENGTH - SIMPLIFIED MODEL FOR STATION ENTRANCE (20 MPH)

MAIN GUIDEWAY SPEED = 30 MPH
STATION SPEED = 5 MPH
(ADJACENT CARS CAN SAFELY DECELERATE INTO STATION)

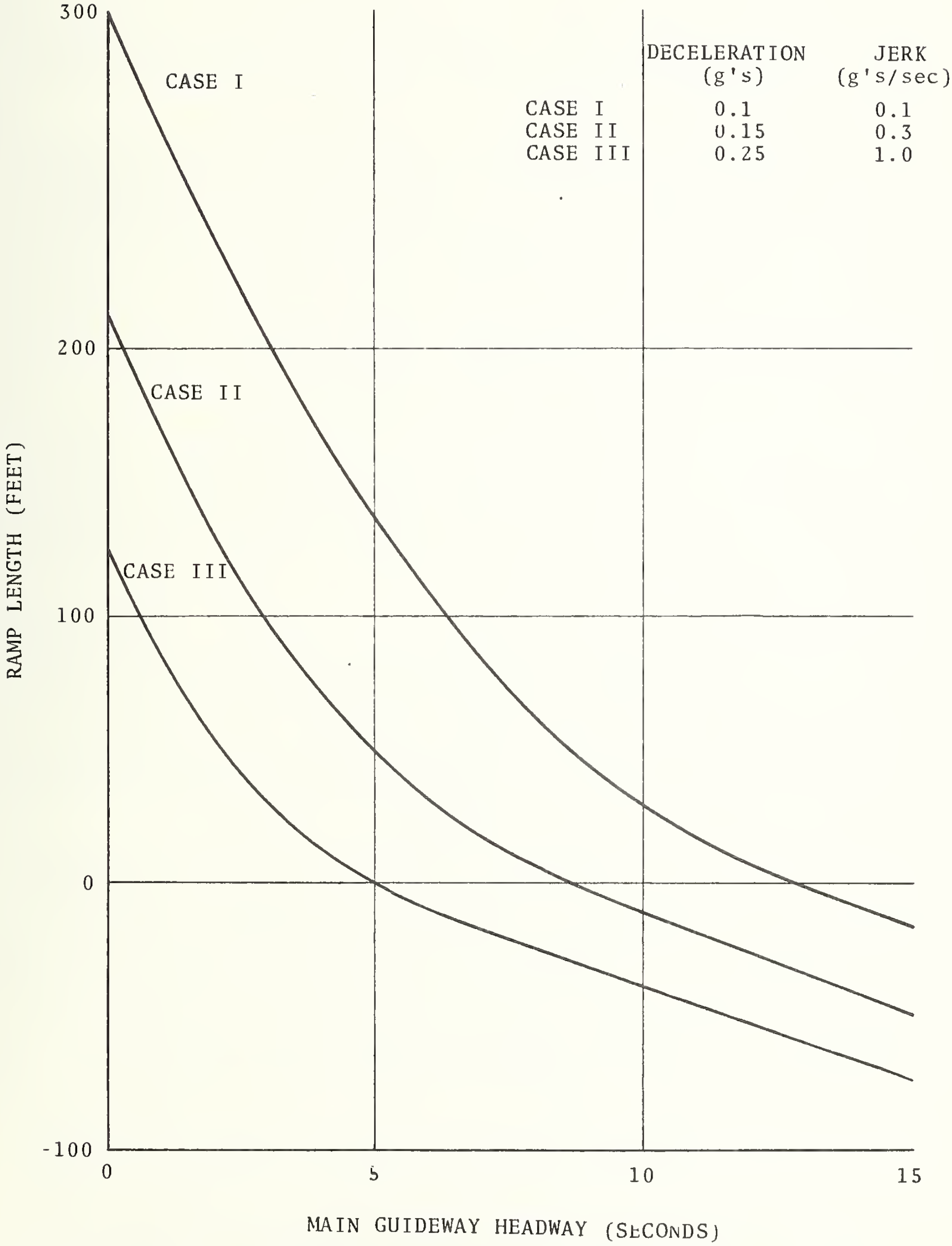


FIGURE 12 DECELERATION RAMP LENGTH-SIMPLIFIED MODEL FOR STATION ENTRANCE (30 MPH)

the distance from B to C. This distance from B to D is plotted against headway on Figures 11 and 12, for the baseline deceleration parameters of Table 1.

Negative ramp lengths indicate that the lead car can actually travel for a distance at station speed before it has to turn off the main guideway.

Note that the curves of Figures 11 and 12 do not define the headway required for safety; rather, they define the ramp length given that the headway is sufficient for successive cars to decelerate into the station. Possible savings are clearly very large. For example, with Case II ("improved" parameters) and a headway of 8 seconds, the ramp can be eliminated. With a traditional station design, the ramp would have to be over 200 feet.

The ramp lengths of Figures 11 and 12 are maximums. The detailed results of Section 2.4 indicate that even shorter deceleration ramps are possible; however, the simplified model remains a very useful approximation.

b. Station Exit

The simplified model for the station entrance may be "turned around" for the station exit, as shown in Figure 13. By the reasoning of the previous section, the maximum ramp length is the distance from B to D, the same distance plotted in Figures 11 and 12.

Later analysis, using the Point-Follower Headway Safety Program, showed, however, that this model was too conservative. In reality, acceleration ramps could be much shorter than deceleration ramps. A better reference model is to assume that the ramp ends at the intersection of the through and accelerating cars; i.e., at point A. The ramp length is A to E (which for the schematic view of Figure 13 is negative). The accelerating car in normal operation just misses the through car at A. Clearly, the cars cannot coincide at A since space must be left for safety margin and the length of the car. However, since these lengths will vary and point A is reproducible for all car lengths and safety margins, it is used in the simplified model. Even though point A defines a

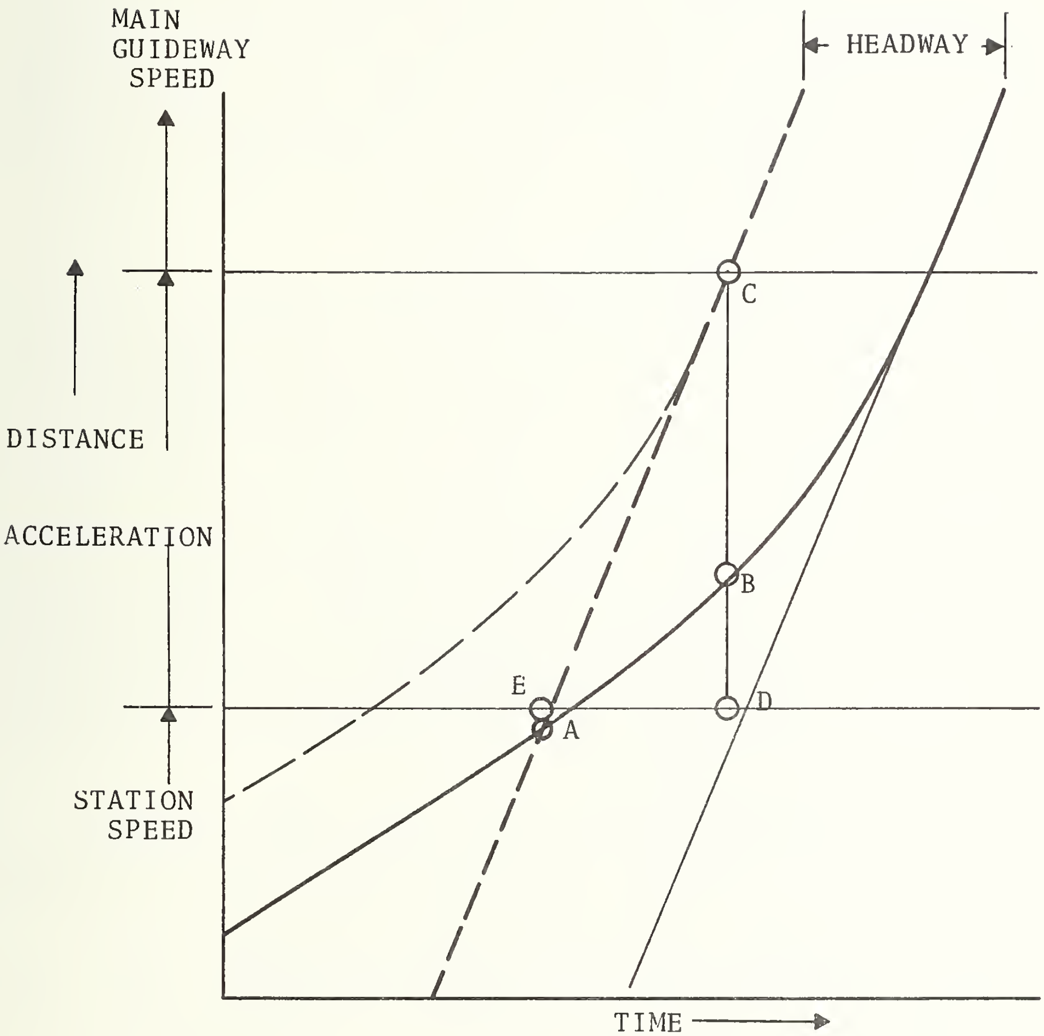


FIGURE 13 SIMPLIFIED MODEL FOR STATION EXIT

minimum ramp length, it is shown in Section 2.4 that with some allowance for safety margin and car length, it reliably predicts the ramp length required for acceleration. The ramp length defined by the length A to E is plotted on Figures 14 and 15 for the three reference acceleration parameters and main guideway speeds of 20 and 30 mph.

As with the deceleration ramp, the required length decreases with increasing headway. The fact that the ramp might be eliminated, even for headways as short as 1.5 seconds (with advanced parameters), is highly significant. We see that the required acceleration ramp lengths are appreciably shorter than the deceleration ramp lengths of Figures 11 and 12.

2.3 POINT-FOLLOWER HEADWAY SAFETY PROGRAM

The Point-Follower Headway Safety Program mechanizes the failure sequences discussed in Section 2.1. This section contains a short description of the program and its operating options.

a. Program Description

The program is written in FORTRAN IV, for the PDP-10. Input is either interactive through a console or by cards through a stored data file. Output is via either a line printer, a display console or a Calcomp plotter. An optional output file is generated for the display and plotting routines. An overall schematic of the program is shown in Figure 16.

The inputs and outputs of the program are shown in Table 2.

For a given set of inputs, the program goes through the following schedule. A range of "just-catch" times is examined for the unexpected stop of preceding cars. Typically, the time range starts a short time before the speed change, and ends a short time after the speed change. Next, the same zone is examined for overspeed of a following car. Both overspeed and unexpected stops are then examined for each specified increment in the main guideway speed. Finally, both overspeed and unexpected stop, for a full range of speeds, are examined for each specified increment in the size of the position or velocity corridor (as specified by the corridor constant).

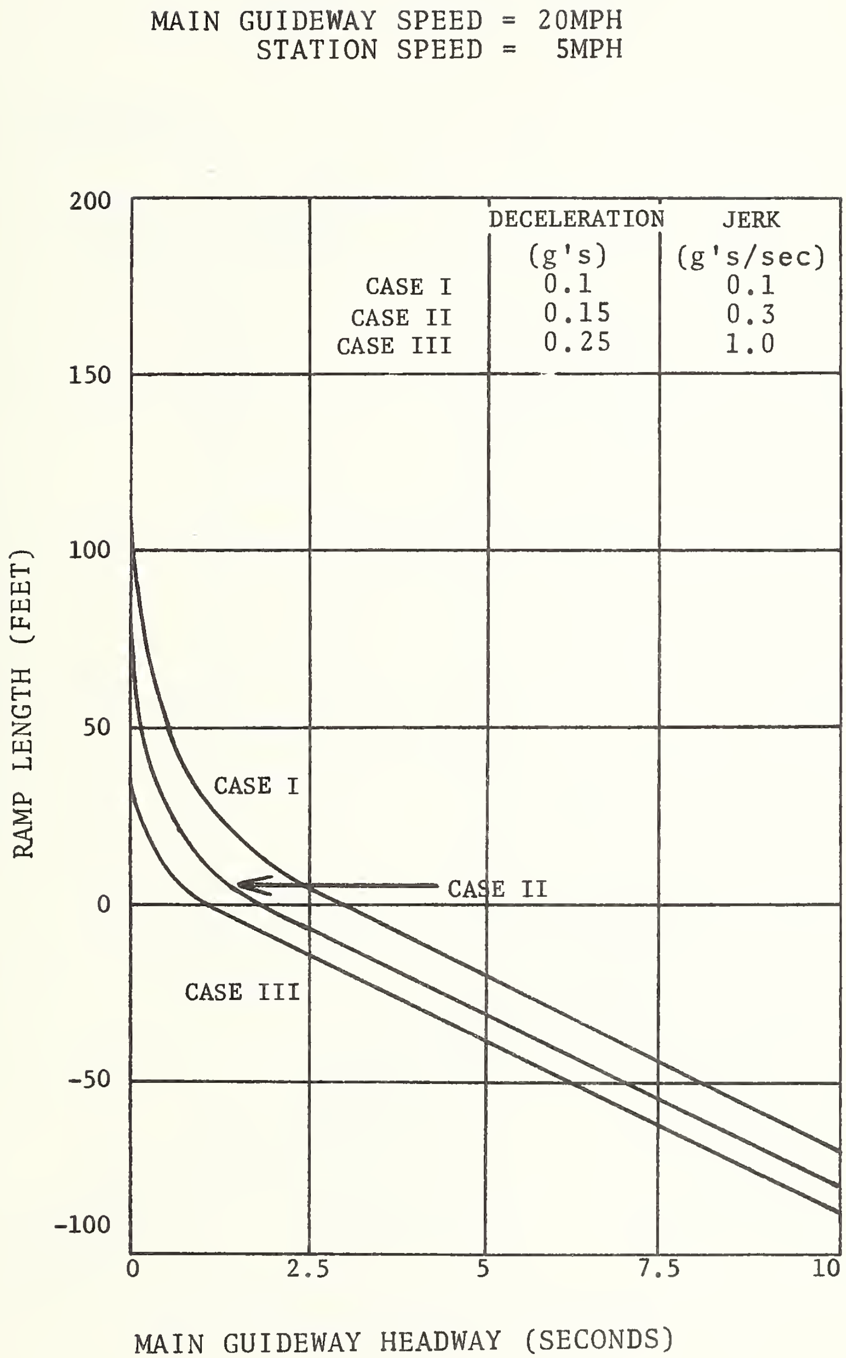


FIGURE 14 ACCELERATION RAMP LENGTH - SIMPLIFIED MODEL FOR STATION EXIT (20 MPH)

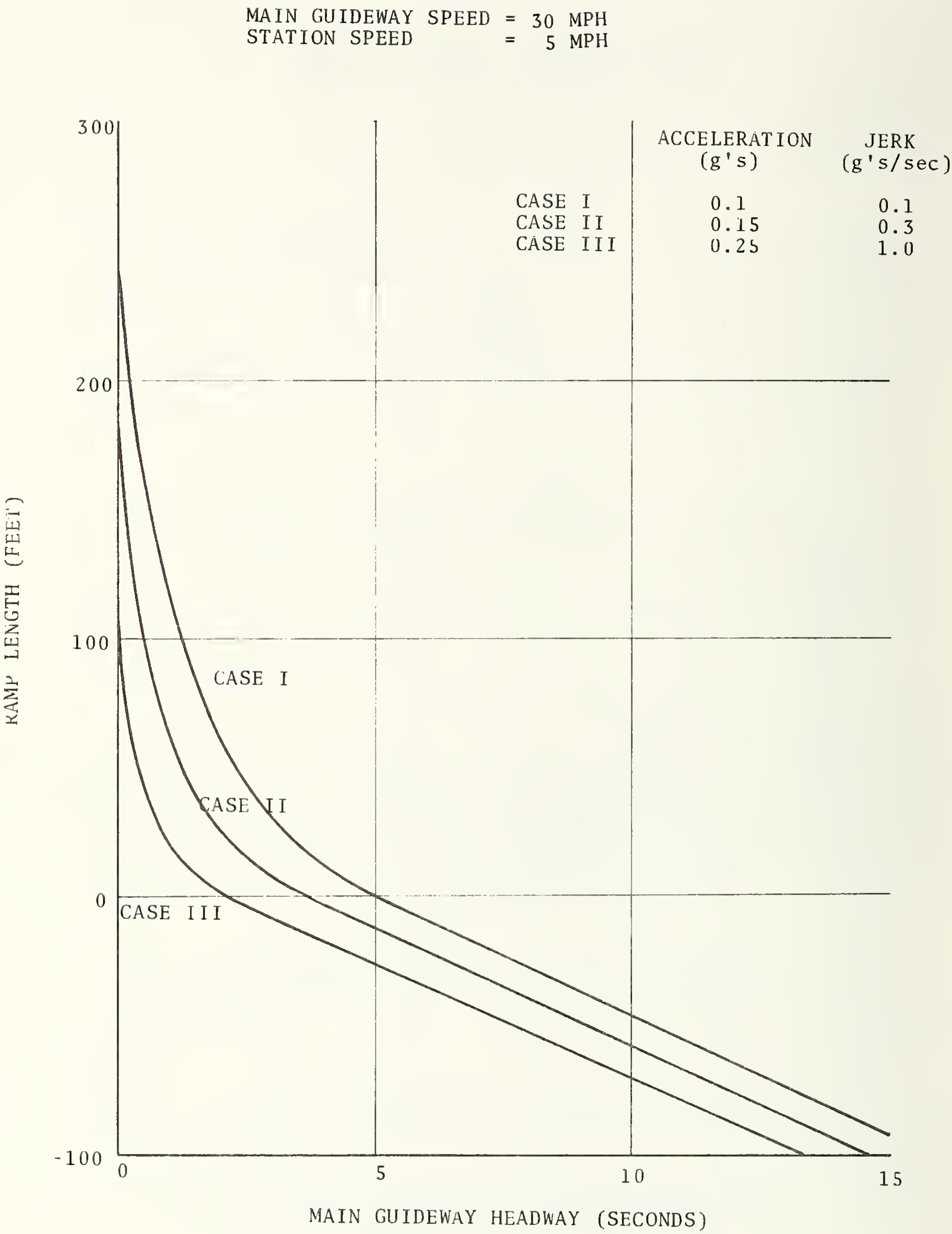


FIGURE 15 ACCELERATION RAMP LENGTH - SIMPLIFIED MODEL FOR STATION EXIT (30 MPH)

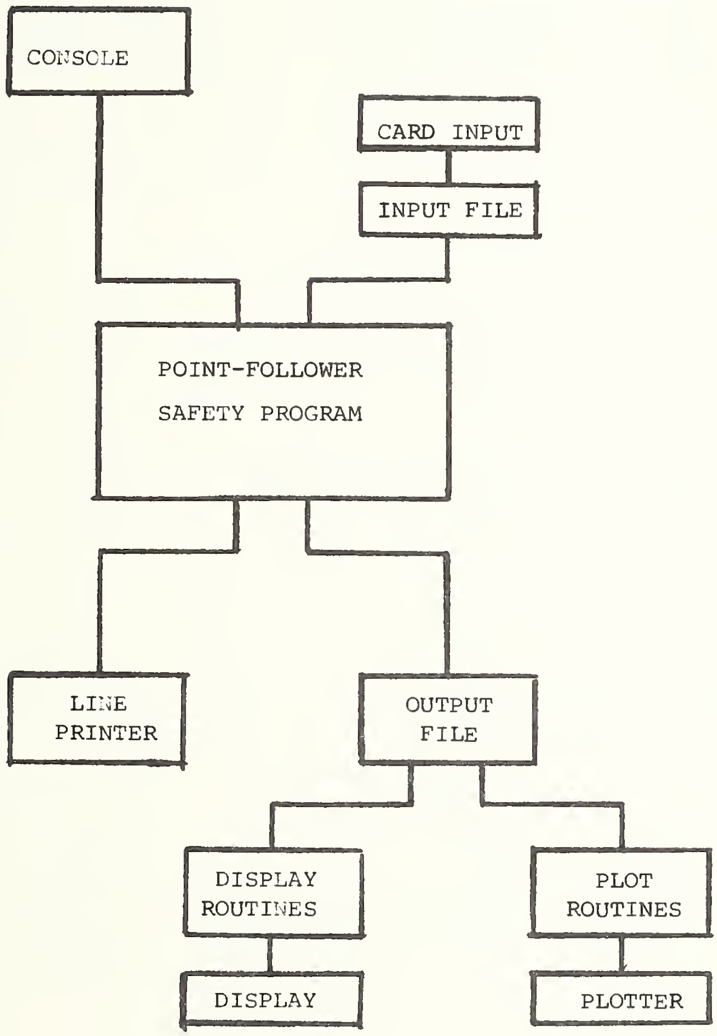


FIGURE 16 POINT-FOLLOWER SAFETY PROGRAM - OVERALL SCHEMATIC

TABLE 2 INPUTS AND OUTPUTS OF POINT-FOLLOWER HEADWAY SAFETY PROGRAM

Inputs

- Control Options
  - Card Input
  - Output File
- Error Detection Option
  - Velocity-error Sensing
  - Position-error Sensing
- Program Option
  - Constant Safety Margin
  - Constant Headway
- Guideway (Short Ramp) Option
  - Cars follow same acceleration or deceleration profile.
  - One accelerating or decelerating car, one through car.
- Ranges of
  - Speed
  - Deviation Corridor
  - Guideway Area to be Investigated
- System Parameters
  - Car Length
  - Brake Tolerance
  - Delay Time
  - Safety Margin
  - Maximum Possible Speed
  - Control Acceleration
- Nominal Acceleration/Decelerations
  - Failed Car Unexpected Stop
  - Failed Car Overspeed
  - Emergency Stop
- Initial Position in Deviation Corridor
- Definition of Nominal Distance-Velocity Profile
  - Acceleration
  - Deceleration
  - Shape

TABLE 2 (CONTINUED)

<u>Outputs</u>

- Speed and car positions at the "just catch" time
- Speed and position when car starts to fail
- Speed and position when failed car's brakes go on (overspeed failure only)
- Stopping point for failed car
- Speed and position of avoiding car when it starts to emergency stop
- Stopping point of avoiding car
- Headway Required
- Safety Margin
- K Factor

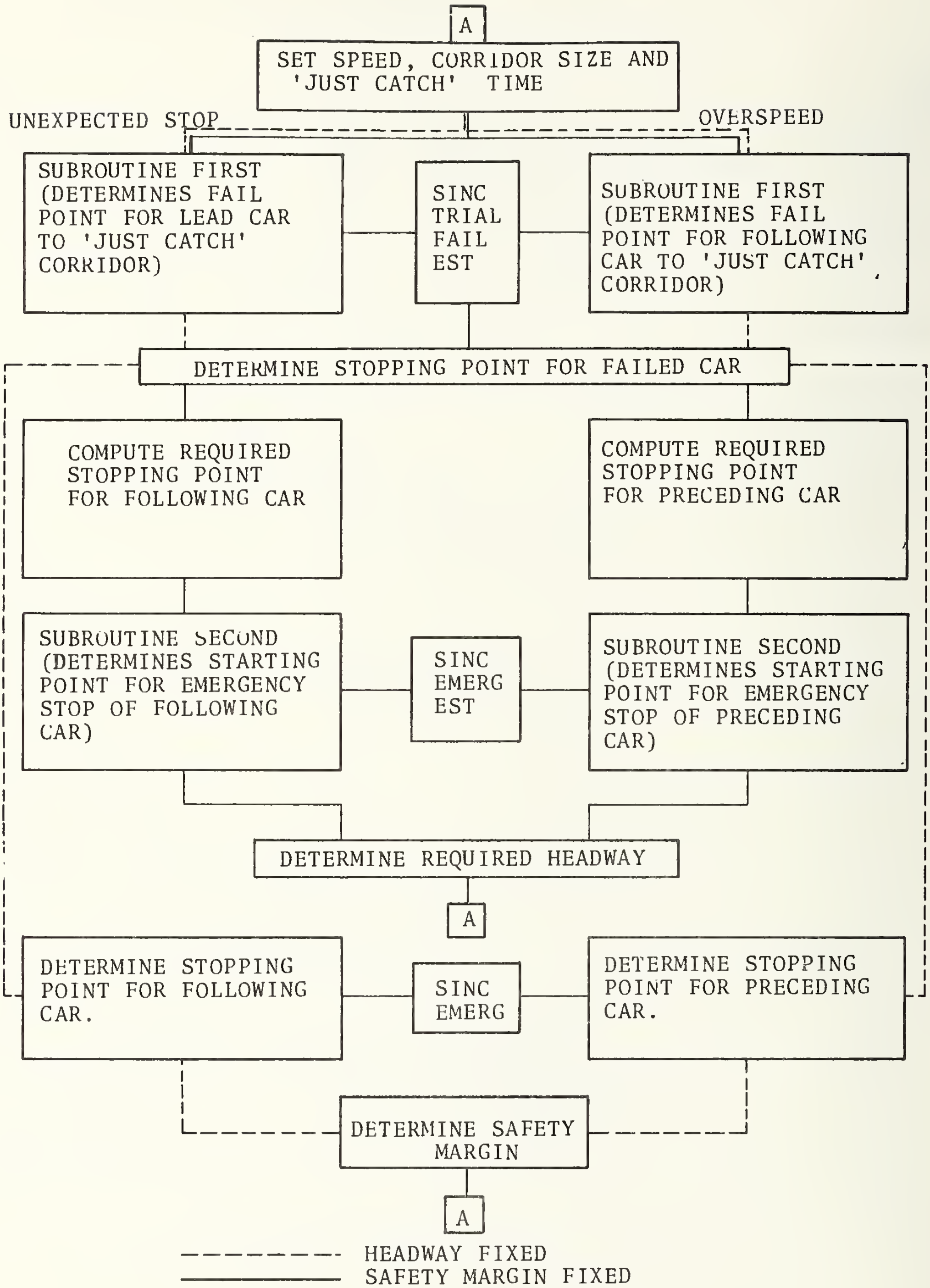


FIGURE 17 POINT-FOLLOWER HEADWAY SAFETY PROGRAM-BASIC COMPUTATION SEQUENCE

A block diagram of the "interior" of the point-follower safety program is shown in Figure 17. It will be noted that there is a parallel structure to the program, allowing multiple use of the subroutines.

