Title

The AHS/Street Interface; Effects of Capacity Concentration on System Performance: Phase 1 Final Report

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The AHS/Street Interface; Effects of Capacity Concentration on System Performance: Phase 1 Final Report

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The AHS/Street Interface
Effects of Capacity Concentration on System Performance
Phase 1 Final Report

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ABSTRACT

This report provides Phase 1 results for **MOU 386,** "The AHS/Street Interface, Effects of Capacity Concentration on System Performance." Additional results **fiom** this project ***can*** be found in **PATH** Working Paper 2000-26. Within this paper, strategic issues in Automated Highway Interface design are discussed, including creation **of** interface components and design alternatives, with emphasis on interchange separation and highway orientation. The report **also** discusses land use issues associated with interchange construction.

EXECUTIVE SUMMARY

Roadway systems provide the infrastructure for rubber-tire vehicles to efficiently travel between trip origins and destinations. By providing a smooth and obstruction-free travel surface, vehicles can move at high velocity, with low risk of damage. By providing traffic control devices, signage and structures, vehicles can also move at large volumes with a high level of safety. Taken as a whole, the roadway/vehicle system provides a mechanism for the movement of people and goods from place to place, with access to most trip origins and destinations, and with the flexibility for travel at almost any time of the day, week, month or year.

The economics of roadways, and their variability in demand, favor construction of multi-layered and inter-connected networks. Different network layers are designed to different standards and to perform somewhat different functions, though all provide the common function of mobility for a reasonably homogeneous class of vehicles. Yet interfaces have been constructed to provide a smooth transition between network layers, with little delay and inconvenience to travelers. This project has investigated interfaces between an automated highway network layer and city streets.

This report provides Phase 1 results for "The AHS/Street Interface, Effects of Capacity Concentration on System Performance". Section 2 summarizes strategic issues in interface design (more project details, and a literature review, can be found in PATH Working Paper 2000-26). And Section 3 provides more detailed results on roadway orientation and interchange separation, including new results on multiple highway systems (not contained in Working Paper 2000-26). Section 4 provides a progress report on investigation of land-use issues. The project is ongoing, and Phase 2 results will be provided in the future

1. INTRODUCTION

Roadway systems provide the infrastructure for rubber-tire vehicles to efficiently travel between trip origins and destinations. By providing a smooth and obstruction-fiee travel surface, vehicles can move at high velocity, with low risk of damage. By providing traffic control devices, signage and structures, vehicles can also move at large volumes with a high level of safety. Taken as a whole, the roadway/vehicle system provides a mechanism for the movement of people and goods from place to place, with access to most trip origins and destinations, and with the flexibility for travel at almost any time of the day, week, month or year.

Accessibility and flexibility are primary advantages of roadway/vehicular systems. Disadvantages include their susceptibility to crowding and congestion, their harmful effects on the environment (e.g., emissions and noise) and their large space requirements. With respect to the latter point, safe vehicle spacing virtually mandates that most of the area used by freeway lanes remains unoccupied for most of the time (i.e., the space between vehicles exceeds the space occupied by vehicles). Except under congested conditions, freeway occupancy (percentage of time that a section of roadway is covered by a vehicle) rarely exceeds 10%; the figure is much smaller for local roadways.

The figures for vehicle occupancy are low for two reasons: (1) drivers are incapable of driving safely at high speed with short separation, and (2) the demand for most roadways is intermittent, time varying and, lastly, small relative to their capacity.[1] As a point of comparison, the length of the United States' roadway system exceeds 4

[1] The occupancy is even lower when one considers *that* most passenger cars carry only one or two people, utilizing, perhaps, just 10% of the *space* occupied by the vehicle. Occupancy is lower still when considering *that* roadway right-of-ways are much wider than *the* widths of the vehicles that they serve. All factors considered, event the busiest roadways are sparsely populated by people.

million lane-miles, a distance sufficient to accommodate in excess of 1.4 billion automobiles, or about 7 times the number of vehicles owned in the country. On average, less than 5% of these vehicles are on the roadway at any given time, making the average vehicular occupancy well below 1%, a striking figure in light of the congestion problems facing many urban areas. The figure becomes even smaller if the lateral occupancy is factored in (i.e., the width of vehicles are far less than the width of the right-of-way occupied by a roadway).

The low demand for most roadways is a direct consequence of their accessibility. By providing connections to virtually all addresses, and by permitting dispersion of these addresses, it is impossible to accumulate high levels of demand on all roads. In fact the US Department of Transportation classifies more than 2/3 of roadway mileage as “local”, with the majority of the remainder falling in the classifications of rural collector or rural arterial. Only 6% of roadway mileage is classified as urban collector, urban arterial or interstate (the types of roadways that are most prone to congestion). Thus, most roadway miles are constructed for the purpose of accessibility, and not for the purpose of serving traffic volumes.

The economics of roadways, and their variability in demand, favor construction of multi-layered and inter-connected networks. Different network layers are designed to different standards and to perform somewhat different functions, though all provide the common function of mobility for a reasonably homogeneous class of vehicles. Because they accommodate less traffic, local roadways may have different surfaces and widths than collectors. An arterial may have more lanes than a collector, along with additional traffic control devices. And an interstate will have barriers and bridges to separate traffic.

These design characteristics produce different attributes for each roadway layer, attributes that include (1) design capacity, **(2)** design speed, **(3)** weight limitation on vehicles, and **(4)** ability to access/egress local addresses. In this way a roadway can be designed to serve its expected demand for an appropriate cost.

Most roadway trips cannot be completed without traveling through more than one roadway layer. The juncture between a pair of layers constitutes a roadway interface. Roadway interfaces are designed to enable merging and diverging of traffic flows in a safe and efficient manner. ***An*** interface can range in complexity from a simple uncontrolled intersection to a fully connected highway interchange, equipped with surveillance and control devices. In all cases, an interface permits vehicles to diverge fiom the traffic stream in one layer and merge into the traffic stream of another, while preventing conflicts and collisions with crossing traffic.

From a strategic perspective, some of the important issues in the design of multi-layered roadway networks include:

- Density (i.e., roadway separation) for each network layer
- Geometric orientation of each network layer (e.g., grid, radial, etc.)
- Design attributes for each network layer (e.g., speed, capacity)
- Design attributes for network interfaces
- Density, frequency and provision of interfaces between each pair of network layers

Recent research **on** vehicular automation presents additional challenges for network design. Currently, vehicles do not change their fundamental mode of operation when they move between network layers, and interfaces permit most (or all) vehicle types to move from one layer to another without restriction. With automation, vehicles may need to transition between human and computer control at the interface. Furthermore, certain roadways may be restricted to vehicles that are capable of automatic control. These issues motivate the research in this paper.

The following sections summarize Phase 1 results on the design of interfaces between automated highways and conventional street systems. The purpose here is to identify the strategic issues in interface design. Phase 2 research will explore the full set of strategic issues in greater depth. The concept of "roadway layers" is used throughout the paper to represent the functions performed by different types of roadways.

The report is organized as follows. Section 2 discusses strategic issues in interface design. Section 3 provides analysis of roadway orientation and interchange separation. Section 4 discusses ongoing analyses of land use issues surrounding case study highways. Section 5 summarizes results and describes future research.

2. INTERFACE ISSUES FOR AUTOMATED VEHICLES

The ease by which vehicles (and their occupants) can transfer from one network layer to another is, perhaps, the single most important factor favoring roadway construction. Roadway interfaces enable people to travel from origin to destination without leaving their vehicle, and with minimal delay and inconvenience at interfaces. As described in PATH Working Paper 2000-26, a transportation network interface comprises four elements, which we refer to as the infrastructure interface, vehicular interface, operational interface and managerial interface. The infrastructure interface represents the physical intersection or interchange that joins roadways in different layers. The vehicular interface represents changes in vehicle functionality that occur when a vehicle transitions between roadway layers (e.g., a transition from electrical power to diesel power in a railway interface). The operational interface represents changes in vehicle operation and control as they transition between roadway layers (e.g., a change in vehicle speed or a change in how the vehicle interacts with roadside traffic control devices and surrounding vehicles). Lastly, the managerial interface represents changes in ownership, as well as strategic and tactical oversight, that occur at the boundaries between network layers.

Well designed interfaces enable the roadway system to serve three objectives: accessibility to all addresses, speed on longer trips, and capacity to accommodate large volumes of traffic on fast roads. As automation is introduced in roadway vehicles, to further enhance capacity as well as safety, it will be highly desirable to retain mobility for moving between roadway layers. **Yet** automation presents special challenges for all aspects of the network interface, including:

- Creation of an additional network layer for automated vehicles will cause an increase in the number and complexity of interfaces.
- Provision of adequate buffers to accommodate bursts in the traffic stream.
- Accommodation of larger traffic volumes exiting and entering highways.
- Design of real-time control systems to prevent queues from obstructing traffic streams.

- Vehicle design to ensure safe transition between automated and manual driving modes.
- Creation of new management structures from the construction and operation of automated highways, and organizational interfaces with traditional transportation departments.

To address these issues, the interface between the AHS and other layers of the roadway system can be defined along several dimensions, which we place in the decision hierarchy: (1) automation concept, (2) roadway layering, (3) interface concept, (4) interchange separation and placement, (5) buffer sizing, and (6) flow control.

Automation Concept is defined by fundamental design decisions, such as control hierarchy (e.g., which decisions are made locally, at roadside or centrally), sensing and communication capabilities, permissible variations in vehicle design (e.g., size, weight and performance standards), car-following methods and standards (e.g., platooned versus free-agent control, and separation as a function of velocity), mixing of automated and non-automated vehicles, and separation of automated vehicles from potential hazards.

Roadway Layers: AHS can be constructed independently of conventional highways, or designed to coexist in some manner (e.g., share right-of-way, operate on adjacent lanes; or possibly even operate within existing roadway layers). The AHS can be constructed to interface solely to a street layer, solely to a highway layer, or to some combination of highways and streets.

Capacity: The capacity of the street/highway system as a whole depends on the capacities of the individual roadway layers combined with the capacity of the interfaces that join the layers. No matter how the roadway system is layered, capacities should be balanced at interfaces, so that receiving roads can accommodate traffic leaving another layer, and vice versa.

Interface Concept The interface concept defines the actions that occur at the interface, along with infrastructure and vehicular characteristics that enable these actions, such as inspections and traffic metering.

Interchange Separation and Placement Interchange separation affects the performance of both the AHS and streets. Larger separations force vehicles to travel longer distances on streets to access entrances, and to reach destinations after exiting from the AHS, thus adding to traffic levels on streets. They also cause traffic to be concentrated in a smaller number of locations, creating congestion on the streets surrounding exits and entrances.

Buffer Sizing Queueing can occur at network interfaces, due to the merging of traffic streams and, potentially, the inspection of vehicles for readiness to enter a new traffic stream. Buffers may be needed both at entrances to an AHS (e.g., to prevent disruption of street traffic) and exits **from** an AHS (e.g., to prevent disruption of AHS traffic).

Flow Control Buffers can be regulated to prevent overflows, and the subsequent disruption of traffic. Regulation entails dynamic control **of** the rates at which vehicles enter and exit the queue as a fbnction of the state **of** the queue.

