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**THE TECHNICAL, ENGINEERING, AND ECONOMIC
FEASIBILITY OF A HIGH-SPEED
GROUND CORRIDOR**

by

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EXECUTIVE SUMMARY

This report presents the preliminary findings of an investigation into the feasibility of a high-speed ground corridor, with special emphasis on the design, implementation, and management of such a facility. The approach adopted in this research effort was a "systems" approach, one in which two teams of researchers from civil and mechanical engineering (each team supervised by one of the principal investigators) addressed the main issues of vehicle characteristics and driver issues. The three basic components of a transportation system — fixed facilities, flow entities, and control entities — were considered with respect to a high-speed facility. But because design specifications related to such high-speed highways are, at least at the moment, extremely limited, most of the results and findings in this report have been extrapolated from present design procedures used on conventional highway systems.

The report concludes that much of the automobile and highway technology necessary for the operation of a high-speed facility is presently available, and, accordingly, such a facility is feasible from all engineering standpoints. With respect to highways, some improvements will be necessary, including identification of an aggregate capable of maximizing highway/tire-surface friction. The study recommends, for reasons of economy, that a rigid pavement section be used for the high-speed highway system (though further research will be needed to determine final design thickness).

With respect to the automobile, a high-speed facility will require vehicles that have high-speed capability, reliable braking systems, excellent fuel economy, minimum engine emissions, light weight, and the ability to use alternative fuels. This study suggests that present technology can produce such a vehicle. At the same time, however, this report recognizes that some aspects of automobile design, including vehicle/driver interaction and driver control at high speeds, could be improved.

Future research should concentrate on the civil and mechanical engineering issues, including associated costs and environmental impacts. And because developments in automotive design result in modifications to the traditional highway design guides, the high-speed facility design will need to consider the implications of these developments in terms of design and costs, including comparisons of life-cycle costs with other modes.

ABSTRACT

Despite the considerable effort devoted to transportation planning and design system development over the past 30 years, there has not been widespread application of the resulting new technology. This is now changing. As city freeways become increasingly congested, the need to incorporate design innovations that provide for safe and efficient transportation facilities becomes greater than ever.

As this paper reports, advanced technology in information systems, automation, and telecommunications can potentially yield not only cost savings and productivity improvement, but new developments in transportation as well. This study, providing an overview of the state of the art of this technology, explores the research opportunities available for implementing such technology in the creation of a safe and efficient high-speed ground corridor, one that will be capable of meeting the alarming projected traffic demand of the future.

ACKNOWLEDGMENTS

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CHAPTER 1. INTRODUCTION

BACKGROUND

Today, perhaps more than ever, transportation represents a vital part of daily life. In the U.S., for example, transportation accounts for almost one-fifth of the gross domestic product (Ref 1), with one out of every eight dollars of personal expenditure going toward some aspect of transportation. More than half the population is licensed to drive, and over four-fifths of all households own one or more motor vehicles. Annual passenger travel in the U.S. averages almost 12,000 miles per capita, with cargo shipments averaging a similar distance per ton per capita annually. The result is that the quality of our mobility has, in effect, become synonymous with our standard of living.

Yet as urban populations continues to grow, the traffic congestion that accompanies such growth threatens to limit that mobility. An efficient, well-designed high-speed ground transportation system could potentially solve many of these traffic-related problems, both now and in the future.

OBJECTIVES OF THE STUDY

The main objective of this study is to determine the technical and engineering feasibility of a high-speed ground transportation system. In making this feasibility examination, this report calls for more intensive research on high-speed ground transportation systems (including the automobile), particularly with respect to the application of current advanced technology and the use of powerful computers in designing the transportation system at all levels. Design engineers (who construct and improve transportation facilities) and computer engineers (who develop the hardware and software for computer-aided systems) are urged to work together in an effort to meet future transportation demands. Only through such cooperation and technology can we expect conventional highway efficiency—currently limited by restrictive design values—to be substantially enhanced. And only through the enhanced efficiency of our highway systems can we expect to overcome the increasingly global problem of urban highway congestion.

SCOPE OF THE STUDY

In this report, we define a high-speed corridor system according to those basic components which define all highway systems: fixed facilities, flow entities, and the control system, as shown in Fig 1.1. Because the design of a safe and efficient transportation system requires a thorough understanding of the interaction between these systems, all components will be treated separately in each of the following chapters of this report.

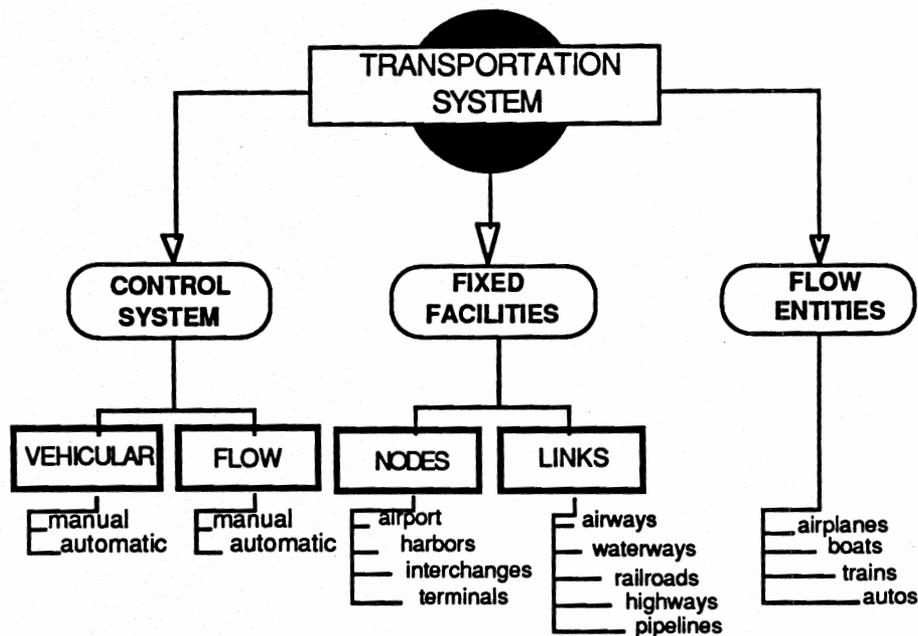


Fig 1.1. Transportation system components.

Chapter 2 considers both the fixed facilities and the highway design. Beginning with a discussion of different alternative designs for high-speed corridor pavement, the chapter next introduces geometric and other design characteristics of the corridor facility, looking in particular at how these characteristics, including ride quality, may be affected by high speeds.

Chapter 3 discusses the flow entities associated with high-speed corridors. It describes an ideal design vehicle for the facility and examines system capacity and the role of advanced technology in improving this capacity at high speeds. Chapter 4 describes both the control system and the flow guidance of the corridor facility. The interface between driver, vehicle, and highway is discussed, along with alternative designs for corridor signing. Chapter 5 examines the use of automated traffic management systems to improve the efficiency of both existing and future transportation facilities. Finally, Chapter 6 provides conclusions, recommendations, and suggestions for future research.

CHAPTER 2. FIXED FACILITIES AND HIGHWAY DESIGN

INTRODUCTION

This chapter analyzes the design feasibility and constructability of a high-speed corridor system in terms of its fixed facilities — that is, those physical components that are fixed in space and which constitute a network of links (e.g., railway/roadway segments, pipelines) and nodes (e.g., interchanges, harbors, airports) within the transportation system. In designing these fixed facilities (sometimes referred to as *fixed guideways*), planners must consider pavements, bridges, drainage systems, and landscaping; in addition, they must look at the overall geometric design, which is concerned with the actual proportioning of these fixed-facility elements (Ref 5).

Unfortunately, specific design information relating to a high-speed highway is extremely limited. Consequently, most of the findings in this report are based on data extrapolated from present design procedures used on conventional highway systems.

HIGHWAY PAVEMENT DESIGN

Although it is expected that a high-speed system will require separate truck and auto lanes for safe and efficient high-speed travel, this report focuses primarily on a mixed-traffic facility (for the projected volumes, alternative designs are presented for both separate and mixed-traffic operations). For comparative purposes, we also present the results of an investigation into the type of pavement structure that will be required by trucks and passenger cars/small trucks. In this way, we hope to determine the most appropriate pavement for use on a high-speed corridor system.

Development of Preliminary Pavement Design

For the following analysis, we referred to the pavement design methods recommended in the AASHTO Guide for Design of Pavement Structures (1986); in making the actual analysis, we used the DNPS86 microcomputer program (Ref 6). The design input used is outlined in the factorial presented in Fig 2.1.

A high-speed highway facility most likely will consist of two sections. One section will have lanes devoted exclusively to passenger cars and small trucks, the other will have lanes devoted to large trucks. Both rigid and flexible pavements were considered in this study, including the two subclasses of rigid pavement: jointed reinforced concrete pavement (JRCP) and continuously reinforced concrete pavement (CRCP) (Ref 7). (Discussion of rigid pavements below will refer exclusively to CRCP type.) Because it is possible that a high-speed facility will cross areas with swelling roadbed soils, we compare pavements extending across both swelling clay and non-swelling soil areas.

Traffic data typical of present rural interstate highways are used as the basis for the projection of the cumulative equivalent single axle loads (ESALs) expected on the facility. The projections assume that there will be no change in the axle weights for each vehicle type and that

vehicle-type distribution will also remain constant over the analysis period. However, studies have shown that, for example, some interstate truck traffic has increased from 6 to 30 percent over a period of 10 to 20 years, and axle weights have in some areas increased by as much as 10 to 25 percent (Ref 8). Accordingly, the study considers four different percentages of truck traffic at three different volume rates (low is about 50,000 to 100,000; medium is about 100,000 to 200,000; and high is about 200,000 to 300,000 vehicles per day). An effective rate factor of 6 percent is used in the estimation of the cumulative ESALs on the highway facility over the 50-year design period (Ref 6). The cumulative ESALs calculated are based on a present serviceability index (PSI) of 4.8 for newly constructed pavement. To achieve an acceptable riding quality level on a high-speed facility, we recommend a terminal PSI of 3.5.

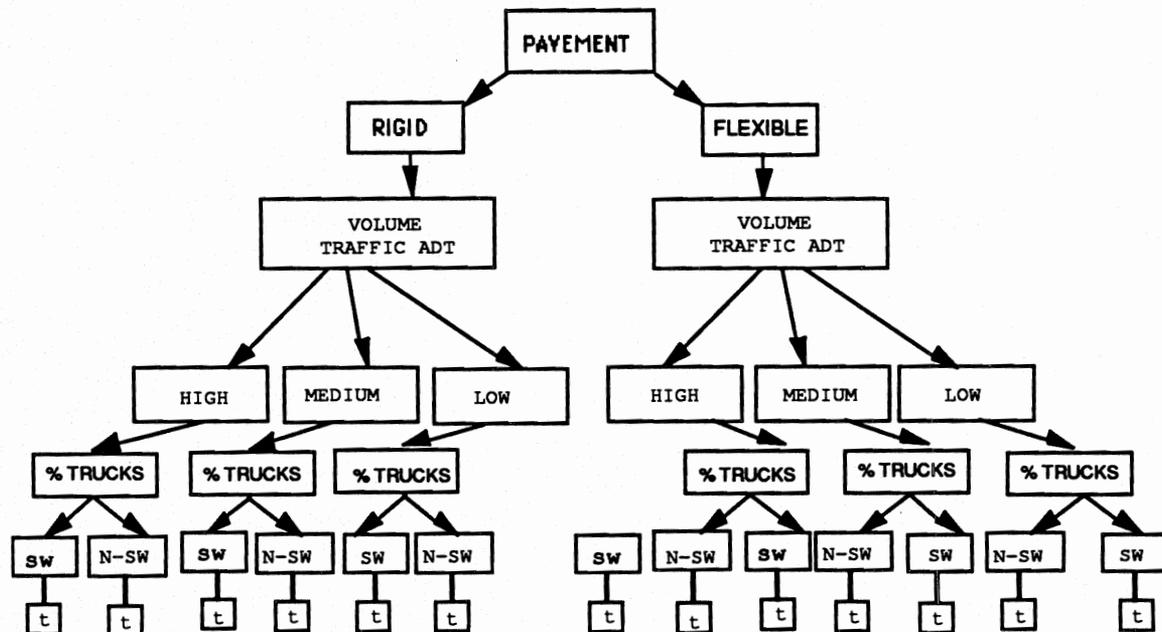


Fig 2.1. Computational factorial (t=thickness).

Using DNPS86 and the input described above, we generated a preliminary design for the cases depicted in Fig 2.1. Where swelling clay is present, we assumed that 1 inch of pavement would be milled every 5 years for roughness, and that an overlay would be necessary at some point during the same period (Fig 2.2). Material costs compatible with Texas Department of Transportation bid prices were used in the analysis. User costs were not taken into account.

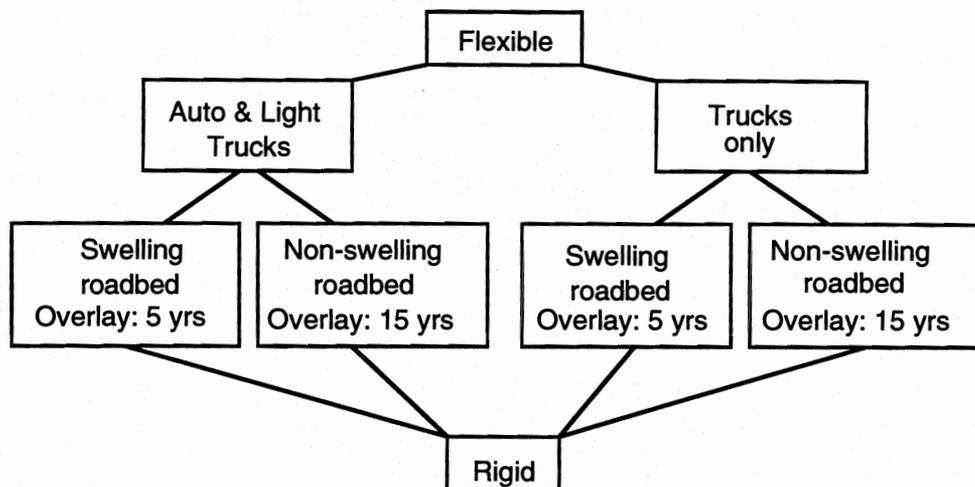


Fig 2.2. Types of pavement and time of overlay.