The functions of the subroutines are brefly discused below.

FIRST follows an iterative procedure to determine the failure time that makes the failing car just catch the edge of its velocity or position corridor.

SECOND follows an iterative procedure to determine when the avoiding car must begin to stop so that at the completion of the stop it will be one safety margin away from the failed car.

SINC accepts time in seconds as an input and outputs the nominal trajectory of an accelerating, decelerating or through car. Alternative profiles are accommodated by branching within the subroutine; no other part of the program is affected.

TRIAL determines the initial trial value of failure time that will cause the car to just catch the edge of the corridor.

FAIL determines the position and speed of a failed car at "just catch" time. It also determines the final stopping point for a car that has unexpectedly stopped and the position of an overspeeding car when it starts to emergency stop. Alternative failure profiles can be introduced independently.

EST estimates new trial values of failure or emergency-stop time using linear prediction.

EMERG computes the emergency-stop point, given initial conditions. At present, it assumes a trapezoidal stopping profile. Alternative profiles can be introduced by branching within the subroutine.

b. Operating Options

Any of the three options (constant headway, velocity error, and on-guideway speed change) described below may be independently specified. There are thus eight possible investigation modes, applicable to either the acceleration ramp or the deceleration ramp. All options consider both unexpected stop and overspeed.

1. Constant-Headway Option

If this option is specified, the program fixes the headway and computes the safety margin. Otherwise, the safety margin is fixed and the program determines the headway required for each failure point. For both cases the corridor constant is also specified. If headway is fixed, corridor width is always adjusted downward to insure an integral number of standard sample-time intervals in one headway time. If safety margin is fixed, the headway is adjusted upward to an integral multiple of the standard sample-time interval. In this way the model remains consistent with a realistic loop or check-in/check-out monitoring system.

The fixed headway option allows the user to examine what occurs on a real system with constant headway. The program determines where cars will be after "worst case" failures at all failure points. The resulting safety margin will vary, reaching a minimum at the critical design condition.

When the safety margin is specified and the headway determined, it is necessary to follow an iterative procedure to determine, for a given failure, what headway just meets the required safety margin. When headway is fixed, however, this procedure is not necessary; this is shown by the by-passing dotted lines in Figure 17. The position of the avoiding car is known through the headway and assumed to be brought to an emergency stop one delay time after the failed car is doscovered. The distance between cars after they have both come to a stop can then be computed directly. The distance may be negative, if insufficient headway has been specified - indicating the possibility of a collision.

2. Velocity-Error Option

For the velocity-error option, the "just catch" criterion is applied to the speed corridor. Otherwise it is applied to the position corridor.

The subroutine FIRST (Figure 17) determines the failure point that makes the car just safe at the specified "just catch" time. At this point, the speed deviation will be equal to the maximum deviation discussed in Section 2.1.b.

Two trial failure times are first obtained from the subroutine TRIAL. Then, the required failure time is determined by iteration.

The SINC subroutine determines nominal speed and position at the trial failure times. Actual position is adjusted to the "worst case" initial position within the deviation corridor.

The subroutine FAIL then determines the associated speeds at the "just catch" times. The subroutine EST chooses subsequent fail times until the speed at the "just catch" time is equal to the maximum allowable deviation.

Exactly the same sequence is followed if position-error sensing is specified except that the position corridor defines the allowable position (rather than velocity) at the "just catch" time.

3. Guideway Option

If the guideway option is chosen, the following car (for a deceleration speed change) or the preceding car (for an acceleration speed change) is assumed to remain on the main guideway at main-guideway speed. Diagrams of this option are discussed in Section 2.1. The adjacent car follows the change in acceleration or deceleration speed.

The guideway option is introduced through the subroutine SINC, which specifies the nominal position of the car as a function of time.

If the guideway option is not specified, both cars follow the same nominal profile.

2.4 RESULTS

The Point-Follower Headway Safety Program, described in Section 2.3, is used to obtain typical results for baseline Cases I, II, and III. The parameters of these cases, representing "state-of-the-art," "improved," and "advanced" PRT, have been tabulated in Table 1.

a. Headway for Adjacent Cars on the Same Profile

This section discusses the headway required for two cars, following the same profile. Required headways, on the main guideway, on the deceleration ramp, and at station speed (5 mph), are tabulated in Table 3 for overspeed and unexpected-stop failures. These results assume a very narrow (essentially zero-width) velocity corridor; i.e., the control system is nearly perfect and there is almost instantaneous detection of vehicle failures. The corridor width is not exactly zero, since this assumption leads to singularities in the program solution.

Results are not tabulated for the acceleration ramp because there is no definable maximum headway. The required headway typically reaches a minimum between the station and the main guideway, rather than a maximum.

The critical headway condition for each case is shown with an asterisk. It always occurs on the deceleration ramp. As the preceding car on a deceleration ramp slows down, the separation between it and the following car decreases. Thus, the hazard to the cars is greater. Unexpected stop is the critical hazard for Cases II and III, and overspeed for Case I.

The headways required on the main guideway are noticeably shorter than those required on the deceleration ramp. The worst hazard is, in all cases, the unexpected stop of a preceding car.

Required headways at station speed are greater than on the main guideway, although not as great as for the deceleration ramp. At low speeds, it takes a long time for the car to move its own length. This time must be added directly to the headway. For example, with a 20-foot car, moving at 5 mph, it takes about 2.7 seconds, while it only takes 0.45 seconds at 30 mph.

The change in main guideway speed from 30 to 20 mph only affects the headways on the main guideway. The critical failure point on the deceleration ramp is far enough down the ramp so as not to be affected by the main guideway speed. Near the end of the ramp, the velocity profile for deceleration from either 30 mph or 20 mph is the same.

TABLE 3 REQUIRED HEADWAYS FOR REFERENCE CASES

"Zero Width" Speed and Position Corridor

	Delay Time (Sec)	Main Guideway Speed (mph)	Required Safe Headway (Seconds)					
			Main Guideway		Deceleration Ramp		Station Speed (5mph)	
			US	OS	US	OS	US	OS
CASE I	0.4	20 30	3.18 3.67	1.57 1.44	5.41 5.41	5.51* 5.51*	4.75 4.75	4.13 4.13
CASE II	0.1	20 30	2.39 2.68	1.11 0.91	4.89* 4.89*	4.58 4.58	4.09 4.09	3.56 3.56
	0.2	20 30	2.49 2.78	1.19 0.98	4.99* 4.99*	4.99 4.99	4.19 4.19	3.67 3.67
CASE III	0.05	20 30	1.12 1.15	0.58 0.47	2.63* 2.63*	2.39 2.39	2.19 2.19	1.87 1.87
	0.1	20 30	1.17 1.20	0.61 0.50	2.68* 2.68*	2.55 2.55	2.24 2.24	1.92 1.92

US -- Unexpected Stop of Preceding Car
OS -- Overspeed of Following Car
* -- Maximum Headway for Given Case

b. Detailed Examination of Case II

In this section, detailed results are presented for Case II parameters at 30 mph with 0.1-second delay time and "zero width," corridor. This case is shown on Line 4 of Table 3. The results make use of curves plotted automatically, using the plotting routines developed under the program.

1. Deceleration Ramp

a) Adjacent Cars Decelerate

Figure 18 is a plot of the nominal headway required as a function of the point at which a car fails--either by overspeeding or by coming to an unexpected stop. The safety margin is held at 5 feet. For each failure point, the plotted headway is required in order to insure that 5 feet separates adjacent cars after the failure. For example, if a following car unexpectedly starts to overspeed 100 feet after it has started to decelerate, the preceding car has to be operating at a nominal headway of about 2.9 seconds in order to insure safety for a worst-case failure. Similarly, if a preceding car starts to come to an unexpected stop 140 feet after it has started to decelerate, the nominal headway has to be about 3.8 seconds.

The length of the deceleration zone is shown by the vertical dotted lines. The constant required headways shown to the left are for the main guideway; those to the right are for the station. The values are the same as those of Table 3. The deviations from these constant headways occur when one or other of the cars is decelerating. Thus, an unexpected-stop failure beyond the deceleration zone will require different headway because the following car is still decelerating. Conversely, the headway will change for an overspeed failure prior to the deceleration, since the preceding car will have already started to decelerate.

As pointed out in the last section, maximum required headways occur for failure near the end of the deceleration -- the unexpected stop requiring a headway of 4.89 seconds. The fact that the critical region of failure is the end of the deceleration ramp suggests that the peak required headway might be reduced if the

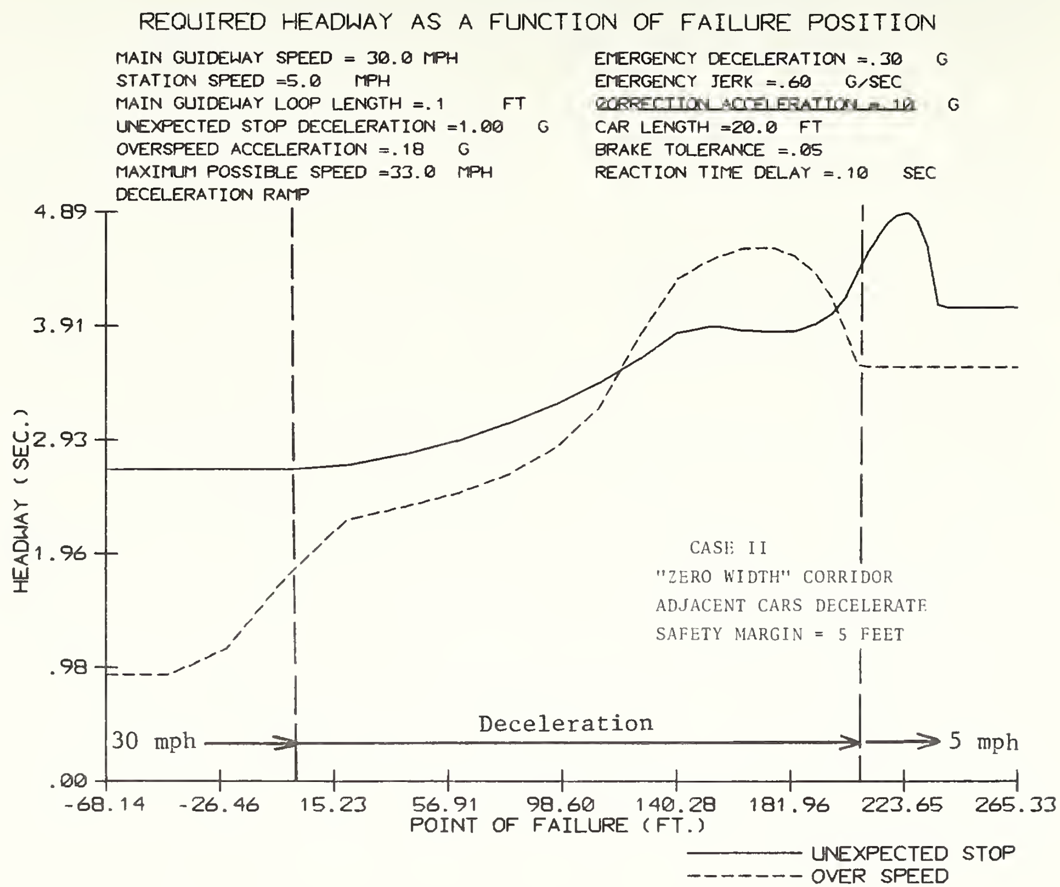


FIGURE 18 REQUIRED HEADWAY AS A FUNCTION OF FAILURE POSITION, ADJACENT CARS DECELERATE

nominal velocity profile were stretched out at the end of the ramp. This point should be investigated further.

A somewhat different perspective is achieved if the headway is fixed at the maximum required for the deceleration, and the safety margin after an emergency is then computed. Results of this operation are shown in Figure 19.

Figure 19 is the case of a real system, operating at a constant headway. Safety margins are very large for main-guideway failure (102.9 feet for unexpected stop) and fall to 5 feet for an unexpected stop at the end of deceleration. It will be noted that a steady-state value for the case of overspeed is not achieved within the range of the graph, as it was in Figure 18. The headway for the failure computation is now 4.89, not 0.91 seconds, and the overspeeding car has to be a full 4.89 seconds, or 215 feet, ahead of the start of deceleration in order for the preceding car still to be on the main guideway. Basically, the dotted curve continues on up to the left.

The plot of K factor for the constant headway condition is shown in Figure 20. Since the headway is fixed, the K factor is the same for overspeed and unexpected stop. Equal values of K factor are offset, however, by the nominal separation of the preceding and following cars. The K factor for an overspeed failure is the same as the K factor for the unexpected stop of a car one separation distance ahead. As would be expected, K factor reaches a minimum of 1.28 at the critical points near the end of the deceleration. Maximum K factor is actually achieved at station speed.

Figures 19 and 20 contrast K factor and safety margin as a measure of relative safety. Both show worst conditions near the end of the deceleration. While safety margin rises rapidly for earlier failure, K factor increases only moderately. While the safety factor is low at station speed, K factor is quite large. The signifigance of these changes is not clear. In a sense, K factor weights the safety margin by a factor of speed squared. Since potential danger may be thought of as proprotional to speed

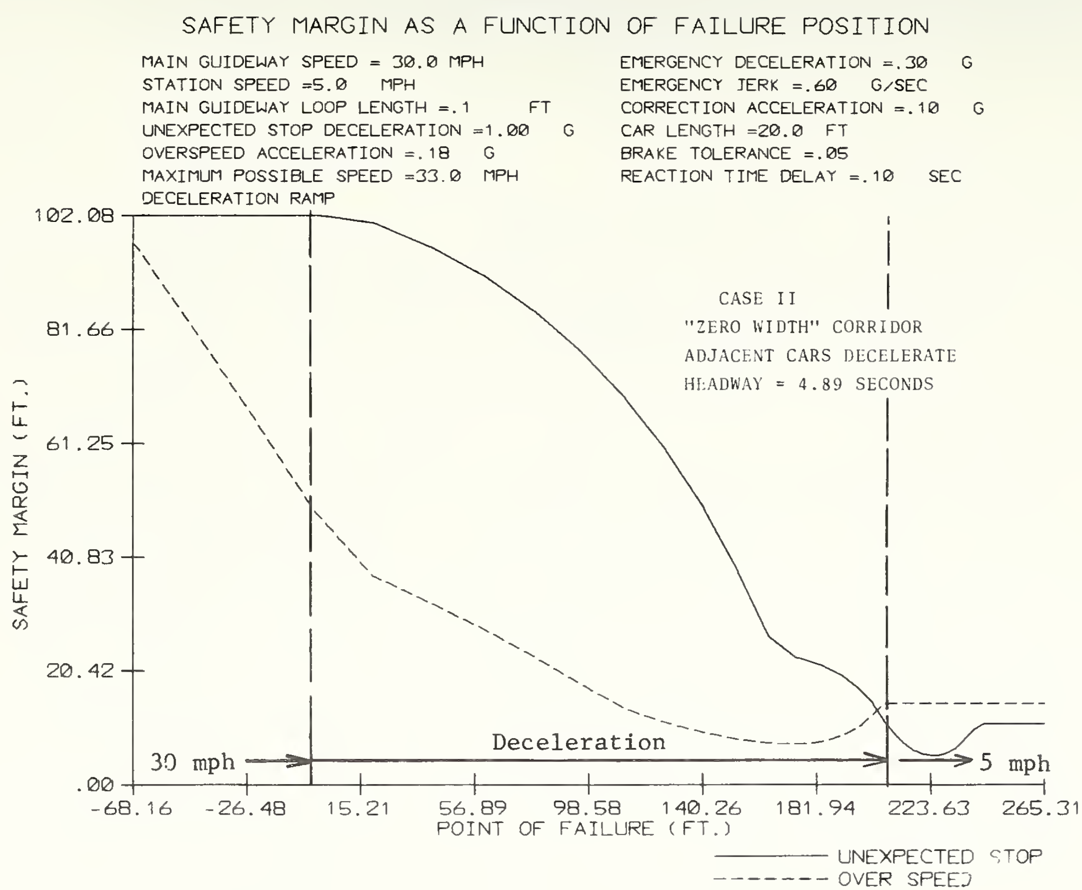


FIGURE 19 SAFETY MARGIN AS A FUNCTION OF FAILURE POSITION, ADJACENT CARS DECELERATE

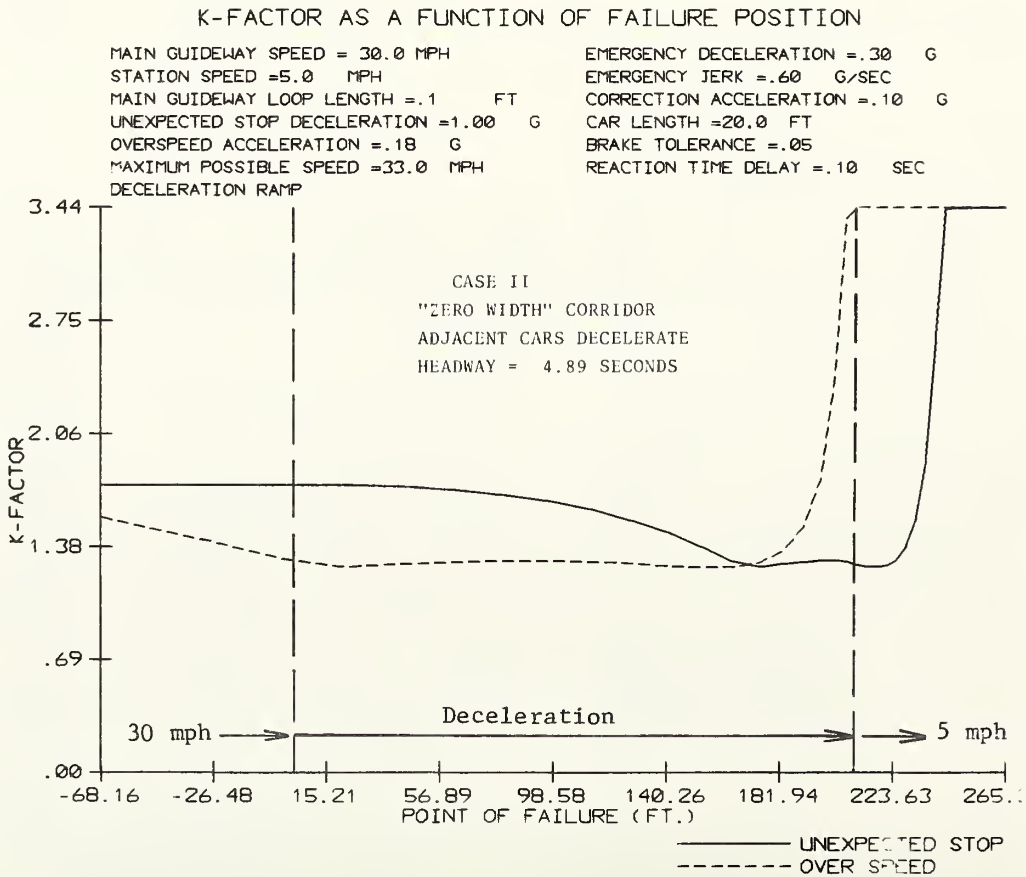


FIGURE 20 K-FACTOR AS A FUNCTION OF FAILURE POSITION, ADJACENT CARS DECELERATE

squared or kinetic energy, K factor may in some cases be a preferable measure of true hazard. Safety margin, however, has the desirable characteristic of telling immediately when there is danger of actual collision. There is no such straightforward reference point for what constitutes a safe K factor.

b) On-Guideway Deceleration

The safety margin, if the following car is not decelerating, is shown in Figure 21. Since the following car will eventually overtake and pass the preceding car, the safety margin decreases as the failure point moves further and further down the guideway. Safety margin goes below 5 feet for overspeed failures beyond about 60 feet and for unexpected-stop failures beyond about 180 feet. If either type of failure occurs beyond these points, the cars would violate safety margins. The position of the preceding (decelerating) car when it comes to a stop, after either failure, defines the point at which it must be clear of the main guideway, as discussed in Section 2.1.f. These points occur at about 202 feet for the overspeed failure and at about 183 feet for an unexpected stop. Unexpected stop thus defines the earliest turnoff point, or the longest ramp. Data on required ramp length for all cases are discussed in more detail in Section 2.4.c.

2. Acceleration Ramp

a) Both Cars Accelerating

The headway required for a failure on the acceleration ramp is shown in Figure 22. Station speed is to the left and main guideway speed is to the right. The constant headways associated with these speeds are the same as those shown in Figure 18. In between, however, the required headway curve is dish-shaped, not dome-shaped like the curve of the deceleration ramp. This is because the faster-moving preceding car is pulling away from the slower-moving following car; hence, both overspeed and unexpected stop pose reduced hazards.

When the headway is fixed at 4.89 seconds (the headway required on the deceleration ramp), the variation in the safety margin is shown in Figure 23.