3. EFFECTS OF STREET ORIENTATION

This section provides analyses on the issues of interchange separation, including new results on multiple highway systems. This decision has the potential to **affect** both the performance of the AHS, and the performance of the street system that accommodates local traffic. Here the issue of travel distances on the street system is examined. Other design decisions will be evaluated in future research.

Hall (1**997)** examined the performance of roadway systems consisting **of** a series of parallel highways and a grid of identically oriented local streets. Local street mileage, highway mileage and congestion were evaluated as a fbnction of highway separation, interchange spacing and various trip characteristics. In reality, street systems frequently have a different orientation than the highways, perhaps rotated by some angle as in Figure 1. Other roadway configurations also exist in real cities, but our focus here is on evaluating the effects of the rotation, as the issue if prevalent in many roadway systems.

We begin by considering a simple system comprising a single highway, along with a dense network of homogeneous streets. The spacing between entrance and exit ramps is assumed to be very small, allowing highway access from any point on the street system without backtracking. Let:

a = local street speed, as a proportion of speed on highways

x = vertical distance from trip origin to highway

(x is positive if origin is below highway, negative otherwise)

y = vertical distance from highway to **trip** destination

(y is positive if destination is below highway, negative otherwise)

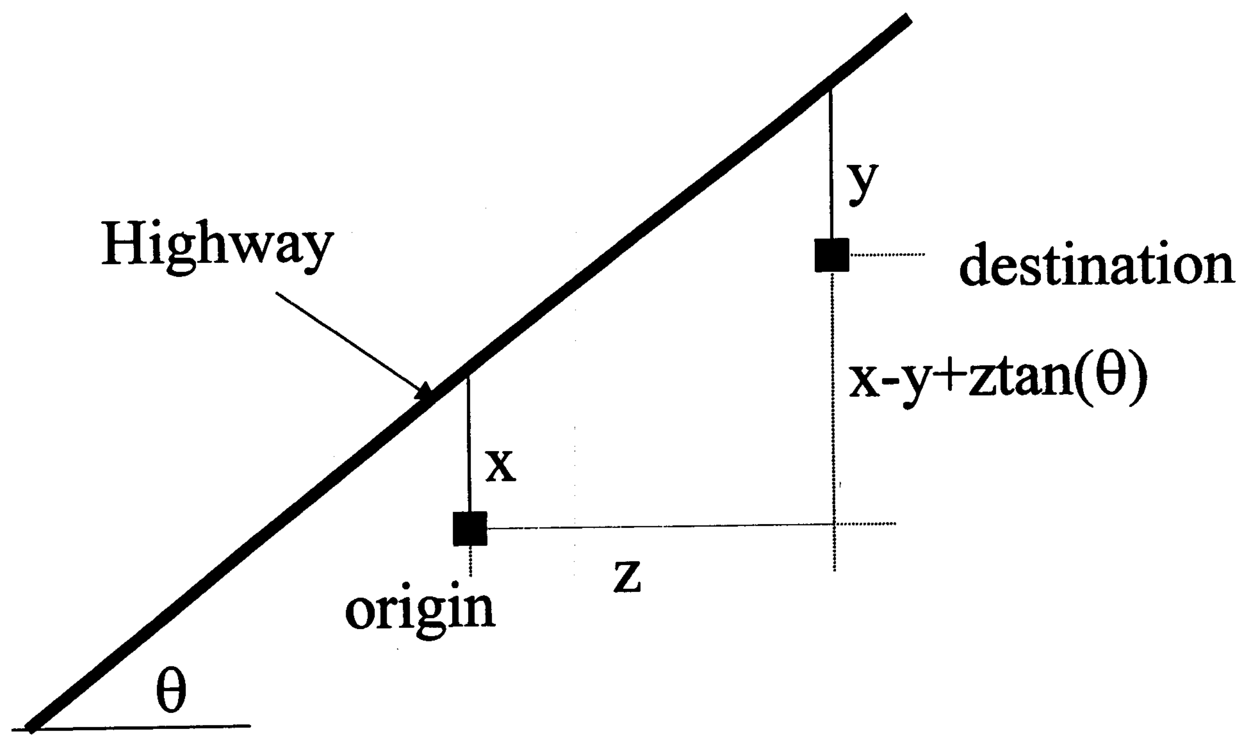


Figure 1. Highway Rotation Relative to Street Systems

z = horizontal distance between trip origin and trip destination

(z is positive if destination is to the right of origin, negative otherwise)

8 = rotation angle for highway relative to streets.

Without loss in generality, θ is assumed to be less than or equal to **45"** in the following analysis (route lengths exhibit a cyclic pattern over 45° intervals). We assume that the highway is no slower than streets and therefore ***a*** ≤ 1.

For any trip, a traveler has the option to travel to his destination entirely by street, or alternatively use the highway for some portion of the trip. If the highway is used, the traveler must also select a place to enter the highway and a place to exit fiom the highway (streets are always used for highway access and egress). We shall assume that the traveler makes these choices with the objective of minimizing travel time.

Travel by street is rectilinear. If a trip is entirely by street, the total travel time **is** defined by the sum of the horizontal and vertical distances (Figure 1):

$$T_s = |z| + |x-y+z\tan(\theta)| \quad (1)$$

Highway trips, by contrast, comprise three segments: access via streets, travel by highway, and egress via streets. Access and egress can occur along either horizontal streets or vertical streets (Figure **2).** With 8 ≤ 45°, vertical access always minimizes street distance, and is therefore preferred for most origiddestination pairs. Nevertheless, horizontal access can still be optimal when it sufficiently reduces travel time in the highway portion of the trip to compensate for the added street travel (especially when 8 and ***a*** are large). Vertical streets are optimal for highway access, independent of origin and destination location, when the following condition holds (and are sometimes optimal when the condition does not hold; Figure 2):

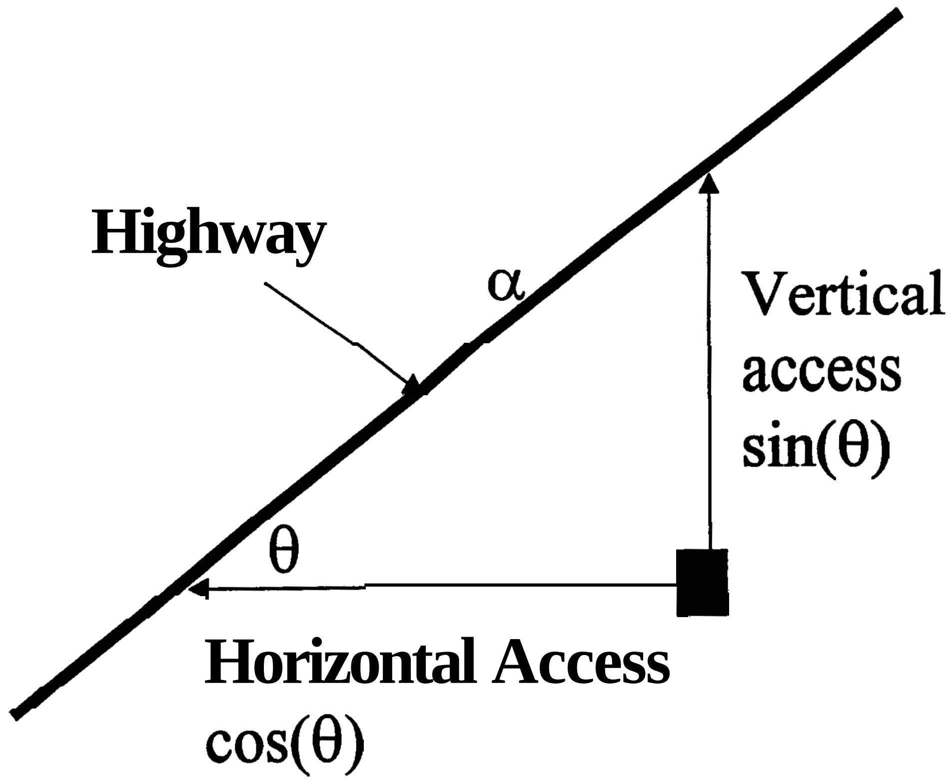


Figure 2. Alternative Highway Access Paths

Vertical Access Always Optimal if $a < \cos(\theta) - \sin(\theta),\ \theta < 45°$ (2)

As an illustration, Figure **3** plots the "breakeven angle" (value of θ for which Eq. **2** is an equality) as a fbnction of ***a*.** When the highway is very fast (small ***a*),** vertical (i.e., shortest distance to highway) access is always optimal for most rotation angles; for slower highways, horizontal access is utilized some of the time, except when the rotation angle is very small (streets and highway have nearly the same orientation).

Route Choice

Whether it is optimal to use the highway for a trip depends on the relative distance between the origin and destination, along with their positions relative to the highway. When $a < \cos(\theta) - \sin(\theta)$ and $\theta < 45°$, access/egress is in the vertical direction, resulting in a travel time **of**

Vertical Access Travel Time: $T_h = |x| + |y| + |\alpha z/\cos(\theta)|$ (3)

Allowance for both horizontal or vertical access complicates the travel time calculation as it presents additional routing options. For a fixed origin with the location shown, Figure **4** divides the travel region into sections. Each section represents a set of potential destination locations, and each section defines a unique travel time equation (provided in Table 1). It should be noted that horizontal streets are only used for highway ***access*** when the destination falls in Section A or **H,** and horizontal streets are only used for highway **egress** when the destination falls in Section **A** or F. Even in these cases, horizontal streets are only used when θ is sufficiently small to satisfy Eq. 1. Outside of these sections, vertical street travel always equals **|x|+|y|,** and highway distance always equals **|z|/cos(θ)**.