Results of Pavement Analysis

A comparison of the two pavement types (rigid and flexible) at three different traffic volume levels and extending across both swelling and non-swelling soils is presented in Tables 2.1, 2.2, 2.3, and 2.4, where four different truck percentages are also considered. The present values associated with pavement types and thicknesses for both swelling and non-swelling roadbed soils are presented in Table 2.5.

For pavement type, the results suggest that, on the basis of the design inputs previously discussed, a rigid pavement is the best pavement choice for use on a high-speed facility. Militating in favor of this pavement type was the fact that, for the 50-year design life, the net present cost of typical rigid pavement sections was, in our analysis, lower than typical flexible pavement sections (using a reliability index of 99.9 percent); moreover, rigid pavements require fewer repairs than flexible pavements.

As shown in Tables 2.1, 2.3, and 2.4, the design option that includes exclusive auto/light-truck lanes and exclusive heavy truck lanes is recommended, no matter what the pavement type. Therefore, two exclusive auto/light-truck lanes at \$29.10 per square yard, with two exclusive heavy trucks lanes at \$51.29 per square yard (average = \$40.20) are more economical than four mixed traffic lanes at \$45.29 per square yard. (These values reflect average Texas 1990 prices.) As expected, typical sections that cross swelling roadbed soil cost more than sections that extend over non-swelling roadbed soil. For those sections that cross swelling roadbed soil, both periodic road-milling of a certain thickness of the pavement and the construction of an overlay are methods considered best for ensuring continued good pavement performance.

As indicated earlier, the typical section for the combined traffic operation was investigated as an alternative. However, the thicknesses obtained by using exclusive traffic lanes are both economical and feasible, and are therefore recommended.

TABLE 2.1. FLEXIBLE PAVEMENT THICKNESS (INCHES) FOR NON-SWELLING PAVEMENT.

Pavement	Flexible											
	Low				Medium				High			
	ADT				ADT				ADT			
% Trucks	0	10	30	100	0	10	30	100	0	10	30	100
HMAC	6	8	9	10	7	10	12	15	8	12	14	18
Flex base	6	7	10	12	8	12	12	14	12	15	15	20
sub	15	18	20	20	15	20	22	25	15	22	25	30

NOTE: 100 percent trucks means exclusive truck lanes

TABLE 2.2. RIGID PAVEMENT THICKNESS (INCHES) FOR NON-SWELLING ROADBED.

Pavement	Rigid											
	Low				Medium				High			
	ADT				ADT				ADT			
% Trucks	0	10	30	100	0	10	30	100	0	10	30	100
slab	8	9	10	12	8	10	12	13	9	12	15	18
base*	6	10	10	10	10	12	15	15	10	12	15	20

*Asphaltic concrete

**TABLE 2.3. FLEXIBLE PAVEMENT THICKNESS (INCHES)
FOR SWELLING ROADBED.**

Pavement ADT % Trucks	Flexible											
	Low				Medium				High			
	0	10	30	100	0	10	30	100	0	10	30	100
HMAC	6	6	8	9	8	9	10	13	9	10	12	15
Flex base	6	6	8	10	10	12	12	14	12	12	15	18
sub	15	15	15	15	18	20	22	25	20	25	25	30

**TABLE 2.4. RIGID PAVEMENT THICKNESS (INCHES)
FOR SWELLING ROADBED.**

Pavement ADT % Trucks	Rigid											
	Low				Medium				High			
	0	10	30	100	0	10	30	100	0	10	30	100
slab	8	8	10	11	8	9	10	12	8	10	12	15
base*	6	10	10	12	10	12	16	18	12	12	18	25

* Asphaltic concrete base

**TABLE 2.5. COST COMPARISON FOR VARIOUS PAVEMENT DESIGNS,
50-YEAR LIFE-CYCLE.**

Traffic Operator Type	Pavement (\$/sq. yd.)*			
	Non-swelling roadbed		Swelling roadbed	
	Rigid	Flexible	Rigid	Flexible
Auto/light trucks	29.1	41.67	50.53	68.43
Trucks only	51.29	84.56	74.19	97.72
Mixed operation	45.29	66.56	63.18	74.25

*Cost is given for medium ADT

HIGHWAY GEOMETRIC DESIGN

Geometric design refers to the physical proportioning of the fixed-facility elements. This section addresses the basic components of geometric design, with emphasis on the effect of high speed on the design elements of highway facilities. The elements examined include access, cross-sections, horizontal alignment, vertical alignment, and ramps.

For balance in highway design, all geometric elements should, as far as economically feasible and structurally possible, provide safe, continuous operation at such speeds as are likely under the general conditions of that highway. Presently, this operational balance (and overall control) is achieved for the most part through the use of design speed. But in the design of a high-speed corridor, different aspects, including electronic management systems and automobile technology, must be considered in addition to design speed.

Cross-Section

Cross-section design refers to the profile of the facility perpendicular to the center line and extending to the limits of the right-of-way within which the facility is constructed. Figure 2.4 illustrates a proposed cross-section of a high-speed facility, with 400 feet of right-of-way accommodating both the auto facility and a high-speed rail facility.

Special attention must be given to the cross-section design—and mainly to superelevation sections—to ensure that the system meets drainage requirements. Various types

Special attention must be given to the cross-section design—and mainly to superelevation sections—to ensure that the system meets drainage requirements. Various types of barriers (including guardrails and concrete structures) may be used along the medians and at the end of the clear zone beyond the shoulders. Drainage ditches and gutters may be incorporated to channel water from the highway.

Access

In the U.S., free access to highways is considered a condition for public funding. Yet unlimited access severely constrains capacity. While the proper balance between these conflicting needs is not easily achieved, strictly controlled access is, in this report, deemed essential for the speed and capacity anticipated on a high-speed facility. Consequently, grade crossings and direct driveway connections are regarded as non-essential. Figure 2.3, a one-directional plan view of the proposed facility, illustrates how frontage roads are expected to control access and permit circulation to either side of the highway.

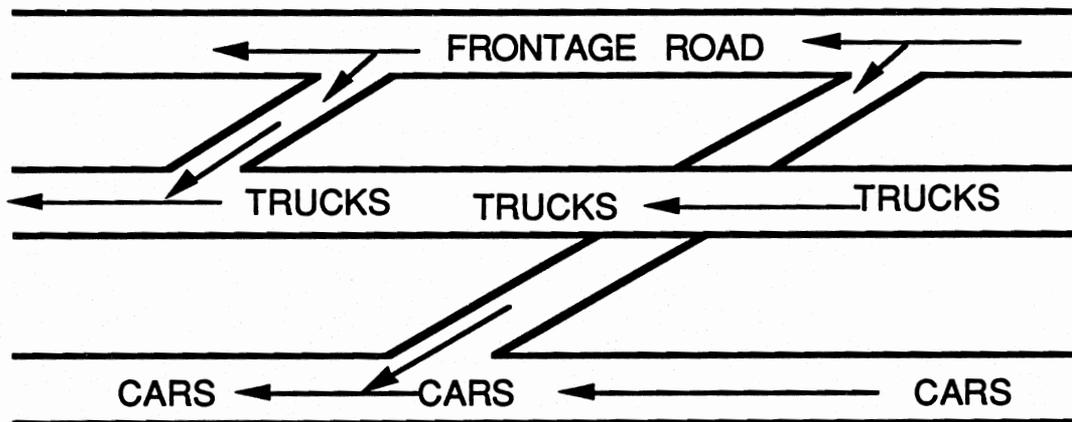


Fig 2.3. A proposed plan view for a high-speed facility.

Horizontal Alignment

The horizontal alignment of a highway, railway, or transit guideway represents the projection of the facility on a horizontal plane. As such, it generally consists of straight-line segments (tangents) connected by circular curves either directly (simple curve) or via intermediate transition curves. For reasons of riding quality and appearance, exclusive use of transition curves should be implemented in the design of a high-speed facility. Additionally, the horizontal alignment should be as straight as possible so as to reduce the large radii required at high design speeds.

Adequate stopping-sight distance (SSD) is another design criteria of horizontal alignment. Because it is critically important that drivers be able to perceive and respond quickly to

hazardous highway situations, the design of a high-speed facility must provide for adequate stopping-sight distances, the minimum length of which should be sufficiently long to enable a vehicle traveling at or near the design speed to stop before reaching an object in its path. The following discussion of stopping-sight distance is based on statistical data extrapolated from tables published in the AASHTO manual, "A Policy on Geometric Design of Highways 1984" (Ref 3). These tables involve design speeds ranging from 10 to 80 mph.

Stopping-sight distance is actually the sum of two distances: first, the distance traveled during perception/reaction time (PIJR), and, second, the distance measured from the point braking begins to the point the vehicle comes to a complete rest. Figure 2.5 shows the SSD for design speeds ranging from 10 to 150 mph for both wet and dry conditions at PIJR = 2 sec.

To calculate stopping sight distance, we use the following equation:

$$SSD = PIJR * V + V^2/(30(f+g))$$

where:

- PIJR = Reaction time (in sec). Two seconds is used here for complex conditions. Although it may not have a noticeable effect on the SSD, PIJR time will decrease in the future as automotive technology advances. Figure 2.5 shows the change in SSD with the change in PIJR. With the application of computers and an electronic management system, SSD will be reduced substantially. Eventually, SSD will be replaced by the more efficient concept of headway, whereby distances between vehicles are fixed.
- f = Coefficient of friction (braking friction) between the tires and the pavement surface (Fig 2.6). This value is a function of many elements, including speed, the weather, and pavement conditions. Figure 2.7 shows the values of f at different speeds. Two conditions are considered here: dry conditions and wet conditions, where $f_{dry} > f_{wet}$. Fig 2.7 shows the effect of speed and both dry and wet conditions on SSD. The figure shows that at 150 mph, the SSD is approximately 3,500 feet under wet conditions, while under dry conditions this value is reduced to about 2,000 feet.
- g = Percent of grade divided by 100 (gradient). Depending on the topography of the area of a proposed corridor, this factor will have a more or less effect on the design. However, because grade affects trucks much more than automobiles (Ref 9), separate truck lanes are recommended.

We next looked at the important relationship between design speed and curvature, including their relationship to superelevation and side friction. The minimum radius R_{min} can be calculated directly from the simplified curve formula as follows:

$$R_{min} = V^2/15(e+f)$$

where:

- e = maximum rate of superelevation, and
- f = side friction.

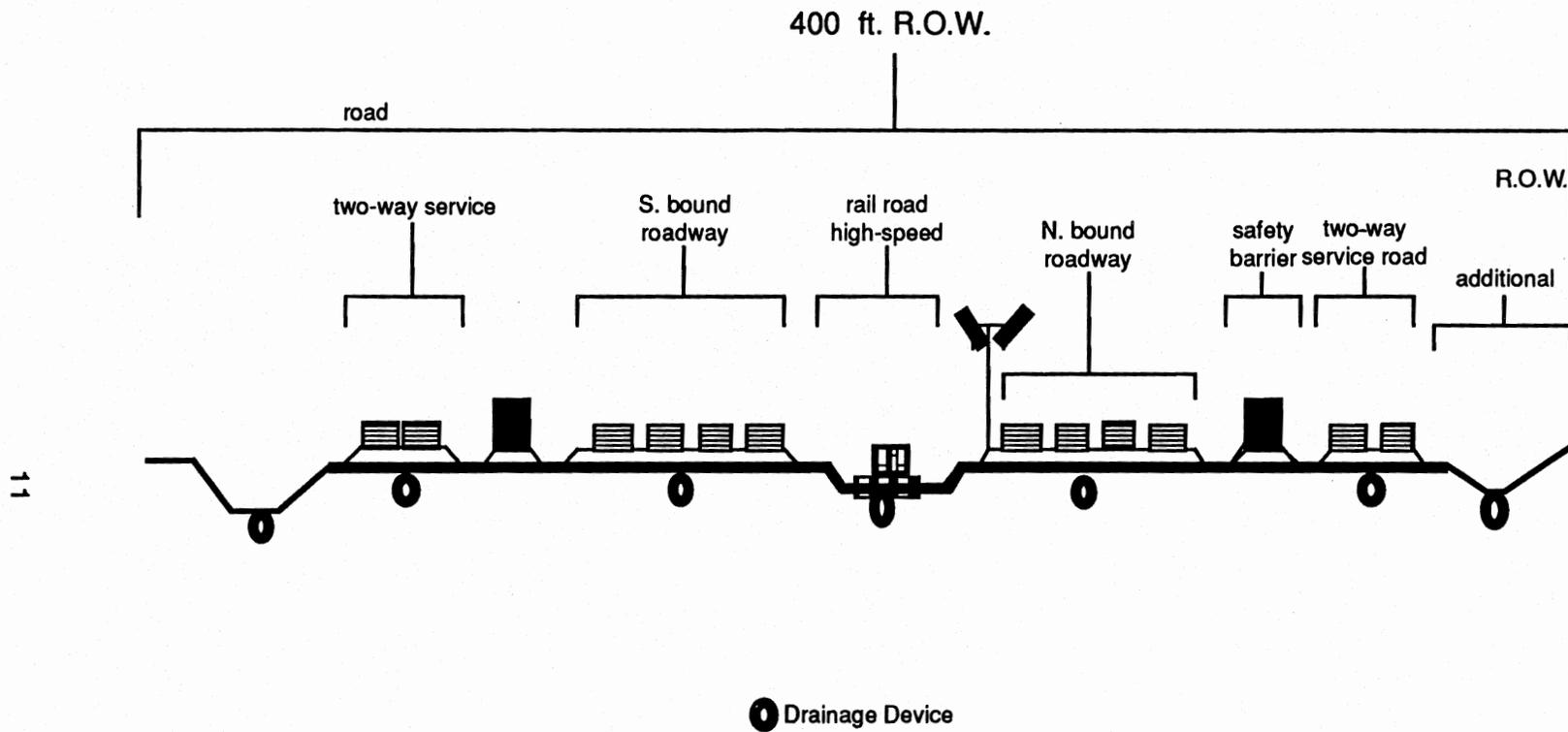


Fig 2.4. A proposed cross-section with 400-ft ROW.