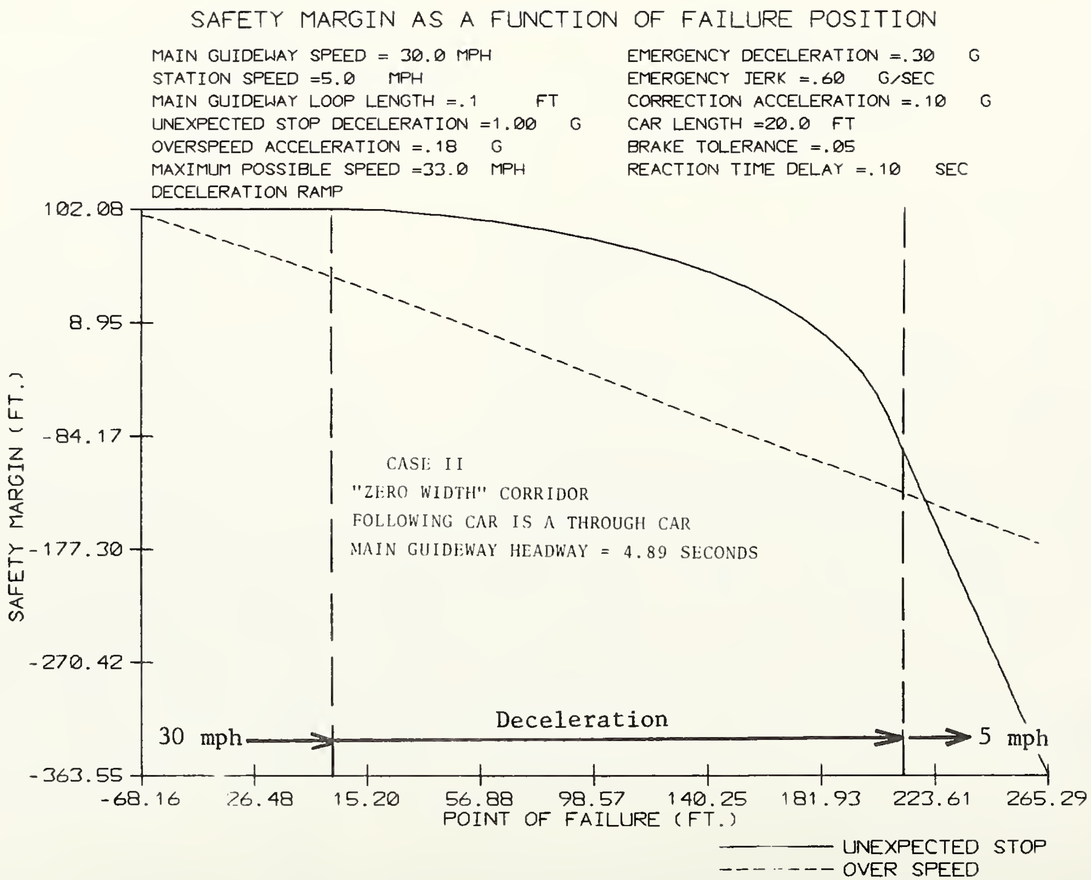


FIGURE 21 SAFETY MARGIN AS A FUNCTION OF FAILURE POSITION, CAR DECELERATES - FOLLOWING CAR IS A THROUGH CAR

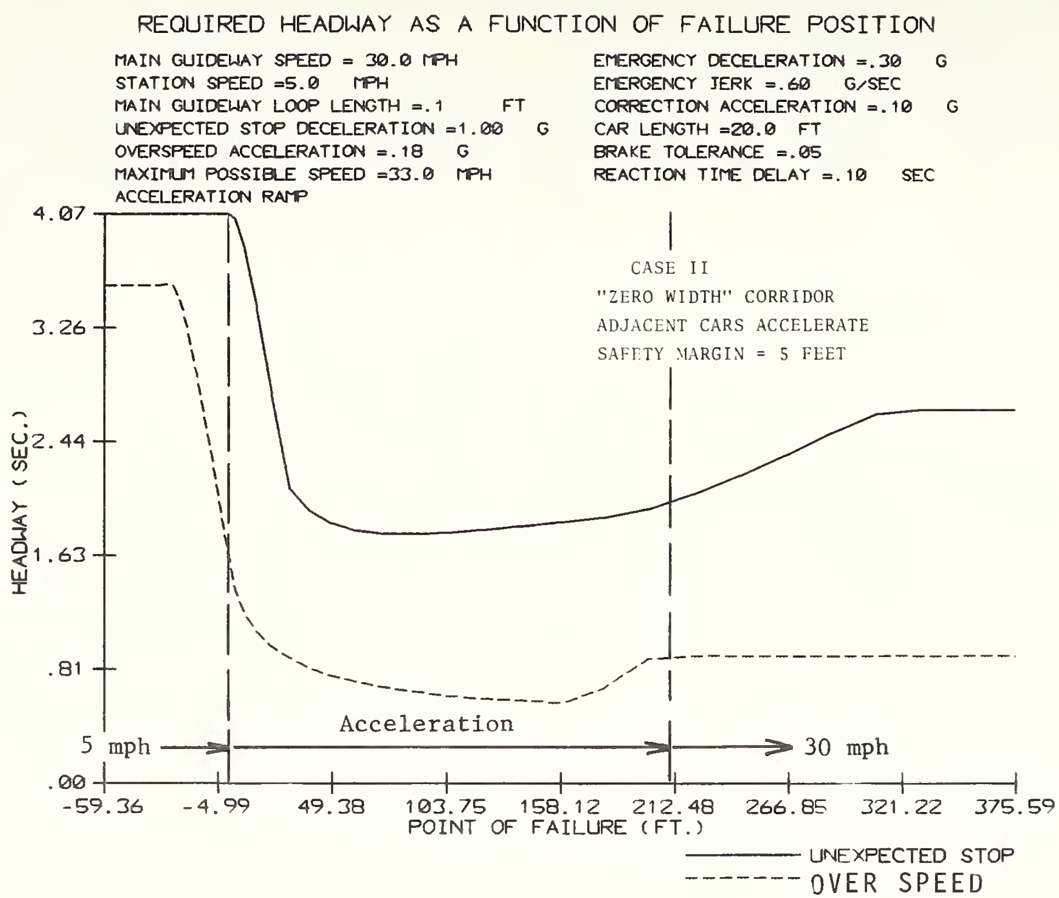


FIGURE 22 REQUIRED HEADWAY AS A FUNCTION OF FAILURE POSITION, ADJACENT CARS ACCELERATE

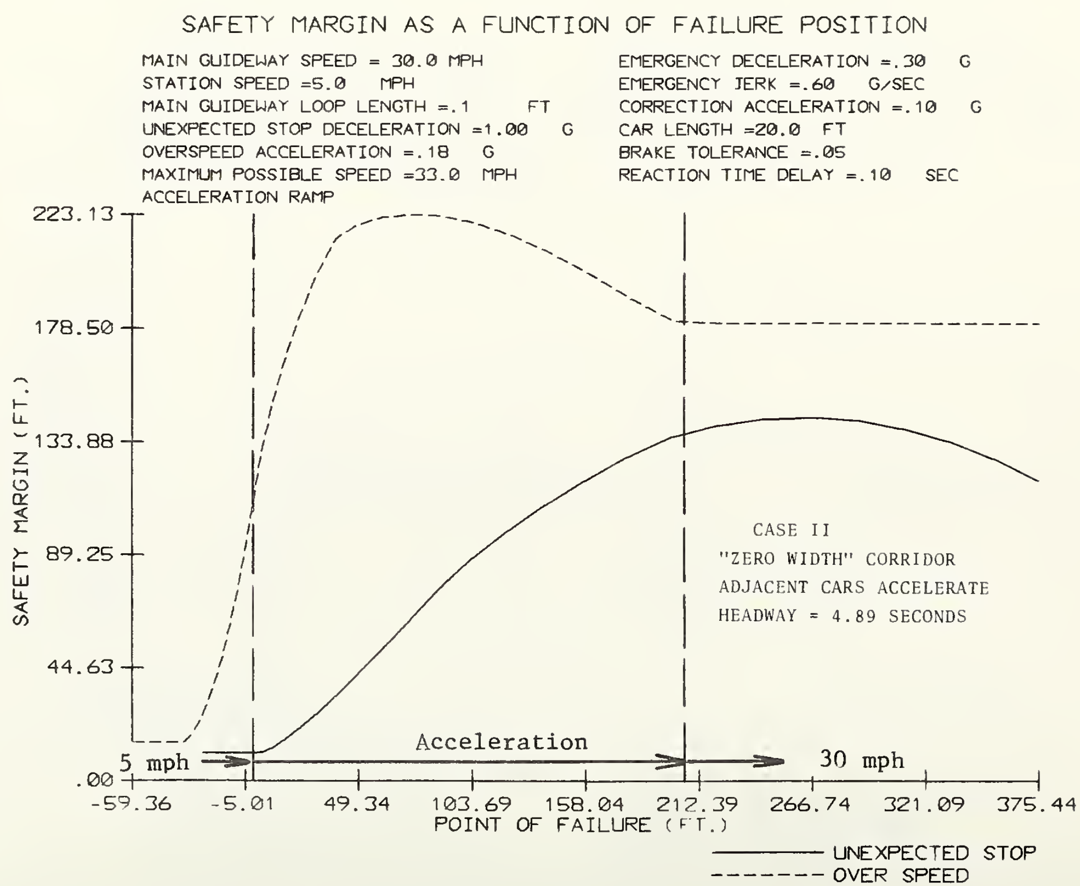


FIGURE 23 SAFETY MARGIN AS A FUNCTION OF FAILURE POSITION, ADJACENT CARS ACCELERATE

The constant values of the safety margin at station speed and main guideway speed are the same as in Figure 19, for the deceleration ramp. The exception is the unexpected stop margin, whose constant value goes "off the curve." With 4.89 seconds' headway, the unexpected-stop car must be 215 feet beyond the end of the acceleration ramp before the accelerating car has reached main guideway speed, in order to generate a true main guideway failure. From Figures 19 and 23, main guideway safety margin may be deduced as 178 feet for overspeed and 103 feet for unexpected stop.

K factor as a function of failure position on the acceleration ramp, given a headway of 4.89 seconds, is shown in Figure 24. Reflecting the large measure of reserve safety inherent on the acceleration ramp, the K factor is very large for failures during acceleration. As in the case of the deceleration ramp, K factors are equal for overspeed and unexpected stop, since the headway is fixed; however, since the abscissa point for a given K factor differs by the separation between the cars, the curves are not coincident. K factor is minumum on the main guideway, and equal to about 1.8.

b) On-Guideway Acceleration

Safety margin for 4.89 seconds' main-guideway headway, given a preceding car traveling at main-guideway speed, is plotted in Figure 25. The main-guideway car is essentially overtaking and passing the accelerating car; thus the safety margin goes from negative to positive. When the accelerating car has reached main guideway speed, the headway will be 4.89 seconds. The following condition determines how long the ramp must be. <u>The failure that results in a 5-foot safety margin must end with the through car on the main guideway and the accelerating car on the acceleration ramp</u>. Even though earlier failures will violate the safety margin, the cars will be laterally separated. The overspeed failure of an accelerating car that starts at about -29 feet results in a 5-foot safety margin. The equivalent unexpected stop of a through car starts at about -14 feet. The accelerating car stops at about -22 feet for the overspeed failure and at about -8 feet for the unexpected-stop failure. Thus, the unexpected stop defines a longer

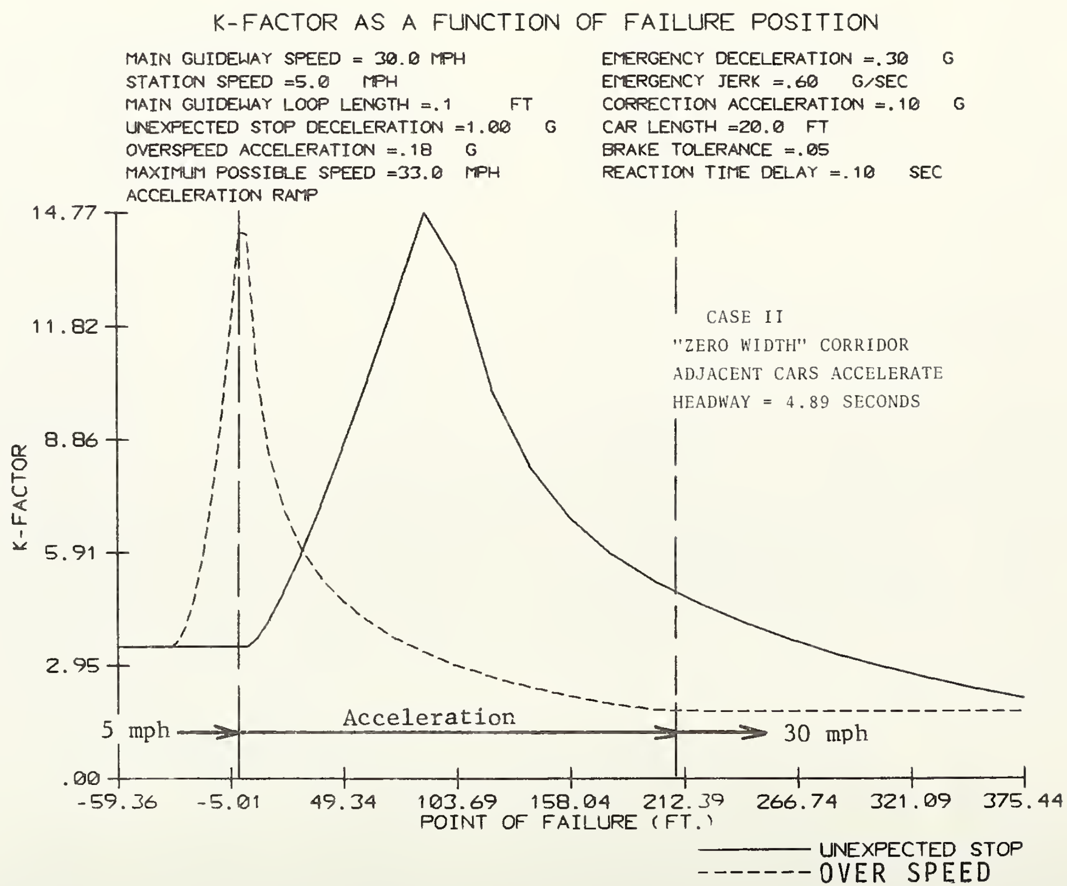


FIGURE 24 K-FACTOR AS A FUNCTION OF FAILURE POSITION, ADJACENT CARS ACCELERATE

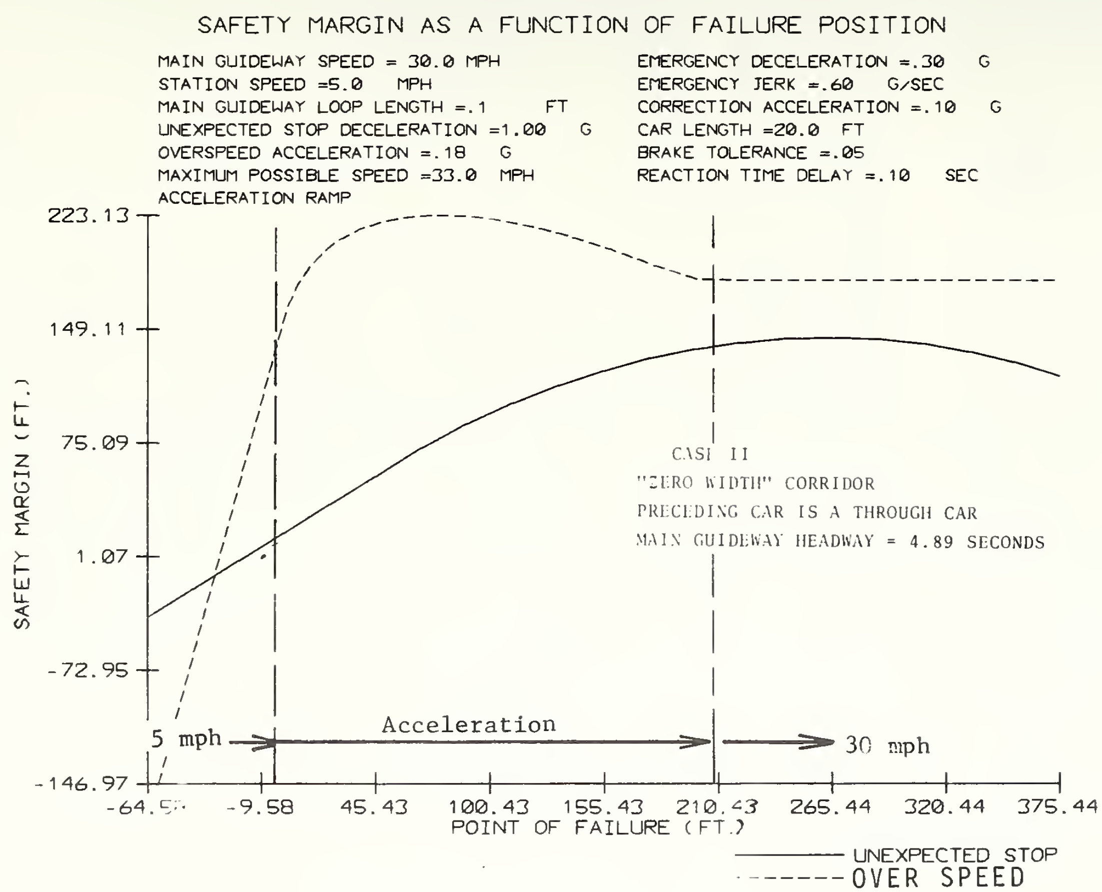


FIGURE 25 SAFETY MARGIN AS A FUNCTION OF FAILURE POSITION, CAR ACCELERATES-PRECEDING CAR IS A THROUGH CAR

ramp requirement, i.e., the ramp can end 8 feet prior to the start of acceleration, while the car is still at station speed. If unexpected stop failures occur beyond -14 feet, there will be more than 5 feet of safety margin after the emergency stop and both cars can be on the main guideway.

c. Required Ramp Lengths

The Point-Follower Headway Safety Program was used to determine required ramp length as a function of the main guideway headway. The results are shown in Figures 26 through 31 for baseline cases of Table 1.

The curves define the ramp length at which the car must be completely clear of the main guideway. The actual ramp length will be longer, to allow for transition from the guideway to the ramp. Since this distance will vary with superelevation, lateral jerk limits, etc., it is not included.

The plots have the same basic form. The scales are adjusted so that:

> The maximum ramp length on the upper panel is equal to the deceleration or speed-change distance. It is the length of a traditional ramp.
>
> The other grid labels are multiples of the acceleration/deceleration distance. The total upper panel is always 1.5 speed-change distances high and the total lower panel is always two distances high.
>
> The length of all panels is equal to the acceleration/deceleration time.

1. Simplified Reference Cases

Reference points and lines from the simplified analyses of Section 2.2 are also plotted. The triangle is the simplified solution, assuming that the main guideway headway is equal to the headway required for adjacent cars to decelerate into the station.

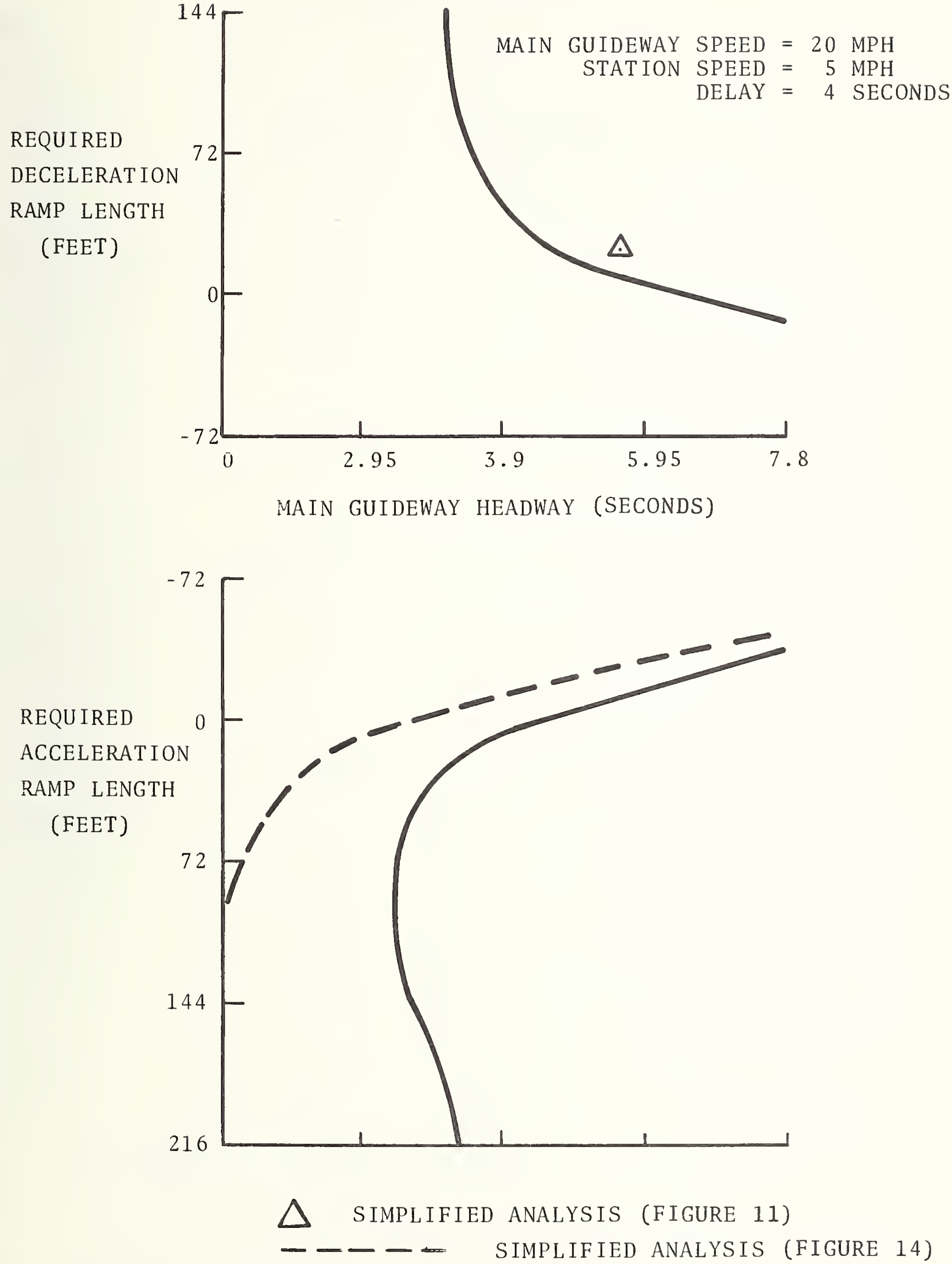


FIGURE 26 REQUIRED RAMP LENGTH CASE I - "ZERO WIDTH" CORRIDOR (20 MPH)

MAIN GUIDEWAY SPEED = 30 MPH
STATION SPEED = 5 MPH
DELAY TIME =0.4 SECONDS

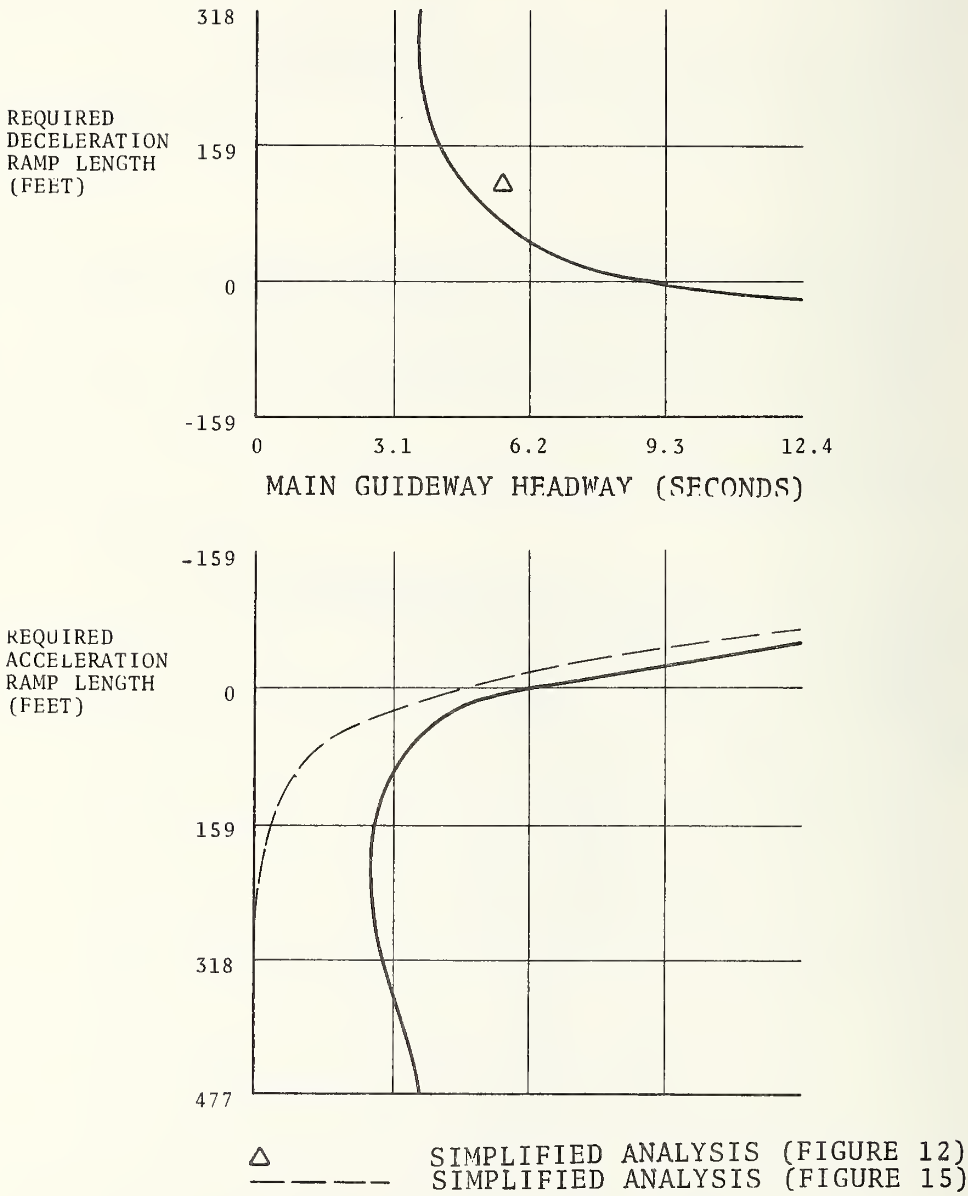


FIGURE 27 REQUIRED RAMP LENGTH CASE I-"ZERO WIDTH" CORRIDOR (30 MPH)