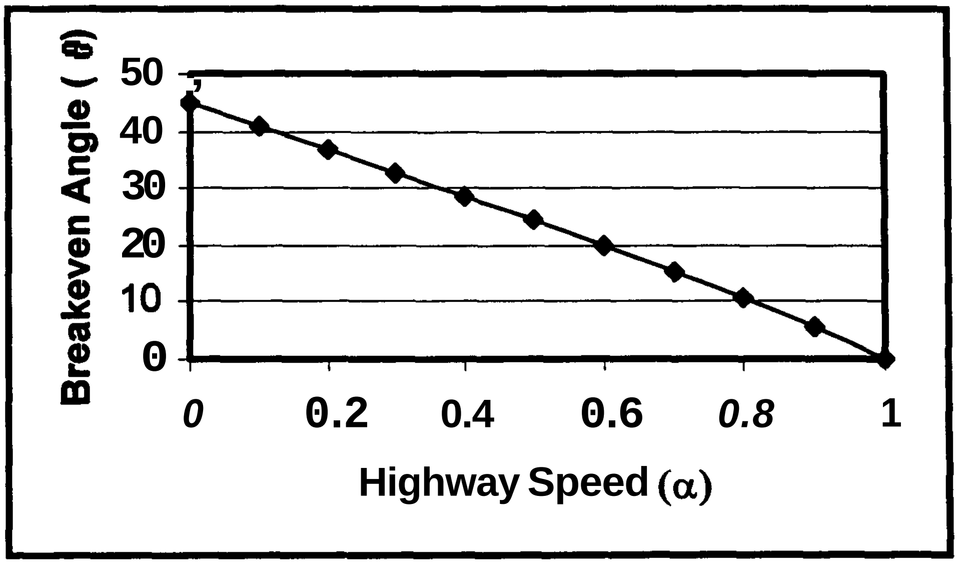


Figure 3. Breakeven Angle for Vertical/Horizontal Access

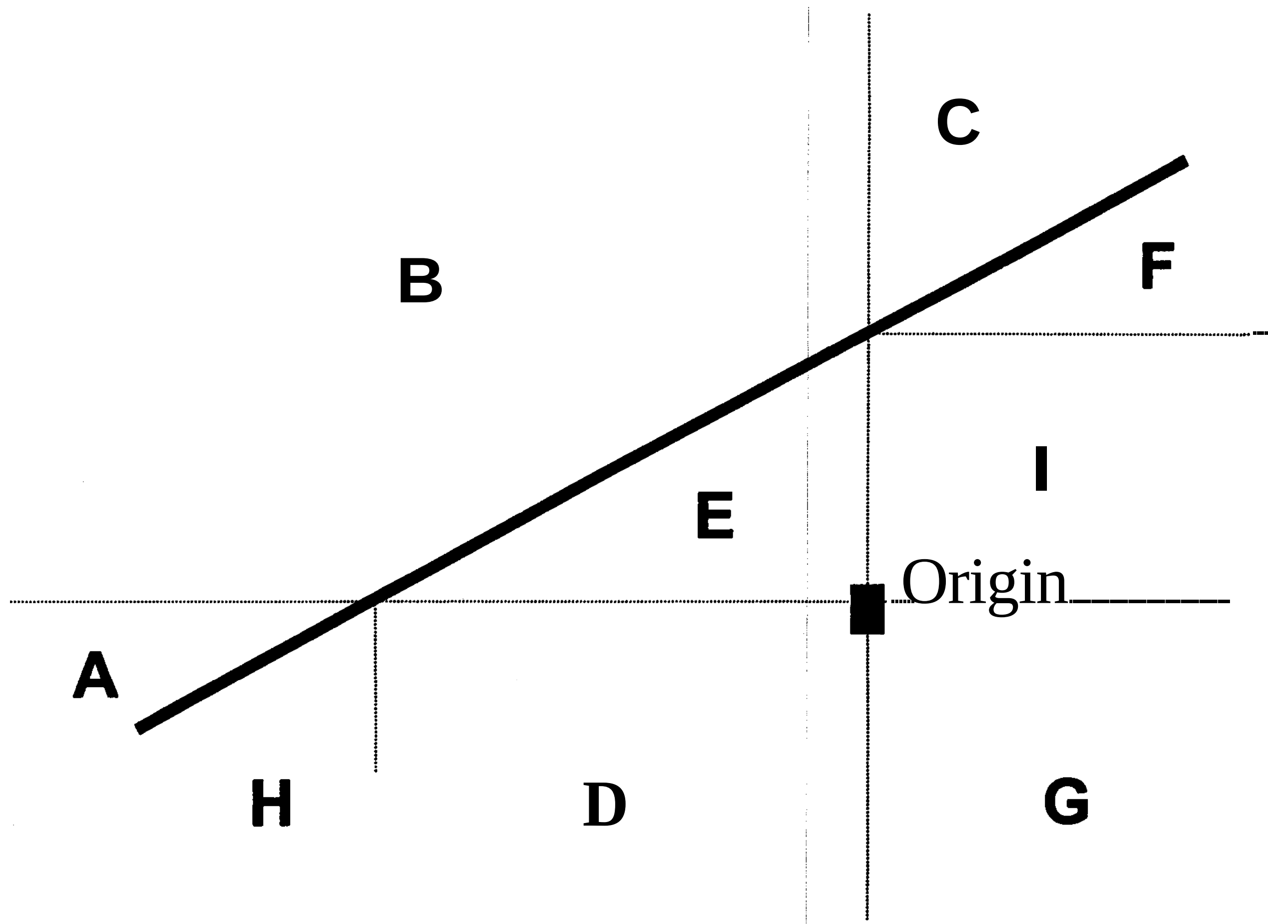


Figure 4. Destination Sections That Define Route Lengths

Table 1. Distance Calculations by Trip Segment for Trips that Use Highway

Section (Figure 4)	Street Horizontal	Street Vertical	Highway
A: $a \leq \cos(\theta) - \sin(\theta)$	0	$x+\|y\|$	$\|z\|/\cos(\theta)$
A: $a > \cos(\theta) - \sin(\theta)$	$(x+\|y\|)/\tan(\theta)$	0	$\|z\|/\cos(\theta)-(x+\|y\|)/\sin(\theta)$
F: $a \leq \cos(\theta) - \sin(\theta)$	0	$x+y$	$z/\cos(\theta)$
F: $\alpha > \cos(\theta) - \sin(\theta)$	$y/\tan(\theta)$	x	$z/\cos(\theta)-y/\sin(\theta)$
H: $\alpha \leq \cos(\theta) - \sin(\theta)$	0	$x+y$	$\|z\|/\cos(\theta)$
H: $\alpha > \cos(\theta) - \sin(\theta)$	$x/\tan(\theta)$	y	$\|z\|/\cos(\theta)-x/\sin(\theta)$
B,C,D,E,G,I	0	$\|x\|+\|y\|$	$\|z\|/\cos(\theta)$

Table 2. Conditions When Highway is Utilized on Fastest Path

Section	Highway Utilized
A	Always
B	$\alpha < \cos(\theta) - \sin(\theta)$
C	Always
D	$(x/\|z\|) < .5[1+\tan(\theta)-\alpha/\cos(\theta)]$
E	$(y/\|z\|) < .5[1-\tan(\theta)-\alpha/\cos(\theta)]$
F	Always
G	$(x/z) < .5[1-\tan(\theta)-\alpha/\cos(\theta)]$
H	Always
I	$(y/z) < .5[1+\tan(\theta)-\alpha/\cos(\theta)]$

Direct and Highway Regions

It is not difficult to derive regions for which travel **is** entirely by streets (called the ***street region),*** and regions for which travel is in part by highway (called the *highway region*). In both cases, "region" refers to the destination's location relative to a fixed origin.

We again, without loss of generality, limit analysis to $\theta < 45$". ***As*** illustrated in Figures ***5*** and ***6,*** two distinct region shapes are possible. The cases are defined entirely by a and θ, and do not depend on the distance from the highway to the origin. The cases are evaluated in the following sections.

Case 1: $a < \cos(\theta) - \sin(\theta)$

In this case the street region falls entirely on the origin's side of the highway, meaning that all destinations on the opposite side of the highway are reached in **part** by highway. The region's boundaries are defined by three vertices:

- Point on the highway having the same horizontal coordinate as the origin.
- Two points having identical vertical coordinate as the origin, with horizontal coordinates displaced from the origin by:

$$\{-2x/[1+\tan(\theta) - \alpha/\cos(\theta)],\ 2x/[1-\tan(\theta) - \alpha/\cos(\theta)]\} = \{b_1, b_2\} \qquad (4)$$

It should be observed that the right-hand boundary (b_2) is greater or equal in magnitude than the left-hand boundary ($|b_1|$), due to the upward tilt in the highway's orientation in that direction. For $\theta = 0$, symmetry exists and the boundaries have identical magnitude