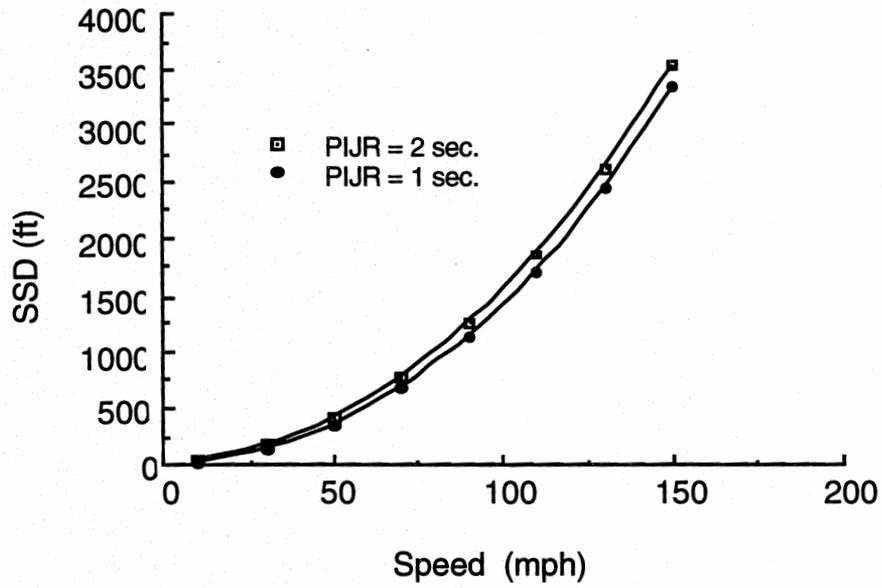


Fig 2.5. Stopping-sight distance vs. speed at different PIJR values.

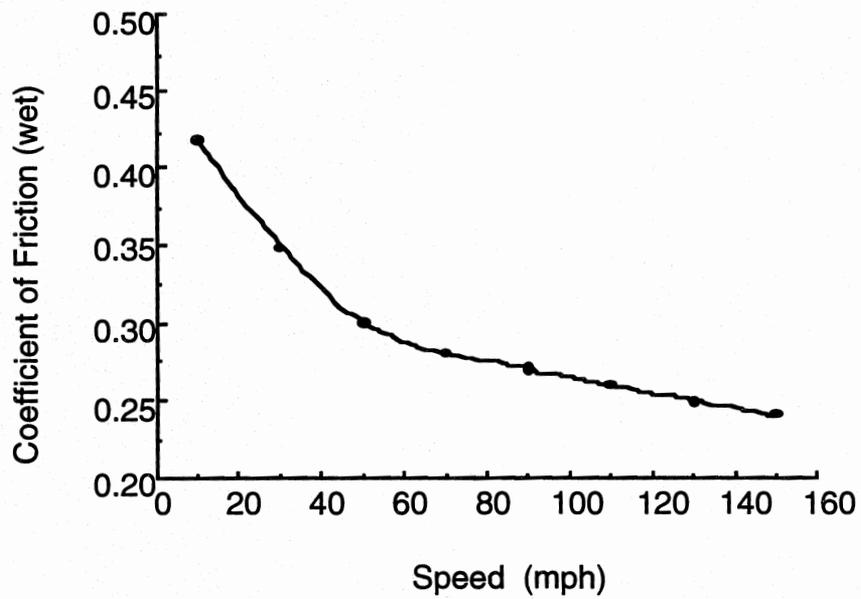


Fig 2.6. Coefficient of braking friction vs. speed under wet conditions.

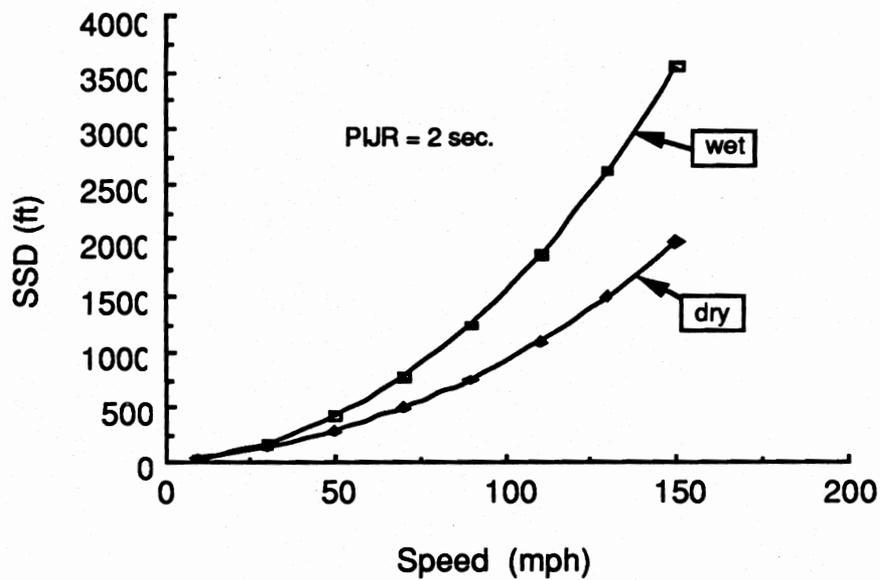


Fig 2.7. Stopping-sight distance for two different conditions (wet and dry) with a PIJR value of 2 sec.

Figure 2.8 shows the minimum radius required for speeds ranging from 10 to 150 mph, the values of which are calculated at different superelevations. It can be seen that at a higher superelevation the radii are smaller (owing to the fact that all the centrifugal forces on curves are counteracted by the superelevation provided). The presence of ice or snow in the proposed area will require a maximum superelevation, a value of about 1.5 percent in most cases. The side friction, a function of both speed and the nature of the road surface, ranges from 0.17 at 20 mph, to 0.07 at 150 mph (Fig 2.9).

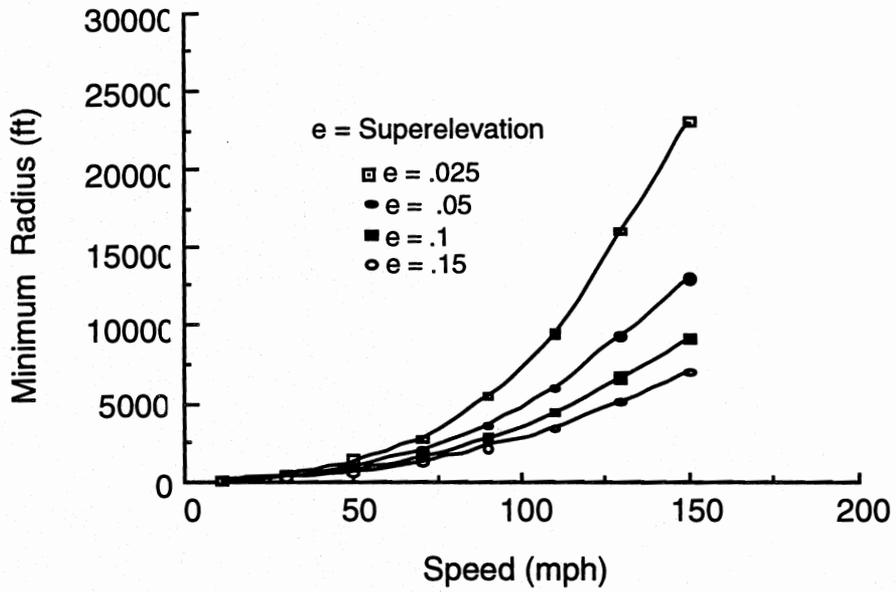


Fig 2.8. Minimum radius vs. speed at different superelevations.

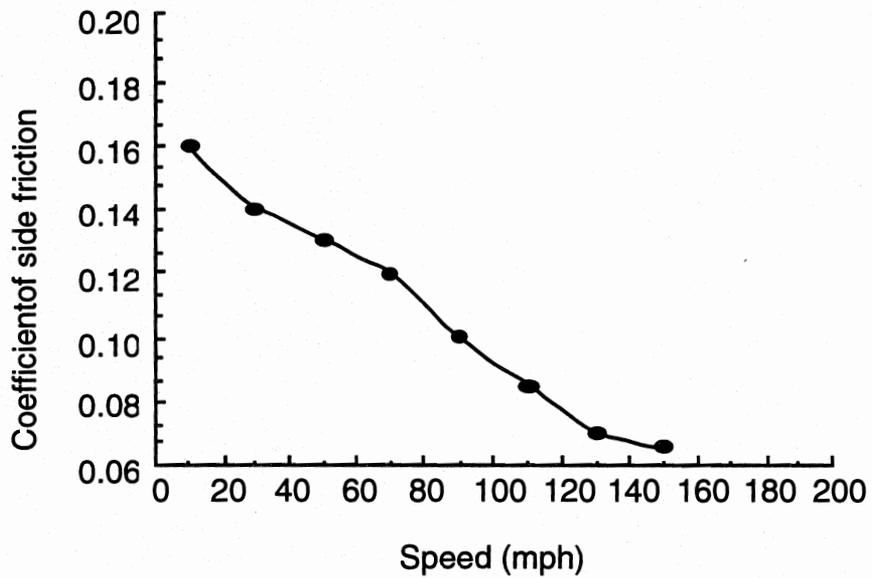


Fig 2.9. Coefficient of side-friction for various speeds.

Vertical Alignment

Vertical curves should be simple in application and should result in a design that is safe, comfortable in operation, pleasing in appearance, and adequate for drainage. Minimum-length-of-crest curves are controlled by sight distance, while the minimum-length-of-sag curves are controlled by the light-beam sight distance, which is nearly the same as the SSD. Figure 2.10 shows the required vertical curvature rate K (length per percent of difference of grade) for sag vertical curves.

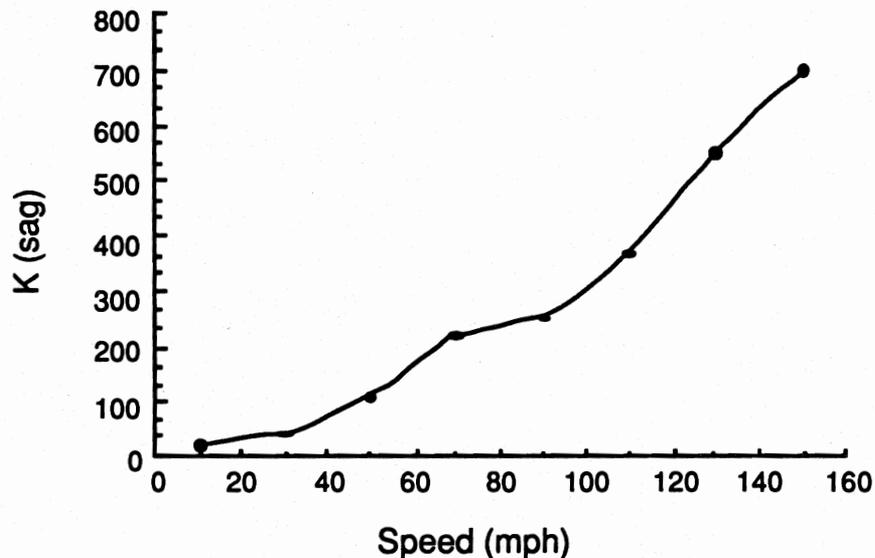


Fig 2.10. Vertical curvature rate K vs. speed.

Acceleration and Deceleration Ramps

As with any other highway system, drivers entering a high-speed highway from a turning roadway accelerate until the desired speed is attained; when exiting, drivers decelerate as they turn onto ramps. In designing a high-speed system, it is very important to have a sufficient number of lanes to enable the driver to make the necessary changes between the operational speed of the highway and the speed on the turning roadway. Moreover, in the case of an acceleration lane, there should be additional length sufficient to permit the adjustment in speed of both entering and on-highway vehicles, so that the driver of the entering vehicle can maneuver into the traffic stream before reaching the end of the accelerating lane. In current design procedures, an accelerating rate of 8 to 10 ft/sec² (normal acceleration) (Ref 9) is used.

Figure 2.11 shows the length of the acceleration ramps as a function of the speed at two different acceleration rates; with the initial speed on the frontage road being 40 mph, and at an

acceleration rate of 8 ft/s (normal acceleration), the length of the acceleration lane is about 1,900 feet. However, the acceleration rate is higher with some current vehicles, many of which can reach a value of 12 to 18 ft/sec² (about 1/3 to 2/3 g). The effect of the change in the acceleration rate on the length is very pronounced (see Fig 2.12). The length of the acceleration lane varies from 1,900 feet at 8 ft /sec² to about 700 feet at 24 ft/sec² (emergency rate) (Ref 3). The length of the deceleration ramps is defined in the same manner as the length of the acceleration lane (this is as expected, because comfort is the controlling factor here, not the vehicle's capabilities). The same values for deceleration lanes are suggested accordingly.

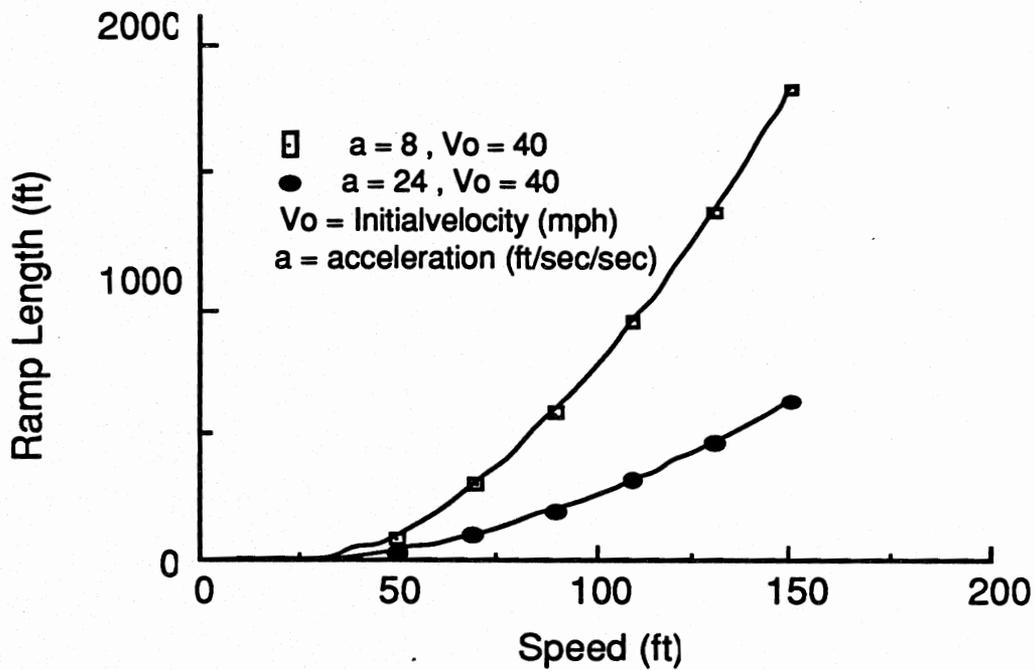


Fig 2.11. Length of acceleration and deceleration lanes at different speeds.