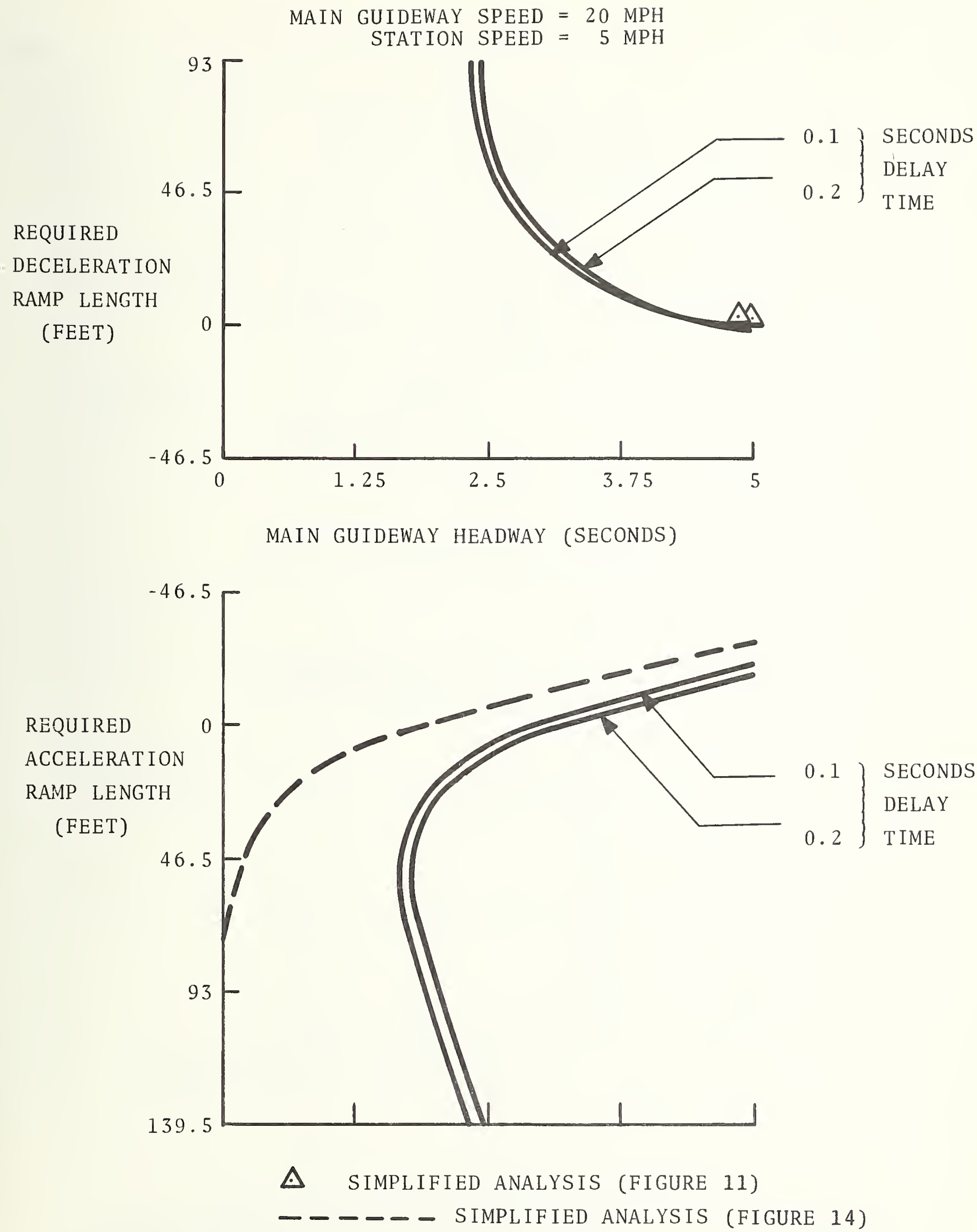


FIGURE 28 REQUIRED RAMP LENGTH CASE II - "ZERO WIDTH" CORRIDOR (20 MPH)

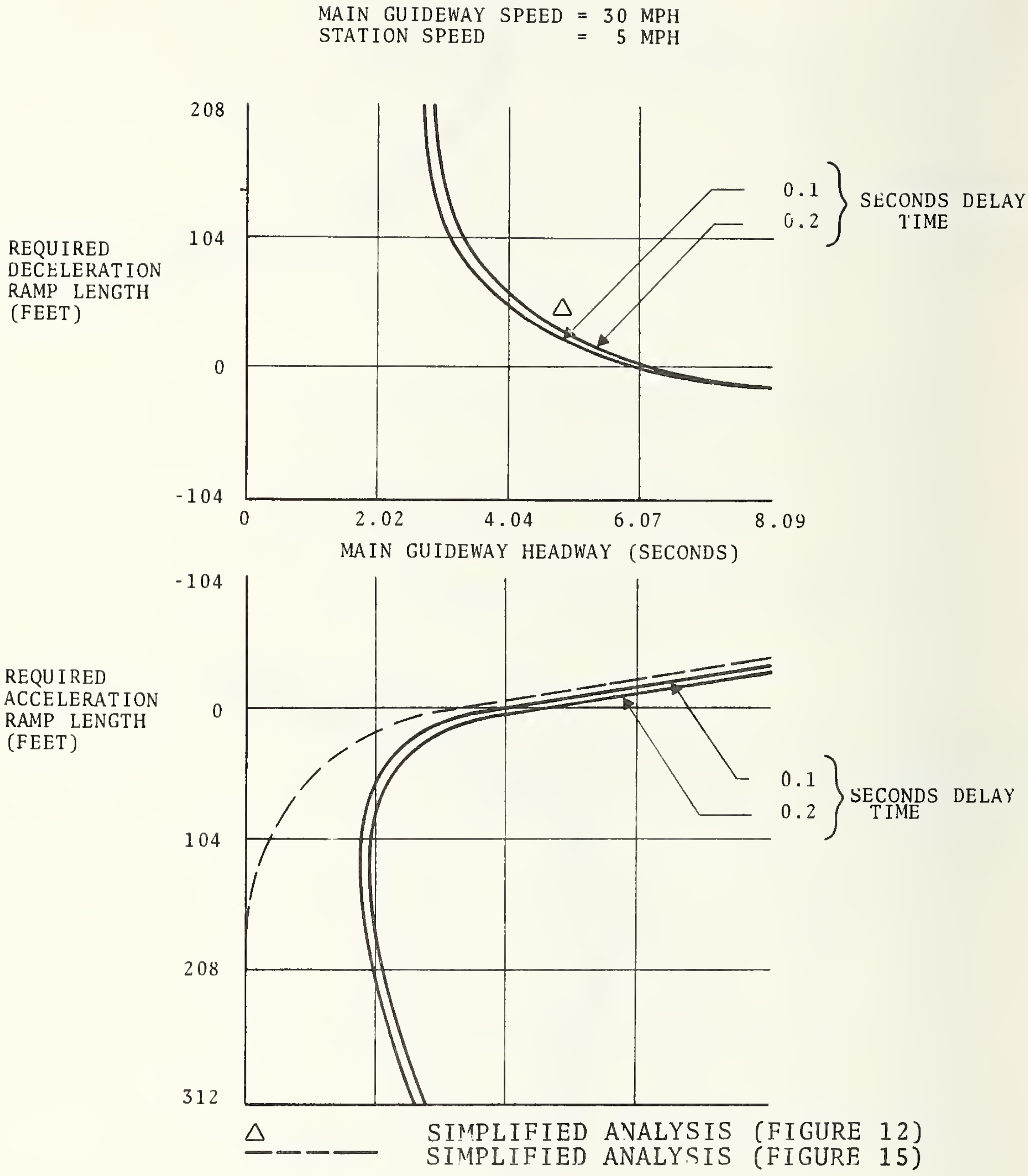


FIGURE 29 REQUIRED RAMP LENGTH CASE II-"ZERO WIDTH" CORRIDOR (30 MPH)

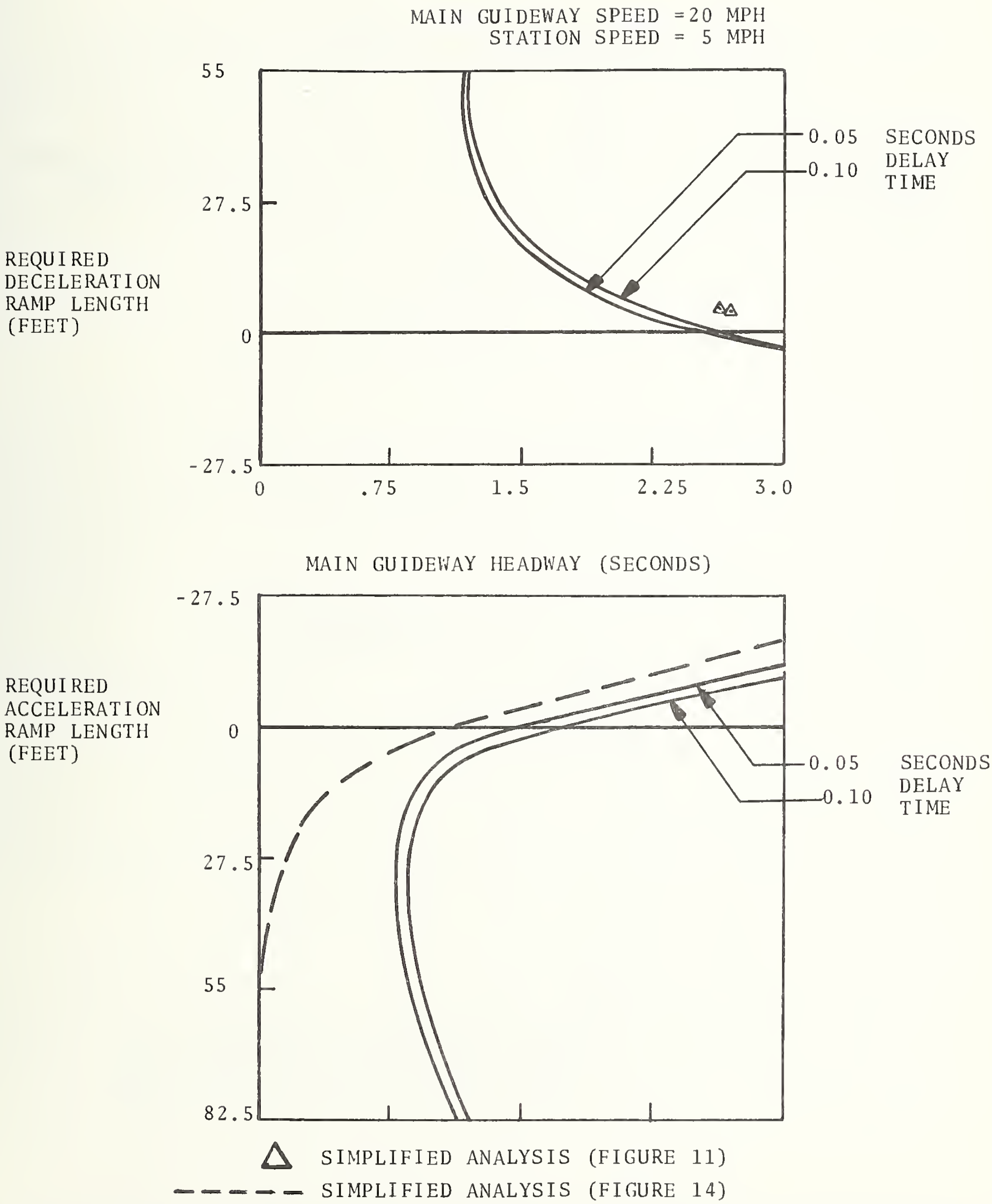


FIGURE 30 REQUIRED RAMP LENGTH CASE III - "ZERO WIDTH" CORRIDOR (20 MPH)

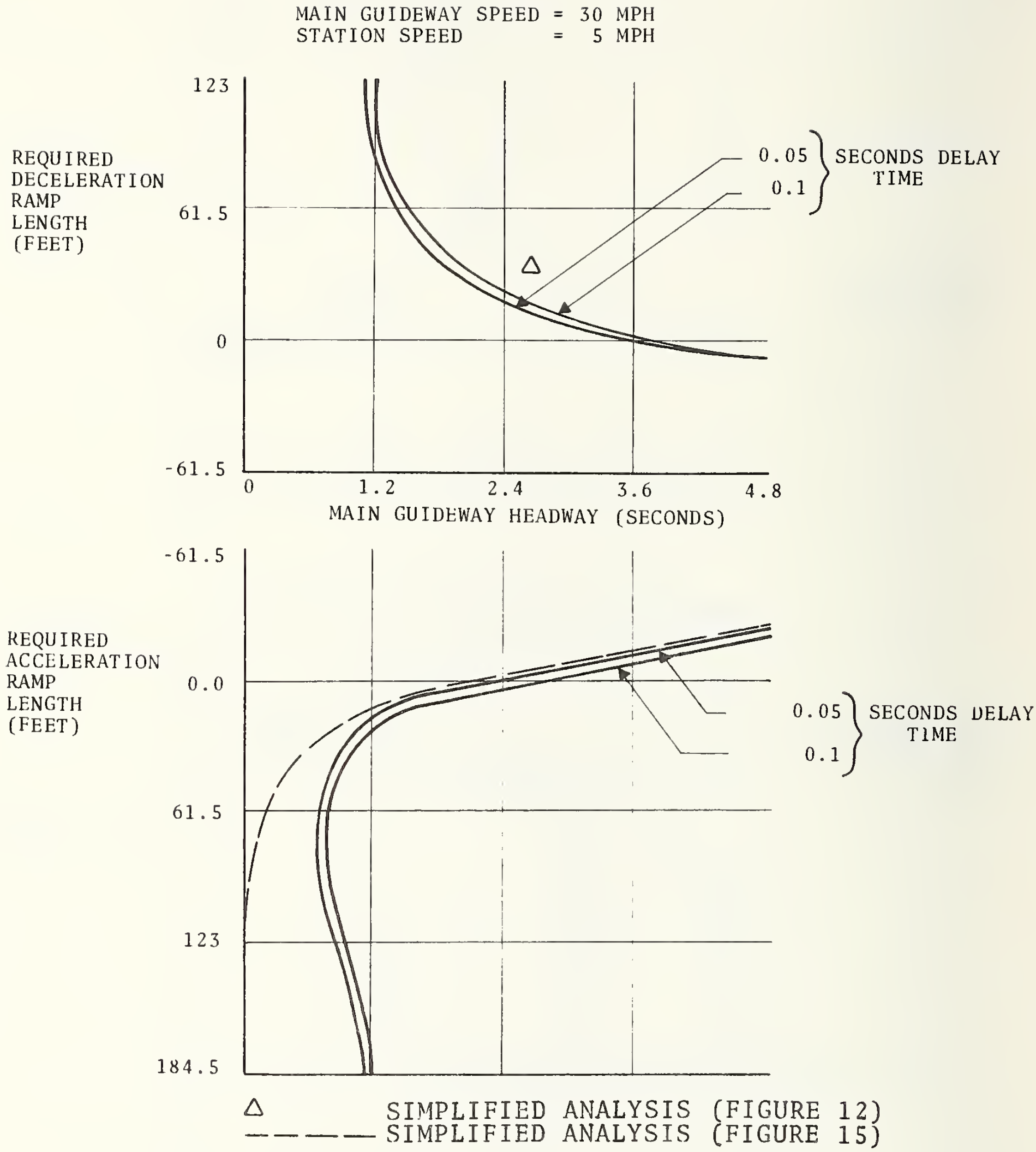


FIGURE 31 REQUIRED RAMP LENGTH CASE III-"ZERO WIDTH" CORRIDOR (30 MPH)

Deceleration-ramp headways have been obtained from Table 3. These values are then used in Figures 11 and 12 to obtain the triangular points.

The dashed lines are the points at which the path of the accelerating car intersects the path of the main guideway car. These lines are the same as those plotted on Figures 14 and 15.

As pointed out in Section 2.2 the deceleration-ramp reference case specifies somewhat longer ramps then are necessary, while the acceleration-ramp reference case specifies somewhat shorter ramps. Both simplifications, however, behave consistently and provide useful predictions.

2. Deceleration Ramps

The headways shown at the top of the top panels and at the bottom of the bottom panels are the minimum headways required on the main guideway. If the system is operating at these headways, the deceleration ramp lengths must be equal to the full deceleration distance. As the headway is increased, the required ramp length decreases. The initial rate of decrease is very rapid. Even small increases in headway lead to large decreases in ramp length. When the headway is equal to the headway required for adjacent cars to decelerate, the ramps can be from 10 to 20 percent of their traditional length. When the headway is equal to the total time required to decelerate, the required ramp length is negative. This result indicates the car does not have to be clear of the guideway until after it has reached station speed.

3. Acceleration Ramps

The acceleration-ramp curves differ considerably from the deceleration-ramp curves. For headway equal to the main guideway headway, the acceleration ramp can essentially be eliminated. For headways equal to the acceleration time, the accelerating car can actually travel a considerable distance on the main guideway at station speed, prior to accelerating.

It is interesting to note that if the ramp ends partway through the acceleration distance, it is actually safe for a car to enter at less than the steady-state main guideway headway. As the car accelerates to main guideway speed, however, the required headway would rise to that required on the main guideway.

d. Effect of Corridor Constant and Error-Sensing Method

The results of Sections 2.4.a and 2.4.b have assumed a "zero-width" position and velocity corridor. In this section, typical results are shown for finite-width corridors, for both velocity-error and position-error failure sensing. Case II, at 30 mph, with 0.1-second delay time, is considered.

A standard sample-time interval is assumed, i.e., the time between speed and position samples is twice the corridor constant, corresponding to a contiguous loop or check-in/check-out system. The loop boundaries or check-in/check-out sensors are separated by the standard sample time as the car moves on a nominal profile.

"Worst-case" initial conditions within the corridor are assumed for the failed and avoiding cars. These correspond to the following corridor phase angles, ωt. in degrees:

	Phase Angle, ωt	
	Overspeed	Unexpected Stop
Position-error sensing	90	270
Velocity-error sensing	270	90

See Figures 6 and 7 and the discussion of Section 2.2.b for the corridor deviations associated with these phase angles. For example, the worst-case initial conditions for an unexpected stop with position-error sensing occur when the car starts to fail from the back of its corridor.

Initial conditions for the non-failing car (the following car for an unexpected stop and the preceding car for an overspeed failure) are assumed to be:

	Phase Angle, ωt
Unexpected Stop	180
Overspeed	90

Exact values will vary with the problem parameters. These initial conditions, however, have been found to be consistently close to the worst case (Reference 10). Precise determinations were not made for each case since the potential changes in required headway and ramp lengths would be very small and the required computer time would have increased greatly.

1. Basic Headway

Runs were made for overspeed of a following car and unexpected stop of a preceding car, both on the main guideway and on a deceleration ramp. Basic headway results for adjacent cars are shown in Figure 32. Required headway is plotted as a function of the corridor constant, for both position-error sensing and velocity-error sensing.

The zero-corridor-constant results correspond to those shown in Table 3. For a "zero-width" corridor, velocity-error sensing and position-error sensing are equivalent. There are no deviations, and failures are discovered immediately in both cases.

Unexpected stop constitutes the worst hazard on the main guideway. Except for very small corridor constants, overspeed is the worst hazard during deceleration.

Velocity-error sensing is uniformly better than position-error sensing. The most striking difference is for the overspeed hazard during deceleration. Since this hazard is the most critical encountered by the cars, the reduction is particularly significant.

2. Required Ramp Length

Required ramp lengths for Case II, with 30-mph main guideway speed and 0.1-second delay time, are plotted in Figure 33. Curves are shown for "zero-width" corridor and for a corridor constant of 0.068 (corresponding to a standard sample time of 0.136 seconds).

The curves for finite corridor width are the same basic shape as those for "zero-width" corridors. The differences might be easily inferred, given the greater main guideway headway requirements with a 0.068 corridor constant, and the general advantage of velocity sensing over position sensing.

CASE II STANDARD SAMPLE TIME

MAIN GUIDEWAY SPEED - 30 MPH
STATION SPEED - 5 MPH
DELAY TIME -0.1 SECONDS

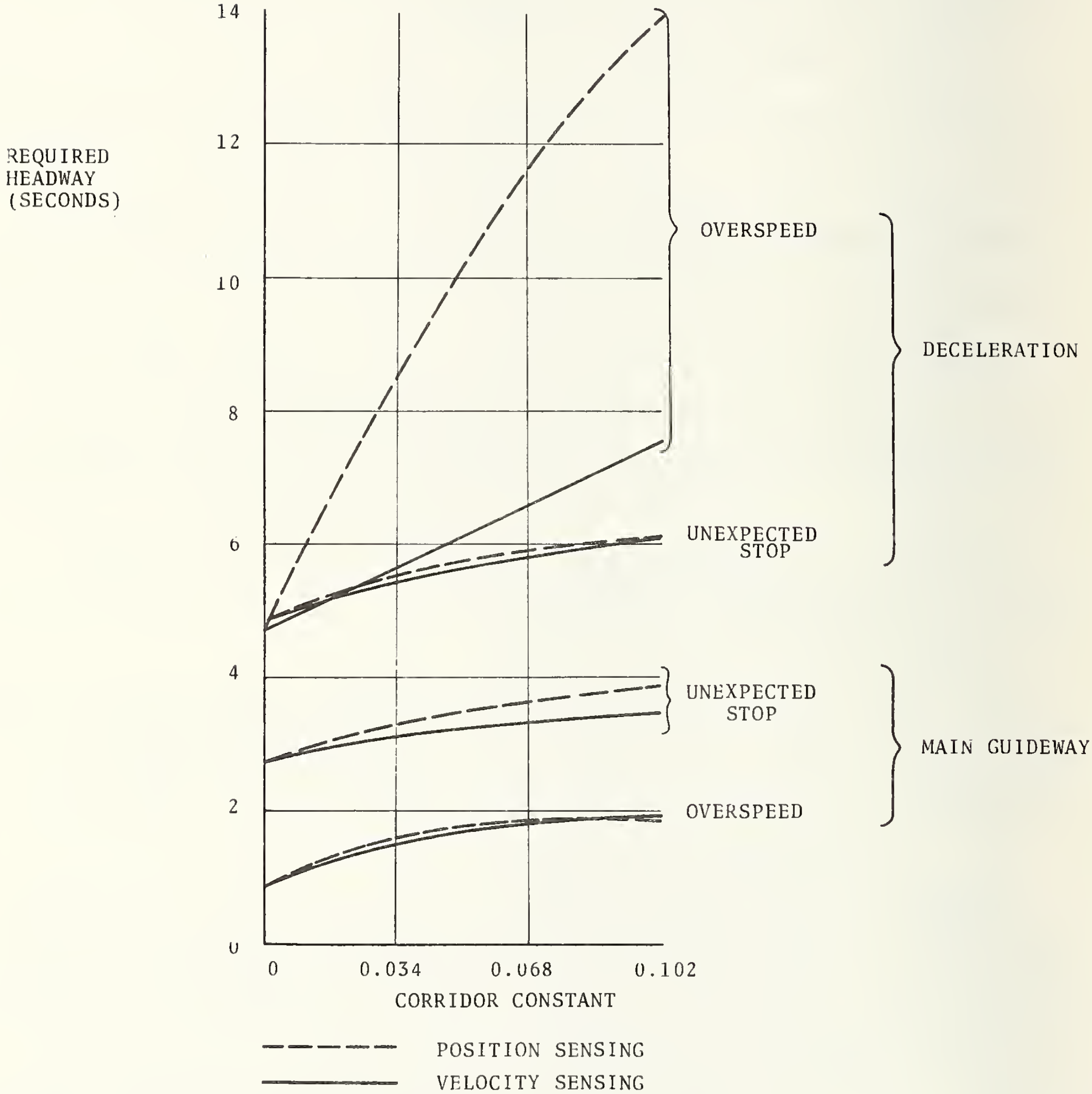


FIGURE 32 EFFECT OF ERROR SENSING AND CORRIDOR CONSTANT ON REQUIRED HEADWAY

CASE II STANDARD SAMPLE TIME

MAIN GUIDEWAY SPEED = 30 MPH
STANDARD SPEED = 5 MPH
DELAY TIME = 0.1 SECONDS

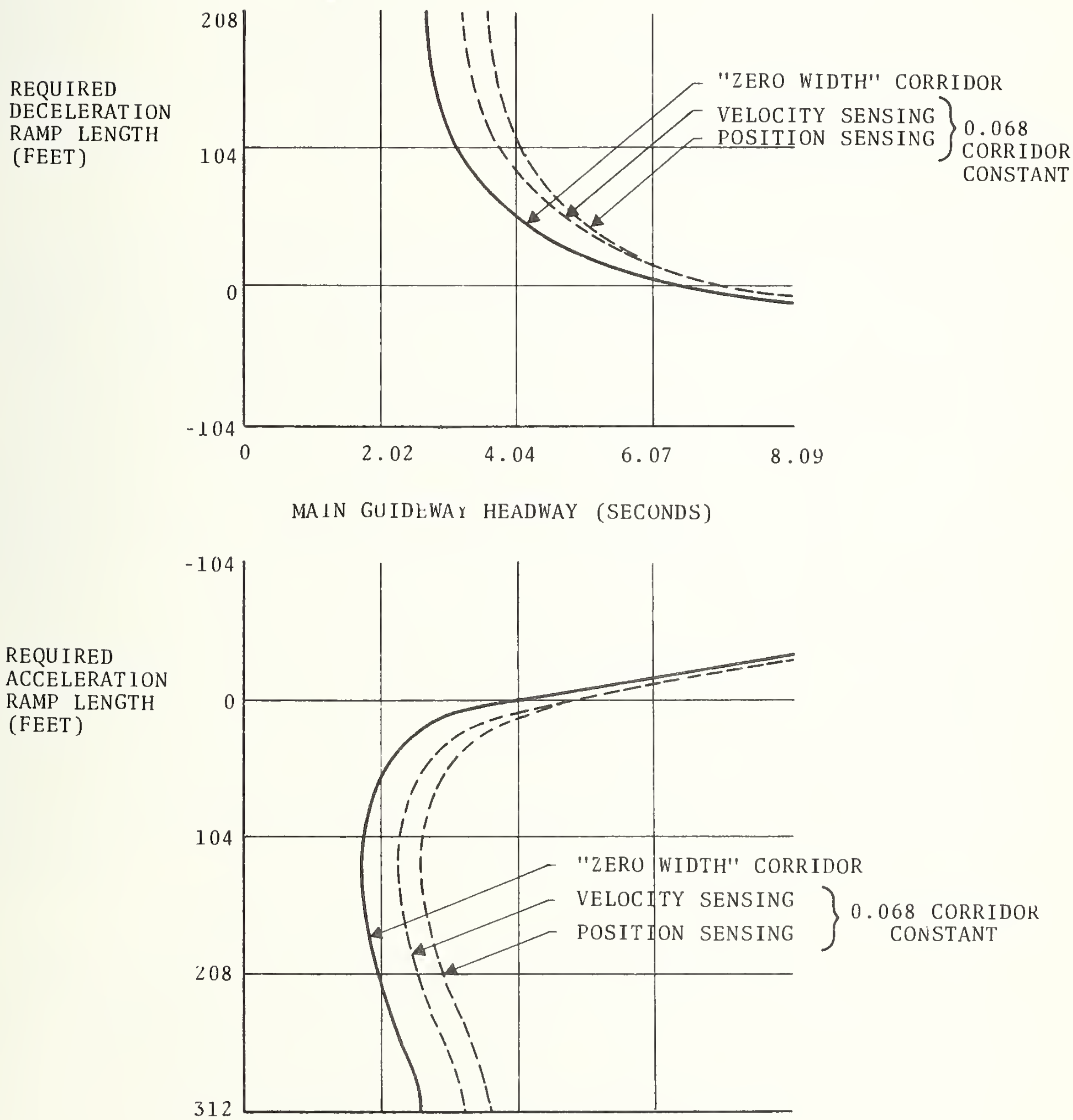


FIGURE 33 EFFECT OF ERROR SENSING AND CORRIDOR CONSTANT ON REQUIRED RAMP LENGTH

The inherent decrease in ramp length with increasing headway is a strong trend. Deriving a deceleration headway from Figure 16 for a 0.068 corridor constant and determining the required ramp length from Figure 33 gives us the following table:

	Dec. Headway (Seconds)	Ramp Length (Feet)
"Zero-Width" Corridor	4.9	50
Velocity Sensing--0.068 Corridor	6.6	7
Position Sensing--0.068 Corridor	11.7	-38

While the above results are hardly an argument for longer deceleration headways, they show that they have at least one advantage. On lightly loaded portions of a system, where headway can be longer, not only can the parameters of the headway protection system be relaxed, but the required deceleration-ramp length will decrease.