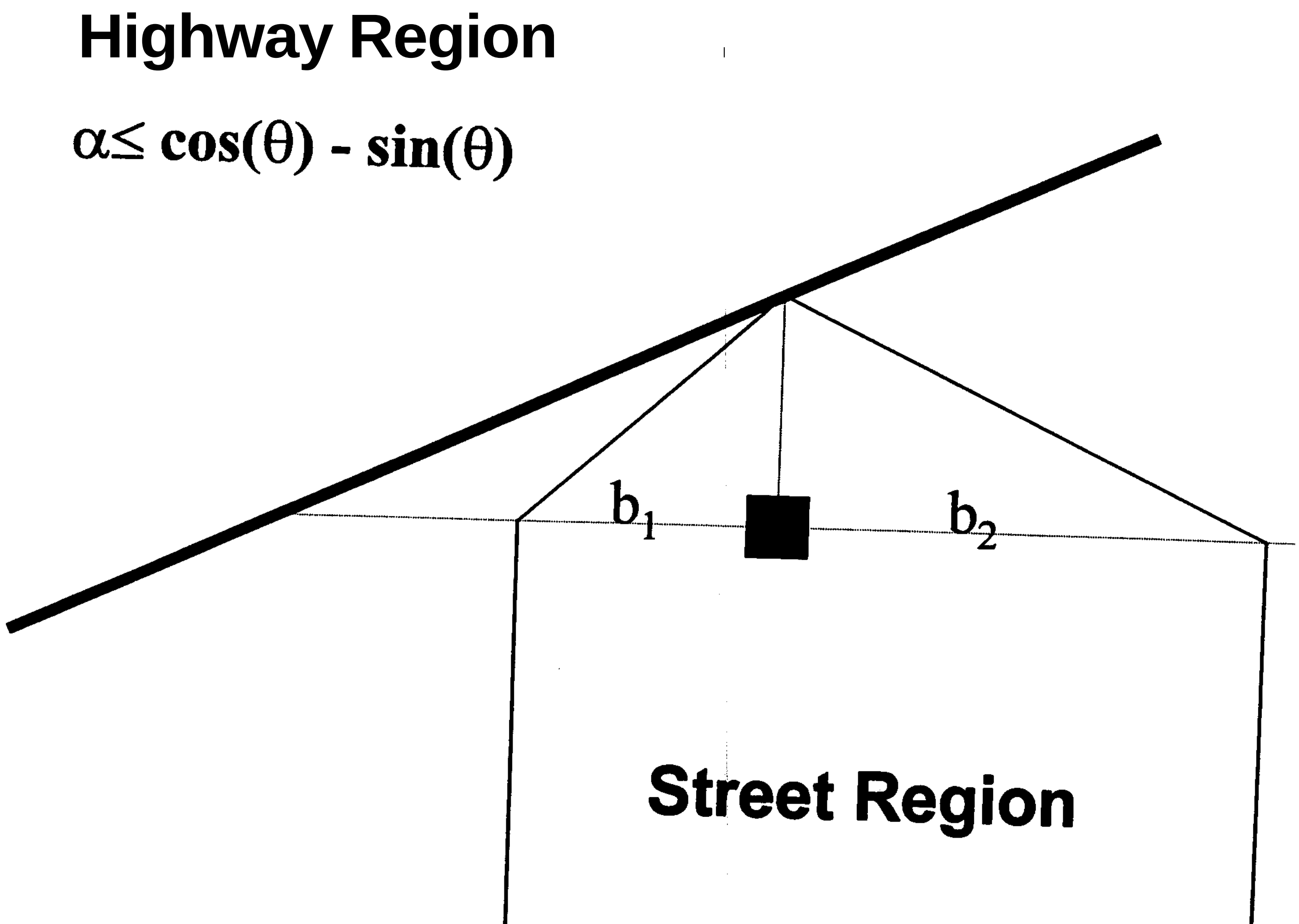


Figure 5. Street and Highway Regions, $a \leq \cos(\theta)-\sin(\theta)$

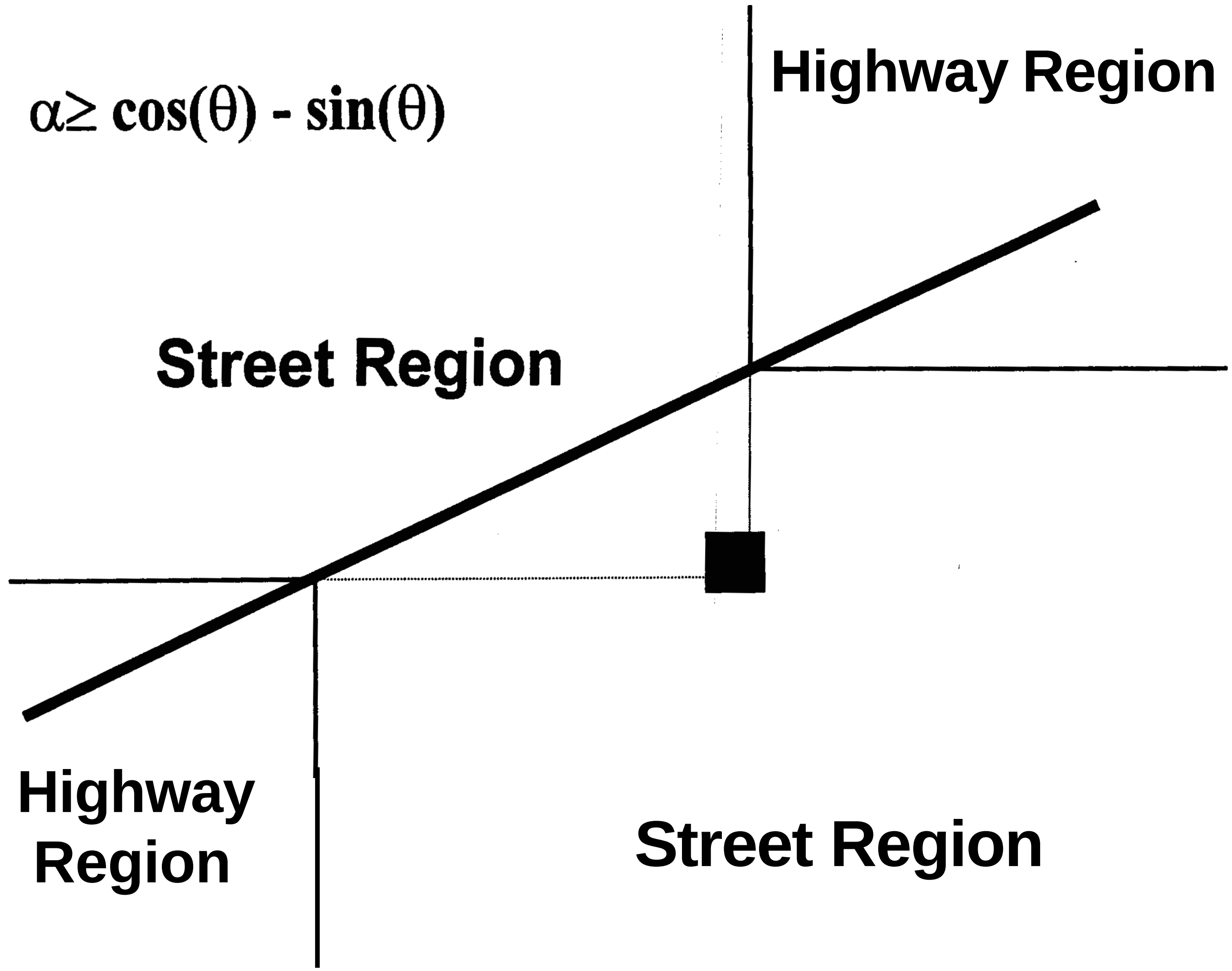


Figure **6.** Street and Highway Regions, $a \geq \cos(\theta)-\sin(\theta)$

equaling $2x/(1-a)$. In the limit as a approaches $\cos(\theta) - \sin(\theta)$, b_2 increases without bound, and b_1 approaches $x/\tan(\theta)$ (situated exactly on the highway).

As a measure of the attractiveness of street routes, the width of the vertical portion of the street region ($|b_1| + b_2$) is plotted in Figure **7** as a ratio to **x,** illustrating these points.

Case **2:** $a > \cos(\theta) - \sin(\theta)$

In this case, **as** shown in Figure ***6,*** the street region occupies two entire quadrants of the plane, plus additional sections defined by the tilt in the highway. **Thus** even destinations that are very **far** away, or on the opposite side of the highway, are better served entirely by streets, as the added circuity in highway access is too large to justify the available travel time savings.

Comparing Sections

Returning to the sections in Figure **4,** Table **2** summarizes the cases where the highway provides the shortest time route. For sections **A, C,** F and H, the highway is always utilized for a portion of the trip, keeping to the assumption that $a \leq 1$. The highway is used in Section **B** if $a \leq \cos(\theta) - \sin(\theta)$. In sections D, E, G and I, the highway is used if the destination falls outside the street region of Case 1 (it is never used **for** Case 2), as indicated by the equations provided.

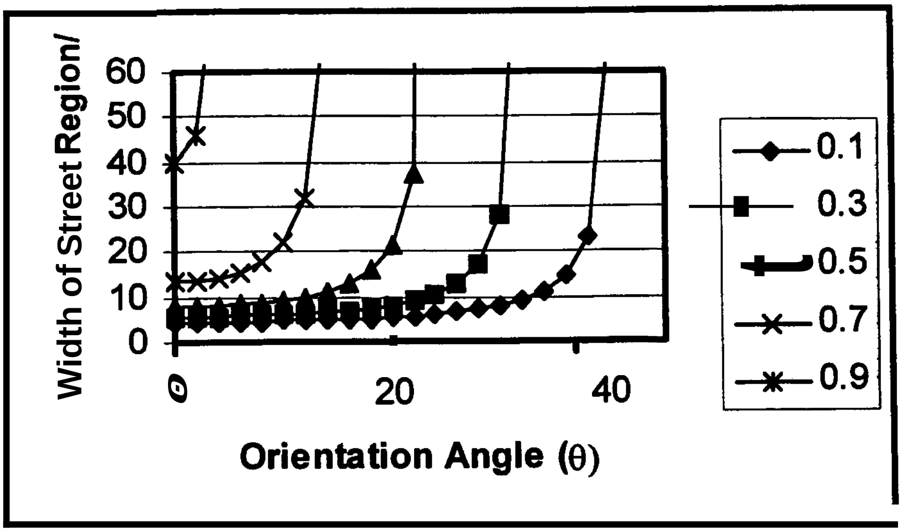


Figure 7. Width of Street Region/x; $\alpha \leq \cos(\theta) - \sin(\theta)$

Ramp Placement

In reality, highway access and egress can only occur at distinct points defined by highway ramps. The spacing between these ramps affects travel time and route choice, as infiequent ramps necessitate more street mileage and greater trip circuity, making highway paths less desirable. In the limit, as the spacing between ramps approaches zero, travel time and optimal routes are identical to those in the prior sections. But when ramps are infiequent, travelers will be affected in the following ways:

1) Travelers will enter/exit the highway at different locations
2) The average distance traveled on streets to/from highway ramps will increase.
3) More travelers will find it advantageous to complete their trip entirely on streets.

Without loss in generality, suppose that a highway passes through the point (0,0). Further suppose that highway ramps are sequentially number from 1 to n, with coordinates $(0,0),(x_2,y_2),\ldots,(x_n,y_n)$ (Figure **8)**. Lastly, let (v_x,v_y) represent the coordinates of the vertical projection of the origin onto the highway (Figure ***6)*** **and** (h_x,h_y) represent coordinates of the horizontal projection.

Theorem: An optimal (i.e., shortest time) path can be found from the street-only path along with highway paths that include the following four alternative ramps for entering the highway:

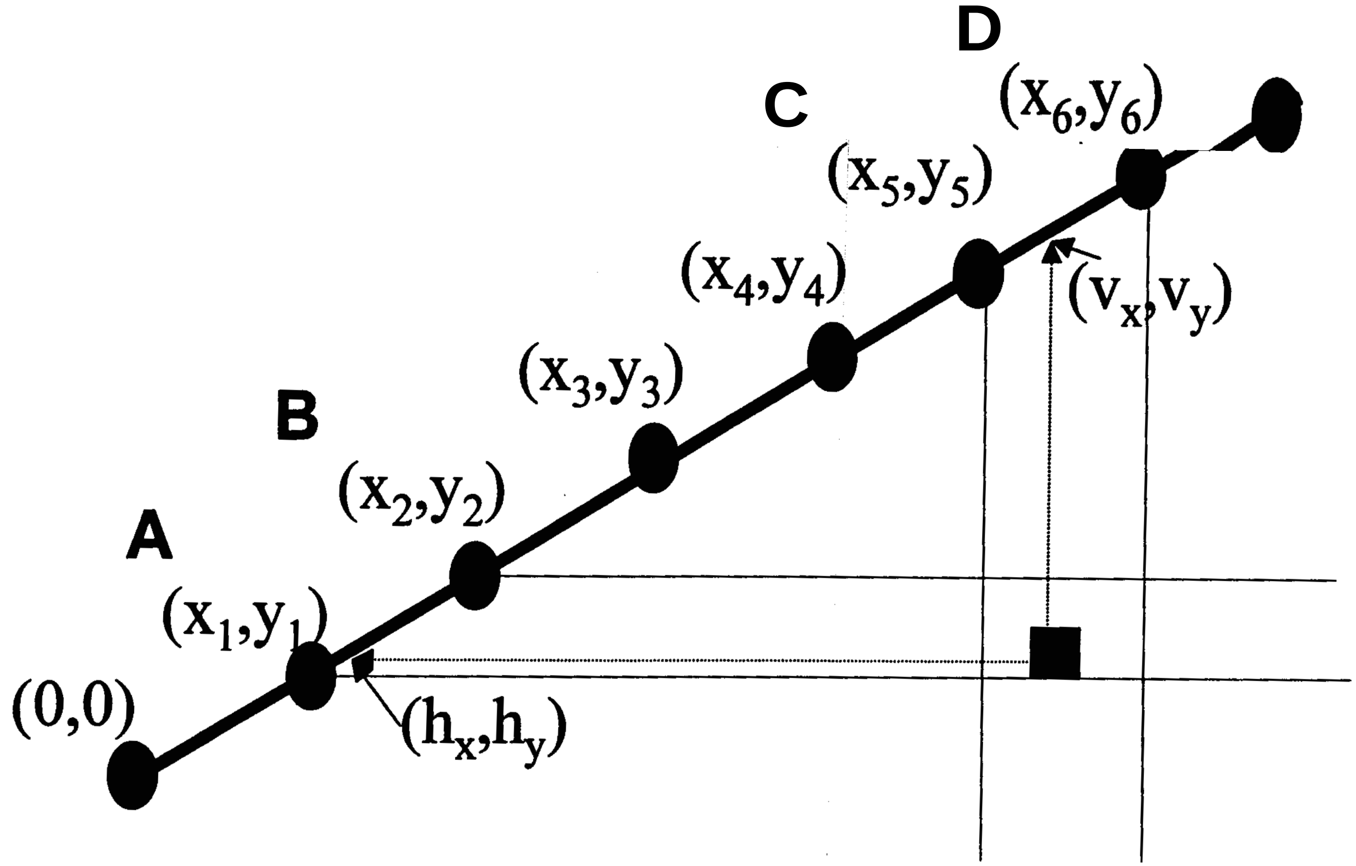


Figure 8. Location of Highway Ramps

A. max $\{(x_n, y_n) \mid y_n \leq h_y\}$, designated as (x_A, y_A) (5a)

B. min $\{(x_n, y_n) \mid y_n \geq h_y\}$, designated as (x_B, y_B) (5b)

C. max $\{(x_n, y_n) \mid x_n \leq v_y\}$, designated as (x_C, y_C) (5c)

D. min $\{(x_n, y_n) \mid x_n \geq v_y\}$, designated as (x_D, y_D) (5d)

We call these the set of candidate ramps for highway entry.

