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The Automated Highway System/Street Interface: Final Report

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University of Southern California

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The Automated Highway System/Street Interface

Final Report

February 3, 2003

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TABLE OF CONTENTS

Abstract iv
Executive Summary v
1. Introduction....................1
2. Placement of Access Points and Highway Spacing 5
3. Traffic Control to Facilitate Entrance and Exit....................15
4. Physical Design for AHS Entrance/Exit 41
5. References 61
Appendix A Site Photographs....................63
Appendix B. Maps And Interchange Designs....................73

LIST OF FIGURES

1. Travel Distances as Function of Highway Orientation....................6
2. Alternative Access to Highway....................6
3. Destination Regions; Regions Correspond to Time Equations 8
4. Highway and Street Regions, Street Speed Small....................8
5. Highway and Street Regions, Street Speed Large 9
6. Drawing Region for Ramp, $\alpha < \cos(\theta) - \sin(\theta)$....................11
7. Drawing Region for Ramp, $\alpha > \cos(\theta) - \sin(\theta)$....................11
8. Worst-case Time Penalty....................12
9. Multi-State Sorting, First Grouped 1-2-3, Then into Subgroups 18
10. Average Waiting Time Versus Number of Lanes....................21
11. Platoon Ratio Versus Number of Lanes, Exponential Trip Length....................21
12. Highway Throughput Versus Number of Lanes 22
13. Green Zone and Red Zone for Lane Changing 23
14. Destination Range Changes at Each Exit (Rule 1)....................24
15. Each Lane Only has Lower Bound on Destination Range....................25
16. Vehicles Change Lane as Platoons....................25
17. Step Exiting....................27
18. Continuous Exiting....................27
19. Flowchart of Simulation....................29
20. Mean Vehicles/Slot by Location, DG1 No Sorting....................33
21. Mean Vehicles/Slot by Location, DG1 Sorting....................34
22. Mean Vehicles/Slot by Location, DG2 No Sorting....................34
23. Mean Vehicles/Slot by Location, DG2 Sorting....................34
24. Mean Vehicles/Slot by Location, DG3 No Sorting....................35
25. Mean Vehicles/Slot by Location, DG3 Sorting....................35
26. Mean Vehicles/Slot by Location, DG1 No Sorting, High Arrival 38
27. Mean Vehicles/Slot by Location, DG1 Sorting, High Arrival Rate....................39
28. Mean Vehicles/Slot by Location, DG2 No Sorting, High Arrival 39
29. Mean Vehicles/Slot by Location, DG2 Sorting, High Arrival Rate....................39
30. Mean Vehicles/Slot by Location, DG3 No Sorting, High Arrival 40

31. Mean Vehicles/Slot by Location, DG3 Sorting, High Arrival Rate.....40
32. Highway Elevations 42
33. Highway with Auxiliary Lanes...44
34. Three Options for Left Turn from Highway to Street..........................44
35. Three Designs for Right Turn from Highway to Street 45
36. Serial Entrance Concept..50
37. Parallel Entrance Concept 50
38. Moving Entrance Concept...50
39. Traffic Dispersion Around Exits..52
40. By Decreasing Exit Spacing, Traffic Concentration is Reduced 52
41. Dispersion of AHS Traffic through a Transition Road........................53
42. Traffic Distribution through Principal and Tributary Roadways.........54

LIST OF TABLES

1. Probability that Platoon Remains Intact..15
2. Summary of Simulation Characteristics...30
3. Failure Rate in Exiting, Moderate Arrival Rate 31
4. Lane Change Frequency, Moderate Arrival Rate.................................31
5. Vehicles Served at Entrances, Moderate Arrival Rate 32
6. Mean Waiting Time at Release, Moderate Arrival Rate 32
7. Mean Lane Change Time, Moving Left, Moderate Arrival Rate.........32
8. Mean Lane Change Time, Moving Right, Moderate Arrival Rate 33
9. Failure Rate in Exiting, High Arrival Rate 36
10. Lane Change Frequency, High Arrival Rate..36
11. Vehicles Served at Entrances, High Arrival Rate 36
12. Mean Waiting Time at Release, High Arrival Rate 37
13. Mean Lane Change Time, Moving Left, High Arrival Rate................37
14. Characteristics of Sites Visited 38
15. Los Angeles County Zoning Classifications..47
16. Characteristics of Sites Visited 60

ABSTRACT

This is the final report for MOU 386 and Task Order 4216, “The AHS/Street Interface, Effects of Capacity Concentration on System Performance.” The report investigates how highway design affects operational performance of automated highways with respect to accommodating entering and exiting traffic. A summary of findings is provided for prior work from PATH Working Paper 2000-26 and PATH Research Reports 2001-37 and 2002-07. These reports investigated vehicle sorting processes for highway entrances, and investigated placement and separation of entrances and exits. In addition to these summaries, this report provides analyses for vehicle sorting on highways, platoon formation on highways and physical design of entrances and exits.