3. VEHICLE-FOLLOWER ANALYSIS

The major difference between vehicle-follower and point-follower systems is that the normal time-position profile for a vehicle in a synchronous system is known a priori, while in the non-synchronous system it is a function of the activity of a lead vehicle. This difference required new analysis and the development of a completely new computer program.

3.1 OVERVIEW

a. Situation

Consider, for this discussion, a block of adjacent vehicles, i.e., vehicles constrained by follower law, proceeding on a guideway. This block of vehicles is sometimes called a platoon.

1. Station Entrance

The situation for station entry is that one car in a platoon wishes to exit into a station. Assuming a certain amount of on-line deceleration, the following vehicles must slow down to avoid colliding and then accelerate back to line speed.

This situation is shown by Figure 34. Note that the subsequent following vehicles are affected less strongly by the maneuver. The difference in time between a vehicle's expected passage of a point and its delayed passage is a measure of the cost to the system of allowing an on-line maneuver. Compare Figure 34 with Figure 3 to see the difference in performance for the two control strategies.

2. Station Exit

Now consider a platoon into which a vehicle must be inserted. Since each vehicle maintains spacing by tracking the vehicle ahead, some procedure must be used to force a selected vehicle to drop back and leave space. At the same time, the vehicle accelerating onto the main guideway must be made sensitive to the vehicle it will follow. This is a much more complicated problem than that of the point follower, where a vehicle accelerates into a prearranged slot.

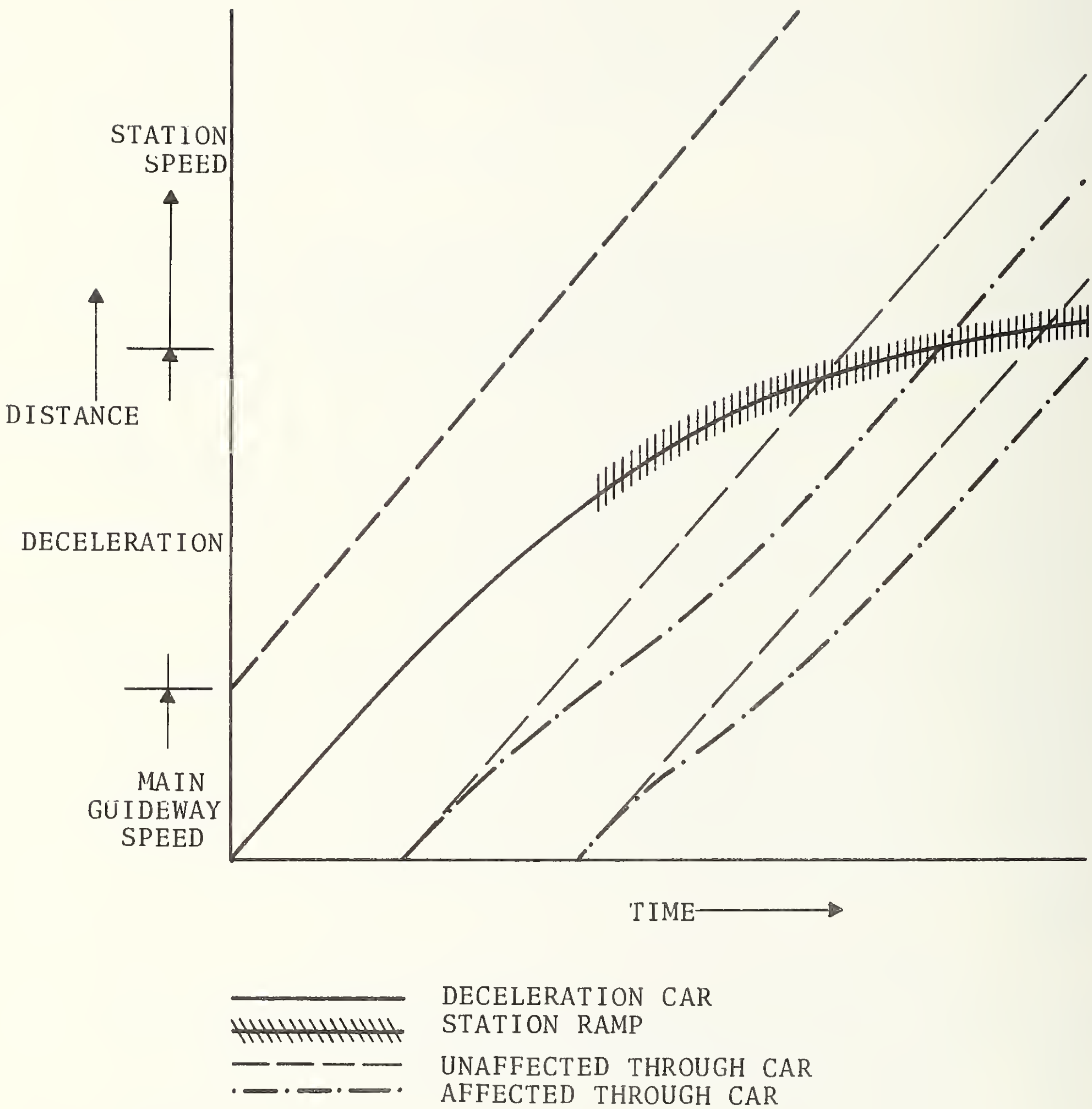


FIGURE 34 VEHICLE-FOLLOWER CARS AT STATION ENTRANCE

The pattern of a normal accelration is shown by Figure 35. In this case, a time loss will be experienced by following vehicles even when a full acceleration ramp is used, since at least one slot must be opened. The penalty for a shorter ramp is the increase in magnitude of time lost over that associated with a full-length ramp. Compare Figure 35 to Figure 4.

b. Merging

The Station Exit situation of the preceding section is complicated by the merge requirement. A mechanism must be derived to assure that the accelerating vehicle will follow a profile which will not cause it to merge too close to a failing vehicle - causing overreaction by the vehicle's on-board following mechanisms - nor cause it to merge too far behind a lead vehicle - causing excessive delay in the system. A different, compatible, mechanism must be created to assure that a space has been opened for the merging vehicle. For the current analysis, the merging vehicle is always the accelerating vehicle, and in general the acceleration is not complete when the vehicle finally completes the merge operation - further complicating the situation. The mechanism chosen and studied for this analysis makes use of "false" or "ghost" vehicles. These dummy vehicles are placed ahead of the vehicle perofrming a maneuver and follow a path which will ultimately coincide with the vehicle which the manuevering vehicle must follow.

Thus, the accelerating vehicle should be following an analog of the vehicle it is to follow when the merge is complete. Similarly, the first affected vehicle should be following an analog of the vehicle it will follow when the merge is complete.

Specifically, given that no emergency occurs, the accelerating vehicle should follow a "vehicle" which is operating one headway distance ahead in the station area. This so-called "ghost vehicle" should then accelerate on a normal profile until it physically merges with, or becomes identical in time and space to, the on-line vehicle which the accelerating vehicle is to follow. Under the follower law, this will have the effect of "drawing" the accelerating vehicle up onto the guidway, which it will enter perfectly spaced behind

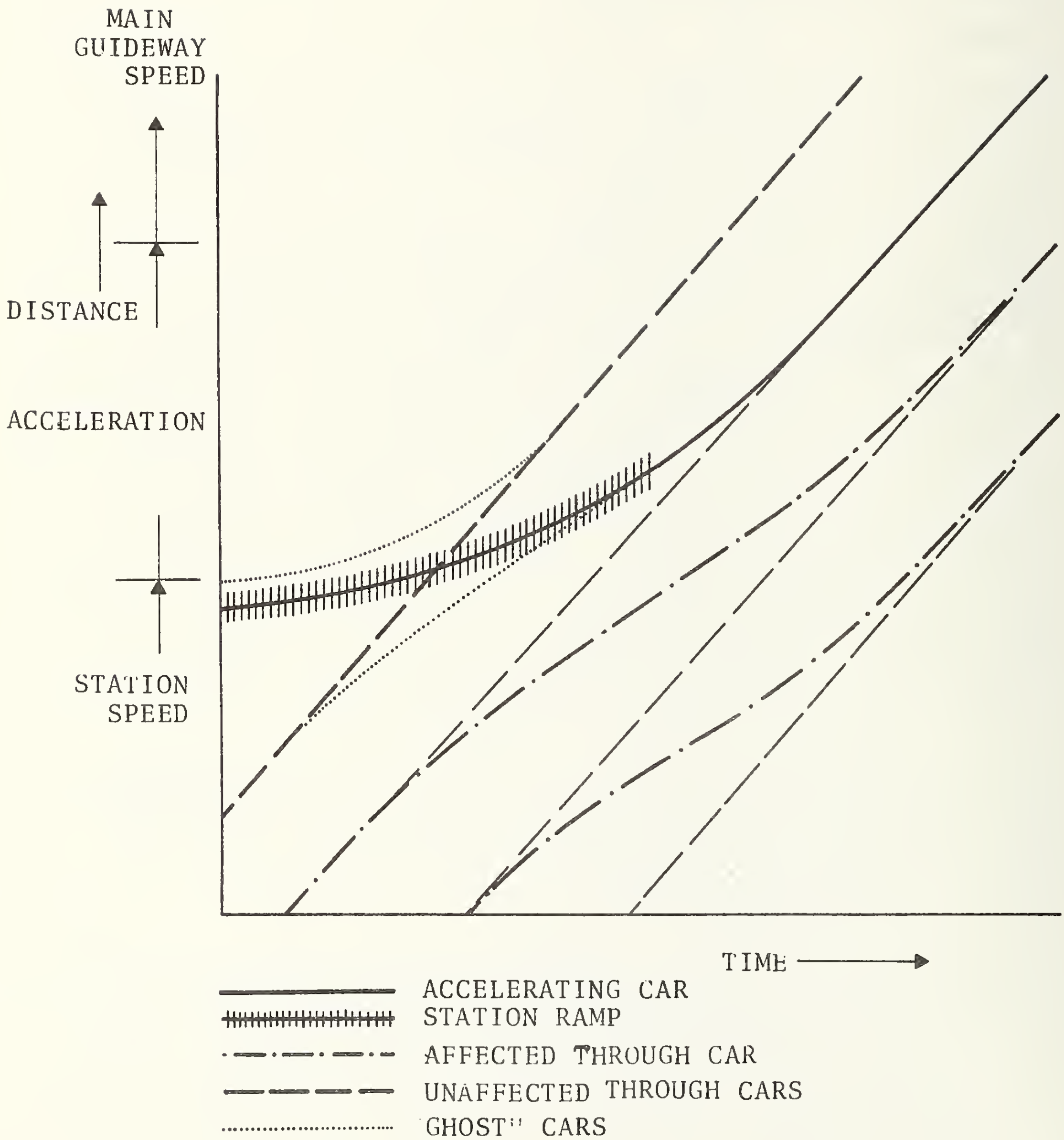


FIGURE 35 VEHICLE-FOLLOWER CARS AT STATION EXIT

the lead vehicle. More complicated is the case of the first affected through vehicle. It must follow a "ghost vehicle" which appears in place of the lead vehicle, and which proceeds in a lower velocity profile to merge into the accelerating vehicle as it enters the main guideway from the ramp. It is obvious that there are many profiles that will satisfy this requirement. For each set of initial conditions, i.e., vehicle performance, follower law, and ramp length, a different profile will cause the least disruption of following traffic. Consider Figure 36. Several linear ghost profiles are shown (B-D). Profile B is gentle, but of longer duration. Profile C is less gentle, and profile D is acute, perhaps requiring extreme maneuvers from the following vehicle. Compare these to the contoured profile A. Notice that profile A accomplishes the maneuver in the same time as profile C, but diverges from the line-velocity profiles more gently, analogously to profile B. Generation and optimization of these merge profiles are a complicated area, requiring more study than appropriate for this project.

c. Deviations from Normal

Figures 34 and 35 show only the normal case. For purposes of this analysis, no inaccuracy in the vehicle control system is assumed. In practice, such inaccuracy may be accounted for by the vehicle-follower law.

It can be seen from Figures 34 and 35 that the two failure modes which are of interest are an unexpected stop of the decelerating vehicle, or, in the case where a vehicle will enter the guideway, an unexpected stop of the last through vehicle, that is, the vehicle which the accelerating vehicle will follow. The acceleration-ramp emergency is complicated by the presence of the ghost vehicles. Not only must the ghost vehicles simulate the appropriate maneuver for a normal merge, they must also react properly in case of a failure. Thus, the position of the ghost which leads the accelerating car onto the main guideway is dependent upon the position of the last unaffected through vehicle. The ghost-vehicle position which causes a gap to open in the platoon is tied to the

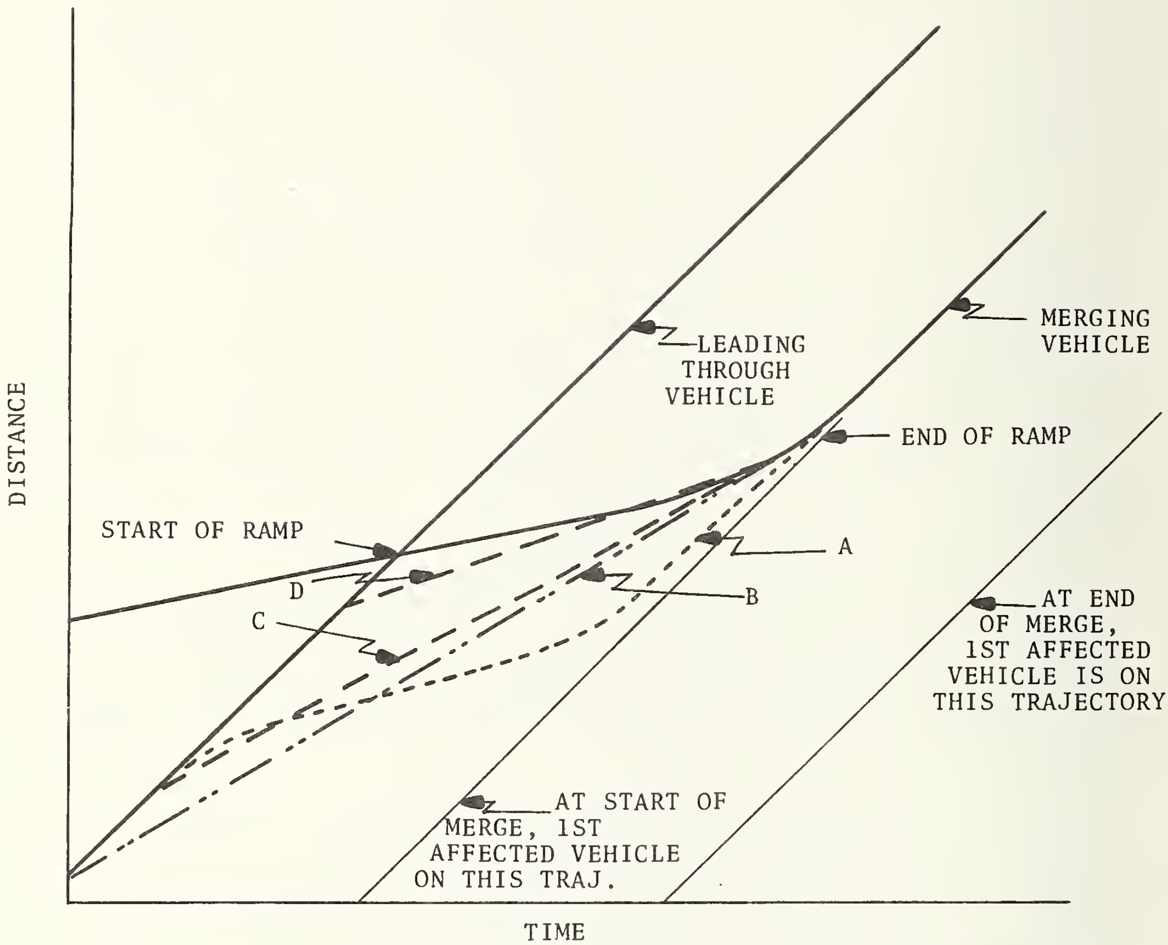


FIGURE 36 FOUR GHOST VEHICLE PROFILES

position of the accelerating car. An emergency stop by the lead vehicle will cause its ghost to stop, in turn stopping the accelerating vehicle, the ghost opening up the slot, and the rest of the platoon. A stop of the entry or accelerating vehicle is analogous to the case in which the lead vehicle stops, since the same sequence is activated except that the lead vehicle continues on its way.

Safety is assured by selection of the proper vehicle-follower law. For example, a system which permits brickwall stops and uses a K-factor less than one to determine required vehicle separation will be unsafe.

In a vehicle-follower system, safety of the system is assured by the individual vehicle-control systems. An operational vehicle will always be able to stop in time for a failed vehicle if design of the system - particularly the follower law - is correct. The design of a vehicle-follower system cannot accommodate an overspeed failure since centralized control of the system is limited to a surveillance function. Direct control of the vehicles resides in an on-board control system, which must be made fail-safe for the overspeed case.

3.2 VEHICLE-FOLLOWER COMPUTER MODEL

a. Method

The computer model must simulate both the kinematics of the automated guideway vehicles and the action of their control system. In a vehicle-following régime, the vehicle's on-board control system is responsible for all vehicle control, and the central system is responsible for setting certain limits to the vehicle-control system and for overall network control. Thus, the model described here is primarily concerned with the vehicle, its output of system delays providing the only information pertinent to an overall network-control system.

Analysis of the point-follower case and preliminary analysis of the vehicle-follower case indicate that the vehicle-control system and physical charateristics should be modeled together as a single system rather than separately. A stepwise integration with interval Δt is used to update successively the position, speed, and acceleration of a string of vehicles. The fundamental step considers two adjacent vehicles. It is assumed that the position, speed, and acceleration of the following vehicle are known at the time t_1. It is further assumed that the position, speed, and acceleration of the preceding vehicle are also known at time

$$t_2 = t_1 + \Delta t. \tag{8}$$

The analysis develops equations to determine the position, speed, and acceleration of the following vehicle at time t_2. By successively applying this fundamental step, the positions of a series of vehicles can be determined.

It is assumed that the jerk is constant in the updating interval. This assumption allows a closed-form solution to be developed.

The position of the following vehicle is assumed to be governed by one of two vehicle-follower laws.

- A linear law:

$$X_s = D + EV, \tag{9}$$

where X_s = distance between the reference lines on two adjacent vehicles, in feet,

D = a constant, in feet,

E = a constant, in seconds,

V = speed of following vehicle, in feet per second.

- A constant K-factor law:

$$X_s = K[X_{sd}] + L_c, \tag{10}$$

where K is K-factor,

X_{sd} is stopping distance for the following car, in feet,

L_c is the length of the car, in feet.

The emergency stopping distance, X_{sd}, is a function of the speed of the car and the allowable jerk and deceleration during an emergency stop; i.e.

$$X_{sd} = \frac{V}{2}\left[\frac{V}{a_e} + \frac{a_e}{j_e}\right], \tag{11}$$

where a_e is the allowable emergency acceleration, in g's,

j_e is the allowable emergency jerk, in g's per second.

Substituting Equation (11) into Equation (10) yields the following expression for X_s:

$$X_s = L + MV + NV^2, \tag{12}$$

where $L = L_c$, (13)

$$M = K \frac{a_e}{2\ j_e}, \tag{14}$$

$$N = \frac{K}{2a_e}. \tag{15}$$

The subscript 1 is now associated with the position, speed, and acceleration of the following car at t_1 and the subscript 2 with the corresponding quantities at time t_2.

At time t_2, the position of the following vehicle is constrained to obey the follower law, i.e.

$$X_2 + X_s = X_{p_2} , \tag{16}$$

where X_2 is the position of the following car at time t_2,

X_{p_2} is the position of the succeeding car at time t_2.

The separation X_s is known as a function of V_2, by substituting V_2 for V in either Equation (9) for the linear-separation law or Equation (12) for the K-factor law.

An expression is now developed for X_2 in terms of X_1, V_1, and A_1 (known quantities at time t_1), and the unknown speed V_2, at time t_2. The acceleration at time t_2 is written in terms of the jerk during the time Δt, defined as J_2.

$$A_2 = A_1 + J_2 \Delta t \tag{17}$$

where A_2 is acceleration of the following car at time t_2, in feet per second squared,

A_1 is acceleration of the following car at time t_1, in feet per second squared, and

J_2 is the jerk of the following car in the interval $\Delta t = t_2 - t_1$ in feet per second cubed.

Letting Equation (17) revert to its indefinite form, and integrating, we obtain an expression for the velocity at t_2.

$$V_2 = V_1 + A_1 \Delta t + J_2 \frac{\Delta t^2}{2} , \tag{18}$$

where V_2 is the speed of the following car at t_2, in feet per second, and

V_1 is the speed of the following car at t_1, in feet per second.

Again, integrating the indefinite form of Equation (18), we obtain the following expression, which defines the position of the following car at time t_2.

$$X_2 = X_1 + V_1 \Delta t + \frac{A_1 \Delta t^2}{2} + \frac{J_2(\Delta t)^3}{6}, \tag{19}$$

where X_1 is the position of the following car at t_1, in feet.

Now solving Equation (18) for J_2, substitutinf the results into Equation (19), and simplifying yields an expression for X_2 in terms of V_2:

$$X_2 = X_1 .+ \frac{2}{3} V_1 \Delta t + \frac{A_1 \Delta t^2}{6} + \frac{\Delta t}{3} V_2, \tag{20}$$

or

$$X_2 = F + GV_2, \tag{21}$$

$$\text{where } F = X_1 + \frac{2}{3} V_1 \Delta t + \frac{A_1 \Delta t^2}{6}, \text{ and} \tag{22}$$

$$G = \frac{\Delta t}{3}. \tag{23}$$

Substituting Equation (9) and Equation (20) into Equation (16) and solving for V_2 gives the following expression for V_2 in the case of the linear-following law:

$$V_2 = \frac{X_{p_2} - F - D}{G + E}. \tag{24}$$

Similarly, for the case of the K-factor follower law; substituting Equations (12) and (20) into Equation (16) and solving for V_2 using the quadratic formula yields the following expression for V_2:

$$V_2 = \frac{1}{2N}\left[-(G+M) + \sqrt{(G+M)^2 - 4N(F+L-X_{p_3})}\right]. \tag{25}$$

Given the speed at time t_2, we can go back and compute the associated acceleration and jerk:

$$A_2 = \frac{2(V_2 - V_1)}{\Delta t} - A_1 \tag{26}$$

and

$$J_2 = \frac{A_2 - A_1}{\Delta t}. \tag{27}$$

Implementation of these results is illustrated by Figure 37.