Proof. Consider three possible contradictions to the theorem: (1) The highway is accessed at a ramp with lower number than ramp A, **(2)** The highway is accessed at a ramp with number between ramp B and ramp C, and **(3)** The highway is accessed at a ramp with number higher than ramp D. ***(No*** ramps exist between **A** and B or **C** and D, **so** these three cases are exhaustive.)

As shown in Figure **9,** Case (1) is clearly non-optimal, at it substitutes street travel for a shorter route by the faster highway. Similarly, Case **(3)** is also non-optimal, as it also substitutes a longer street route for a shorter highway route.

For case (2), consider the example in Figure 10. Suppose that the freeway can be entered at any point between ramps B and C, and that the position of the entrance point is designated $\{x_B+m, y_B+m\tan(\theta)\}$ (m is the horizontal separation between ramp B and the intermediate point). Potentially, this entrance point could be used to travel to the left on the highway or to the right. However, it is clearly non-optimal to travel to the right, as the path would entail backtracking (i.e., greater street mileage than alternative paths without a commensurate reduction in highway mileage).

If travel occurs to the left of the intermediate entrance point, the exit can be between B and the intermediate point, or to the left of B. Suppose first that the destination falls between B and the intermediate entrance point. In this case the entrance

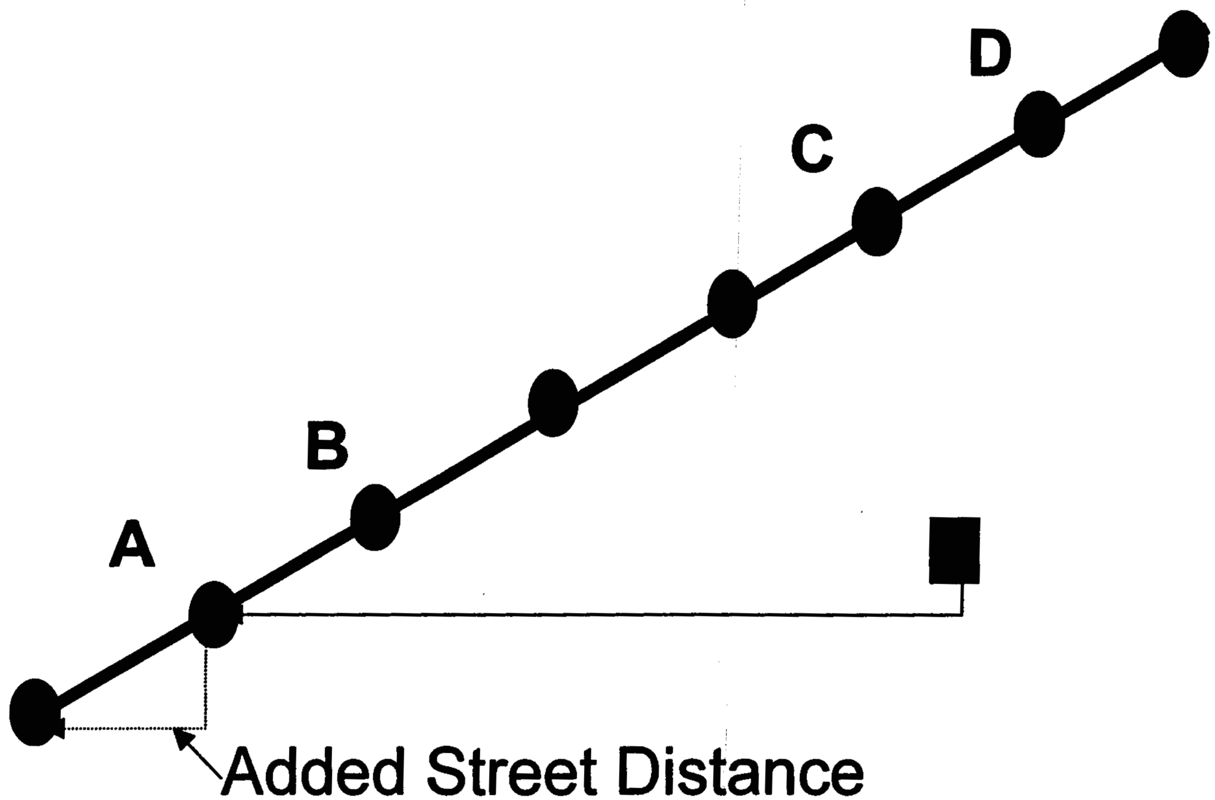


Figure 9. Entrance Ramps Beyond A are Inferior

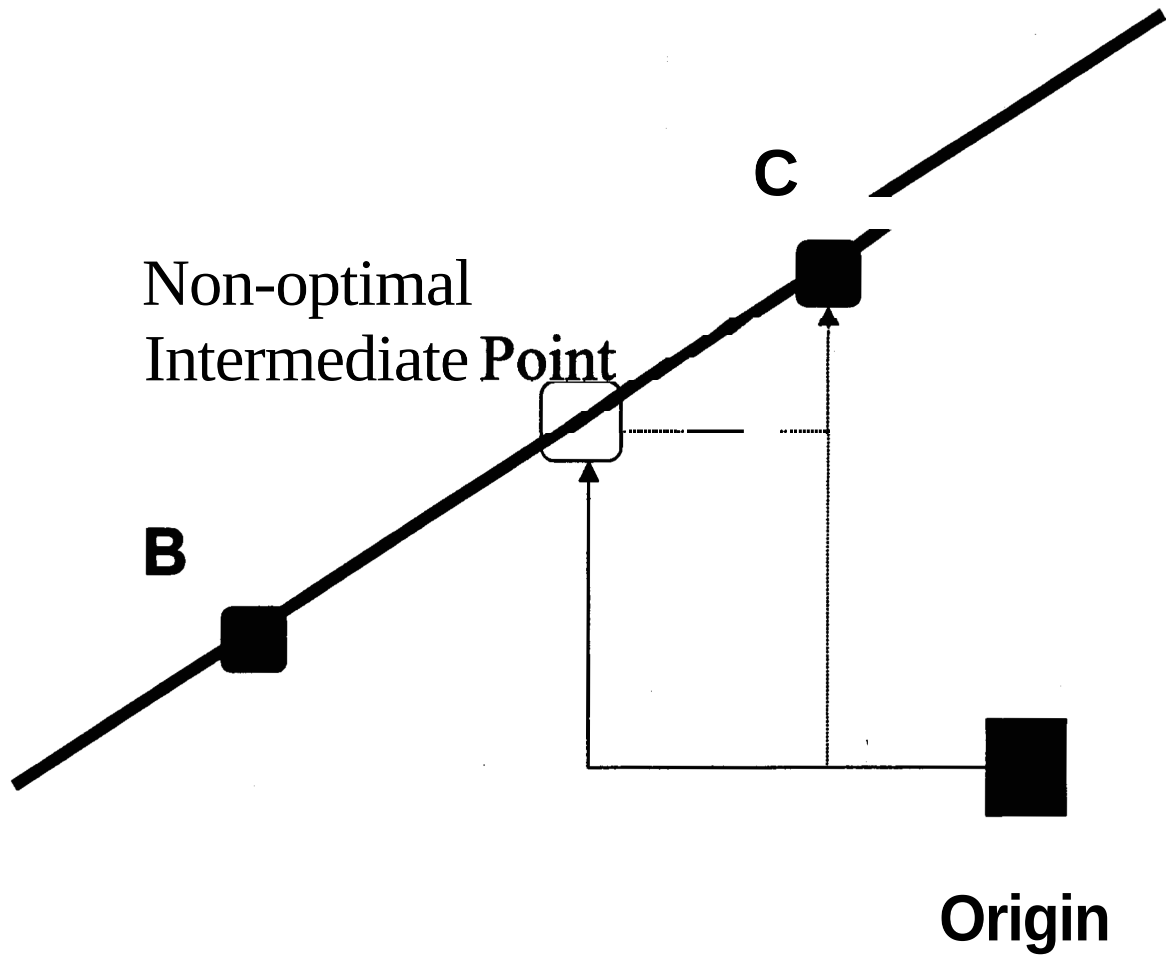


Figure 10. Entrance **Ramps** Between B and *C* are Inferior

point will still be non-optimal. When $a > \cos(\theta) - \sin(\theta)$, any point on the highway between **B** and **C** falls in the street region, making a street only route preferable. When $a \leq \cos(\theta) - \sin(\theta)$, any point on the highway between **B** and **C** can be reached in shorter (or equal) time by accessing the highway at ramp C. Thus, in either case an alternative path is no worse than using the intermediate point.

Finally, consider a highway exit to the left of point **B,** again for case **(2).** Then total travel time is the following function of m:

$$T(m) = k + (x_C - x_B - m) + m\tan(\theta) + \alpha m/\cos(\theta) \quad (6)$$

Where **k** is a constant representing the time traveled from ramp **B** to the destination. **Eq. 6** can be optimized by taking the derivative of T(m) with respect to m:

$$dT(m)/dm = -1 + \tan(\theta) + \alpha/\cos(\theta) \quad (7)$$

The derivative is a constant, meaning that T(m) is optimized at an extreme point, either ramp **B** or ramp **C.** Hence, no ramp located between **B** and **C** can be preferred to the better of **B** or **C,** when the exit ramp is to the left of ramp **B.** This completes case (2), thus proving that no entrance ramp can be better than the best of **A,B,C** or **D.**

The value of the derivative in **Eq. 7** also determines whether ramp **C** is preferred to ramp D, or vice versa:

Ramp **C** is Preferred to D if $a > \cos(\theta) - \sin(\theta)$ **(8a)**

Ramp D is Preferred to **C if** $a < \cos(\theta) - \sin(\theta)$ **(8b)**

The similarity of Eq. **8** to the cases defined by Equation 2. Specifically, when ***a*** is large (i.e., freeway is relatively slow) or when 8 is large (highway orientation has large angular displacement relative to the street system), then entry at ramp B is preferred **for** destinations to the left of B, increasing travel on horizontal streets with a reduction in total trip length. For smaller values of ***a*** and 8, ramp C is preferred for destinations to the left of B, with an increase in trip length, and the benefit of increasing the proportion of miles traveled by highway.