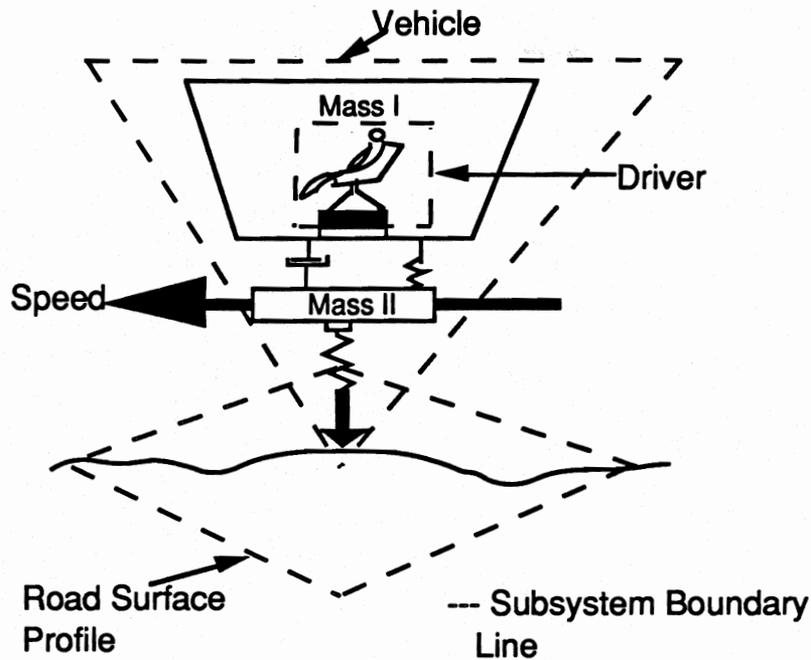


Fig 2.12. Road-Vehicle-Passenger System.

Finally, it should be mentioned that the process of selecting, designing, and locating the final alignment of a facility is a highly complex undertaking. Given that the need for a facility has been established, a sequence of interrelated steps follow, including collecting topographic maps, conducting photogrammetric reconnaissance surveys, identifying alternative alignments, making the preliminary selection of the preferred alignment, surveying and mapping the corridor through which the preferred alignment passes, and designing the final alignment. These activities take place within a variety of economic, legal, and environmental constraints.

RIDING QUALITY EVALUATION AT HIGH SPEED

Operating from a user point-of-view, we evaluated the riding quality using two pavement types (rigid and flexible) and two roughness levels (smooth and rough). Existing methods for obtaining acceptable ride quality were also evaluated to determine their suitability for a high-speed facility analysis. Focusing on the road system, we first considered its three principal elements: the road surface profile, the vehicle, and the passenger subsystem (see Fig 2.12).

Road Profile

A road surface profile is a complex irregular wave composed of a set of waves with different wavelengths and amplitudes. A road profile in its original form as a combined wave gives little information about road roughness, and the portion of wave bands pertaining to roughness

are related only when the profile is separated (using a mathematical filter) into a series of wave bands; only at that point does it become a useful means for characterizing roughness. This series of waves is arranged according to their wavelengths.

A group of wavelengths is called a spectrum. Short waves are associated with the diameters of stones in the road surface, while long surface waves are associated with road surface terrain; lying between these two extremes is a series of waves defining road roughness (Ref 10).

Vehicle

The vehicle is an important part of the system. As it travels over a road surface, a vehicle vibrates, bounces, or sways to one side. This motion causes discomfort to the road user, with the degree of the discomfort depending on (1) the degree of road surface distortion and irregularity, (2) the vehicle characteristics (mass, springs, etc.), and (3) the user.

Passenger Subsystems

The vehicle subsystem consists of two types of masses—termed *sprung* and *unsprung*—connected by suspension springs and shock absorbers. The sprung mass consists of the wheels, the wheel-braking system, and the wheel axle; all other parts above the suspension system make up the unsprung mass.

These passenger subsystems can be analyzed using full-, half-, and quarter-car models described mathematically with second-order differential equations (Ref 10). One important characteristic of a mechanical vibrating system is the frequency response or transfer function (T), which can be defined mathematically as the ratio of system output to system input. The output of a system can be displacement, acceleration, or force. The value 1 indicates that the system output is equal to its input. The system is amplified when (T) is greater than 1, and is attenuated when (T) is less than 1.

Because a road surface is built to serve the user, the passenger subsystem is most important. Yet human reaction to mechanical vibration is not fully known, and further research must be conducted to understand this reaction. It has been established, however, that frequencies higher than 20 CPS are filtered out by the vehicle, while vibrations having frequencies lower than 20 CPS are perceived by vehicle passengers.

Roughness Evaluation at Higher Speed

Goldman (Ref 10) has formulated three levels of human subjective response—perceptible, unpleasant, and intolerable—that could be useful criteria for evaluating roughness from the point of view of the user. Keeping these responses in mind, two key assumptions are made in this investigation: (1) the road roughness and profile used in this study represent general type of roads, and (2) vehicle suspension characteristics used for the simulation represent normal cars.

The roughness measuring systems presently available can be classified into two groups. The first group consists of those systems that measure a longitudinal profile directly, such as the

Profilometer(Ref 10). The second group consists of those systems that measure a vehicle's response to longitudinal road profile (e.g., Maysmeter and the BPR Roughometer).

To evaluate roughness at high speed, four profiles were obtained with the Surface Dynamic Profilometer: two for flexible pavements and two for rigid pavements, each 0.2 miles long. These profiles were analyzed using the present serviceability index concept (SI), quarter-car index (QI) (see Fig 2.13 for quarter-car simulation), and half-car simulation.

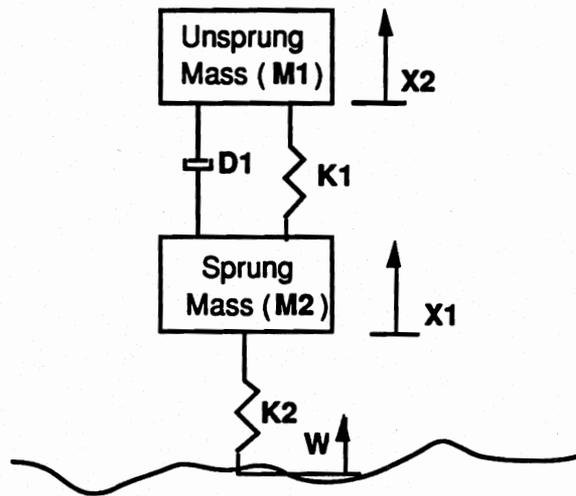


Fig 2.13. Mechanical model for quarter car (QI) simulation.

Among these tests, the quarter-car simulation model is the best alternative for eliminating extrapolation in other tests, such as PSI, at higher speed. The results obtained in the quarter-car test show that, depending on the suspension and the transform function of the vehicle, the rough road provides a more comfortable ride at higher speeds. The roughness parameter(QI) obtained using simulation can be later used to calculate PSI independent of the speed. The improvement in the different components of the road system, including the design vehicle, may make road roughness more tolerable at higher speeds.

The SI values for the QI were calculated using the following equation:

$$PSI = 5e^{(-0.004117QI + 0.198)}$$

The values are reported in Table 2.6. Figures 2.14 and 2.15, respectively, show QI and SI results versus the speed. It can be seen that the SI values change very little in general (see Fig 2.16).

TABLE 2.6. QI AND SI RESULTS FOR FOUR SECTIONS OF PAVEMENT AT FOUR DIFFERENT SPEEDS.

Section	Test	Speed (mph)			
		50	70	90	100
Flex. smooth SI=4.59	QI	72.4	62.2	52.0	108.6
	SI	4.52	4.71	4.91	3.89
Flex. rough SI=0.9	QI	771.2	737.3	581.9	519.8
	SI	0.25	0.29	0.56	0.72
Rigid smooth SI=3.5	QI	210.9	171.0	165.5	165.6
	SI	2.6	3.01	3.09	3.09
Rigid rough SI=2.4	QI	324.7	296.3	325.6	314.0
	SI	1.6	1.8	1.6	1.6

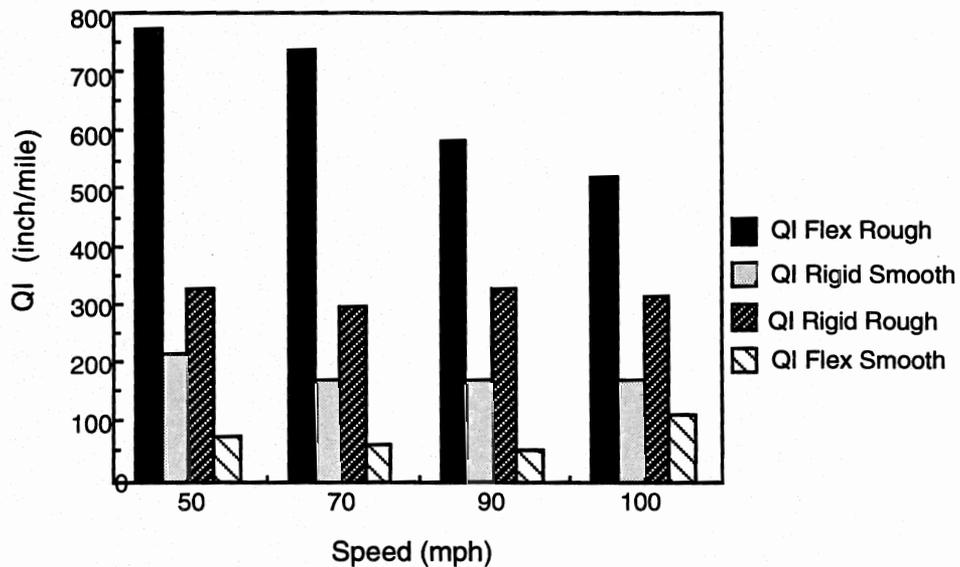


Fig 2.14. Quarter-car simulation at various speeds.

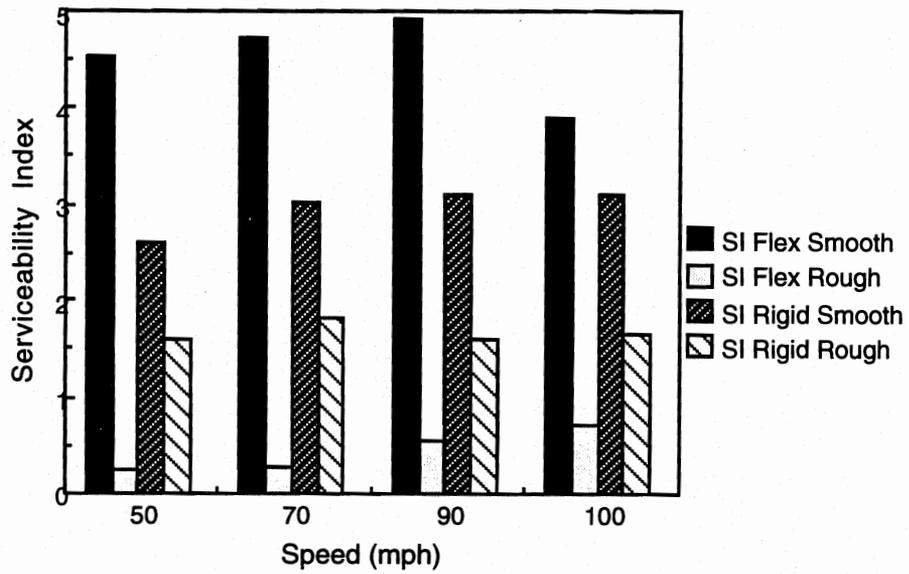


Fig 2.15. Serviceability Index at various speeds.

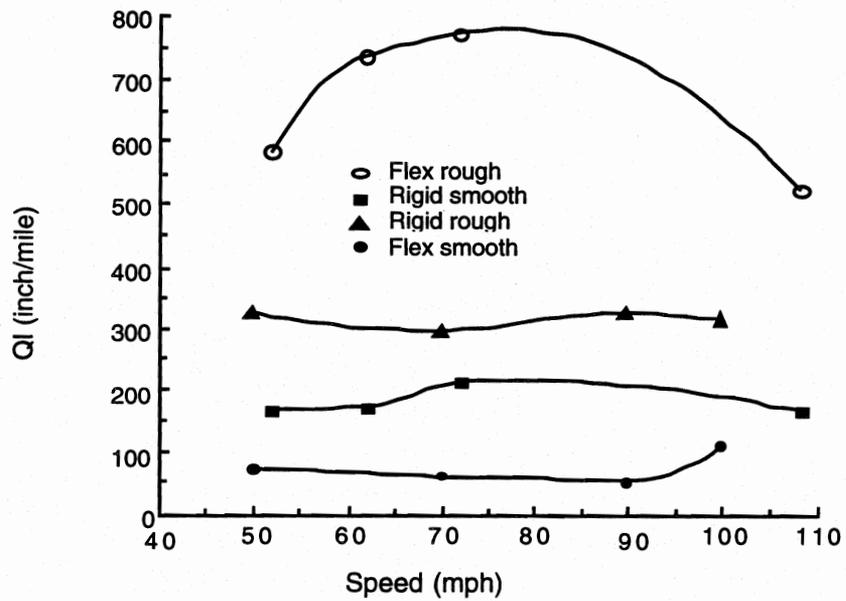


Fig 2.16. QI values for two types of pavement at different speeds.

A simulation of a quarter car running at high speed is the best approximation of the actual conditions expected on a high-speed facility. The suspension characteristics of the model used include the following:

- (1) suspension spring rate 200 lbs./in.,
- (2) suspension damping coefficient 6 lbs-sec/in., and
- (3) tire spring rate 1000 lbs./in.

The types of cars (smart cars) that will be used on a high-speed facility will have suspension characteristics capable of tolerating road roughness more efficiently. However, it must be understood that high road roughness tends to wear out suspension parts faster at high speed; therefore, it is advisable that road roughness levels be kept as low as possible. A PSI of 3 or a QI of less than 150 should be the maximum acceptable roughness for a high-speed facility.