Keywords: Automated Highways, Deployment, Entrance/Exit, Roadway Interfaces

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.

The report investigates two aspects of AHS entrance and exit: (1) organization of vehicles into platoons, with the objective of facilitating exits, and (2) physical design of highways to enable entrance and exit. With respect to the former, analyses were completed for sorting vehicles into platoons according to destination, first when sorting occurs at the entrance, and second when sorting also occurs on the highway. With respect to the latter, analyses were completed for the effects of entrance/exit separation, and case studies were examined for the design of entrances and exits.

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-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.

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 four 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 road at any given time, making the average vehicular occupancy well below 1%, a striking figure in light of the congestion facing many urban areas. The figure becomes even smaller if the lateral occupancy is factored in (i.e., the widths of vehicles are far less than the widths 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

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[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.

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 from the traffic stream in one layer and merge into the traffic stream of another, while preventing conflicts and collisions with crossing traffic.

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:

- An additional network layer, and concomitant access/egress points, adds strategic variables in the design of highway systems.

- Construction of physical facilities, to buffer against bursts in the traffic stream, to accommodate increased traffic volumes exiting and entering highways, and to provide inspection as vehicles enter and exit the highway, requires additional investment.
- Design of real-time control systems to enable traffic to smoothly enter and exit the highway presents operational challenges.
- 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 function of the state of the queue.

Issues Addressed in Report

This report concentrates on three issues in the design of AHS network interfaces: (1) strategic design of networks, including the spacing between highway interchanges and the highway orientation relative to the street system, (2) link level flow control on the automated highway, to facilitate highway exiting, and (3) interface concept and physical design of roadway interfaces, accounting for current highway construction in urban areas. These three issues are considered in order in the following three chapters, which is followed by a conclusions chapter. Supplemental case study material is provided in the appendix.

Chapter 2 is a summary of research already completed under this project on strategic highway design, documented in PATH Working Paper 2000-26 and PATH Research Report 2001-37. Chapter 3 summarizes results from PATH Research Report 2002-07, and provides new results in which platoon sorting occurs both on the highway and at highway entrances. Chapter 4, which examines specific highways, and the conclusions (Chapter 5), are entirely new.

2. PLACEMENT OF ACCESS POINTS AND HIGHWAY SPACING

This section summarizes analyses on the issues of interchange separation and placement from PATH Working Paper 2000-26 and PATH Research Report 2001-37. These decisions have the potential to affect both the performance of the AHS, and the performance of the street system that accommodates local traffic.

Route Selection and Highway Orientation

Street systems frequently have a different orientation than highways, perhaps rotated by some angle as in Figure 1. Consider 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. Later, in this chapter, entrance/exit placement will be evaluated explicitly. Let:

α = 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)
z = horizontal distance between trip origin and trip destination
(z is positive if destination is to the right of origin, negative otherwise)
θ = 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 $\alpha \leq 1$.

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 from the highway (streets are always used for highway access and egress). If a trip is entirely by street, the total travel time is defined by the sum of the horizontal and vertical distances (Figure 1):

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

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 $\theta \leq 45°$, vertical access always minimizes street distance, and is therefore preferred for most origin/destination 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 θ and α are large). When the highway is very fast (small α), 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).