Though this section has addressed trip origins only, symmetry dictates that the same rules apply to trip destinations. Hence, there are at most **4** entrance ramps to consider and at most **4** exit ramps, producing no more than 16 distinct highway routes. When the origin and destination are close to the highway, the number of candidate entrance ramps and exit ramps reduces to two each, producing no more than **4** distinct highway routes (even less if origin and destination are close to each other).

Selecting Among the Four Candidate Ramps

The optimal entrance ramp among the four candidates (A,B,C and **D)** depends on the ultimate destination, along with ***a*** and 8. From the calculations in the prior section, it is relatively simple to construct “drawing regions”, representing the set of origin locations that would utilize each ramp. These regions depend on the ultimate destination. Examples are shown in Figure 11, representing the cases $\boldsymbol{a} < \cos(\theta) - \sin(\theta)$ and $\boldsymbol{a} > \cos(\theta) - \sin(\theta)$, and for destinations to the far left of the origin. **As** noted in earlier sections, street-only routes are also preferred for some nearby destinations.

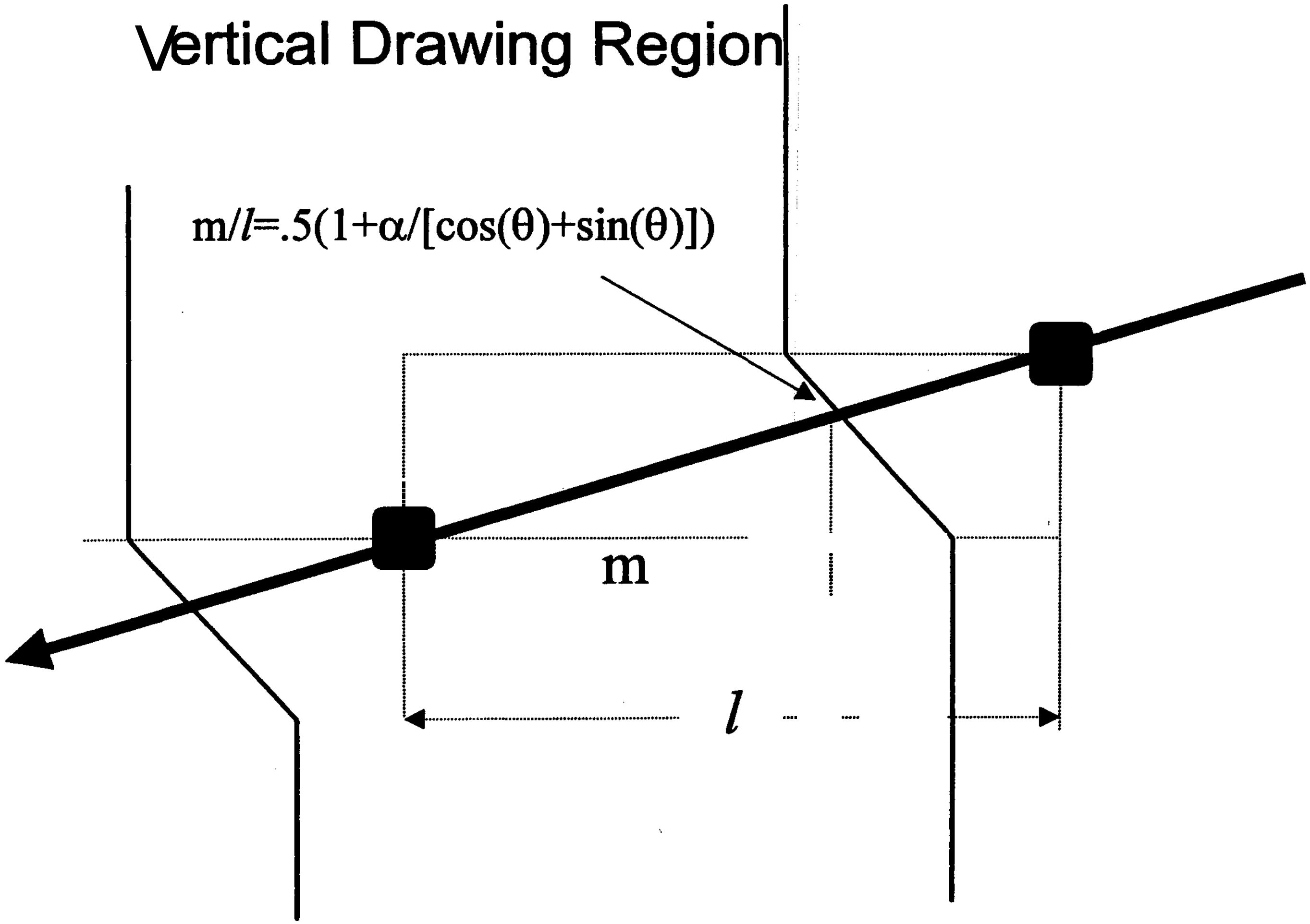


Figure 11. Drawing Region for Ramp, $\alpha \leq \cos(\theta)-\sin(\theta)$

For the case $a < \cos(\theta) - \sin(\theta)$, the drawing region is oriented vertically relative to the highway, and street travel is predominantly in the vertical direction. For the latter, the drawing region takes an L shape, with vertical travel dominant for origins above the highway and horizontal travel dominant for origins below the highway.

Travel time is identical for all points on the boundary (iso-time) line with respect to a pair of adjacent ramps. The iso-time line crosses the highway at a point satisfying:

$$m(1 + \tan(\theta)) = (l\text{-}m)(1 + \tan(\theta)) + \alpha l/\cos(\theta) \qquad (9)$$

where l is the horizontal separation between adjacent ramps. The left-side of Eq. 9 represents travel time via the left ramp and the right-side represents travel time via the right ramp (minus a constant on both sides, representing travel time beyond the left ramp). Equation 9 can be reduced to:

$$m/l = (1/2)(1 + \alpha/[\cos(\theta)+\sin(\theta)]) \quad , \qquad (10)$$

It can be noted that for very fast highways (a close to zero), the iso-time line intersects the highway midway between the terminals. In another extreme, when $\theta = 45°$ and a = 1, the intersection is moved to the right at $m/l = .853$. And in still another extreme, when $\theta = 0°$ and a = 1, the intersection moves all the way to $m/l = 1$. It can be further concluded that when the highway is rotated ($\theta > 0°$), it is still used when its speed is no faster than city streets, because route length can be shortened by using the highway. When the highway is not rotated, it offers no advantage over streets if a = 1.

A circuity penalty is easily calculated as a fbnction of the separation between adjacent ramps. This penalty represents the added travel time, relative to the alternative of continuous entry points along the highway. The penalty is naturally a linear fbnction of the ramp spacing. The worst-case penalty occurs along the iso-time line at the point of intersection with the highway. Figure 12 shows that the worst-case penalty (represented as a ratio to the ramp spacing) increases as 8 increases, though at declining rate; the penalty decreases as α increases. Thus, frequent ramp spacing is most important for large orientation angles and fast highway speeds.

The iso-time line as a whole consists of a diagonal segment (45° angle), and horizontal and vertical segments, which terminate at the rectangle enclosing the pair of adjacent terminals. The pattern is similar for trip destinations to the right of the origin. It should also be noted that symmetry exists for orientation angles greater than 45°. That is, the patterns are identical to those shown, with the exception that horizontal and vertical axes are exchanged (e.g., an orientation of 50° relative to the horizontal axis is equivalent to a 40" orientation relative to the vertical axis).

Multiple Roadway Systems

We now generalize results from the prior section to a system of parallel highways, which intersect a rectangular street grid system. We assume that highway interchanges are equally spaced, with unit distance separation, and highways are also equally spaced from each other. Streets are equally spaced as well, though spacing in the vertical dimension can be different from spacing in the horizontal dimension. Last, we assume that streets are aligned such that highway interchanges coincide with the intersection of a horizontal street with a vertical street, and interchanges are vertically aligned on parallel highways. The system is further defined by 8, *a* and the following parameters:

s_h = distance separating highways in the vertical dimension

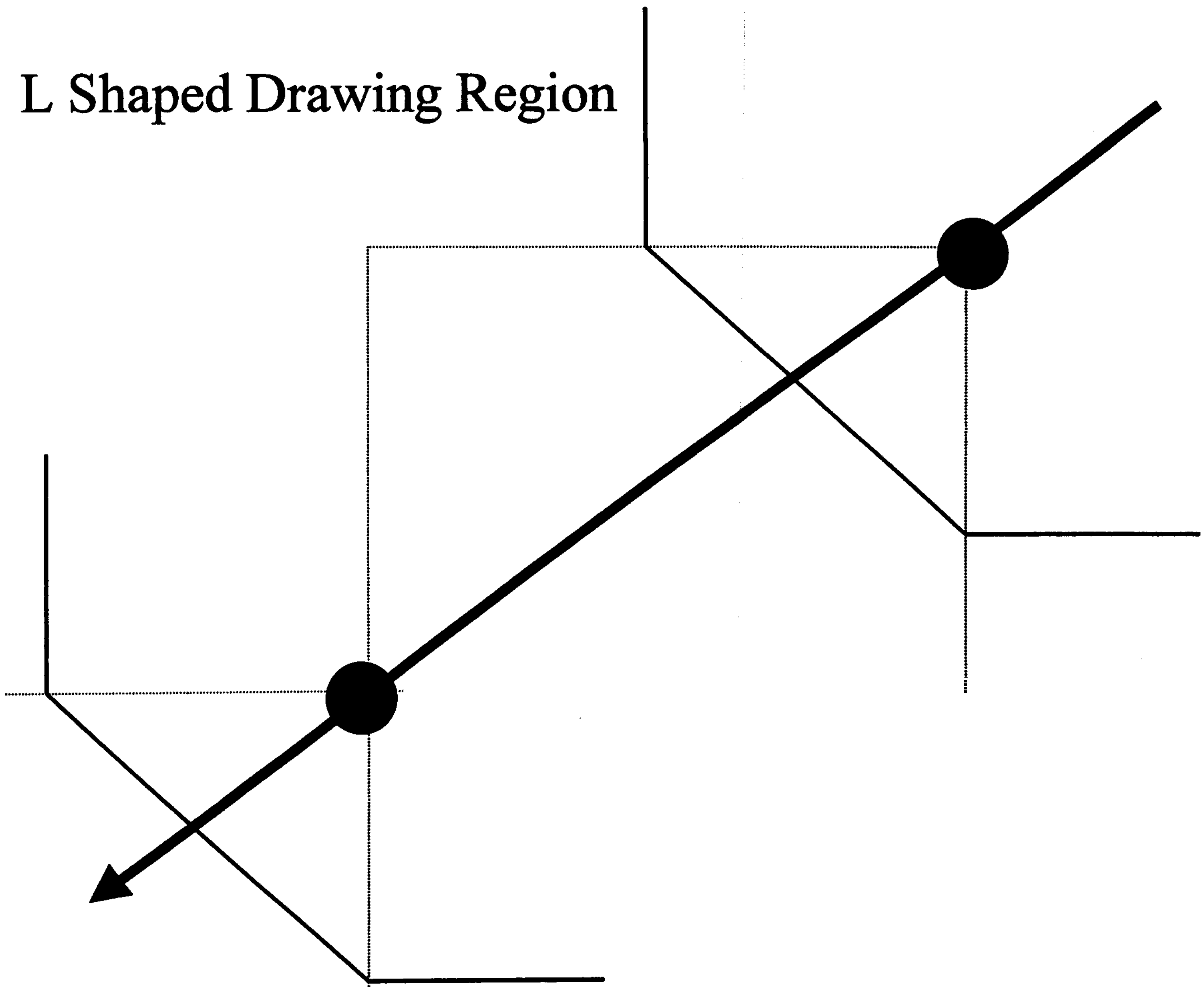


Figure 12. Drawing Region for Ramp, $\alpha \geq \cos(\theta)-\sin(\theta)$

γ = number of major blocks per unit distance (e.g., distance separating arterials)

It should be noted that this model differs from the prior section in the following respects: (1) vehicle paths are restricted to following streets at discrete locations (defined by blocks), rather than following a pure rectilinear path, and **(2)** multiple highways are available. Because of the added complexity, the system is modeled through simulation, as a function of the listed parameters. In addition, within the simulation, trip pairings (origiddestination) are randomly generated in a three step process, first generating an origin location, second generating a distance fiom origin to destination and third generating an angular displacement of the destination relative to the origin (thus defining the destination's coordinates).