The accelerations and jerks determined by the vehicle-follower law must now be checked to insure that they are within civil and/or emergency limits. This is done following the algorithms outlined in Figure 38.

For figure 38 when the vehicle-follower law dictates that the car speed up, A_2 is greater than 0 on the left side. For this case, there is plenty of room between the preceding and following cars, and the car's acceleration and jerk must be kept within civil limits. The diagram of Figure 38 is self-explanatory with the exception of the lower-right-hand corner; this sub-sequence of operations insures that the acceleration is gradually reduced (following the jerk constraint), as the car completes its acceleration to civil speed.

On the right branch, the follower law specifies a deceleration. Since the car is being forced to slow down, the basic limits are emergency jerk and acceleration, rather then civil jerk and acceleration. The car must generate maximum deceleration, if specified by the follower law, in anticipation of a critical emergency. Note that the system is designed so that normal operations will not result in vehicles' maneuvering at emergency limits.

The lower-right-hand quadrant of the decision tree provides the mechanism that reduces the acceleration as the car approaches a stop, in order not to violate the jerk limits.

KNOWN DATA:

X = CURRENT VEHICLE

V = CURRENT VEHICLE VELOCITY

A = CURRENT VEHICLE ACCELERATION

J = CURRENT VEHICLE JERK

X_P = NEW POSITION OF PREC. VEHICLE

Δt = TIME OF ONE UPDATE INTERVAL

FIRST COMPUTE

A_T = TRIAL POSITION

$= X + 2/3\ V\ \Delta t + 1/6\ A(\Delta t)^2$

AND

B_T = TRIAL VELOCITY = $1/3\ \Delta t$

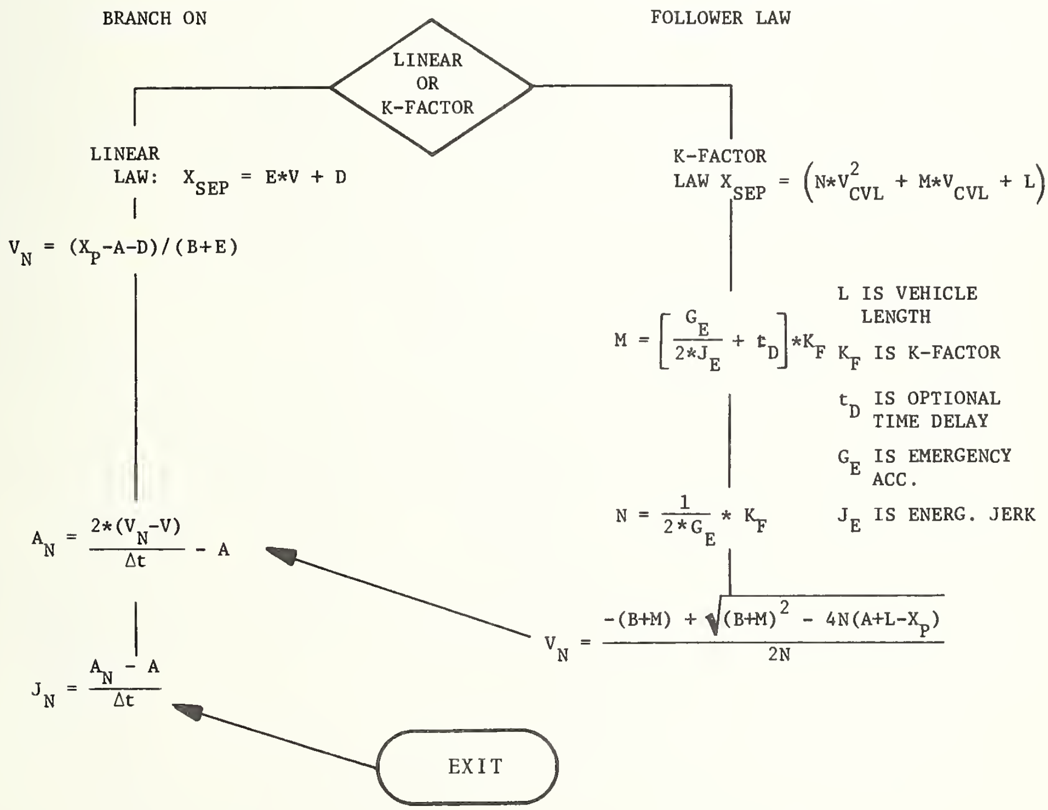


FIGURE 37 CALCULATION OF SINGLE VEHICLE UPDATE

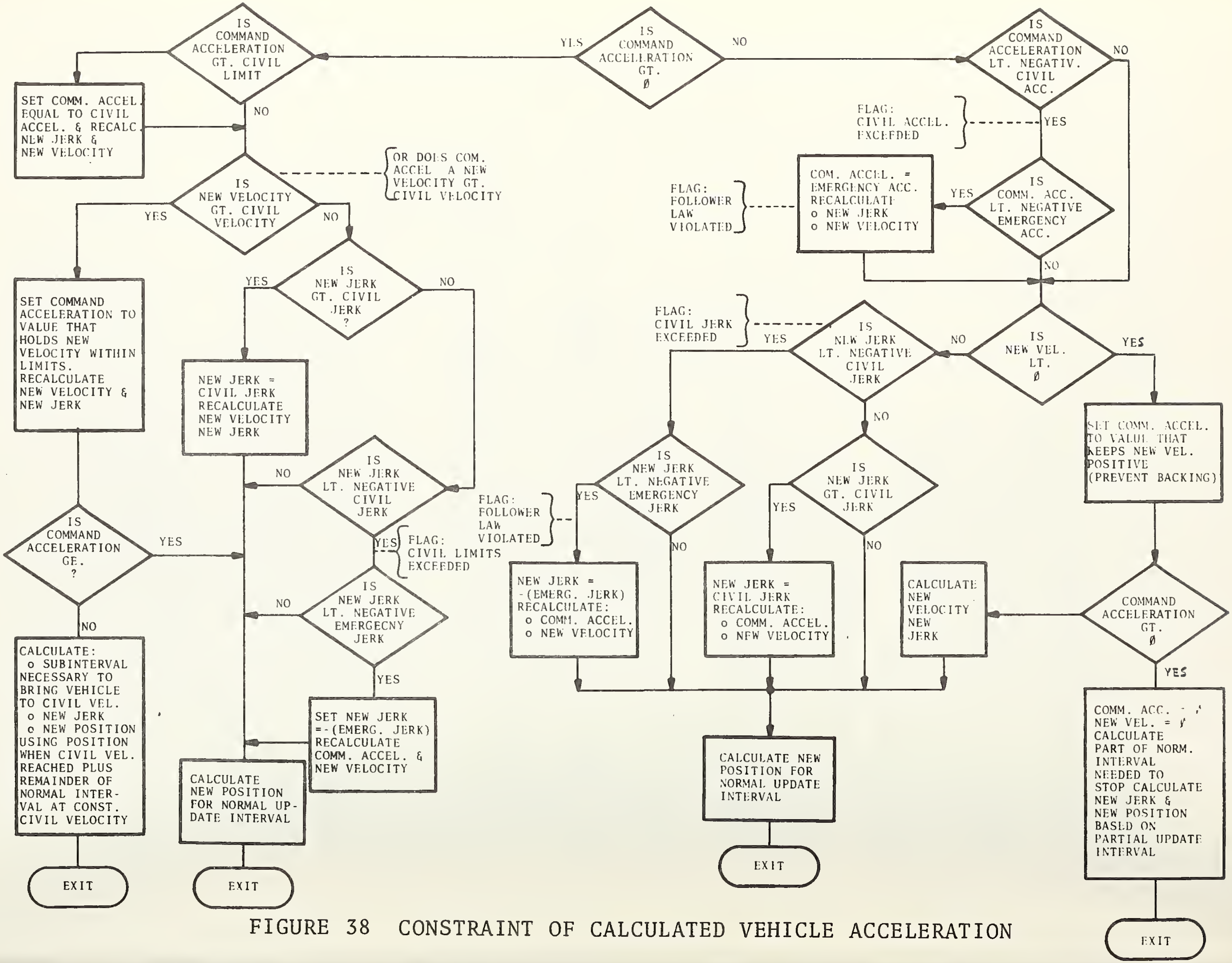


FIGURE 38 CONSTRAINT OF CALCULATED VEHICLE ACCELERATION

b. Ghost Vehicles

Two ghost vehicles are used by the vehicle-follower system modeled. One leads the accelerating vehicle up onto the guideway, and the other slows the first affected vehicle, in order to open a slot for the accelerating vehicle.

In the case of the first ghost, the subprogram SINC generates a profile which will accelerate the ghost to a perfect merge with the last unaffected through vehicle. The starting point of the profile is determined by the parameters of the system modeled, and subsequent positions are provided by SINC. Subprogram SINC has been only slightly modified from the subprogram of the same name used in the point-follower analysis.

A procedure derived from the reasoning of Section 3.1.b is used for the second ghost vehicle. To simplify programming, a linear profile was chosen. This means that the ghost vehicle is identical to the lead vehicle before the merge operation, follows a constant velocity profile at a velocity less than line speed during the merge operation, and finally becomes identical with the merging vehicle at the end of the maneuver. The location of the starting point of the ghost vehicle was chosen to occur at the same time as the start of the merge vehicle's acceleration. Thus, both ghost vehicles exist at the same time, and no ghost vehicle is created before any real vehicle accelerates.

The linear profile for the second ghost created some problems in the actual operation of the computer model. If a full-length ramp is in use, the accelerating vehicle will spend a period of time on the ramp at higher velocity than the ghost. This has the effect of opening too wide a gap, resulting in excessive delay. This fact is reflected in the analysis of results in Section 3.3. The solution to this problem would be to use a contoured ghost profile that accelerated, pacing the merge vehicle once that vehicle passed a certain base velocity. The profile would be fixed at the base velocity before the accelerating vehicle achieved base velocity. The ideal base velocity would have to be calculated in each case.

For medium-length ramps, the linear profile chosen approximates an ideal profile fairly closely, and delays due to the ghost are minimized. For very short ramps, however, the ghost does not exist long enough, and requires a very acute maneuver by the following vehicle. Thus, emergency limits are often reached, and the delays are adversely affected. A solution here would involve extending the ghost profile's starting point back in time before the accelerating vehicle starts, so that the ghost vehicle's velocity would never fall below a certain minimum. The minimum would have to be calculated for each case.

The final problem is the emergency stop. If the lead vehicle stops, the accelerating vehicle must also stop, for otherwise it could run up onto the guideway and collide with the lead vehicle. Likewise, the possible emergency of a merging vehicle in an emergency stop profile requires the following first affected vehicle to stop. The critical situation forms after the start of the merge maneuver when the lead through vehicle passes the end of the ramp. For purposes of this program, all emergency stops are treated the same. The function relating the ghost to its parent vehicle is fairly complicated, relating a linear to a non-linear profile in each case. Instead of deriving the relationship and performing the appropriate calculation, the program calculates the positions of each ghost and its parent vehicle for each update period under normal operations and constructs a table. Then for each new position of the parent vehicle, the ghost vehicle's position is read from the table. Linear extrapolation is used for intermediate points. It is obvious that if a "parent" vehicle does not maneuver as expected, the ghost vehicle will respond accordingly. Before modeling the acceleration merge situation, the two tables, one for each ghost, are calculated by the computer program.

c. Computer Program

The vehicle-follower model was implemented in a FORTRAN IV computer program. The program accepts inputs as listed in Table 4. Processing follows several steps, which are diagrammed in Figure 39.

TABLE 4. VEHICLE-FOLLOWER COMPUTER PROGRAM INPUT PARAMETERS

- PARAMETER INPUT SOURCE: BASE-LINE, USER VIA DISK, OR USER VIA TERMINAL
- VEHICLE-FOLLOWER LAW: LINER OF K-FACTOR
- FOLLOWER LAW PARAMETERS: EITHER CONSTANT AND FIRST-ORDER TERM FOR LINEAR, OR VALUE OF K-FACTOR FROM K-FACTOR LAW
- TYPE OF MANEUVER: ACCELERATION/DECELERATION
- ENABLE/DISABLE PLOTTING

o VEHICLE CHARACTERISTICS:	LENGTH	(FEET)
	BEAMWIDTH	(FEET)
	MAXIMUM SPEED	(MPH)
	MAXIMUM ACC/DEC	(G)
	MAXIMUM JERK	(G/SEC)
o GUIDEWAY PARAMETERS:		
	TIME DELAY	(SEC)
	CIVIL SPEED LIMIT	(MPH)
	CIVIL ACC/DEC	(G)
	CIVIL JERK	(G/SEC)
	CIVIL STATION SPEED	(MPH)
	EMERGENCY ACC/DEC	(G)
	EMERGENCY JERK	(G/SEC)
	FAILURE DEC:	(G)
o MODEL PARAMETERS:	UPDATE TIME	(SEC's & FRACTIONS)
	EMERGENCY STOP FACTOR	(# OF UPDATE INTERVALS BETWEEN EMERGENCY STOPS)
	PRINTOUT FACTOR	(# UPDATES BETWEEN PRINTER OUTPUTS)
	NUMBER BACK TO TRACK	(# VEHICLES)
	RAMP LENGTH	(FEET)
	MAXIMUM TIME	(SEC) (TIME AT WHICH SIMULATION STOPS)
	LONG/SUMMARY PRINTOUT	

- PRINTOUT OF GHOST VEHICLE TRAJECTORY OPTION

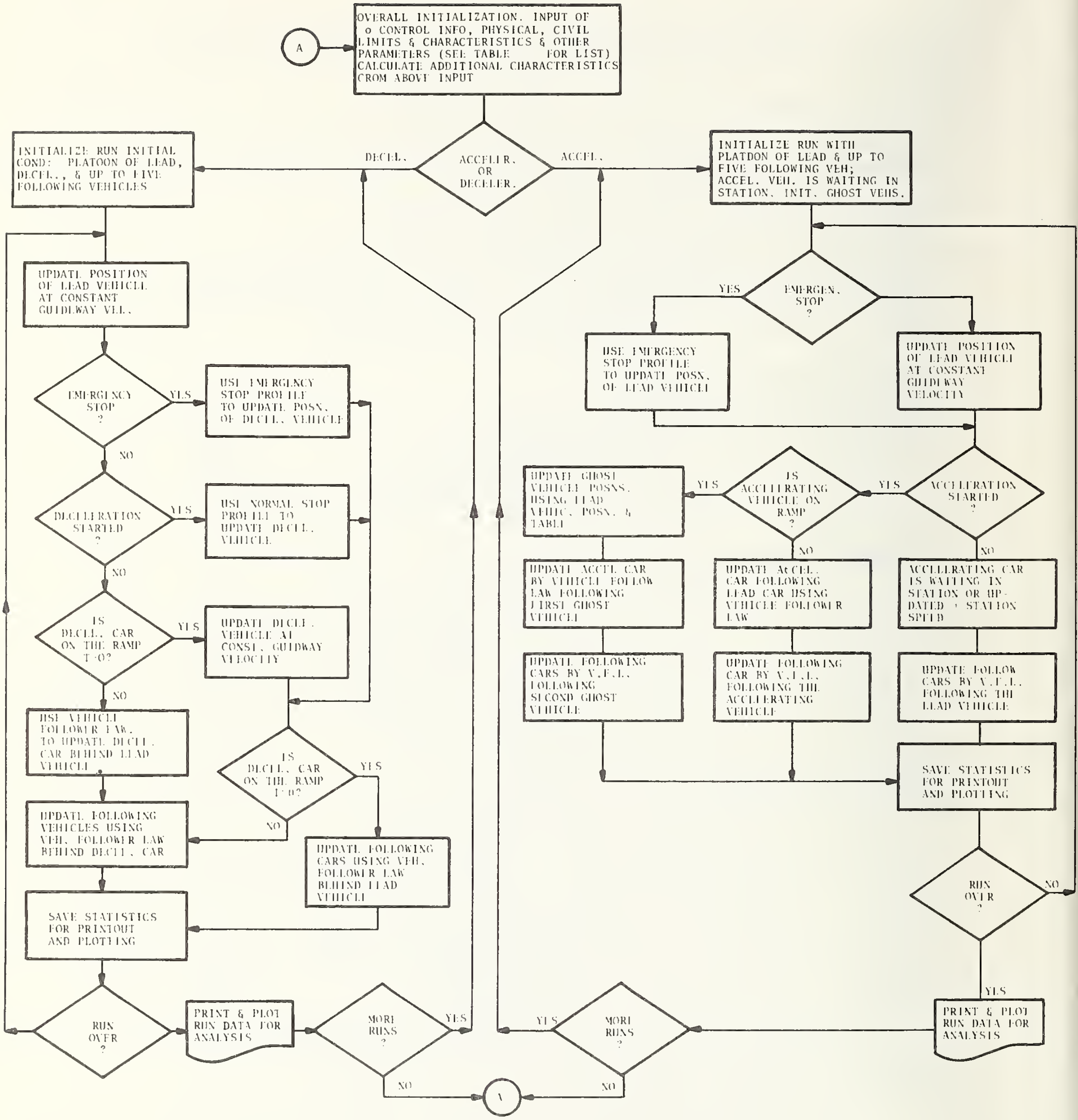


FIGURE 39 VEHICLE-FOLLOWER PROGRAM FLOW

The user of the program controls the model by means of a master loop. The program treats acceleration and deceleration ramps separately. Once the initial conditions of a run have been established, the program re-executes the run automatically to show the effects of a series of further displaced emergency stops as specified by the user. The user may also specify how often he/she wants the vehicle's status (position, velocity etc.) printed out, or only a set of summary statistics for each run. Plotter output, several examples of which (Figure 42, for instance) may be seen in this report, is also available.

The user also informs the program of the number of vehicles to model up to five, and the size of the ramp to be used. Before stopping, the program permits the user to specify additional runs.

Parameters may be entered into the model in any of three forms. The first is the baseline case, which is stored as part of the computer porgram. (Parameters for this case are listed in Table 5.) Input may also be stored on disk. In this case, the user specifies a series of runs and stores them on disk. The program will execute all required runs from disk and then return to interactive mode. In the third, input mode, the user enters all necessary data in a dialogue with the system. Details of computer program operation such as plot file specifications are always input by the user, regardless of the mode in which the program is operating.

Program output is contained primarily in a line-printer tabulation, with plotter-output as an option. Output consists of three section. Section one is a reiteraiton of the system inputs to permit identification of the run, and assist in analysis. Section two is optional and consists of a periodic report of the state of each vehicle in the model. These vehicles are the lead, or last unaffected through vehicle, the transition (accelerating or decelerating) vehicle, and up to five (optional with the user) affected through vehicles. The periodic report shows the current position, velocity, acceleration and jerk of each vehicle. The report cycle is set by the user and may occur as often as every update cycle. The third section is a summary report showing extremes of position and its derivatives reached by each vehicle during the run. An example of this output may be seen in Tables 6A, 6B, and 6C.

d. Improvements

The vehicle-follower computer program would be enhanced by the following improvements and additions. First, more accurate and detailed modeling of vehicle-control systems' deviations from normal. This aspect becomes more important when we realize that a vehicle-follower system has much coarser monitoring, under the assumption that the vehicles are reliable. Thus, a failure may go undetected too long to avert disaster. Also, differences of vehicles with respect to one another will have a more important effect on the overall system.

The second area of improvement involves using the simulated transit system's performance to calculate separation laws. The current program assumes the input system is feasible given the input separation law, i.e., cars will operate within normal design limits. This may not necessarily be the case, since the program accepts whatever parameters are put in. A mode which calculates a safe separation law for a given system and uses that law would be desirable.

The third area of improvement involves ghost vehicles. The procedure here would be to analyze further and quantify the merge trajectory problem, as outlined in Section b. The solution or solutions to this problem would be used to write a much more sophisticated ghost-profile-generation algorithm. This improvement would make the use of the program as a design tool much more feasible. In addition to estimates of ramp-shortening consequences, the program would also suggest merge strategies.

A complementary effort to study ways in which a ghost vehicle would be implemented under various control strategies would be an important adjunct to this effort. In general, it is not known what sorts of devices would be necessary to cause a vehicle to sense and

TABLE 5. VEHICLE-FOLLOWER COMPUTER PROGRAM BASE-LINE PARAMETERS

VEHICLE LENGTH:	15.	FEET
VEHICLE BEAMWIDTH:	5.	FEET
VEHICLE SPEED:	35.	MPH
VEHICLE ACC/DEC:	.25	G
VEHICLE JERK:	.375	G/SEC
EMERGENCY ACC/DEC:	.25	G
EMERGENCY JERK:	.375	G/SEC
TIME DELAY:	.2	SEC
CIVIL SPEED:	30.	MPH
CIVIL ACC./DEC	.1	G
CIVIL JERK:	.1	G/SEC
STATION SPEED:	5.	MPH
MAXIMUM TIME:	3600.	SEC
UPDATE TIME:	.1	SEC
EMERGENCY STOP FACTOR:	100	UPDATES = 10.0 SEC
PRINTOUT FACTOR:	10	UPDATES = 1.0 SEC
PRINTOUT FLAG:	'S'	FOR SUMMARY
NUMBER BACK:	3	VEHICLES
RAMP LENGTH:	=	ACC/DEC DISTANCE
TYPE OF MANEUVER:	'D'	FOR DECELERATION

NOTE: FLAGS AND PARAMETERS CONTROLLING OPERATION OF THE PROGRAM ITSELF ARE ALWAYS UNDER USER CONTROL.

NOTE: CORRESPONDS ESSENTIALLY TO CASE I OF POINT FOLLOWER ANALYSIS react to a ghost vehicle. This area of research requires much more attention.

3.3 RESULTS

Preliminary analysis, analysis of point-follower results, and test runs of the vehicle-follower computer program led to a prediction of delay increase due to ramp shortening. This expected delay is illustrated by Figure 40.

Other factors entering into the analysis, primarily due to the ghost-vehicle profile and to the lower limits on acceleration and jerk necessary when increasing velocity, generated a delay curve of a somewhat different shape.

Limits on resources permitted only one detailed analysis. The case chosen is that of a vehicle-follower having characteristics similar to those of Case II in the point-follower analysis. Table 6A contains a list of these characteristics.

For the acceleration ramp case, runs were performed for ramps of length 200, 150, 100, 75, 50, 30, 25, and 0 feet. The full acceleration distance is 211 feet. Results of these runs are shown in Figure 41. It was discovered that several additional data points are required for short ramp values since the delay changes much more rapidly for this range. In the acceleration case, delays include a component from the shortened ramp and a component caused by the need to open a slot for the merging vehicle. The rapid growth of delay with decreasing ramp length does not start until a ramp length of about 50 feet, or about one-fourth of the total acceleration distance. Even so, the value does not grow to twice the delay at 200 feet before the ramp length has dropped to zero. Also, vehicle-kinematics lag in reacting to the follower law and the nature of the follower law itself cause the delay to have less impact for subsequent vehicles. The delay generated by any one particular ramp entry will eventually be absorbed, and will not propagate indefinitely through the system.

Reduction of deceleration-ramp length is much easier under vehicle-follower strategies than under point-follower strategies. In a vehicle-follower strategy, the follower law is constructed so that a vehicle may perform an emergency stop and yet have the following vehicle come also to a safe stop in response. This provision automatically includes the on-guideway deceleration case. Following vehicles respond less strongly to a small change, so a lead vehicle will not cause serious disruption until its change in speed is quite large. A following vehicle will begin to react to a change in velocity of a lead vehicle, but before its own reaction is large, the lead vehicle disappears into a ramp. This situation is illustrated by the results of the Case II deceleration-ramp analysis. Figure 42 is a position profile for the zero-length ramp. Figure 43 shows the ramp-length-vs.-delay function analogous to that shown for the acceleration ramp case. One should also consider that it is not necessary to slow following traffic for a demerge as it is in a merge operation, so that the lower limit on delay is zero. Again, it is clear that incurred delays are inconsequential until the ramp length is 50 feet, or one-fourth the full deceleration distance. Also, the delay decreases with subsequent vehicles, as expected.