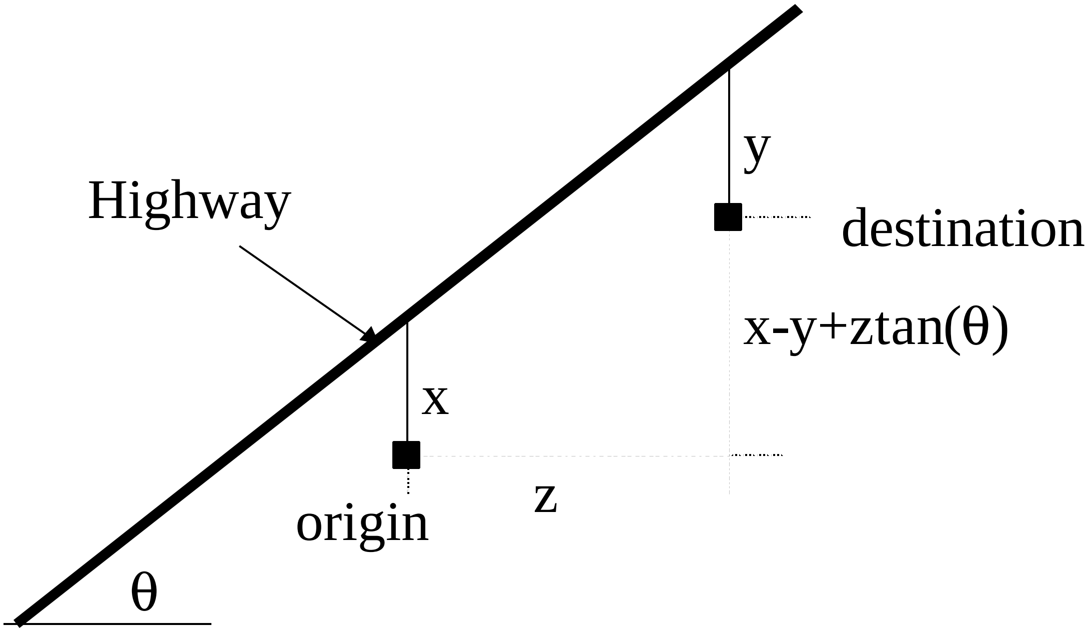


Figure 1. Travel Distances as Function of Highway Orientation

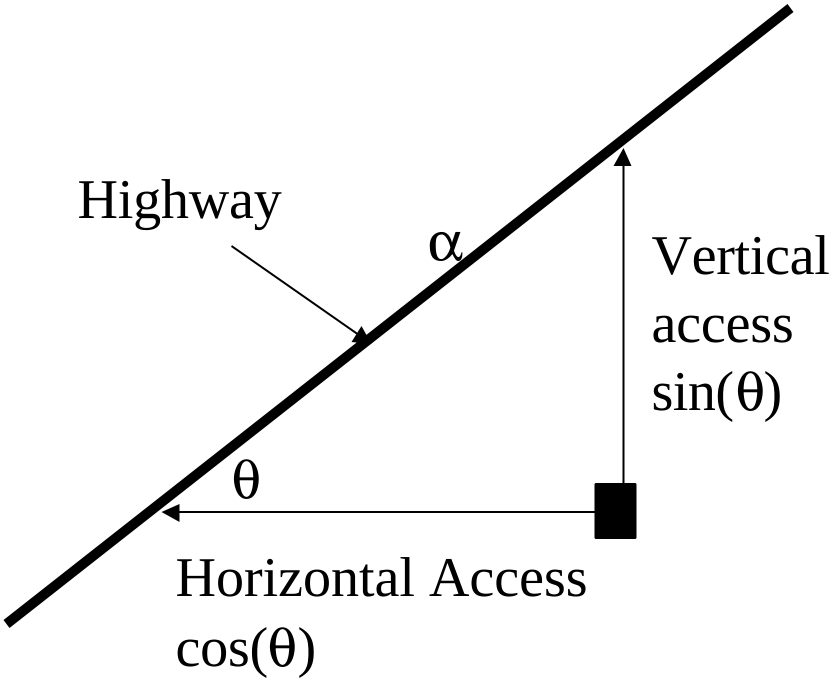


Figure 2. Alternative Access to Highway

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 $\alpha < \cos(\theta) - \sin(\theta)$ and $\theta < 45°$, access/egress is in the vertical direction, resulting in a travel time of:

$$\text{Vertical Access Travel Time:} \quad T_h = |x| + |y| + |\alpha z/\cos(\theta)| \qquad (2)$$

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 3 divides the travel region into sections. Each section represents a set of potential destination locations, and each section defines a unique travel time function (see Hall, 2000). 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 $|z|/\cos(\theta)$.