Origins are randomly selected according to a uniform distribution, making all locations between highways and interchanges equally likely. The distance fiom origin to destination is generated according to the exponential distribution, with mean ä, reflecting the non-uniform distribution of actual trip lengths. The angular displacement of the destination is simulated according to a uniform distribution over [0,360°]. It should be noted that these assumptions tend to underestimate highway usage, as trip origins and destinations in reality tend to concentrate in the vicinity of interchanges.

To create individual simulation experiments, the parameters are set to equal a "base case", and are then varied around the base case to measure sensitivities. The base case follows:

$\mathbf{a} = 4.9$, $s_h = 3.9$, $\theta = \mathbf{11.3°}$, $\alpha = .333$ (free-flow), $\mathbf{y} = 5.1$

This case could represent highway systems with the following features: **(1)** ramp spacing of **2** miles, **(2)** average trip length **of 9.8** miles, **(3)** highway spacing of **7.8** miles, **(4)** moderate rotation of street grid relative to highway, ***(5)*** freeway speed of **60** miles per hour combined with street speed of **20** miles per hour, and **(6)** arterials spaced **.4** miles apart. These parameters are somewhat representative of grid-oriented highway systems in the United States under free-flow conditions. Non-integer values are used for some distances to align interchanges are with vertical and horizontal streets.

We also consider the following variations in parameter values, relative to the base case:

$a = 1,2,2.9,3.9,4.9,5.9,9.8$

$s_h = 2.0,3.9,5.9$

$\theta = 11.3°,21.8°,30.9°,38.7°$

$a = .2,.25, .333,.5,.667$

The analysis produces estimates of freeway "benefits", which represent reductions in travel time, and reductions in street traffic, that occur as the consequence of highways. We define these measures as follows:

$$e_t = \frac{\text{average travel time by fastest path}}{\text{average travel time by street path}}$$

$$e_x = \frac{\text{average vehicle miles by streets in x dimension, permitting highways}}{\text{average vehicle miles by streets in x dimension without highways}}$$

$$e_y = \frac{\text{average vehicle miles by streets in y dimension, permitting highways}}{\text{average vehicle miles by streets in y dimension without highways}}$$

Results are provided in Table **3,** which can be summarized as follows:

- Increased trip length leads to greater overall efficiency. For long trips in particular, highways substantially reduce trip length in the x direction (direction most aligned with the highway), but have little effect on travel in the y direction.
- Increased highway spacing causes average travel time to increase, with increased travel in both x and y directions. Counter-intuitively, travel increases the most in the x direction.
- Increased angle **of** rotation causes travel time to increase. Travel in the x direction exhibits a discontinunity, with a large jump when $a > \cos(\theta) - \sin(\theta)$ (simultaneously, travel in the y direction decreases. This trend is consistent with earlier findings, which showed that the street-only region enlarges substantially when $a > \cos(\theta) - \sin(\theta)$.
- Decreased highway speed causes travel time to increase, with increased travel in the x direction. Travel in the y direction is only slightly affected, and can either increase or decrease.

It should be noted here that in reality trip origins and destinations tend to cluster around highway interchanges, thus leading to greater highway usage than these simulation results predict.

Table 3. Average System Efficiency As Function of Parameter Values

	Uniform/Exponential		
	e_t	e_x	e_y
ä			
1.0	0.96	0.85	1.03
2.0	0.89	0.54	1.07
2.9	0.83	0.34	1.05
3.9	0.82	0.32	1.07
4.9	0.80	0.25	1.09
5.9	0.76	0.20	1.05
9.8	0.74	0.14	1.02
$\underline{s_h}$			
2.0	0.76	0.18	0.99
3.9	0.79	0.25	1.09
5.9	0.82	0.30	1.09
$\underline{\theta}$			
11.3	0.79	0.25	1.09
21.8	0.82	0.26	1.23
30.9	0.88	0.26	1.21
38.7	0.88	0.75	0.89
$\underline{\alpha}$			
0.2	0.74	0.23	1.06
0.25	0.75	0.24	1.13
0.333	0.79	0.25	1.09
0.5	0.88	0.36	1.09
0.667	0.91	0.38	1.02

Basecaseparameters: ä = 4.9, s_h = 3.9, θ = 11.3, α = .3333, γ = 5.1

4. LAND USE ISSUES

Surrounding land uses constrain AHS design in two ways: (1) they may limit the amount of space available to construct the AHS, and (2) once the AHS is in operation, they may limit the modes of operation. Though the mainline portion of an AHS is envisioned to be space efficient, land requirements are significantly greater at interfaces, due to the requirements of inspection, buffering, acceleration/deceleration, and extra ramps needed to inter-connect various roadways. The project is concerned with the availability of land in the vicinity of interchanges, the ability of streets to absorb traffic in the vicinity of interchanges, and the challenges in acquiring land in the vicinity of interchanges.

In this project, a series of case studies are being developed to analyze the effects of interchange construction around real highways. The work is focusing on a set of highways that were analyzed in the project "Automated Highway System Field Operational Tests for the State of California: Potential Sites, Configurations and Characteristics" (Hall et al, 1997), and within the Precursor Systems Analysis program (Hall, 1995). These highways were selected because they fall in urbanized areas, where land is less plentiful due to surrounding development. For the same reason, these highways may offer the greatest potentia1 benefits for AHS, due to the presence of highway congestion. The specific highways being investigated follow:

- Interstate 5: area south of Downtown Los Angeles
- Interstate 80: from Downtown San Francisco east through Alameda County
- Interstate 105: in Los Angeles, connecting to Los Angeles International Airport

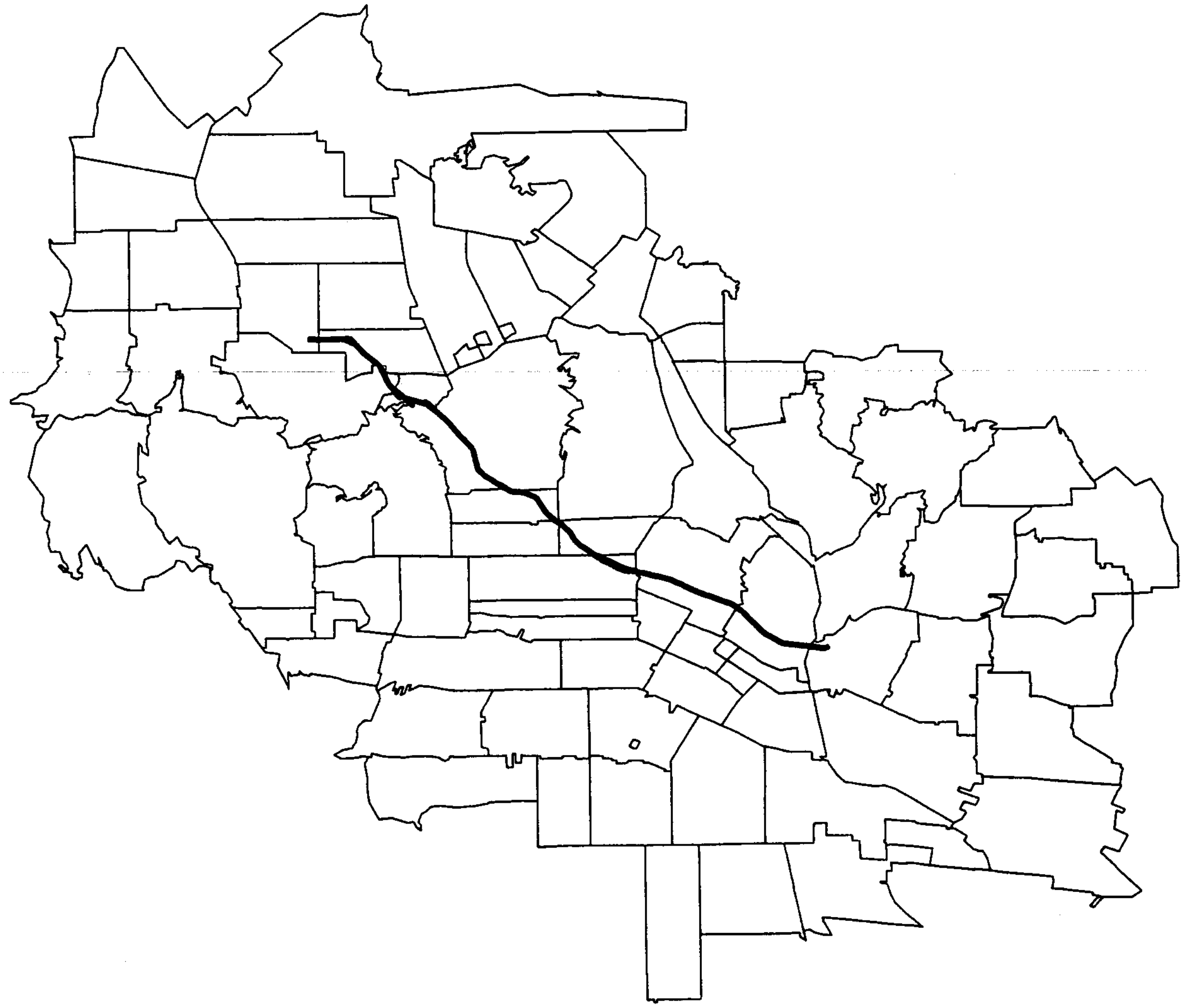
- US 101: from Downtown Los Angeles north through San Fernando Valley
- US 101/I280: from San Francisco International Airport north to Downtown San Francisco

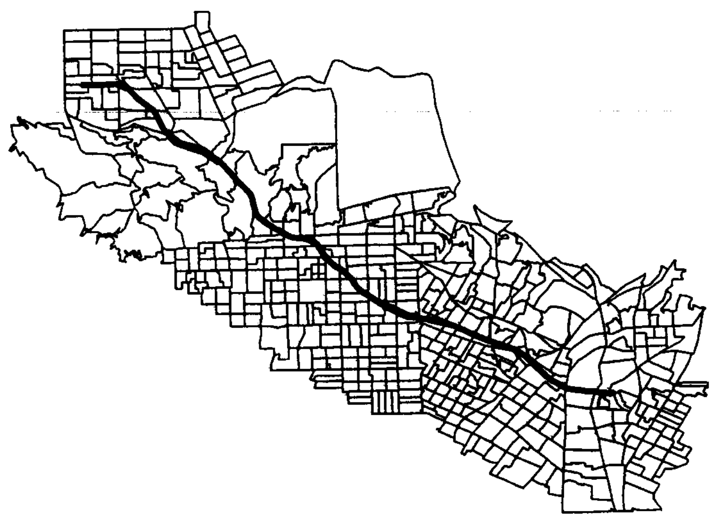
To support our analyses, geographic-information-system (GIS) data-sets were obtained for highway corridors, running approximately ½ mile to each side of each highway. Data include: (1) digital street maps, (2) employment and retailing data (based on zip codes), and (3) census data/populations statistics (based on census block groups). Examples of the data are provided in Figures 13-15 and Tables 4-5, for the US 101 corridor.