From the above discussion, we can summarize as follows:

- (1) The SI calculated with RMSVA decreases or maintains its value as speed increases.
- (2) The quarter-car index (QI) simulation shows no definite trend, and in general the roughness decreases as speed increases. The same conclusion is obtained for SI calculated with QI.
- (3) The simulation model should be modified to allow simulation of different types of car suspensions. QI was modified to run at more than 100 mph.
- (4) Based on this study, a maximum roughness of 150 inch/mile or a minimum PSI of 3.5 is recommended.
- (5) The facility should be designed to minimize maintenance.
- (6) Discomfort curves for high speeds should be obtained to study human reaction.
- (7) Further research should determine the variation in roughness with different types of profiles, including swelling clays.

SUMMARY

From a preliminary analysis, it is recommended that a rigid pavement section be considered for a high-speed highway system. The results of the present study indicate that in all instances, on the basis of the design used, the typical rigid pavement section was the more economical alternative. Further analysis using more reliable design inputs is recommended for obtaining the final design thickness for implementation.

The process of selecting, designing, and locating the final alignment of a facility connecting two points is a highly complex undertaking. Once it has been determined that there is in fact a need for such a facility, a sequence of interrelated steps follows. These steps include preparing topographic maps, conducting photogrammetric reconnaissance surveys, identifying alternative alignments, selecting the preferred alignment, surveying and mapping the corridor

through which the preferred alignment will pass, and designing the final alignment. These activities take place within a variety of economic, legal, and environmental constraints.

More intensive research at all levels is required to understand the effect of higher travel speeds on the different variables and components of the traffic system. Such research can reveal the best relationships and mathematical models necessary for the construction of an efficient and economical high-speed system.

CHAPTER 3. FLOW ENTITIES

INTRODUCTION

Flow entities are those units that traverse (travel on) the fixed facilities. The design of the fixed facility requires consideration of the flow entities at all stages and, indeed, the characteristics of some elements of the flow entities must be identified as a prerequisite to designing the system's fixed facilities. The geometric design of a highway, for example, is highly dependent on the design vehicles using the facility.

Within a conventional highway system, the fixed facilities are expected to accommodate a wide variety of vehicle types, ranging from motorcycles to large tractor-trailer combinations. A high-speed highway facility, on the other hand, is designed to accommodate only automobiles and trucks (one unit, trailers, etc.). While mixed or separate operations may exist on the lanes of such a facility, it is presumed that a separate traffic operation will facilitate the flow, creating a safe and economical transportation system. American Association of State Highway and Transportation Officials (AASHTO) (Ref 5) procedures regarding design vehicles are used in this report to evaluate the engineering design of a high-speed corridor.

VEHICLE TYPE AND TRAFFIC OPERATION

The size and proportion of the system's allowable vehicles are very important considerations in the design and maintenance of the system. Thus, it is necessary in designing a highway to examine all vehicle types, select a general class grouping, and establish representative vehicles within each class to determine design requirements, specifications, and types of vehicles allowed on the proposed facility. In current highway design, the largest design vehicles are usually accommodated. In this examination of a high-speed corridor, two general classes of vehicles have been selected, namely, passenger cars and trucks.

The proportion of each class of design vehicles on the roadway has a big impact on travel speed, travel density, travel safety, system capacity, and, therefore, system efficiency. And because geometric design requirements and capacity considerations for trucks and larger vehicles are much more restrictive than those for passenger vehicles, separation of traffic on a high-speed facility is worth considering.

Design Vehicle for a High-Speed Facility

It is expected that a high-speed facility will employ a sophisticated and advanced design vehicle, one that will permit individuals to travel faster and more safely than is presently possible. Design specifications for such a vehicle will include high-speed capabilities, a highly reliable braking system, excellent fuel economy, light weight, alternative fuel capabilities, and minimum engine emissions.

Present vehicle design comes close to meeting all these design specifications. Many engine and vehicle functions, for example, are now controlled by computers capable of analyzing

both highway and weather conditions. Using artificial intelligence, these computers are capable of handling the large amounts of data that must be exchanged between driver, vehicle, and the transportation network. The combination of efficient mechanics and artificial intelligence found in current concept cars requires not only great precision, but advanced design analysis as well. Present concept cars, including the Chevrolet Express, Pontiac Banshee, Jaguar XJ220, and the Ferrari 408 (Ref 11), have, at the present time, specifications commensurate with the requirements of a high-speed facility.

Understanding the resistive forces that work against a car traveling in a straight line is very important in designing vehicles for a high-speed facility. For example, aerodynamic drag is not the only force acting against a car in motion; forces such as rolling resistance (the result of mechanical losses in the drive train and wheels) and friction play a considerable role in determining the efficiency of a vehicle (Ref 11). In terms of aerodynamic drag, the overall efficiency of a vehicle's shape is indicated by its drag coefficient (C_d) (Ref 12). The drag coefficients of simple shapes range from 0.05 for an airfoil, 0.10 for a sphere, 1.17 for a flat square plate, and 1.35 for a parachute (Ref 11). While the C_d s of current cars range from a little under 0.25 to about 0.50., several concept cars developed since the mid-1970s have been attempts at establishing the practical limits of aerodynamic car design. One of these cars, a 1981 Renault with a C_d of only 0.25, can provide 94 miles per gallon in mixed city and highway driving carrying four passengers and luggage (Ref 11). Two 1985 prototypes built by Ford and Chevrolet reached a C_d of 0.14 (Ref 13), a drag coefficient previously attained only in land-speed-record cars and jet aircraft. While these coefficients have important implications for a high-speed facility, it should be noted that automobile aerodynamics is complicated and very different from aircraft aerodynamics. For example, reducing drag to the point where lift is achieved would, of course, be disastrous for a ground vehicle.

In addition to expanding our understanding of aerodynamics, the computer is revolutionizing other technical aspects of vehicle design and manufacturing. Computer-aided engineering (CAE), computer-aided design (CAD), and computer-aided manufacturing (CAM) are increasingly being favored over older and more traditional engineering methods. CAE and CAD, for example, have been useful in greatly reducing both the cost and lead time in developing such concept cars as the Buick Wildcat (with a V-6 230-bhp engine driving all four wheels), the Dodge M4S, the Porsche 962 (with 200 mph capabilities), and the Buick Skyhawk Turbocharger (Ref 11), to name only a few of the concept cars leading the way toward high-speed automated travel. Figure 3.1 outlines some specific design features required for a high-speed passenger vehicle.

Another proposed feature of a high-speed vehicle is a detection system that would be capable of determining the distance and location of any object in the vicinity of the vehicle in all directions. This system would also be capable of displaying on the vehicle dashboard an image of the object, with an accompanying warning or message that might help the driver avoid an accident. The transmission/reflection/receiving of ultrasonic waves in all directions around the vehicle is one possible mechanism; a sonar radar device (Fig 3.2) is another. In any case, such a system would need to be highly reliable and free of those problems that currently plague the performance of such radar technologies as Collision Avoidance Radar (CAR), the interest in which

has declined due to that system's complexity, false alarms, and poor response under harsh weather conditions (Ref 14).

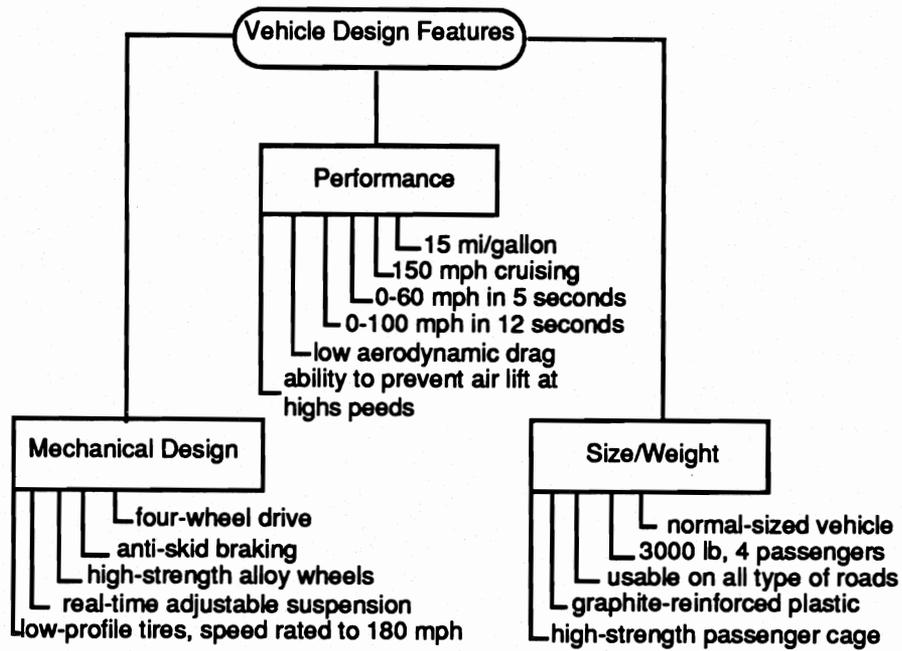


Fig 3.1. High-speed vehicle design features.

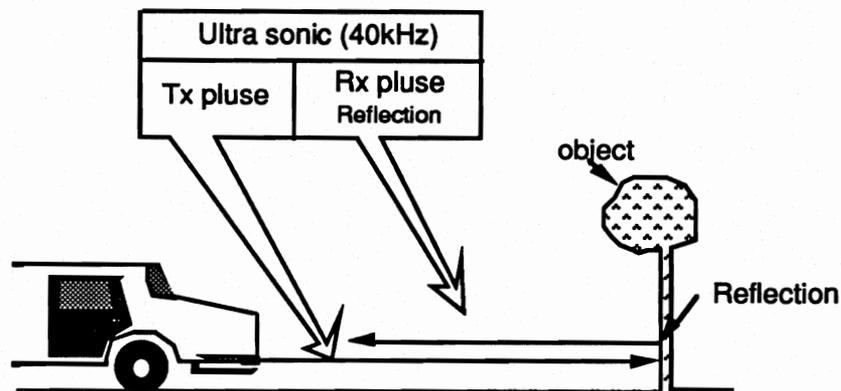


Fig 3.2. Sonar detection system (Ref 14).

Impact of Separation of Traffic on System Efficiency

Because of their slow and cumbersome maneuvering, trucks and heavy vehicles tend to disrupt the overall operation of a facility. Indeed, in terms of capacity, trucks and heavy vehicles are often the primary cause of highway congestion.

For a high-speed facility, separate truck lanes may be necessary in order to avoid potential problems of traffic congestion. And because it represents less pavement cost, traffic separation is, in addition, economically sound. Thus cost savings, system safety, and system effectiveness can be improved by providing separate heavy-vehicle lanes. Figure 3.3 shows the V/C ratio versus various percentages of heavy vehicles in the traffic stream. The effect of heavy vehicles is more pronounced in the case of rolling terrain. For mixed traffic with about 35-40 percent heavy vehicles (which is about the percentage expected on a high-speed facility), the volume carried on the highway is reduced to about 20 percent in the case of level terrain, and to about 50 percent in the case of rolling terrain. Again, exclusive truck lanes will increase the overall safety and efficiency of a high-speed facility.

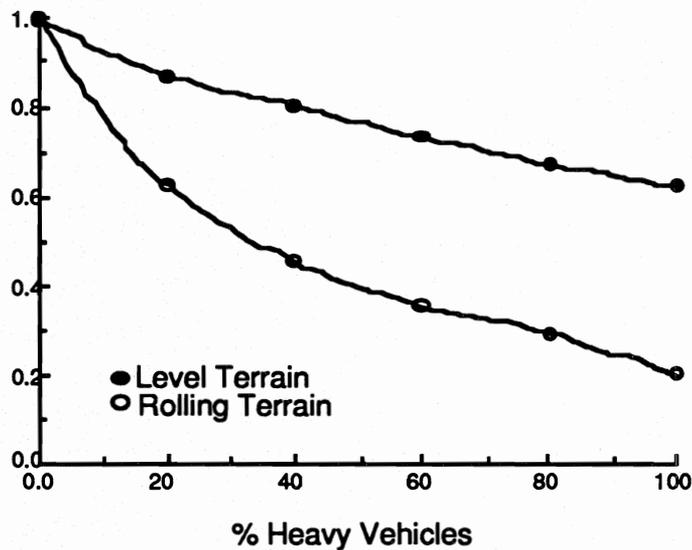


Fig 3.3. The change in capacity resulting from the presence of heavy vehicles.

SYSTEM CAPACITY

For highway users, speed is one of the most important indicators of a facility's level of service. In order to provide a safe, high-travel-speed facility, attention must be given not only to the geometric design, pavement design, and vehicle design, but also to traffic flow volumes and guidance.

Capacity and Level of Service

While freeway *capacity* is measured by the number and speed of the vehicles that the facility can safely accommodate (see Fig 3.4), traffic *flow* is measured in terms of volume, average speed, and traffic density (Fig 3.5). The relationship between the three variables of traffic flow is described in the following equation:

$$\text{Volume (flow)} = \text{Speed} * \text{Density}$$

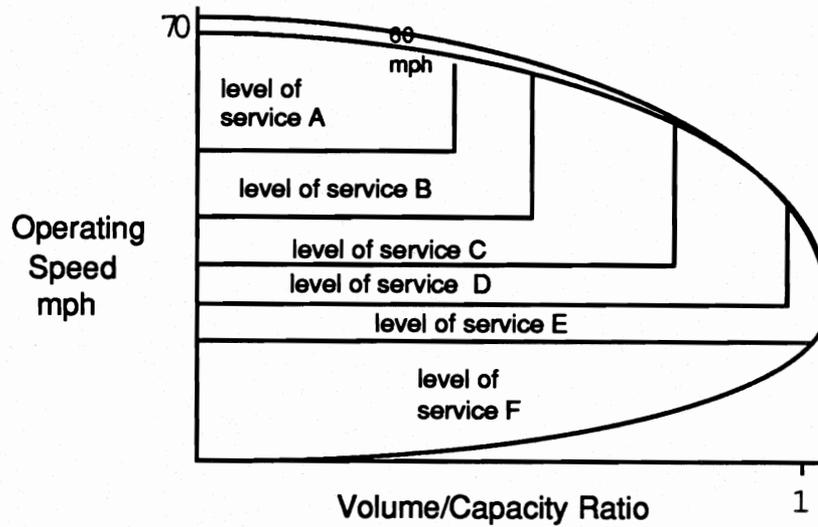


Fig 3.4. Levels of service (Ref 4).