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. As illustrated in Figures 4 and 5, two distinct region shapes are possible. The cases are defined entirely by α 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: $\alpha < \cos(\theta) - \sin(\theta)$

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:

$$\{-2x/[1+\tan(\theta) - \alpha/\cos(\theta)],\ 2x/[1-\tan(\theta) - \alpha/\cos(\theta)]\} = \{b_1, b_2\} \qquad (3)$$

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 (Figure 4). For $\theta = 0$, symmetry exists and the boundaries have identical magnitude equaling $2x/(1-\alpha)$. In the limit as α approaches $\cos(\theta) - \sin(\theta)$, b_2 increases without bound, and b_1 approaches $x/\tan(\theta)$ (situated exactly on the highway).

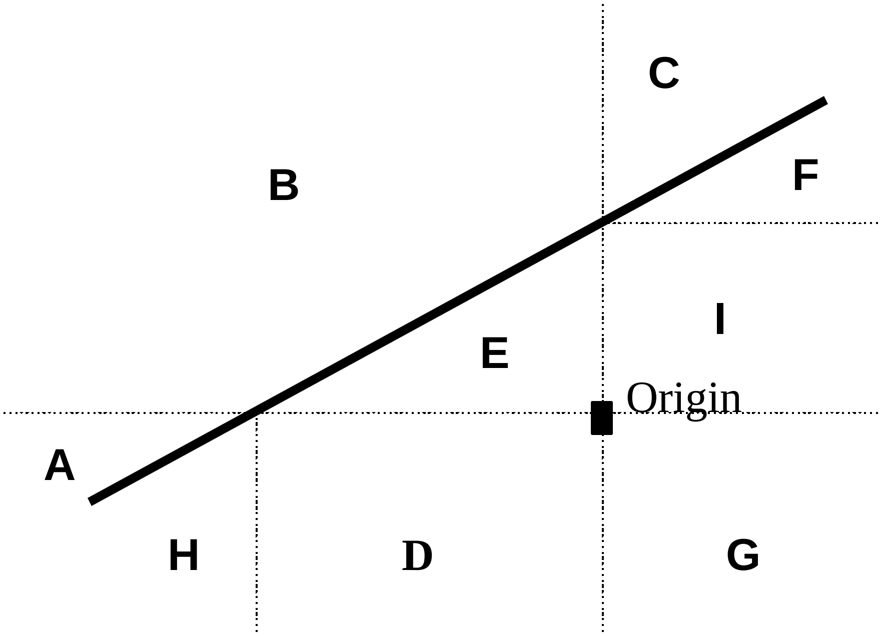


Figure 3. Destination Regions; Regions Correspond to Time Equations

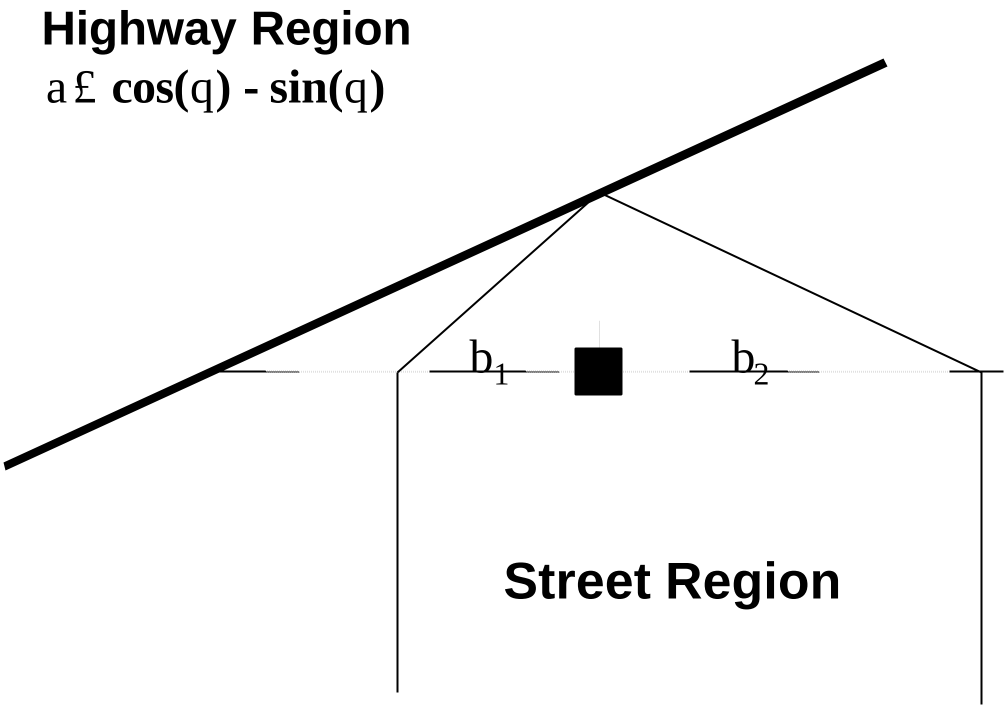


Figure 4. Highway and Street Regions, Street Speed Small

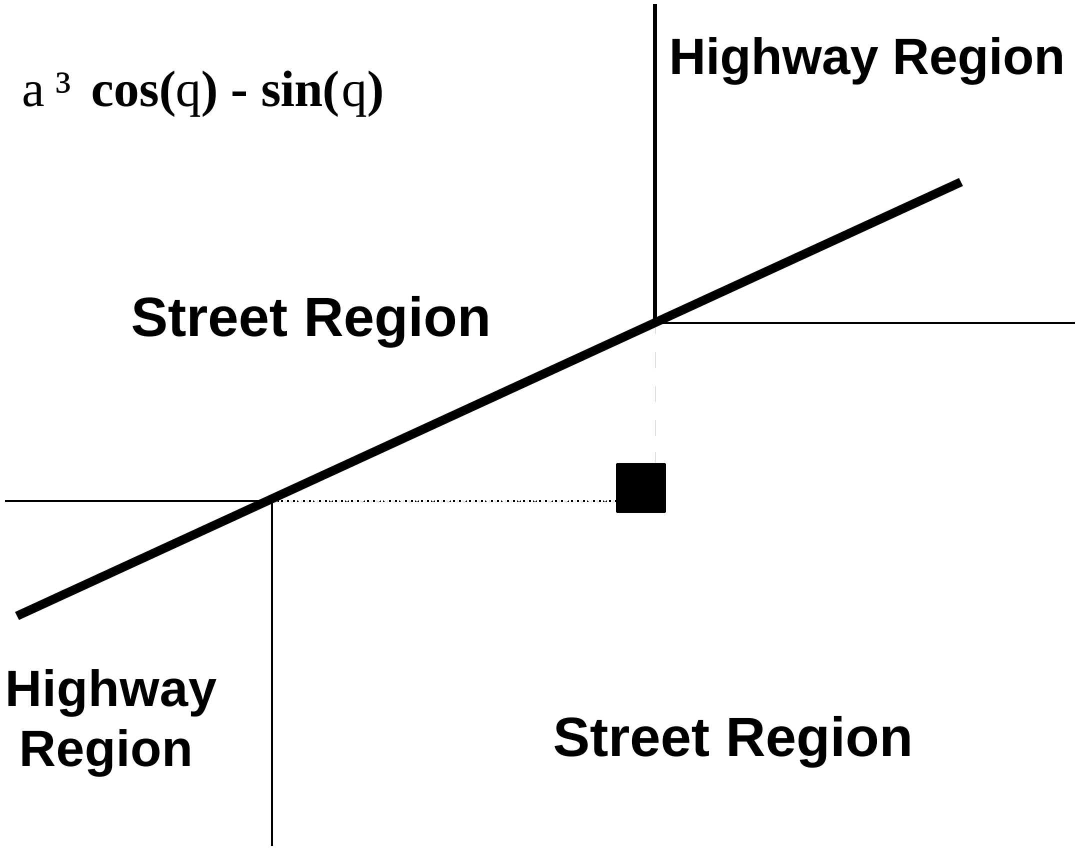


Figure 5. Highway and Street Regions, Street Speed Large

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

In this case, as shown in Figure 5, 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.

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 infrequent 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 infrequent, 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.

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:

A. $\max \{(x_n,y_n) \mid y_n \leq h_y \}$, designated as (x_A,y_A) (4a)
B. $\min \{(x_n,y_n) \mid y_n \geq h_y \}$, designated as (x_B,y_B) (4b)
C. $\max \{(x_n,y_n) \mid x_n \leq v_y \}$, designated as (x_C,y_C) (4c)
D. $\min \{(x_n,y_n) \mid x_n \geq v_y \}$, designated as (x_D,y_D) (4d)

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

The optimal entrance ramp among the four candidates (A,B,C or D) depends on the ultimate destination, along with α and θ. 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. Examples are shown in Figures 6 and 7, representing the cases $\alpha < \cos(\theta) - \sin(\theta)$ and $\alpha > \cos(\theta) - \sin(\theta)$, and for destinations to the far left of the origin. As noted in Hall (2000), street-only routes are also preferred for some nearby destinations.