TABLE 6A. SIMULATION RUN PARAMETERS

```
SIMULATION PARAMETERS

CALCULATION UPDATE:  .100 SEC
EMERGENCY STOP FACTOR  300.0 TIMES UPDATE
PRINTOUT FACTOR  5.0 TIMES UPDATE
NUMBER OF AFFECTED CARS TO TRACK (0 TO 5):  3
RAMP LENGTH:  150.00 FEET
MAXIMUM SIMULATION TIME (TOVER):    15.00 SEC

CAR COMPLETES MANUVER IN     8.1 SEC AND 207.68 FT
    K-FACTOR IS: 1.00
LONG OUTPUT MODE.
ACCELERATION RAMP
DATA INITIALIZATION BY USER.


GUIDEWAY PARAMETERS

SAFETY MARGIN:  0.0 FT.
SYSTEM RESPONSE TIME DELAY:  .300 SEC.
CIVIL SPEED:  30.0 MPH
CIVIL ACC/DEC:  .15 G      CIVIL JERK:  .30 G/SEC
STATION SPEED:   5.0 MPH
EMERG. ACC.:  0.3000 G      EMERG. JERK:  0.6000 G/SEC
FAILUR DEC.: 1.0000 G     FAILUR JERK 1.0000 G/SEC


VEHICLE PARAMETERS

LENGTH:  14.0     BEAMWIDTH:  0.00
MAX. VELOCITY:  33.00 MPH
MAX. ACCELERATION:  .3000 G
MAX. JERK:  .6000 G/SEC
```

TABLE 6B. SIMULATION RUN DETAIL DATA

NO VEHICLE FAILURE OCCURS

TIME	LAST UNAFFECTED VEHICLE POS	VEL	ACC	JER	ACCEL/DECEL VEHICLE POS	VEL	ACC	JER	1ST AFFECTED VEHICLE POS	VEL	ACC	JER	2ND AFFECTED VEHICLE POS	VEL	ACC	JER	3RD AFFECTED VEHICLE POS	VEL	ACC	JER
-8.29	-259.2	30.00	0.00	0.02	-161.7	5.00	0.00	0.00	-391.4	30.00	0.00	0.00	-523.6	30.00	0.00	0.00	-655.8	30.00	0.00	0.00
-7.79	-237.2	30.00	0.00	0.07	-158.1	5.00	0.00	0.00	-369.4	30.00	0.00	0.00	-501.6	30.00	0.00	0.00	-633.8	30.00	0.00	0.00
-7.29	-215.2	30.00	0.00	0.02	-154.4	5.02	0.00	0.00	-347.4	30.00	0.00	0.00	-479.6	30.00	0.00	0.00	-611.8	30.00	0.00	0.00
-6.79	-193.2	30.00	0.00	0.07	-150.7	5.02	0.00	0.00	-325.4	30.00	0.00	0.00	-457.6	30.00	0.00	0.00	-589.8	30.00	0.00	0.00
-6.29	-171.2	30.00	0.00	0.02	-146.9	5.82	0.15	0.30	-303.4	30.00	0.00	0.00	-435.6	30.00	0.00	0.00	-567.8	30.00	0.00	0.00
-5.79	-149.2	30.00	0.00	0.01	-142.0	7.47	0.15	0.00	-281.5	29.33	-0.07	0.20*	-413.6	30.00	0.00	0.00	-545.8	30.00	0.00	0.00
-5.29	-127.2	30.00	0.00	0.03	-135.9	9.12	0.15	0.00	-260.4	28.39	-0.09	-0.12:	-391.6	30.00	0.00	0.00	-523.8	30.00	0.00	0.00
-4.79	-105.2	30.00	0.00	0.02	-128.6	10.76	0.15	0.00	-239.9	27.48	-0.07	0.14	-369.6	30.00	0.00	0.00	-501.8	30.00	0.00	0.00
-4.29	-83.2	30.00	0.00	0.00	-120.1	12.41	0.15	0.00	-220.0	26.64	-0.08	-0.12	-347.6	30.00	0.00	0.00	-479.8	30.00	0.00	0.00
-3.79	-61.2	30.00	0.00	0.04	-110.4	14.06	0.15	0.00	-200.8	25.85	-0.06	0.15	-325.6	30.00	0.00	0.00	-457.8	30.00	0.00	0.00
-3.29	-39.2	30.00	0.00	0.02	-99.5	15.70	0.15	0.00	-182.1	25.12	-0.07	-0.13	-303.6	30.00	0.00	0.00	-435.8	30.00	0.00	0.00
-2.79	-17.2	30.00	0.00	0.02	-87.4	17.35	0.15	0.00	-163.9	24.45	-0.05	0.16	-281.7	29.51	-0.06	-0.24*	-413.8	30.00	0.00	0.00
-2.29	4.8	30.00	0.00	0.03	-74.1	19.00	0.15	0.00	-146.2	23.85	-0.06	-0.15	-260.3	28.97	-0.04	0.24	-391.8	30.00	0.00	0.00
-1.79	26.8	30.00	0.00	0.02	-59.5	20.64	0.15	0.00	-129.0	23.30	-0.04	0.18	-239.3	28.41	-0.06	-0.26	-369.8	30.00	0.00	0.00
-1.29	48.8	30.00	0.00	0.02	-43.8	22.29	0.15	0.00	-112.2	22.81	-0.05	-0.16	-218.6	27.85	-0.04	0.28	-347.8	30.00	0.00	0.00
-0.79	70.8	30.00	0.00	0.07	-26.8	23.94	0.15	0.00	-95.5	22.37	-0.03	0.19	-198.4	27.29	-0.07	-0.29	-325.8	30.00	0.00	0.00
-0.29	92.8	30.00	0.00	0.00	-8.7	25.58	0.15	0.00	-79.2	21.97	-0.04	-0.18	-178.6	26.73	-0.04	0.29:	-303.8	30.00	0.00	0.00
0.21	114.8	30.00	0.00	0.07	10.7	27.23	0.15	0.00	-63.1	22.22	0.10	0.30	-159.2	26.20	-0.05	-0.22	-281.8	30.00	0.00	0.00
0.71	136.8	30.00	0.00	0.02	31.0	27.74	-0.03	0.19*	-46.5	22.95	0.07	0.30:	-140.1	25.81	-0.02	0.26	-259.8	29.78	-0.05	-0.15:
1.21	158.8	30.00	0.00	0.00	51.4	27.98	0.02	0.72:	-29.4	23.62	0.05	-0.05*	-121.3	25.53	-0.03	-0.24	-238.1	29.37	-0.03	0.16
1.71	180.8	30.00	0.00	0.03	72.0	28.19	0.02	-0.03	-11.9	24.16	0.05	0.03	-102.7	25.34	0.00	0.28	-216.7	28.97	-0.04	-0.17
2.21	202.8	30.00	0.00	0.02	92.7	28.38	0.02	0.02	6.0	24.65	0.04	-0.05	-84.1	25.23	-0.02	-0.27	-195.6	28.59	-0.02	0.20
2.71	224.8	30.00	0.00	0.02	113.6	28.55	0.01	-0.03	24.3	25.10	0.04	0.04	-65.6	25.19	0.01	0.30	-174.8	28.24	-0.04	-0.20
3.21	246.8	30.00	0.00	0.02	134.6	28.70	0.01	0.02	42.8	25.51	0.03	-0.06	-47.2	25.21	-0.01	-0.28	-154.2	27.92	-0.02	0.23
3.71	268.8	30.00	0.00	0.03	155.7	28.83	0.01	-0.03	61.7	25.88	0.04	0.05	-28.7	25.26	0.02	0.30	-133.8	27.64	-0.04	-0.24
4.21	290.8	30.00	0.00	0.02	176.9	28.95	0.01	0.02	80.8	26.21	0.03	-0.06	-10.1	25.35	-0.00	-0.29	-113.7	27.39	-0.01	0.27
4.71	312.8	30.00	0.00	0.03	198.2	29.06	0.01	-0.03	100.1	26.52	0.03	0.06	8.5	25.47	0.03	0.30	-93.7	27.18	-0.03	-0.28
5.21	334.8	30.00	0.00	0.02	219.5	29.15	0.01	0.03	119.7	26.81	0.02	-0.07	27.3	25.61	-0.00	-0.29	-73.8	27.00	-0.00	0.29
5.71	356.8	30.00	0.00	0.02	240.9	29.24	0.01	-0.03	139.4	27.07	0.03	0.07	46.1	25.76	0.03	0.30	-54.1	26.86	-0.03	-0.28
6.21	378.8	30.00	0.00	0.07	262.4	29.32	0.01	0.03	159.4	27.31	0.02	-0.08	65.0	25.92	0.00	-0.29	-34.4	26.74	0.01	0.30
6.71	400.8	30.00	0.00	0.02	283.9	29.39	0.00	-0.03	179.5	27.53	0.02	0.07	84.1	26.09	0.03	0.30	-14.8	26.66	-0.02	-0.28
7.21	422.8	30.00	0.00	0.02	305.5	29.45	0.01	0.03	199.7	27.73	0.01	-0.08	103.3	26.26	0.00	-0.30:	4.7	26.61	0.01	0.30
7.71	444.8	30.00	0.00	0.02	327.1	29.50	0.00	-0.04	220.1	27.91	0.02	0.08	122.6	26.43	0.03	0.30	24.2	26.58	-0.02	-0.30
8.21	466.8	30.00	0.00	0.07	348.8	29.55	0.01	0.03	240.7	28.08	0.01	-0.09	142.1	26.61	0.00	-0.30:	43.7	26.58	0.01	0.29
8.71	488.8	30.00	0.00	0.02	370.5	29.60	0.00	-0.04	261.3	28.24	0.02	0.09	161.7	26.78	0.03	0.30	63.2	26.59	-0.01	-0.29
9.21	510.8	30.00	0.00	0.07	392.2	29.64	0.01	0.04	282.1	28.38	0.01	-0.10	181.4	26.95	0.00	-0.30:	82.7	26.62	0.02	0.30
9.71	532.8	30.00	0.00	0.02	413.9	29.67	0.00	-0.04	302.9	28.51	0.02	0.10	201.2	27.11	0.03	0.30:	102.2	26.66	-0.01	-0.29
10.21	554.8	30.00	0.00	0.00	435.7	29.71	0.00	0.04	323.9	28.64	0.01	-0.11	221.1	27.27	-0.00	-0.30:	121.8	26.72	0.02	0.28
10.71	576.8	30.00	0.00	0.02	457.5	29.74	0.00	-0.04	344.9	28.75	0.02	0.11	241.2	27.42	0.03	0.30	141.4	26.79	-0.01	-0.30
11.21	598.8	30.00	0.00	0.07	479.3	29.76	0.00	0.04	366.1	28.85	0.00	-0.12	261.3	27.57	-0.00	-0.30:	161.1	26.87	0.02	0.30
11.71	620.8	30.00	0.00	0.00	501.1	29.79	-0.00	-0.05	387.2	28.94	0.01	0.13	281.6	27.71	0.03	0.30	180.8	26.95	-0.01	-0.30:
12.21	642.8	30.00	0.00	0.02	523.0	29.81	0.00	0.05	408.5	29.03	0.00	-0.14	302.0	27.84	-0.00	-0.30:	200.6	27.04	0.02	0.30
12.71	664.8	30.00	0.00	0.02	544.9	29.83	-0.00	-0.05	429.8	29.11	0.01	0.14	322.4	27.97	0.03	0.30	220.5	27.14	-0.01	-0.29:
13.21	686.8	30.00	0.00	0.07	566.7	29.84	0.00	0.05	451.2	29.18	-0.00	-0.15	343.0	28.10	-0.00	-0.30:	240.4	27.23	0.02	0.29:
13.71	708.8	30.00	0.00	0.02	588.6	29.86	-0.00	-0.05	472.6	29.25	0.01	0.15	363.6	28.22	0.03	0.30:	260.4	27.33	-0.00	-0.29:
14.21	730.8	30.00	0.00	0.07	610.5	29.87	0.00	0.05	494.1	29.31	-0.00	-0.16	384.4	28.33	-0.01	-0.30:	280.5	27.43	0.02	0.30
14.71	752.8	30.00	0.00	0.02	632.4	29.89	-0.00	-0.06	515.6	29.37	0.01	0.17	405.2	28.43	0.02	0.30:	300.7	27.53	-0.00	-0.29:

TABLE 6C. SUMMARY OF DETAIL DATA

VEHICLE IDENT	MINIMUM VELOCTY	POSN.	MAXIMUM VELOCTY	POSN.	MAXIMUM ACEL.	POSN.	MAXIMUM JERK	POSN.
LAST UNAFF	30.00	761.6	30.00	761.6	0.00	761.6	0.00	761.6
ACC./DEC.	5.00	-150.7	29.89	641.2	0.15	10.7	0.30	43.2
1ST AFECTD	21.88	-72.8	30.00	-299.0	0.13	-59.9	0.30	-43.1
2ND AFECTD	25.19	-61.9	30.00	-303.6	0.03	130.4	0.30	405.2
3RD AFECTD	26.57	39.8	30.00	-273.0	0.02	288.6	0.30	296.6

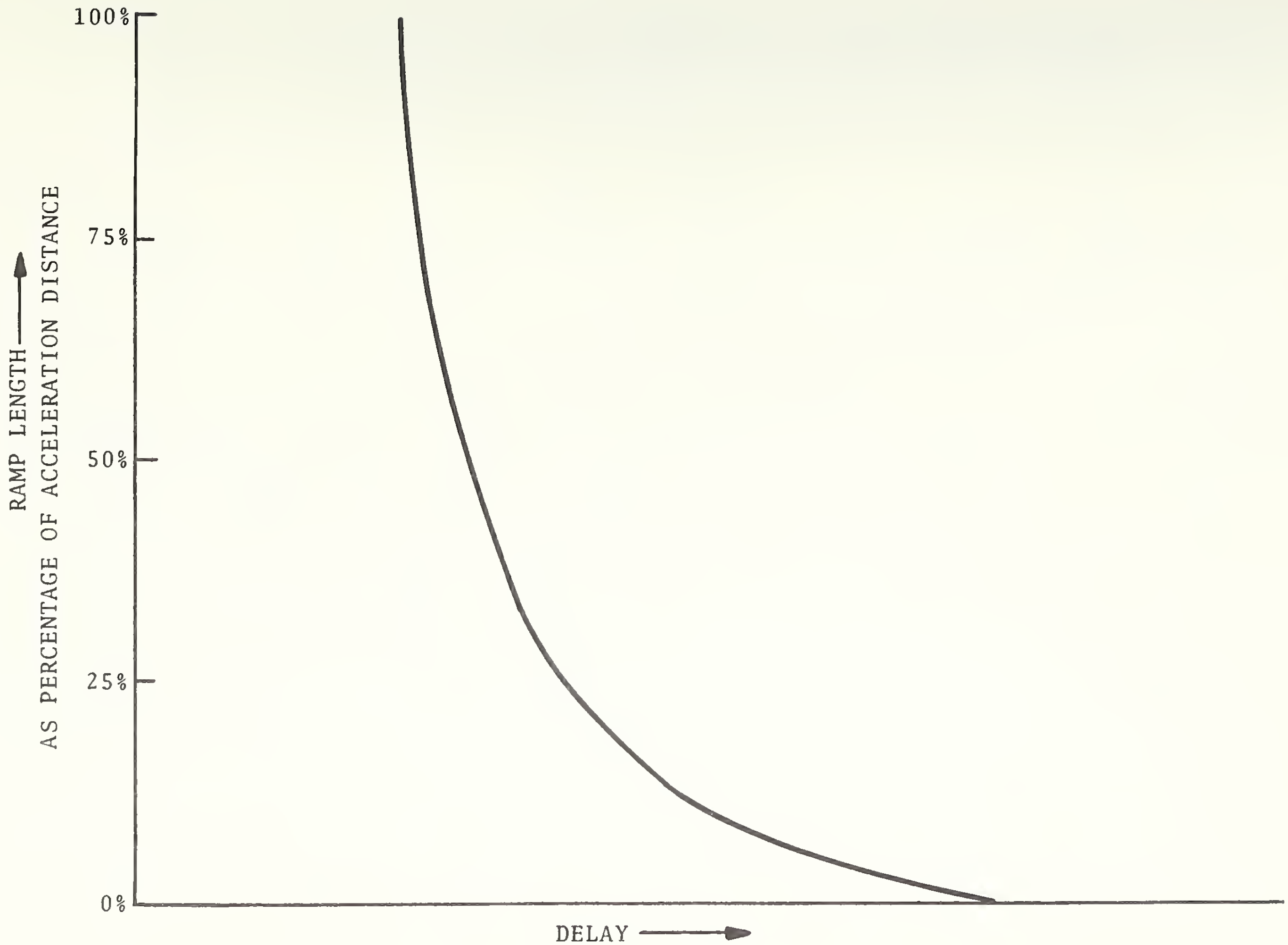


FIGURE 40 EXPECTED DELAY PENALTY FOR INCREASED RAMP LENGTH

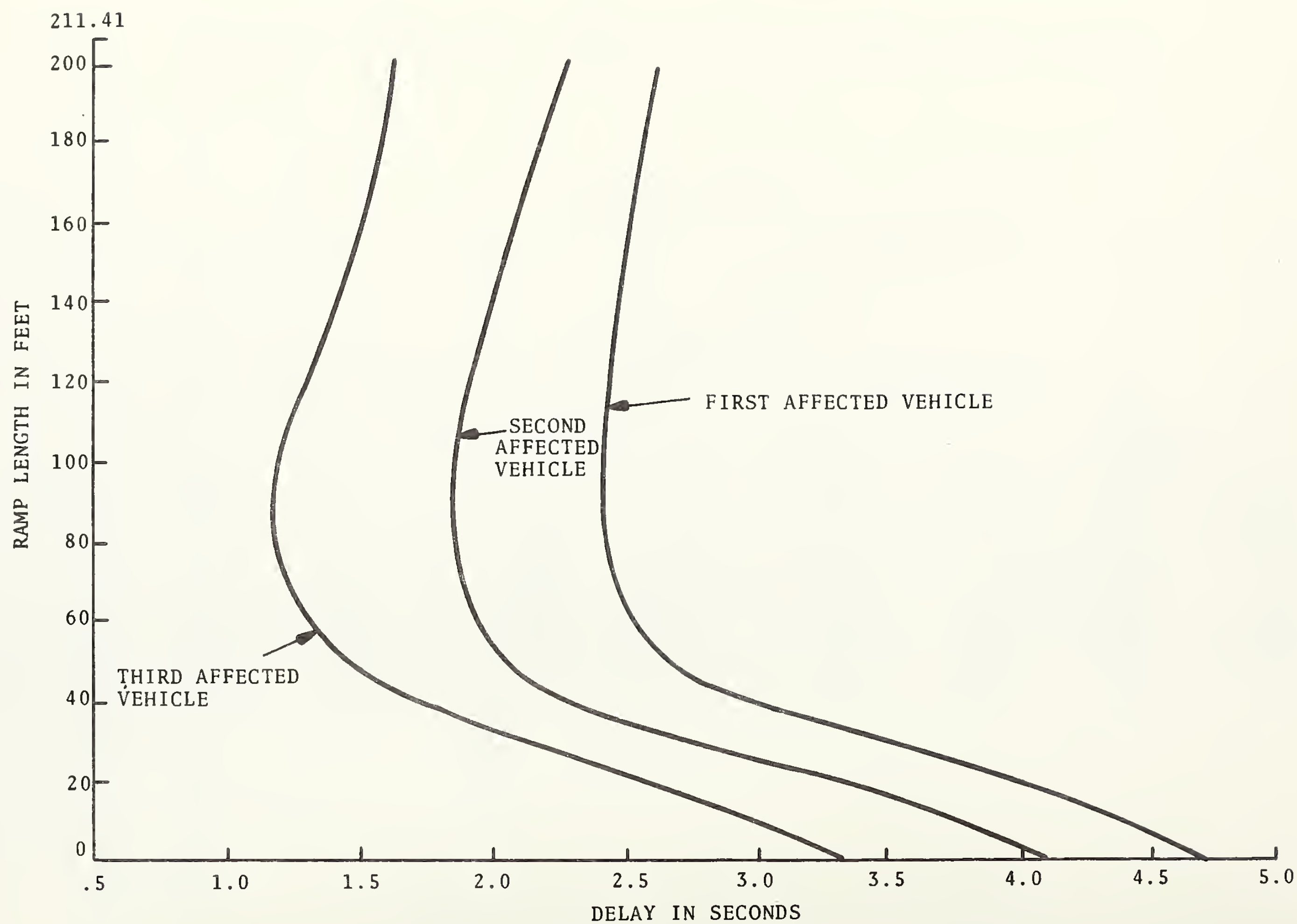


FIGURE 41 ACCELERATION-RAMP DELAYS DUE TO RAMP-LENGTH CHANGES

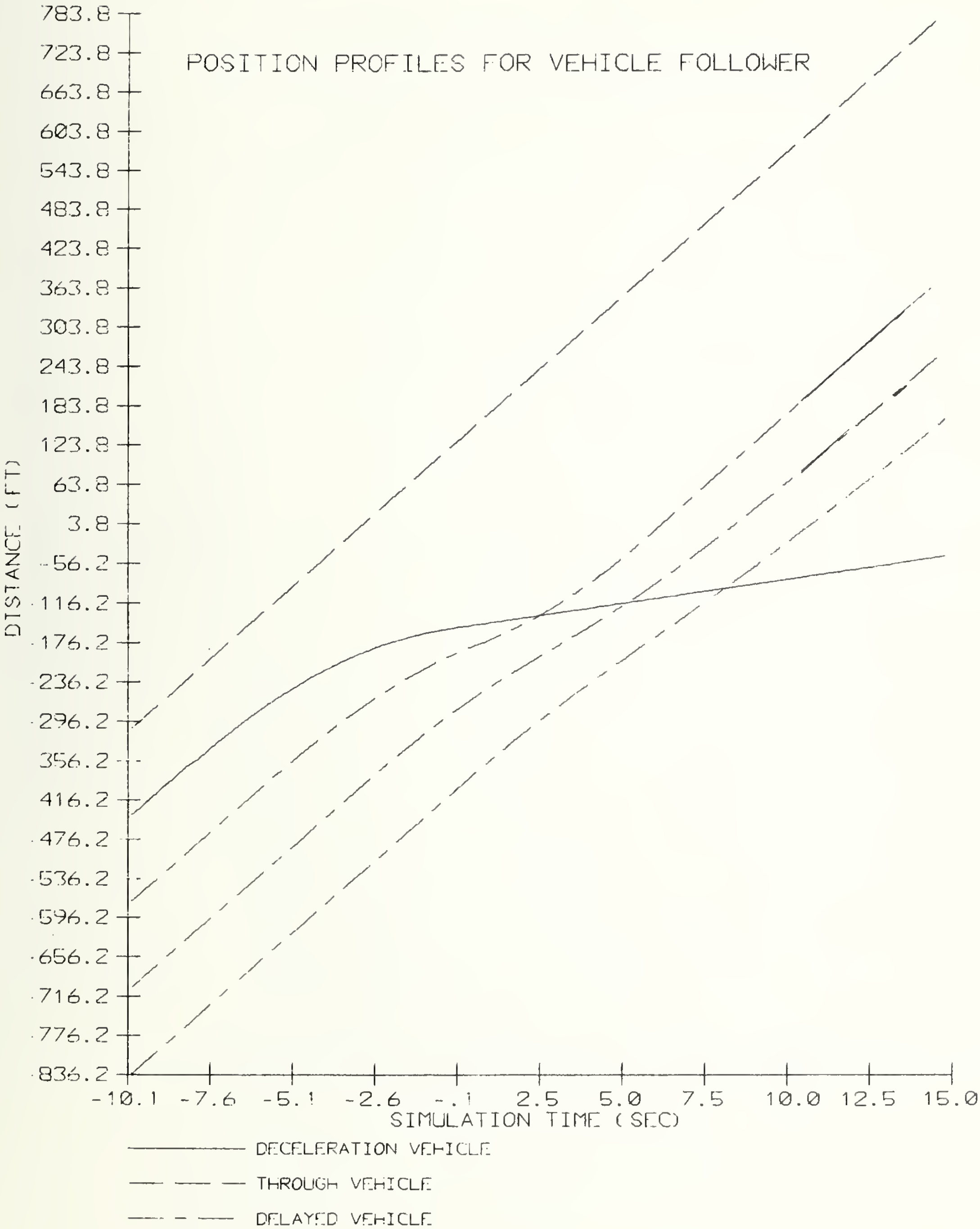


FIGURE 42 DECELERATION PROFILES WITH NO RAMP DECELERATION

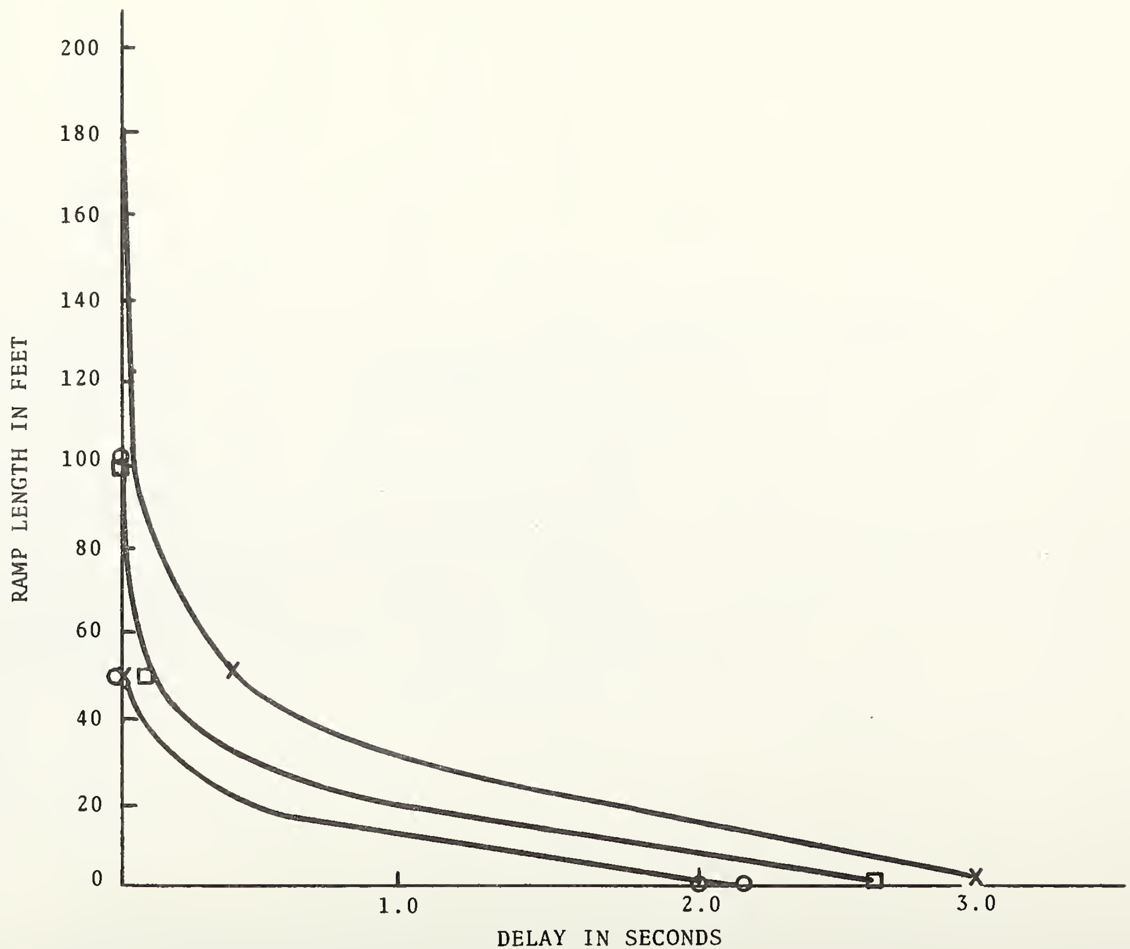


FIGURE 43 DECELERATION DELAYS DUE TO RAMP LENGTH

4. DEMONSTRATION

Part of the original Alden contract called for a demonstration of short station ramps on the Alden test track. The implementation of the demonstration was dropped, but the design of the "short ramp" station was completed, and the design rationale is presented in this section. The test track has since been dismantled.