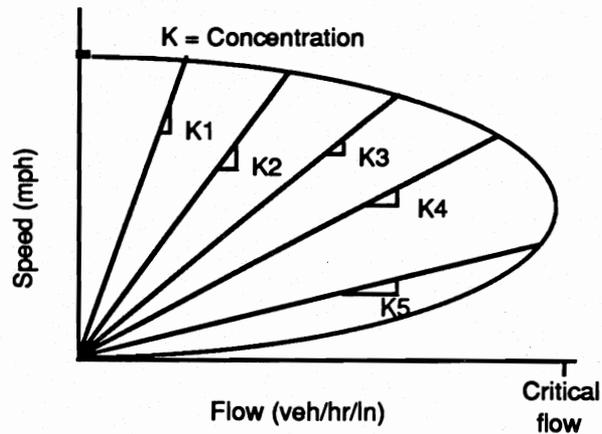


Fig 3.5. Traffic density as a function of speed.

In Fig 3.5, volume is expressed in vehicles per hour, speed in mph, and density in vehicles per mile. The level of service for a given freeway determines the traffic conditions on that roadway (Fig 3.4). The traffic conditions on a road segment range from almost free flow (when few vehicles occupy a roadway) to highly congested (when the road is crowded with slow-moving vehicles). The traffic conditions on a roadway are well described by the level of service on that road segment.

Level of service **A** represents the best possible condition existing at a speed of 70 mph, with a density of 12 or fewer vehicles/mile (flow = 700 vehicles/lane/hour). The next best condition is level of service **B**, which occurs at a flow of about 1,100 vehicles/ lane/hour; level of service **C**, **D**, and **E** are represented by a flow of about 1,550, 1,850, and 2,000 vehicles/lane/hour, respectively (Ref 4). At level of service **F** the traffic is unpredictable and exists at such reduced speeds that stop-and-go traffic results. Thus, the desired level of service for a high-speed facility is level **A** or **B**.

Headway, or the distance between vehicles, is another consideration in evaluating level of service. For present vehicle-driver-road conditions, headway is estimated to be an average of 1.8 seconds and can be attained at a speed of about 35 mph and with a capacity of 2,000 vehicles/hour/lane. Improving both the roadway and the vehicle design may decrease this average headway on a high-speed facility.

Capacity as a Function of Spacing

Figure 3.6 shows the relationship between speed, PIJR (perception-reaction time), and spacing. This relationship is represented by the following equation:

$$\text{Spacing (S)} = V\delta + \frac{V^2}{2d_f} - \frac{V^2}{2d_l} + NL + X_0$$

where:

- V = speed (mph),
- d_f = deceleration of the following vehicle,
- d_l = deceleration of the leading vehicle,
- N = number of cars vehicle,
- L = length of vehicle (ft),
- X_0 = safety distance (ft), and
- δ = perception reaction time in seconds.

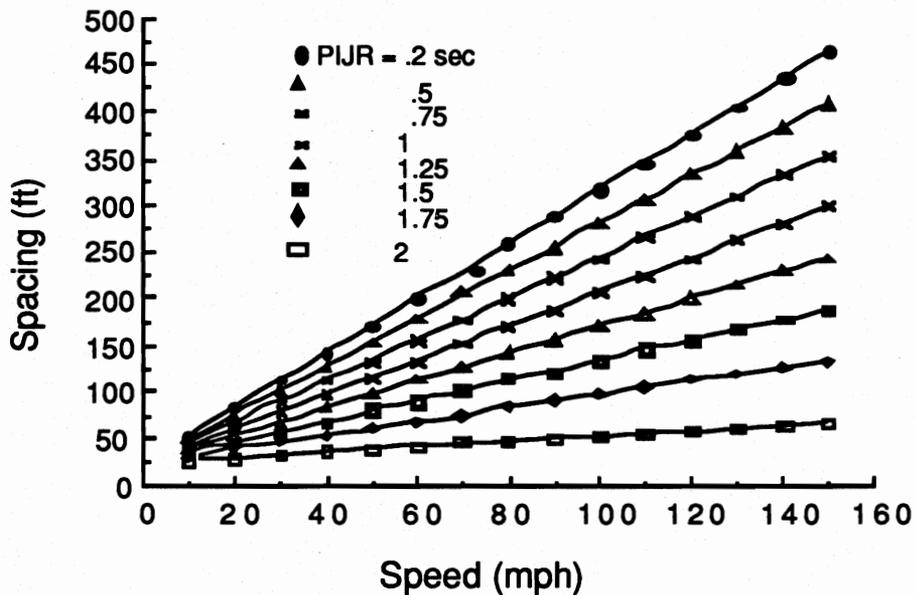


Fig 3.6. Spacing vs. speed.

This equation is used to calculate the density (K) and the flow (q) at different design speeds (see Figs 3.7 and 3.8) using different values of PIJR (the PIJR values are given in the range of 0.25 to 2.0 sec). While the present design calls for a PIJR value of 2.0, an advanced automotive system will necessarily reduce this value dramatically to the range of 0.5 to 1.0 sec. As indicated in Fig 3.7, the density ranges from over 200 vehicles/mile at PIJR = 0.25 sec and speed = 10 mph, to near 12 vehicles/mile at PIJR = 2.0 sec and speed = 150 mph. Flow ranges from 12,000 vehicles/hour/lane at PIJR = 0.25 sec and speed = 10 mph, to 1,800 vehicles/hour/lane at PIJR= 2.0 sec and speed = 150 mph. These figures, representing superior system efficiency, can be achieved by reducing highway headways through the automation of the transportation system.

Capacity as a Function of Stopping-Sight Distance

As introduced in the previous chapter, stopping-sight distance (SSD) refers to the length of visible highway required for a vehicle traveling at or near the design speed to stop before reaching a stationary object in its path. Again, stopping-sight distance is actually the sum of two distances: (1) the distance traveled by the vehicle from the instant the driver sights an object to the instant the brakes are applied (PIJR time); and (2) the distance required to stop the vehicle once brake application begins. SSD is represented by:

$$SSD = 1.47V\delta + V^2/(30(f+g))$$

where:

- f = coefficient of friction,
- g = grade, and
- δ = perception reaction time in seconds.

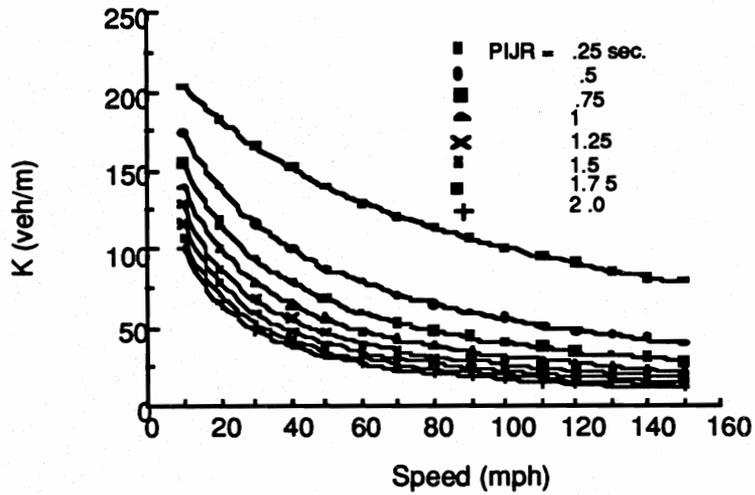


Fig 3.7. Density as a function of speed.

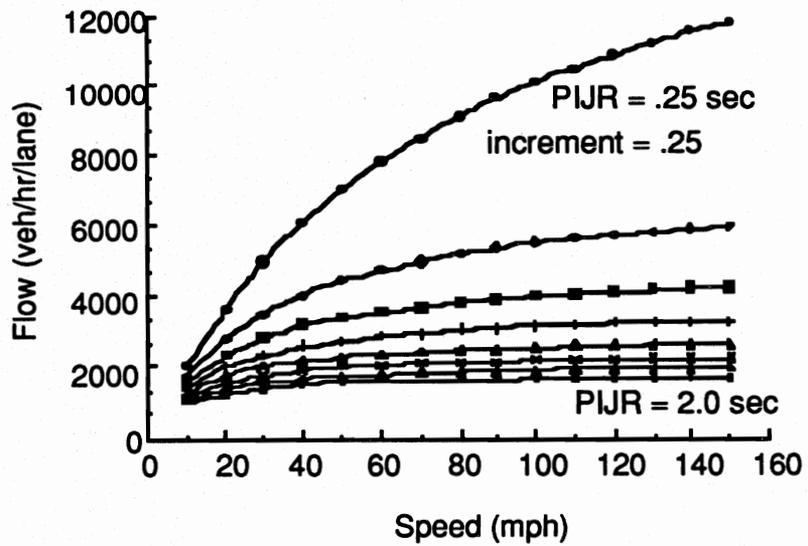


Fig 3.8. Traffic flow vs. speed.

This criterion is used in freeway designs to ensure the safety required under present conditions. It predicts a very low efficiency and system effectiveness at high speeds, mainly because of the increase in the distances required between vehicles at high speeds (about 2,800 ft at 150 mph, PIJR = 2 sec; see Fig 3.9). Under these conditions, density drops to less than two vehicles per mile at a speed of 150 mph (Fig 3.10) and results in a flow of nearly 400 vehicles/hour/lane. These estimated values represent a dramatic decrease in capacity and, hence, defeat the goal of a high-speed system. The highway facility, as well as every other aspect of the system, must be improved in order to reduce SSD. (It should be noted here that the above formula was developed many years ago under conditions and circumstances that differ from present ones; moreover, it was applied to facilities whose overall quality does not compare with the higher quality that should characterize a high-speed system.)

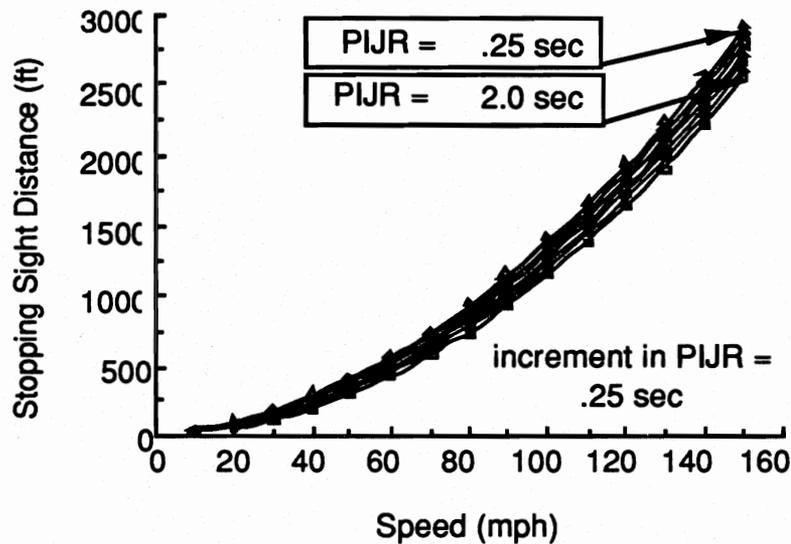


Fig 3.9. Stopping-sight distance vs. speed.

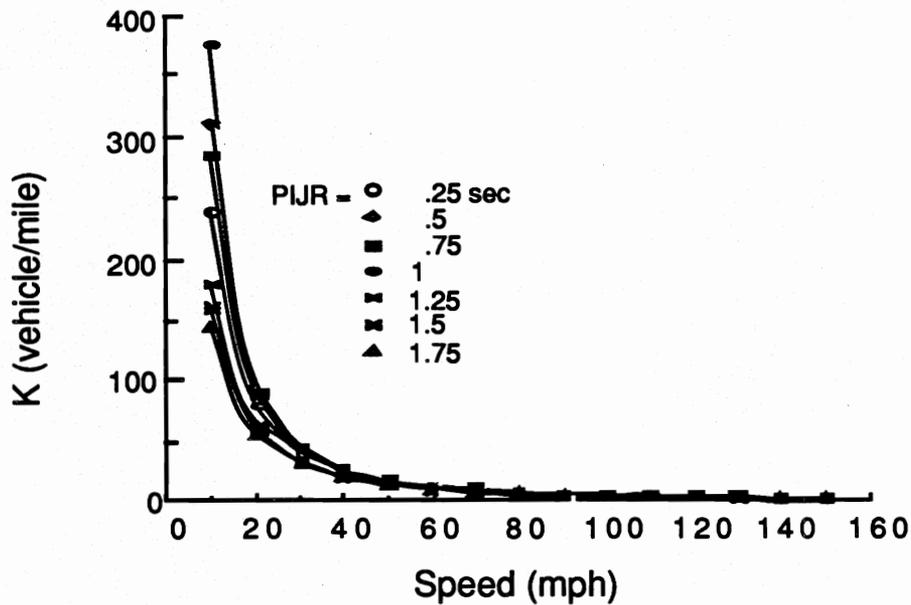


Fig 3.10. Density vs. speed (using spacing category).

Capacity as a Function of Fixed Headways

Short fixed headways, capable of increasing freeway capacity and speed, will be possible with an automated system (relative spacing is considered). Figure 3.11 shows a flow-headway curve that gives a capacity of about 1800 vehicles/hour/lane at 3 sec headway. However, using a deceleration rate of 1g (32 ft/sec/sec) and substituting this value in the following kinetic formula

$$v_f = v_0 + a(t)$$

where:

- v_f = final speed (ft/sec),
- v_0 = initial speed (ft/sec),
- a = deceleration rate (ft/sec/sec), and
- t = time (sec).

it is found that it takes the vehicle about 6.8 sec to come to a complete stop from 150 mph (220 ft/sec) at a deceleration rate equal to 1g. This headway of about 7 sec yields a road capacity of nearly 600 vehicles/hr/lane.

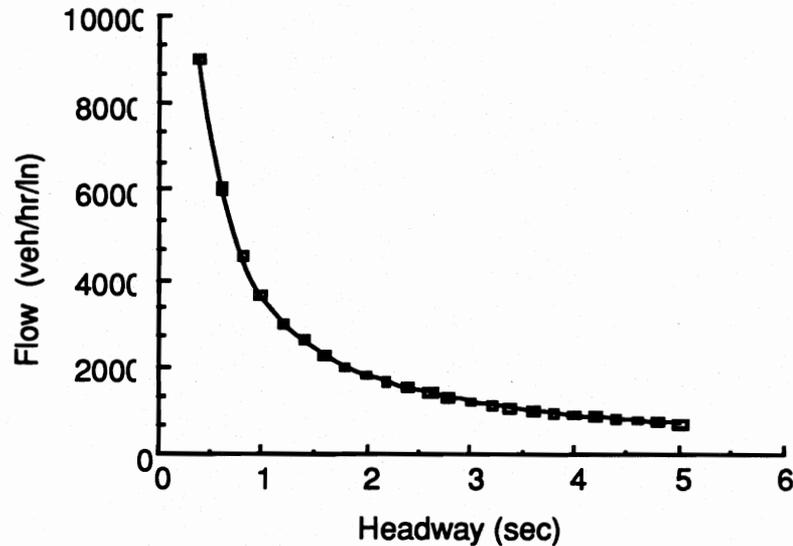


Fig 3.11. Traffic flow as a function of headways.