For the case $\alpha < \cos(\theta) - \sin(\theta)$, 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.

A circuity penalty is easily calculated as a function 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 function of the ramp spacing. Figure 8 shows that the worst-case penalty (represented as a ratio to the ramp spacing) increases as θ 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.

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 θ, α and the following parameters:

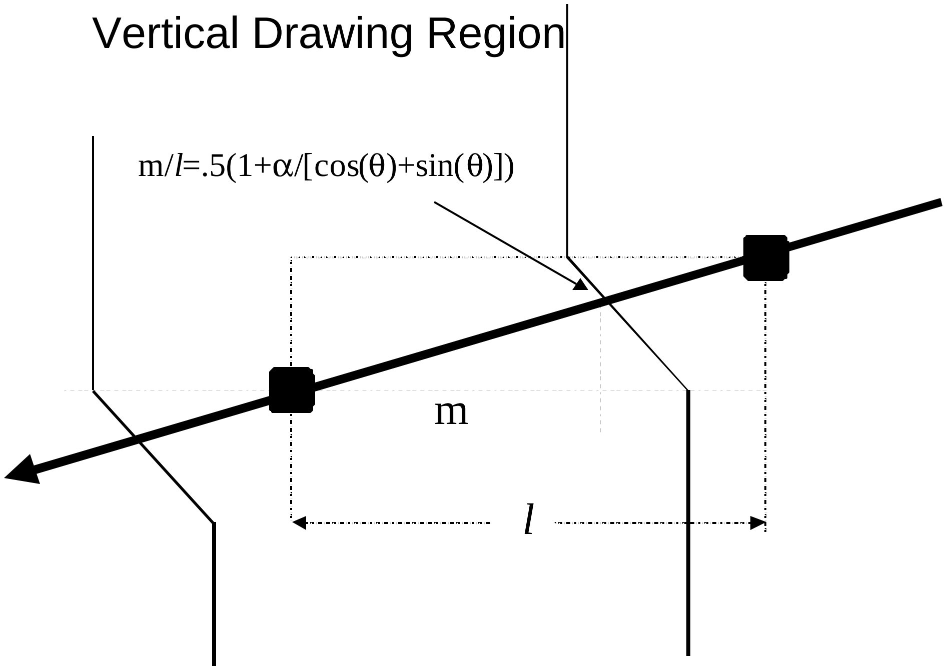


Figure 6. Drawing Region for Ramp, a **< cos(**q**) – sin(**q**)**

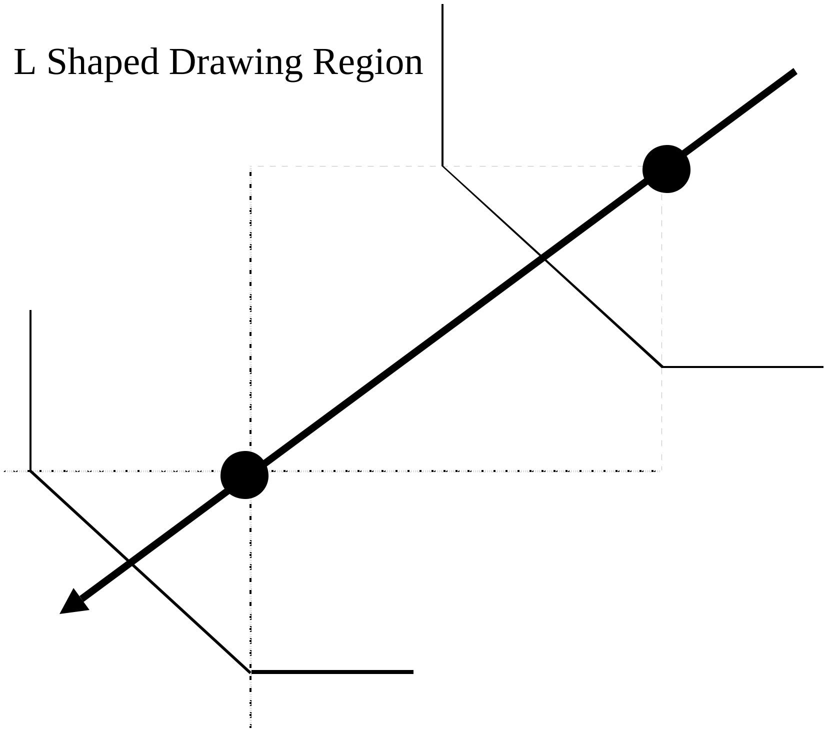


Figure 7. Drawing Region for Ramp, a **> cos(**q**) – sin(**q**)**

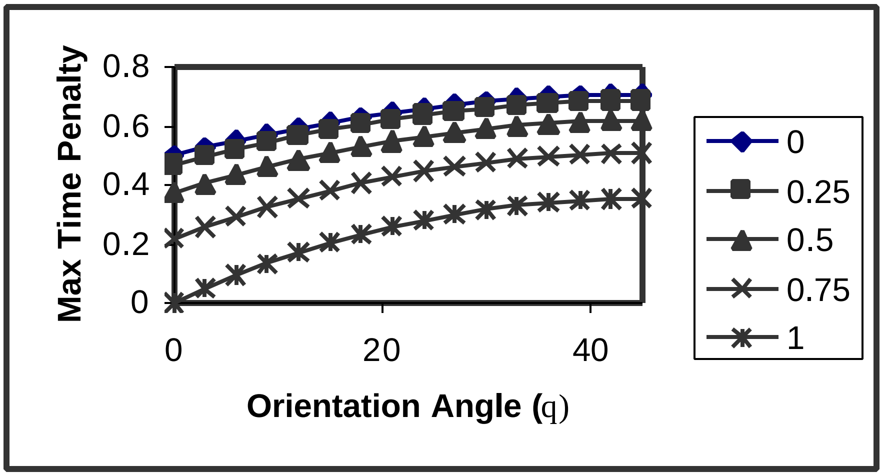


Figure 8. Worst-case Time Penalty

s_h = distance separating highways in the vertical dimension
ä = ratio of average trip length to average ramp spacing
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 (origin/destination) are randomly generated in a three step process, first generating an origin location, second generating a distance from 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 from 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:

ä = 4.9, s_h = 3.9, $\theta = 11.3^{o}$, α = . 333 (free-flow), γ = 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 cases to ensure that interchanges are aligned with vertical and horizontal streets.

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

ä = 1,2,2.9,3.9,4.9,5.9,9.8
s_h = 2, 3.9,5.9
$\theta = 11.3^{o},21.8^{o},30.9^{o},38.7^{o}$
α = .2,.25,.333,.5,.667
γ = .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 Hall (2000), which can be summarized as follows:

- Increased trip length leads to greater overall efficiency. For long trips in particular, highways substantially reduce street travel 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 street 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. Street travel in the x direction exhibits a discontinuity, with a large jump when $\alpha > \cos(\theta) - \sin(\theta)$ (simultaneously, travel in the y direction decreases). This trend is consistent with earlier findings, which showed that the street-only region grows substantially when $\alpha > \cos(\theta) - \sin(\theta)$.

- Decreased highway speed causes travel time to increase, with increased street travel in the x direction. Travel in the y direction is only slightly affected, and can either increase or decrease.

Implications for Automated Highway Design

Automated highways have potential to both increase average highway speed and, depending on mode of construction, decrease highway spacing. Both would have the positive effects of reducing travel on streets, especially on streets running parallel to the highway. If the highway's orientation differs somewhat from the street grid, travel may be reduced in both directions of street travel, or perhaps decline in one direction and stay the same in the other. Though not the focus of this work, changes in street travel would not be uniformly distributed. Access roadways in the immediate vicinity of highway entrances and exits would experience traffic increases, whereas roadways elsewhere would likely experience decreases. This may necessitate reconfiguration of roadways.

It should be observed that, from the perspective of minimizing travel time and street traffic, it is advantageous to minimize highway spacing, Therefore, for a given total highway capacity, it would be advantageous to have many low capacity roads than a few high capacity roads. It should also be observed that additions in capacity may result in more traffic, thus counteracting other benefits.