4.1 TEST TRACK

The geometry of the Alden test track is shown in Figures 44 and 45. The main guideway loop was 476 feet and there were two off-line stations. On each side of the guideway, there were vertical guiderails. The cars (there were two test track cars) were guided on the track by horizontal wheels, coupled to the cars' steering (Figures 46 and 47). Cars were always switched left or right. When switched left they followed the left guiderail, and when switched right they followed the right guiderail. Except in switch areas, only one side of any guideway path had to have a guiderail. For this reason, the separators between the station and main guideway, shown on Figure 44 and 45, had been removed. (They are crossed out on Figure 44.) The hazard of the separation rail was eliminated and installation of a shorter station was simplified.

Under contract DOT-TSC-421, a headway safety system was developed for the test track, as described in references 8 and 9. It was also going to be used to insure safety for the short-ramp demonstration. The parameters of the headway safety system provided for safe operation under the following conditions.

Main Guideway Speed	10.82 mph
Station Entry Speed	3.0 mph
Headway	7.5 seconds
Ramp Deceleration	0.1 g's
Ramp Jerk	0.1 g's/second
Emergency Deceleration	0.3 g's
Minimum Safety Margin	1.0 feet

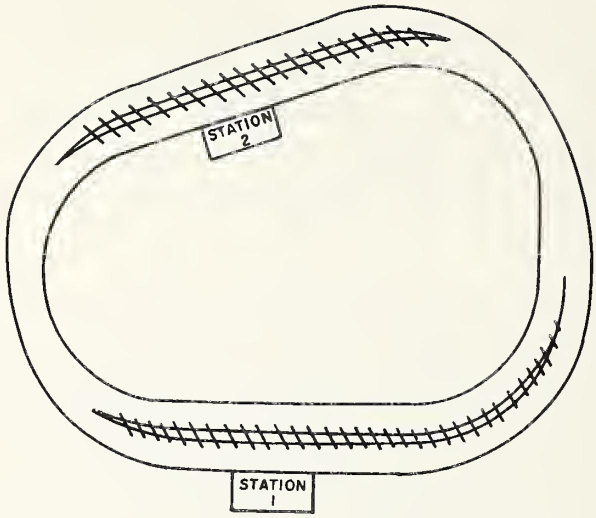


FIGURE 44. TEST TRACK OUTLINE

FIGURE 45. PHOTO OF TEST TRACK

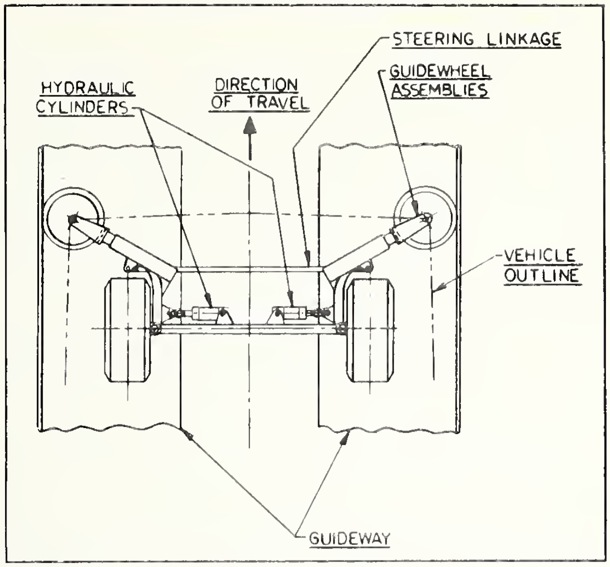


FIGURE 46. CAR STEERING ON GUIDEWAY (OVERHEAD VIEW)

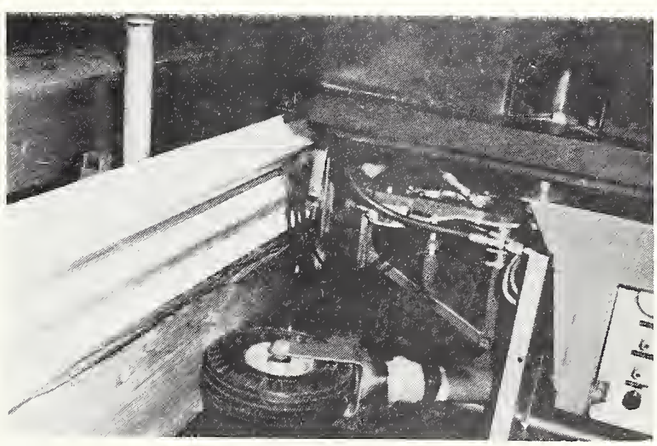


FIGURE 47. GUIDEWHEEL AND POWER PICKUP

Length of Acceleration Ramps 47 feet
Length of Deceleration Ramps 46 feet

Since the cars were controlled using point-follower vehicle control, the implications of on-guideway acceleration and deceleration can be investigated using the point-follower analysis techniques developed in Section 2.

4.2 ANALYSIS

An analysis was conducted to determine a station guiderail profile that would clearly demonstrate the safety of short station ramps. Station guiderails are basically "S" curves that provide transitions from the guideway to the station. The design discussed here is not a fine-grained optimization. Refinements were not possible within the cost constraints of the program and given the dimensional uncertainties of the cars and track. The procedure followed is nonetheless like that which would be followed with more exact design information and with more sophisticated tradeoffs.

The first step in the analysis was to use the Point-Follower Headway-Safety-Program, with track parameters, to determine at what point on the acceleration and deceleration ramps the cars had to be clear of the guideway.

It was determined that with the existing headway protection geometry, an accelerating car could safely enter the guideway as soon as it starts up. It did not have to reach guideway speed while on the station ramp.

A car that is decelerating from 10.83 mph to a station speed of 3 mph did not have to be clear of the main guideway until the front of the car was 20 feet past the end of the deceleration ramp. However, the headway safety system only operated 3.5 feet past the end of the deceleration ramp. Thus, if a car failed when beyond the safety system, there was no way of sensing it. To prevent possible collisions with a following car that is on the guideway and receives no stop signal, it was specified that a car turning into the station must be clear of the main guideway before it leaves the operating zone of the headway safety system.

Since there was a normal clearance between the station lane and the main guideway, an entering car was clear of the main guideway when it had reached an angle of about 5 degrees, relative to the center line of the station guideway. Stated another way, the rear of the car could "hang out" 5 degrees and still be safe.

The discussion above is summarized in Figure 48, which shows the geometric constraints for safe operation.

In addition to the exit and entrance conditions discussed above, the guideway profile had to satisfy several other conditions.

The sides of the car could not hit the guiderail on the convex part of the "S" curve that leads into the station. The critical measure here was the overhang of the power pickup, halfway back on one of the cars. If it cleared the guiderail, the other parts of both cars would clear.

The concave portion of the "S" curve had to have a radius greater than the minimum turning radius of the cars. This translated into a guiderail radius of about 19 feet.

The clearance at the center of one of the cars had to be less than 12 inches on the concave portion of the "S" curve. If it were greater, the power pickup would disengage.

The cars had to be parallel to the station platform to expedite passenger loading. The 5-degree condition noted above insured that they would meet this condition.

The lateral acceleration on the "S" curve had to be within reasonable limits.

To insure that the limits for clearance, turning radius, and lateral acceleration were met, it was necessary to write a computer program that determined the position of the cars as they followed a curved guideway. The characteristics of this program, called OFFTRK, are summarized in Table 7.

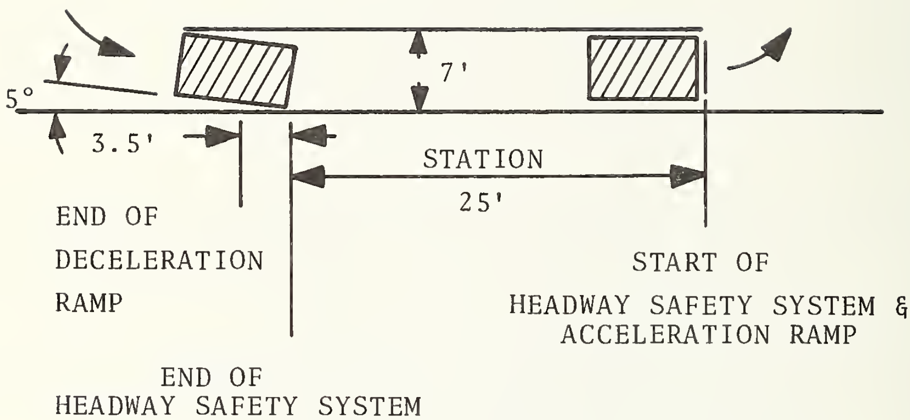
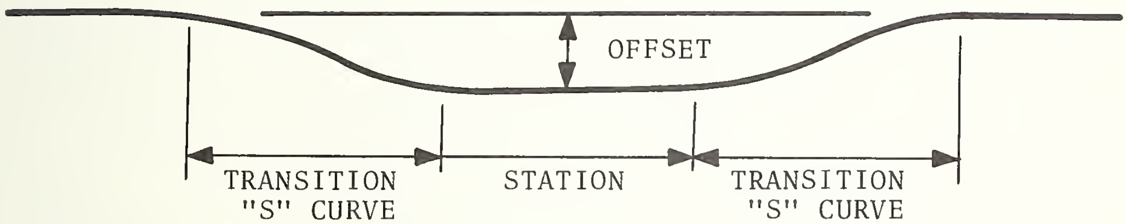


FIGURE 48. CAR CONSTRAINTS FOR SAFE OPERATION

TABLE 7 CHARACTERISTICS OF OFFTRK COMPUTER PROGRAM

PURPOSE: TO DETERMINE THE POSITION OF A FRONT-WHEEL-STEERING CAR, WITH GUIDEWHEELS, AS IT FOLLOWS A CURVED GUIDERAIL.



INPUTS:

- o GUIDERAIL DEFINITION

  OFFSET
  STATION LENGTH
  LENGTH OF TRANSITION (SPECIFIED THROUGH RADIUS JUNCTION ANGLE)
  RATIO OF RADIUS OF CONVEX TO CONCAVE PORTIONS OF "S" CURVE.

- o CAR DEFINITION

  WHEEL BASE
  FRONT WHEEL OFFSET
  OVERHANG HALF WAY BACK
  OVERHANG AT REAR

- o COMPUTATION DEFINITION

  INITIAL OFFSET OF REAR
  START, FINISH AND INTEGRATING INTERVALS
  PRINTOUT INTERVAL

OUTPUTS:

- o PARAMETERS OF GUIDERAIL
- o COORDINATES OF GUIDERAIL
- o CAR ANGLE VERSUS VERSUS DISTANCE
- o CAR CLEARANCE IN MIDDLE AND REAR OF CAR VERSUS DISTANCE

The program assumes an "S" curve, made up of two linked radii. This adequately models the critical aspects of the problem, considering the installation accuracy possible on the test track.

The program also assumes a "quasi-linear" station, i.e., that guideway and station are parallel. In effect, the "S" curve is considered a perturbation on the overall curvature of the test track. We did not feel that the more exact formulation, incorporating the overall curvature, was warranted for this application, although it could have been incorporated into the program. The reason is that the net offset of a car that followed the existing station profile was quite small. As a result, the model slightly underestimates the clearance on both the convex and the concave curve.

A series of design runs with the OFFTRK program is summarized in Figure 49. The key design parameters are plotted as a function of length of the "S" curve and the ratio of the convex-curve radius to the concave-curve radius. The chosen design point is a compromise among the following:

Assurance that the maximum clearance range of the power pickup (12 inches) is not exceeded.

Assurance that a minimum clearance is maintained at the side of the car.

A desire to minimize the length of transition in order to provide a better demonstration.

The design point chosen calls for a transition distance of 26 feet, and a radius ratio of 1.3. With allowance for the overall curvature of the track (which, as discussed above, will slightly increase both side clearances) there is about 2 inches of clearance margin at the design point. Transition distance is 26 feet, and 31 feet must be traveled to bring the angle of the car to 5 degrees.

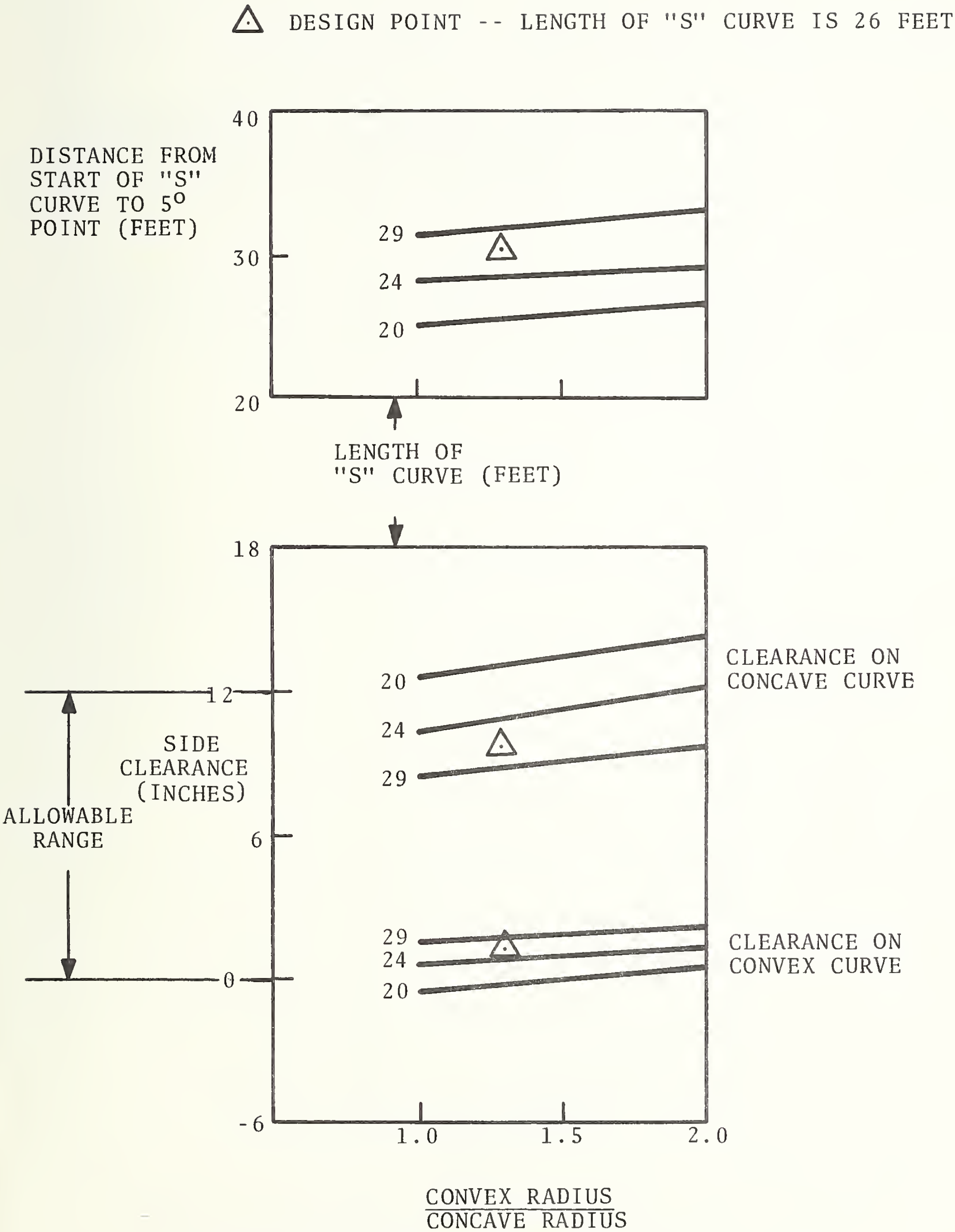


FIGURE 49. DESIGN CHARTS FOR STATION RAMPS

The parameters determined above are translated into the design-guiderail profile shown in Figure 50. The outside lines define the existing track; the upper two lines define the modified track. It is apparent that the station length is cut appreciably.

The station design is essentially symmetrical; the concave radii are 28 feet and the convex radii are 36 feet. A check indicates that lateral accelerations are about 0.15 g's and are well within reasonable tolerances.

Note that the original station was laid out with a relatively short deceleration ramp (it was based on a higher ramp deceleration) and a very long acceleration ramp (due to the low power of the early test cars).

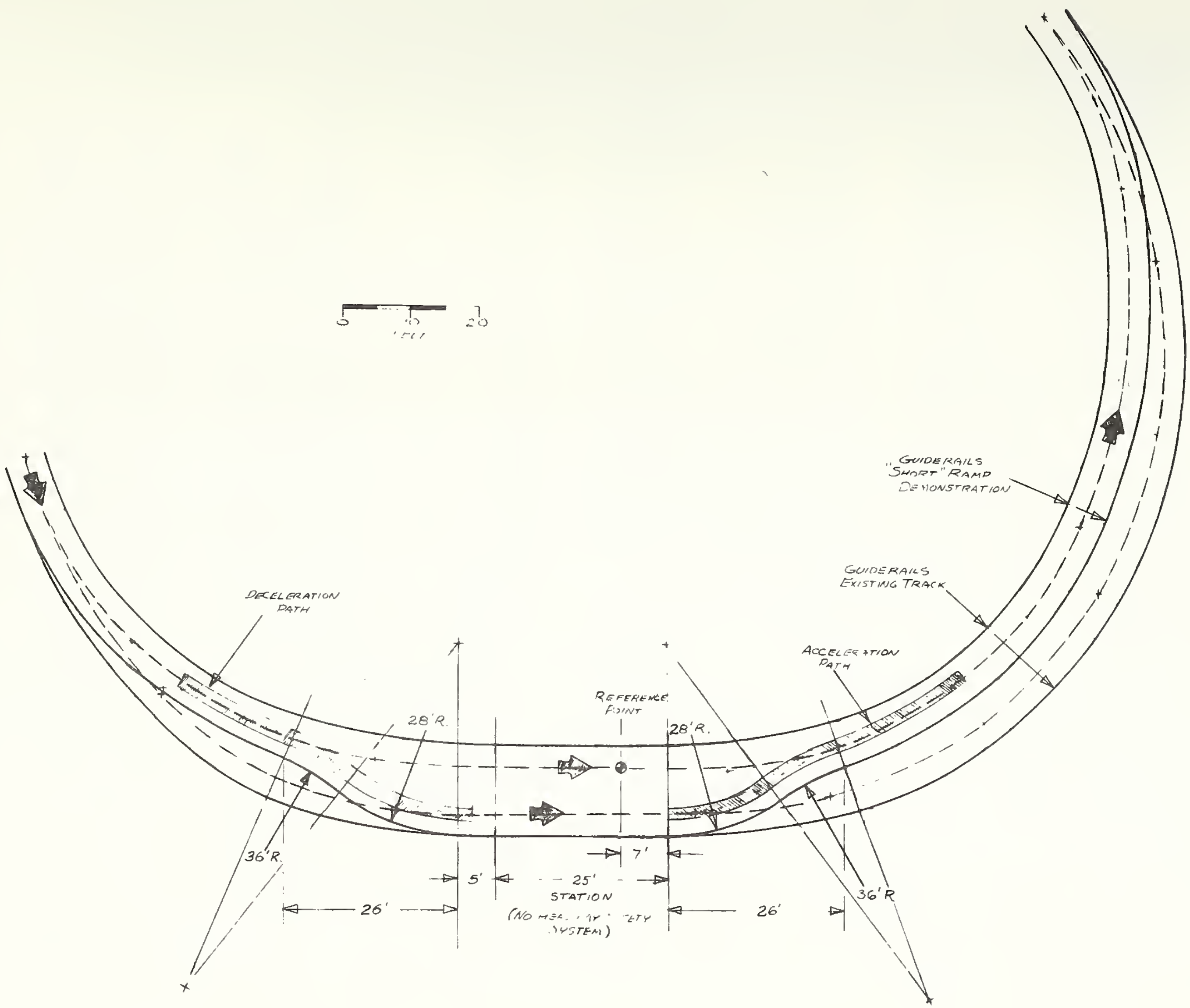


FIGURE 50. MODIFICATION TO TEST TRACK FOR SHORT RAMP TEST

5. CONCLUSIONS

5.1 POINT-FOLLOWER SYSTEMS

a. The acceleration ramp leading from an off-line PRT or dual-mode station can usually be eliminated with no reduction in safety or increase in main-guideway headway. Most, if not all, of the acceleration can take place on the main guideway.

b. Conclusion (a) appears to be relatively independent of system parameters and the resolution of the control and failure-detection systems.

c. Appreciable portions of the deceleration ramps can be eliminated if headway is only moderately greater than what is required on the main guideway, since there is a rapid initial decrease in ramp length with increasing headway.

d. Assuming that main guideway headway must be equal to the headway required for successive cars to enter a station, deceleration ramps only have to be about 20 percent of the deceleration distance.

e. Conclusion (d) is valid given reduced resolution in the control and failure-detection systems.

5.2 VEHICLE-FOLLOWER SYSTEMS

a. Unlike the case in point-follower systems, ramp length is reflected in a vehicle-follower PRT or dual-mode system by a disturbance of through traffic. A vehicle-follower system whose follower law is safe will never be made less safe by the use of shorter ramps.

b. Acceleration ramps may be greatly shortened before appreciable effect is noticed on the system delays. In most cases, acceleration ramps may be 25 percent of the acceleration distance without penalty.

c. Deceleration ramps may be as much as 25 percent of the deceleration distance, with small penalty. In addition, the vehicle follower performs far better than the point follower in the deceleration maneuver.

d. The system is very sensitive to the techniques used to implement merges. In a practical situation, the merge-control technique must be tailored to the ramp situation to insure efficient operation.

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APPENDIX
NEW TECHNOLOGY

This report is the conclusion of the TSC-conducted research project into the on-line velocity modification effort. This work was substantially completed by October 1974.

In performance of this work, the following items are novel to the area of automated guideway transit systems:

1. The extensive use of short acceleration/deceleration ramps,

2. The detailed merge/demerge computer model for synchronous systems used to study the short ramp problem,

3. The detailed computer model used to study the asynchronous control system, including the use of the false or ghost vehicle strategy, and

4. The computer models used to study and design the guideway configuration of a system using short ramps.

Although novel to the area of automated guideway systems, the above techniques and control strategies have been proposed and used in the past in other disciplines and do not constitute patentable material.

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