Automated System and Higher Capacity

Both intrametropolitan shifts and the suburbanization of the national population have been concerns of many public planners and forecasters. "The strongest competitive effects" says John Kasarda, "are in the suburbs" (Ref 15). What does this suburbanization trend mean to the transportation system? It means more congestion and traffic problems. And automated systems, in attempting to address these problems, must begin integrating computers and microprocessors as a way of increasing the productivity of existing and future transportation facilities.

A fixed headway system—one that uses computers and advanced technology to reduce the work of the driver—is certainly possible. However, it is not presently known how much control will be transferred from the driver to the computers onboard the vehicle and at the central traffic control center. As discussed above, the system's effectiveness will be greatly enhanced with the short headways allowed by system automation; however, this enhancement will depend on the sophistication, practicality, and cost of the automated system.

The Research Program for Advanced Technology for the Highways (PATH) conducted by the Institute of Transportation Studies for the California Department of Transportation (Ref 16) has been a very successful freeway automation experiment, one that has demonstrated that such systems can reduce accidents, increase capacity, decrease trip time, and reduce driver stress. Highway automation, as stated by PATH, involves three sets of control:

- (1) navigation information and control,
- (2) lateral control of vehicle, and

- (3) longitudinal control between sequential vehicles.

This automated system will, according to PATH planners, increase capacity by reducing headways, providing in the process a more efficiently routed traffic flow. The PATH project suggests the following as stages toward full automation of all roads:

- (1) navigational aid,
- (2) longitudinal and lateral control on board the vehicle,
- (3) dedicated lanes (left-hand lanes) and inter-vehicle communication,
- (4) full automation of all freeway lanes, and
- (5) full door-to-door automation of all roads.

As each stage advances to the next, increasingly smaller headways will be attained, resulting in higher capacity even at higher speed.

Much of the success of this progression to full automation will depend on onboard vehicle computers—items which will most certainly be standard features on tomorrow's cars. As forecast in *Business Week* (Ref 13), "By the mid-1990s there may be two or three master computers, each with the capacity of IBM's latest PC, that are able to handle as many as 6 million operations per second." The "smart cars" resulting from this research will help to reduce human error while increasing safety at higher speeds.

SUMMARY

This chapter presented the flow entities and the capacity characteristics of a high-speed transportation system. The basic flow-speed relationships of the high-speed ground corridor were discussed, with the concept of system level of service also introduced.

This report urges that technology be better incorporated into current transportation planning and design, and that the expected benefits of new technologies be applied in meeting the demand for high-quality transportation facilities. A better understanding of the relationships and interfaces among the different elements involved in the design of the transportation facilities is needed, and intensive research is required at all levels to establish the accurate design of the high-speed facilities of the future.

CHAPTER 4. CONTROL SYSTEM AND FLOW GUIDANCE

INTRODUCTION

This chapter describes the control and guidance requirements of a high-speed corridor system. Such control and guidance of the flow entities traversing the fixed facility is considered essential in the planning of an efficient and safe transportation system.

A control system consists of *vehicular control* and *flow control*. Vehicular control—the mechanism by which individual vehicles are guided on the fixed facilities—can be either manual (as with present highway systems) or automated (as in the case of automotive trains) (Ref 11). The flow control system includes signing, signal systems, and the rules and regulations of traffic operation, all of which permit the smooth and efficient flow of vehicle streams.

DRIVER-VEHICLE-HIGHWAY INTERFACE

The most important element in the highway system is the driver, or, more precisely, the driver's sensory apparatus; indeed, it is this human apparatus that determines highway facility design constraints. For example, in conventional highway design, the driver depends on visual cues alone to determine traffic condition, lane position, headway, vehicle speed, and weather conditions. And while improvements in highway signing and landscaping have facilitated driver perception of highway condition information, the design speed and geometric design of these highways are ultimately controlled by such human factors as perception/reaction time (PIJR).

In a high-speed facility, new technology (e.g., smart cars and smart highways) will allow better communication between the driver, the vehicle, and the highway system. As a result, regulation, capabilities, guidance, and other driver issues will have to be redefined (see Table 4.1).

TABLE 4.1. DRIVER ISSUES (REF 14).

Regulations	Capabilities	Guidance
Special vehicle	Vision	Driver in control or "hand-off"
Special vehicle inspection	Reaction time	CTR displays of mapping, engine functions
Special license	Training	Emergency breaking

Driver/Vehicle Interface

The driver-vehicle interface will be very important in the design and operation of a high-speed facility. Through new concepts in seating configuration, safety features, advanced suspension systems, and handling, the concept vehicle will provide the driver with safer, more

comfortable travel. Driver-vehicle communication will be enhanced by such visual and hearing aids as message displays and speakers; in addition, the driver may communicate with the vehicle subsystem through either a computer keyboard or through some other electronic mechanism.

Vehicle/Highway Interface

Vehicle and highway design includes consideration of three basic elements: (1) the central communication facility, (2) the roadway, and (3) the vehicle. The central communication center, located along the corridor facility, will collect and store information on traffic flow, headways, weather conditions, and traffic incidents. Real-time data will then be communicated from these central stations to each vehicle (using both transmission points or wires and electronic signs along the roadway). Interpreting this data, the artificial intelligence subsystem on board the vehicle will either actively guide the vehicle through necessary action or will simply pass the information on to the driver. Finally, in addition to providing for maximum friction between tire and road surface, other important vehicle features will include sensors for reading highway roughness and geometric features, a back-up system, and driver override capabilities. A summary of some of the elements involved in the interface of highway, vehicle, and driver subsystems is presented in Fig 4.1.

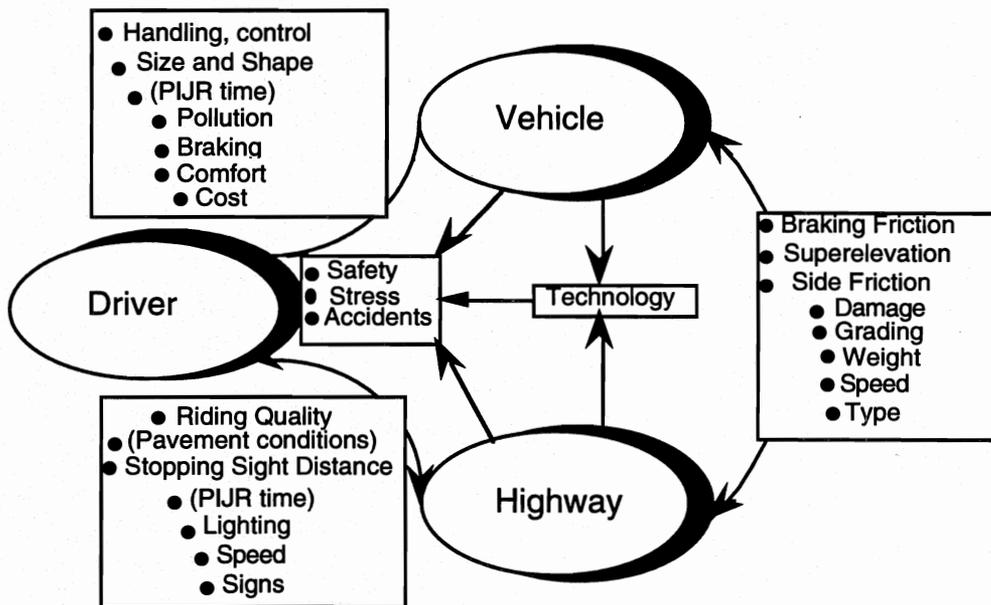


Fig 4.1. Highway-vehicle-driver interface.

The next section describes a signing system as an interface between the driver and the highway facility. This signing system—highway signs, signals, and messages—will be important in providing real-time information about weather and traffic conditions for those instances in which the driver chooses to override the automated system.

CORRIDOR SIGNING

A freeway signing system is primarily for the benefit of travelers who are not regular commuters on a specific route. Accordingly, these signs must furnish drivers with clear instructions for orderly progress to their destinations. And because signs and their installation are essential parts of a highway facility, their planning must be concurrent with other important considerations, including alignment and geometric design. While the following discussion is derived from the *Manual on Uniform Traffic Control Devices* used on current conventional highways, the standards and prescriptions provided in that manual are applicable to any freeway system.

An Approach to Selection of Alternatives

A high-speed highway should offer superior traffic service to population centers located on or near the facility. For this reason, the course of the highway route and the major destination or control cities along that route must always be clearly identified. Destination messages should provide the driver with the best highway orientation possible. Both continuity in the successive sign messages and consistency with available map information are considered essential considerations in the design of a signing system.

In terms of a high-speed corridor, its unique characteristics necessitate a more advanced signing system. The following alternatives are proposed in this study. Any one alternative or a combination of alternatives may be considered, including the do-nothing alternative:

- (1) Visual: Do-nothing alternative or improvement of existing system
- (2) Partially computerized system
- (3) Fully computerized signal navigations

Visual Approach

The do-nothing alternative proposes full implementation of the existing system of freeway signing described in the *Manual on Uniform Traffic Control Devices* (MUTCD) (Ref 19). However, because high speed limits driver visual perception, the do-nothing alternative is not recommended.

Improving the existing system represents a better alternative. Research has shown that a driver can perceive an event every half second (Ref 15); thus, for every 88 feet traveled at 60 mph, the driver can assimilate two events in a second. Table 4.1 shows the required spacing between meaningful signs with respect to time at different levels of speed. Under this alternative,

sign layouts, designation of destinations, legends, routing, overhead sign installation, and all other characteristics of freeway signing described in MUTCD will apply to a high-speed facility, with the exception of the lettering and spacing between signs.

According to Table 4.1 and Fig 4.2, nothing can be done to improve the number of events humans can perceive in a unit of time. Unless some type of computer-aided system is employed, the only improvement that can be made involves enhancing the existing signing system by improving the lettering and the legend spacing, the spacing between signs, and perhaps the sizes of letters and signs. But driver visual perception can be enhanced indirectly: Because the design vehicle of the high-speed corridor will have computer equipment to assist in many of the traffic operation activities, the driver will not have as many duties, which means a lighter workload, and, consequently, more time and attention to focus on road signs. Such a decreased workload would, in effect, represent an improvement in the visual perception of the driver (possibly doubling the number of perceived events at higher speeds). In this case, then, the existing signing system could be an adequate—though perhaps not ideal—alternative for the signing of a high-speed facility.

TABLE 4.2. DISTANCE REQUIRED TO PERCEIVE TWO CONSECUTIVE EVENTS AT VARIOUS SPEEDS.

Speed (mph)	Distance between events (ft)
20	14.7
40	29.3
60	44
80	58.6
100	73.3
120	88
140	105.7
160	117.3

Partially Computerized System

The second alternative, a partially computerized system, is the one most likely to be suitable for the signing design of a high-speed facility. In this system, a sophisticated camera equipped with high-sensitivity lenses would be mounted on the vehicle to enhance viewing. The information collected would be displayed on message signs along the highway. After the data are analyzed and interpreted by an electronic device programmed to provide information easily understood by the driver, this information would then be displayed on a television-like screen on

the dashboard of the vehicle, providing the driver with an efficient method of collecting data for decision-making.

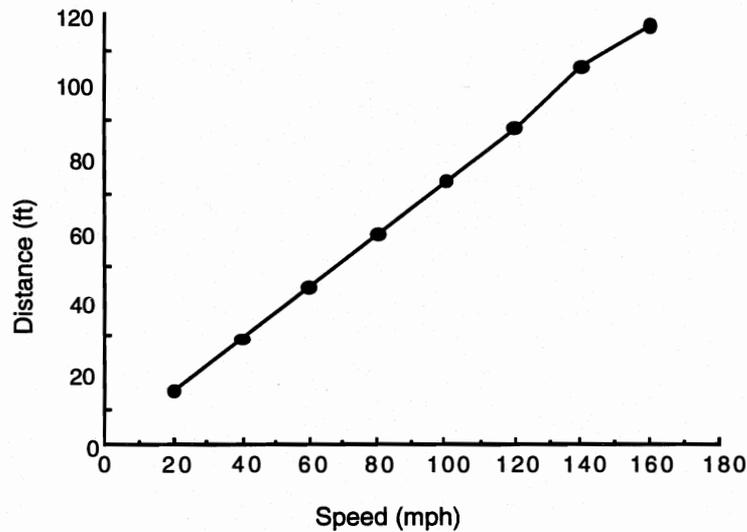


Fig 4.2. Distance between two meaningful events perceived by driver at different speeds.

Fully Computerized Signal Navigation

In some respects, a fully computerized signing system will be somewhat similar to the air navigation systems used in air transportation. Such a system will provide for communication between the high-speed facility, the driver, the vehicle, and the environment.

In this signing system, the vehicle will be equipped with a radar that covers all directions at all times. Signs will be installed along the side of the corridor, with precision electronics built into each sign according to what information is needed at that point. The number of signs depends on how much information can be stored and how far it could be received. In addition, navigation stations will be located in the major cities or at strategic points along the corridor. These stations, similar to area navigation stations used in air traffic control, will identify each vehicle using the facility through a unique code given to that vehicle as it enters the system—thus providing a way of identifying the vehicle anywhere on the facility. As the unique code is given, the vehicle's navigation system will be activated; then the vehicle will begin receiving the signals that are transmitted throughout the whole network. These signals are translated by a computer into meaningful information easily understood by the users of the system. Finally, the corridor will be divided into different segments, each segment covered by the closest traffic control station.

The facility's communication network may also be tuned to radio networks, weather networks, police departments, emergency departments, and to many other networks that might be of interest to the transportation system.

SUMMARY

The control system consists of vehicular control and flow control. Vehicular control is the mechanism by which individual vehicles are guided on the fixed facilities. There are two types of vehicular control: manual and automated. The flow control system consists of the means by which efficient and smooth operation of streams of vehicles is permitted.