In the future, we will be evaluating the characteristics of neighborhoods in the vicinity of highways, and in the vicinity of highway interchanges, utilizing the GIS datasets. This work is scheduled to take place in Phase 2 of the project, which is underway.

5. SUMMARY AND FUTURE RESEARCH

The economics of roadways, and their variability in demand, favor construction of multi-layered and inter-connected networks. Different network layers are designed to different standards and to perform somewhat different functions, though all provide the common function of mobility for a reasonably homogeneous class of vehicles. Yet interfaces have been constructed to provide a smooth transition between network layers, with little delay and inconvenience to travelers.





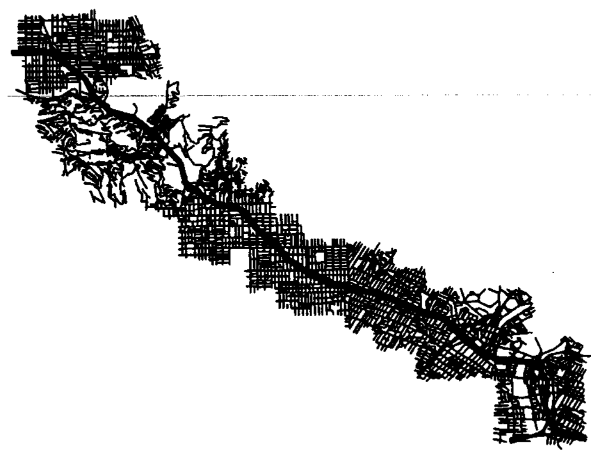


Table 4. Example Census Block Group Data Taken from GIS

Shape	Area	Zip	Po_name	State	Samblkpop	[illegible]	[illegible]	[illegible]	[illegible]
Polygon	3.55	90001	Los Angeles	CA	51845	52763	07–	90001	07–
Polygon	3.45	90003	Los Angeles	CA	53938	56056	15–	90003	15–
Polygon	3.11	90004	Los Angeles	CA	64062	67310	15–	90004	15–
Polygon	1.51	90005	Los Angeles	CA	40638	42368	15–	90005	15–
Polygon	1.89	90006	Los Angeles	CA	63389	66214	20–	90006	20–
Polygon	2.70	90007	Los Angeles	CA	47029	49366	15–	90007	15–
Polygon	3.76	90008	Los Angeles	CA	33331	33348	15–	90008	15–
Polygon	4.37	90011	Los Angeles	CA	96074	97101	20–	90011	20–
Polygon	3.74	90012	Los Angeles	CA	28780	33726	20–	90012	20–
Polygon	0.63	90013	Los Angeles	CA	5416	5404	20–	90013	20–
Polygon	0.29	90014	Los Angeles	CA	2590	2626	40–	90014	40–

Tot_estb	Emp1_4	Emp5_9	Emp10_19	Emp20_49	Emp50_99	E100_249	E250_499	E500_999	[illegible]
1	0	1	0	0	0	0	0	0	0
15	9	1	4	0	1	0	0	0	0
41	31	3	4	1	0	2	0	0	0
11	8	2	1	0	0	0	0	0	0
38	19	6	4	5	3	1	0	0	0
14	7	2	4	1	0	0	0	0	0
12	9	2	1	0	0	0	0	0	0
197	56	23	39	44	20	12	2	1	0
108	33	10	24	28	8	5	0	0	0
74	31	10	7	16	8	0	2	0	0
25	12	5	3	3	1	0	1	0	0

Table 5. Example Economic Zip Code Data Taken from GIS

Shape	[illegible]	Bkgkey	Pop1990	Pop90_sqmi	Households	Males	Females	[illegible]
Polygon	0.11683	060373112001	1280	10956.1	620	643	637	1150
Polygon	0.11646	060373112003	814	6989.5	283	432	382	686
Polygon	0.15350	060371253001	1543	10052.1	540	749	794	1083
Polygon	0.12613	060371253003	377	2989.0	125	201	176	188
Polygon	0.14101	060371253004	1438	10197.9	469	750	688	669
Polygon	0.12061	060371252001	1359	11267.7	617	758	601	748
Polygon	0.12087	060371251001	1351	11177.3	731	672	679	1086
Polygon	0.06600	060373112002	365	5530.3	166	157	208	329
Polygon	0.09571	060373115004	545	5694.3	237	265	280	484
Polygon	0.29082	060371252002	1055	3627.7	535	464	591	882
Polygon	0.19391	060371251002	2806	14470.6	1572	1389	1417	2371
Polygon	0.12366	060371253002	2683	21696.6	924	1333	1350	959
Polygon	0.11068	060371253005	542	4897.0	291	271	271	370
Polygon	0.18810	060373114001	1083	5757.6	467	506	577	943
Polygon	0.09347	060373114003	584	6248.0	227	321	263	521

[illegible]	[illegible]	Asian_pi	Other	Hispanic	Age_under	Age_5_17	Age_18_29	Age_30_49	[illegible]
11	7	26	86	250	62	156	298	419	165
4	12	55	57	148	53	159	170	273	86
0	0	171	289	587	90	240	262	538	162
0	16	0	173	220	7	83	102	99	45
22	36	0	711	1111	158	260	408	493	51
106	0	72	433	573	88	201	373	514	94
97	0	58	110	232	42	119	374	434	158
4	0	32	0	0	36	52	33	114	35
8	0	0	53	179	40	78	70	236	56
31	0	75	67	177	62	86	183	442	119
154	34	134	113	382	96	186	705	1187	318
299	16	67	1342	1555	340	570	797	824	67
12	0	0	160	266	33	27	141	96	20
0	0	58	82	167	79	178	116	432	102
42	0	0	21	39	40	64	69	244	89

[illegible]	Nevermarr	Married	Separated	Widowed	Divorced	Hshld_1_m	Hshld_1_f	[illegible]	[illegible]
180	355	477	9	83	147	9	42	30	190
73	192	307	7	20	114	0	19	19	131
251	323	674	9	99	155	4	31	51	284
41	145	87	8	27	36	0	7	4	37
68	414	395	26	24	160	39	15	27	177
89	470	354	53	49	166	43	6	15	160
224	496	398	33	71	210	9	11	5	197
95	21	175	0	54	27	0	10	4	82
65	90	253	10	44	34	10	0	33	92
163	357	422	10	82	54	10	29	7	188
314	1149	796	31	179	388	32	97	47	355
85	926	629	102	50	104	81	137	25	288
225	163	84	46	119	47	37	0	0	39
176	264	407	0	79	113	6	30	12	193
78	144	261	8	30	25	5	22	26	102

Roadway interfaces consist of four components: (1) infrastructure (i.e., physical) interfaces, (2) vehicular interface, (3) operational interface, and (4) managerial interface. Automated vehicles present special challenges for all four components. Unlike conventional vehicles, they must undergo a fundamental change in their mode of operation at the interface. Special infrastructure facilities will be needed to support this mode change. Changes in vehicle operation must also occur under automation. Lastly, the personnel requirements for managing an automated highway are quite different than conventional roadways, likely necessitating a different managerial structure.

The interface design can be described along seven dimensions, which form a type of hierarchy: (1) automation concept, (2) roadway layering, (3) capacity, (4) interface concept, (5) interchange separation and placement, (6) buffer sizing, and (7) flow control. The automation concept, roadway layering, and design capacity impose requirements on the interface, which must be satisfied to ensure that vehicles are properly prepared before entering the highway. These in turn affect the requirement for interchange separation, along with the provision of buffers to accommodate flow fluctuations as well as real-time strategies for controlling flows entering and leaving the AHS.

One of the strategic issues in interface design – interchange separation -- was examined in this paper. Access, and usage, of the AHS (or highway) depend on this spacing, along with the speed of the highway and the orientation of the highway relative to local streets. Slower highway speeds (relative to street speeds) cause vehicles to travel longer distances to reach the highway, and cause more vehicles to bypass the highway completely. A consequence is increased traffic on streets, especially on those that are more horizontally oriented relative to the highway.

Future research will examine highway orientation and interchange separation in greater depth through computer simulations of more detailed scenarios. In addition, models will be developed for determination of capacity requirements for the interface, lateral streets, critical intersections and transitional streets. Future research will explore specific case studies, including visits to sites for potential AHS roadways.

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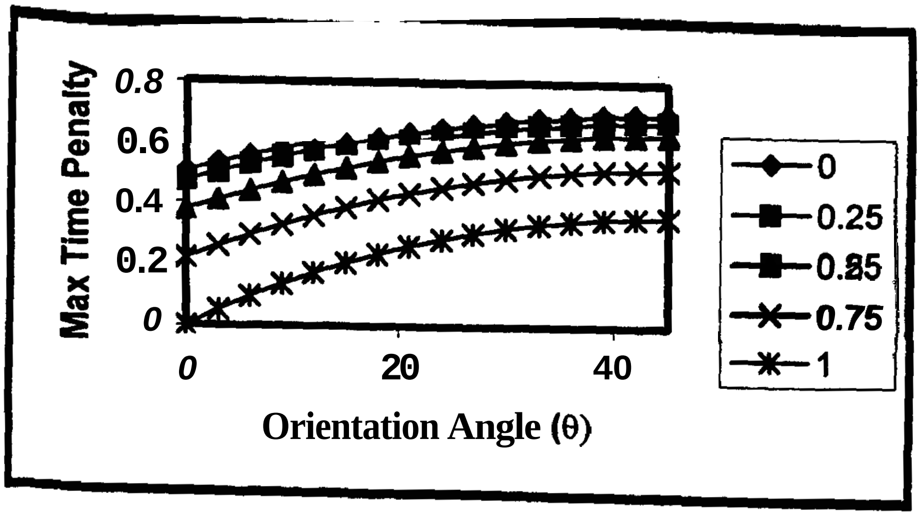

Figure 13. Maximum Time Penalty Due to Ramp Spacing