A high-speed facility will require different rules and regulations. Automated systems will be used to communicate with the driver, and the driver will have the power to override the system while traveling on the corridor facility.

CHAPTER 5. AUTOMATED TRAFFIC MANAGEMENT SYSTEM

INTRODUCTION

Traffic congestion, a problem affecting metropolitan areas globally, is usually the result of an inefficient traffic management system. Although there is renewed interest in improving traffic management and safety, at the present time traffic management systems are not given adequate attention in the design process, nor enough attention in the implementation of the transportation system (Ref 15). In view of the rapidly growing problem, all aspects and components of the transportation system should be optimized to provide the best services and the highest capacity possible. One solution is to improve the existing network with an efficient automated traffic management system (ATMS). A better alternative is an ATMS combined with a high-speed automated ground corridor.

WHY AN AUTOMOTIVE MANAGEMENT SYSTEM?

The primary goal of an ATMS is to increase safety by minimizing highway congestion. At the present time, traffic volumes on many metropolitan freeways exceed capacity on a daily basis. The resulting congestion has been identified as consisting of two different types of congestion: one is recurrent congestion, which repeats daily and is the result of a poor traffic management system; the other is nonrecurrent congestion, a result of an incident or other unexpected events (an incident in this case may consist of an accident, unusual weather conditions, a stalled vehicle, or some other temporary obstruction). In a study of freeway congestion in the Los Angeles area, it was found that nonrecurrent congestion accounted for 57 percent of the total congestion, while recurrent congestion accounted for 43 percent of the total (Ref 19). Since the impact of an incident on the overall traffic operation is highly dependent on the time required to clear the obstruction (response time), an ATMS would provide an effective mechanism for managing such nonrecurrent congestion; in other words, the ability to respond quickly to incidents would minimize the negative impact of an incident on the traffic operation, thus resulting in less congestion. A current example of such an ATMS function is an emergency service operated by the Arizona Department of Transportation (Ref 20). In 1987, this service (called ADOT Local Emergency Response Team, or ALERT) cleared 57 highway incidents, each of which averaged 3 hours and 13 minutes (Ref 19). And both San Diego's Urban Traffic Control System (UTCS) (Refs 19 and 20) and Seattle's Freeway Management System (Ref 20) have already provided increases in capacity as well as decreases in delay caused by incidents.

COMPONENTS AND FUNCTIONS OF THE ATMS

As illustrated in Fig 5.1, an ATMS consists of three primary subsystems: (1) the field equipment, (2) the Central Computer Control Facilities (CCCF), and (3) the Central Traffic Control Center (CTCC). The field equipment continually monitors traffic flow through loop detectors and

television cameras; it includes message and control signs that receive information from detectors, from TV cameras operated by the computer facilities to control traffic through ramp meters, and from radar stations located along the facility. The field equipment is connected (by wires or radar) to the CCCF via a large communication network. The CCCF consists of sophisticated computer hardware and software and a radar station; it is directly connected to the Emergency Response Center, to the CTCC, and to other agencies or departments related to the system (the police department, for example).

The CTCC consists of terminals (to feed information to the system and make changes through wire or radar signal connections), map displays and TV monitors (to view the system's condition through the field equipment at all times), teleprinters, and control consoles.

In one possible scenario, speed and volume of a road segment would be monitored with loop detectors installed in each travel lane—including entrance and exit ramps and frontage roads—of the roadway. Television cameras, installed at strategic locations along the roadway, would identify and locate for the CTCC any problems, including congestion and incidents, as they occur. If traffic flow is impeded for any reason (traffic accidents, spilled cargos, stalled vehicles), the CTCC operator would dispatch appropriate emergency vehicles to the scene.

Ramp metering represents another potential control device for a high-speed system. It has been demonstrated over the years that ramp meters, as a way of minimizing congestion, are very successful in regulating demand onto freeways. As part of a high-speed facility's ATMS, ramp meters would control the access at a rate contingent upon upstream traffic flow volumes, so that the downstream traffic flow volumes do not exceed capacity. Thus, by ramp metering the system will be controlled at all times, and the intended level of service on high-speed highway lanes will be maintained.

Variable message signs could also be used as control devices. Currently, signs are used on the highway to advise motorists of hazardous roadway conditions. These signs may also advise motorists of lanes that are obstructed, in which case they would take necessary avoidance measures miles in advance. The same or perhaps a different type of message sign could be used in the CTCC to convey traffic information from the highway to the central computer and then to the traffic control center. The vehicle would then provide the driver with needed information by means of a video display and/or audio device (Ref 20).

Both the CCCF and the CTCC will be operated by a sophisticated state-of-the-art computer system, including perhaps a 32-bit machine using Pascal and an advanced communication system connecting the different components of the system. The system would need to be highly reliable, cost efficient, and capable of handling different types of data for the many different types of devices to be used within the overall system. The communication medium could be fiber-optic cable, a microwave system, coaxial cable, and/or any other medium that technology is capable of providing at that time.

In the CTCC, operators would identify the location of the congestion or incident through a system of indicator lights on a message board. Through monitors in the CTCC, the operator could identify incidents and varying levels of highway congestion by different colors. Although software

designs will in most cases control the highway system automatically, the operators at the CTCC should have the ability to override computer control manually when necessary.

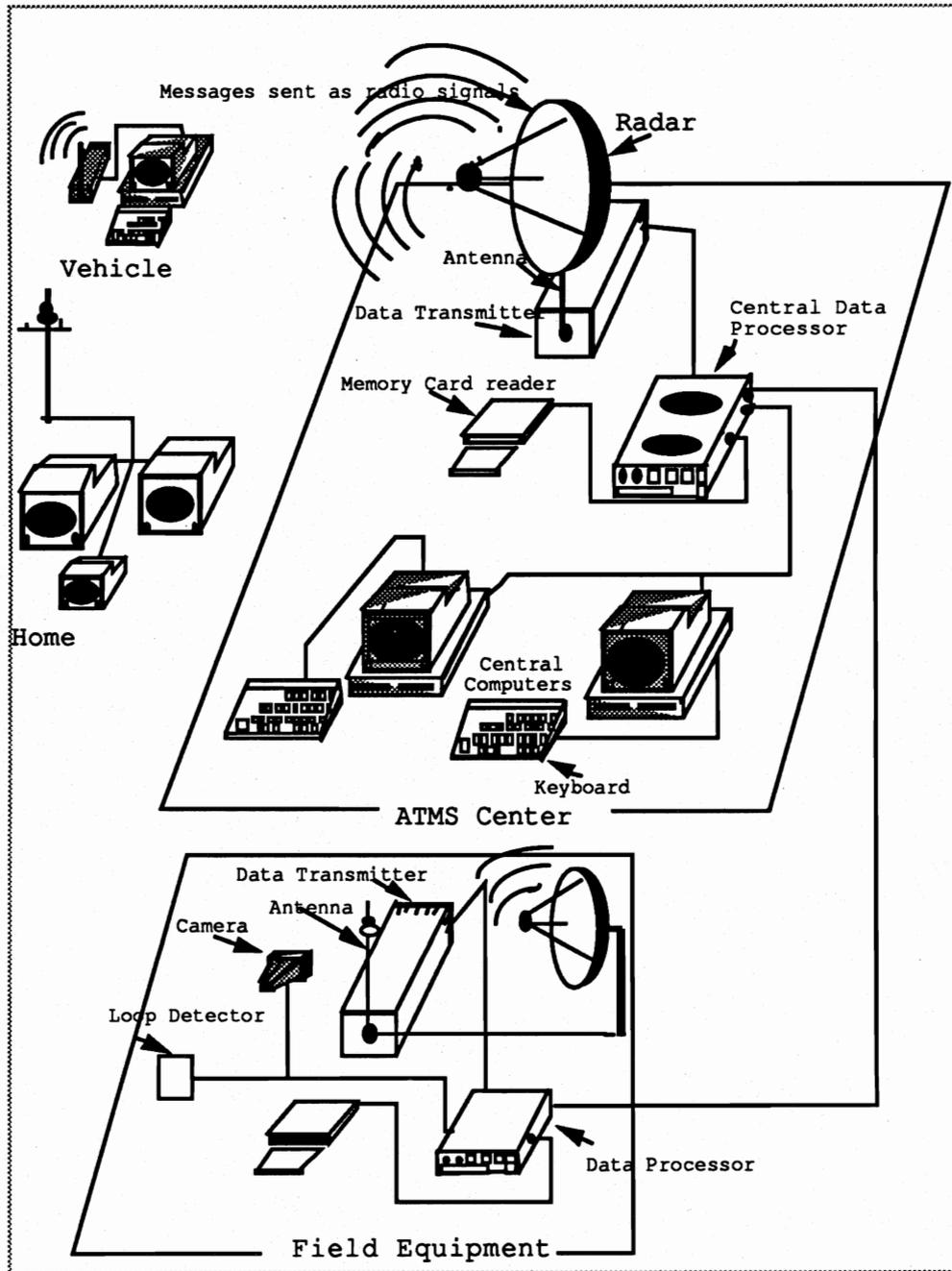


Fig 5.1. Automated Traffic Management System Network.

Many other subsystems and activities involved with the transportation system may be served and controlled by an ATMS. For example, the drainage system, which greatly affects traffic flow (especially during high water and flooding conditions), could be controlled and monitored. Also, a communication system would allow local media and other public agencies to tune into the highway network for up-to-date information on current highway conditions. A high-speed facility management system may also use advanced electronic identification techniques to monitor and locate each vehicle entering the system.

Finally, since the purpose of an ATMS is to manage traffic on both the main highway lanes and the frontage roads, it is important to include, as a part of the system, the operation of existing and future roadway networks, especially with respect to the interchanges along the facility.

SUMMARY

The operation of a high-speed facility requires an automated traffic management system (ATMS) that works through electronic surveillance. The ATMS must have the ability to identify and locate incidents on roadways through computer hardware/software equipment. An ATMS should implement control strategies to deal with those incidents and conditions that might impede the intended free-flow operation of the highway system. It should provide the road user with all the information needed to assure safe, fast, and convenient travel. The system should also be able to interface with other agency systems, including computerized traffic networks in the vicinity of the corridor. These control strategies will help increase the capacity of not only the main highway, but the entire corridor as well. An ATMS must have access to an efficient emergency operation center to ensure quick response to accidents. Most important, an ATMS should continuously provide the corridor user with real-time data on the system and the surrounding traffic networks. In addition, in the case of joint modes between highway and railroad, the system would serve both modes throughout the corridor. Such an arrangement would increase system efficiency while reducing operation cost.

In summary, an ATMS would minimize highway breakdown conditions, would ensure safe, fast travel, and would maximize highway system use.

CHAPTER 6. CONCLUSIONS AND RECOMMENDATIONS

Highways are no longer merely strips of pavement providing routes for wheeled vehicles. Rather, they represent complex networks connecting modern society. As such, they should be made as safe and as efficient as possible. We believe that capacity on these highways can be increased—without the concomitant traffic congestion—in ways that can accommodate growing demand. Through the advancements of modern technology, a fully automated highway infrastructure is now possible.

SUMMARY OF RESEARCH

This review of a high-speed corridor calls for better development and utilization of technology in transportation—not only to expand the carrying capacity of current facilities, but also to meet the travel demands of the future.

Our study of highway pavement design suggests the following:

- (1) The cost of a high-speed facility's pavement design can be reduced by segregating traffic lanes according to vehicle types. Such a design will also improve system safety.
- (2) A typical rigid pavement section is the most economical alternative. However, further analysis using more reliable design inputs is recommended for obtaining the final thickness needed for implementation on a high-speed facility.

With respect to the geometric design of a high-speed facility, we suggest the following:

- (1) The facility must be a limited- and controlled-access facility.
- (2) Results obtained by the extrapolation of the current design formulas are somewhat unreliable. Therefore, different design procedures incorporating advanced technology are necessary. Current design procedures could perhaps be modified and updated under current conditions to meet the demand for automated facilities.
- (3) Controlling traffic flow to and from the facility through special ramps will be very important in determining system capacity.

Using current systems, higher speeds result in very low capacity. However, the results obtained using different criteria (assisted by computers) are very promising.

The implementation of a sophisticated ATMS, in both the corridor and the neighboring facility, will increase system capacity, improve system efficiency and safety, and will perhaps mark the beginning of a new era in transportation.

CONCLUSIONS AND RECOMMENDATIONS

A survey of the current literature reveals that much of the automobile and highway technology necessary for a high-speed facility is presently available. Accordingly, this report concludes that such a facility is feasible from all engineering standpoints. With respect to highways, some improvements will have to be made, including determination of the proper type of

aggregate permitting maximum friction between the highway and the tire surface. With respect to the automobile, present technology can produce a vehicle capable of operation on a high-speed facility; increasingly, innovations such as active suspensions and advanced materials are gaining acceptance in the automobile industry. However, some aspects of automobile design need improvements, including the interaction between the vehicle and the driver, driver control at high speeds, and the characteristics of the vehicle itself. Yet the improvements proposed for a high-speed facility could also be applied to current interstate systems, allowing faster and safer travel while increasing highway capacity.

This feasibility study of a high-speed ground corridor suggests that a successful and profitable high-speed highway system will require a design that integrates the automobile, the highway, and the human driver. Investigation has also revealed the following:

- (1) The benefits from smart vehicles and smart roads in terms of free-flow, non-urban traffic are yet to be utilized.
- (2) There is a move toward corridor designs that require subsidies for their construction, operation, and rehabilitation. Life-cycle cost analysis should be used to guide project selection (Ref 2).
- (3) Projects are not demand-oriented, and user-data are lacking in most current project evaluations.
- (4) Future technology will provide for safer and improved movement of people and goods throughout cities.
- (5) Programs such as California's PATH, Washington's FLOW, Great Britain's AUTOGUIDE, and Sweden's ARISE show promising results in the move toward automated highway systems (Ref 15).
- (6) Future technology will allow a balanced flow of traffic along the metropolitan system of highways, super streets, and traffic corridors, which in turn will reduce congestion, vehicle emissions, fuel consumption, and accidents.
- (7) Future technology will provide for the integration of smart highways with smart vehicles.

Future research should concentrate on the civil and mechanical engineering issues, including associated costs and environmental impacts. And because developments in automotive design result in modifications to the traditional highway design guides, the high-speed facility design will need to consider the implications of these developments in terms of design and costs, including comparisons of life-cycle costs with other modes.

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