3. TRAFFIC CONTROL TO FACILITATE ENTRANCE & EXIT

The physical design of highway entrances and exits must support the operational strategy for the highway. For instance, if vehicles are sorted and inspected at the entrance, then physical space may be needed to stage and queue vehicles. In addition, surrounding roadways must provide sufficient capacity to absorb traffic that is exiting and entering the highway.

Under the "platoon" concept for AHS, vehicles travel on highways in closely spaced groups. To maximize benefits, it is desirable to form platoons that are reasonably large (five or more vehicles), and it is also desirable to ensure that platoons remain intact for considerable distances. Unfortunately, when an individual vehicle needs to exit from the highway, it may need to be separated from its platoon. The separation process can force vehicles to travel farther apart, consuming more highway capacity. It also exposes vehicles to additional safety risk. Thus, the frequency at which vehicles enter and exit platoons can affect highway performance.

As a simple illustration, suppose that a highway is homogeneous with respect to origin/destination patterns, has an average trip length of L, spacing between exits of x and platoons designed to be size N. The probability that a randomly selected vehicle will choose to leave the highway at an exit is then x/L. If platoons are formed through an independent selection process, the probability that a platoon has no exiting vehicles is $(1-x/L)^N$. Example calculations are shown in Table 1.

Table 1. Probability that Platoon Remains Intact at Exit

	Designed Platoon Size (N)									
x/L	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
0.20	0.80	0.64	0.51	0.41	0.33	0.26	0.21	0.17	0.13	0.11
0.10	0.90	0.81	0.73	0.66	0.59	0.53	0.48	0.43	0.39	0.35
0.05	0.95	0.90	0.86	0.81	0.77	0.74	0.70	0.66	0.63	0.60

For example, with exits spaced 2 miles apart, an average trip length of 20 miles and a platoon size of 5, there is only a 59% chance that a platoon will remain intact between one exit and the next, thus creating considerable instability. On the other hand, if vehicles are grouped by destination, platoons would remain intact over longer distances, adding to the safety and throughput of the highway.

This chapter develops and evaluates strategies for organizing vehicles into platoons, with the objective of maximizing the distance that platoons stay intact. Fundamentally, this entails grouping vehicles according to their destination. There are, however, many ways to accomplish this goal, along with significant trade-offs with respect to construction costs, queueing and throughput. Both analytical and simulation results are provided. Our analysis is limited to a single class of vehicles, thus precluding sorting vehicles by characteristics other than destination (such as size; see Hall and Li, 1999, for instance). The chapter both summarizes findings from PATH Working Paper 2002-07, and provides new results. The prior work only considers sorting vehicles on entrance ramps. The new work considers sorting both on highways and on entrance ramps.

We do not explicitly model the merging of vehicles on the entrance ramp with vehicles on the mainline and instead concentrate on the formation and characteristics of platoons that can be created on ramps. System performance is evaluated along the following dimensions:

Platoon Ratio: Ratio of vehicle miles traveled to platoon miles traveled

Highway Throughput: Upper bound on highway throughput, derived from the platoon ratio, combined with inter- and intra- platoon spacing parameters.

Waiting Time: Average waiting time for platoon formation.

Strategies for Forming Platoons at Entrances

The focus of this section is first to define a set of platoon formation strategies at entrances, and second to develop analytical models for performance measures. All strategies assume that vehicles are grouped by lanes, and that each platoon represents an uninterrupted sequence of vehicles within an individual lane. In a later section, grouping vehicles while traveling on the highway is considered.

Destination Group (DG)

Under the DG strategy, platoons are formed at the entrance ramp on the basis of destination groups. Each entrance lane represents one group, which comprises a set of adjacent highway exits. Each exit is assigned to exactly one destination group. Vehicles enter the highway as platoons, which remain intact until a distance *y* upstream from the first ramp in the group. At this point, the platoon separates, and vehicles travel individually until reaching their exits. The distance *y* must be sufficient for completion of de-platooning maneuvers, and to maneuver into appropriate exit lanes.

Dynamic Grouping (DYG)

Under the dynamic grouping strategy, destination groups are not permanently assigned to lanes. We propose the following policy:

- Platoons are constrained to have a maximum destination range of r, representing the difference in index between the closest and the furthest destinations in the group.

- An arriving vehicle is assigned to a feasible platoon (i.e., satisfying the range r), if one exists. If no feasible platoon exists, the largest waiting platoon is released, and the arriving vehicle initiates a new platoon in this lane.
- If more than one feasible platoon exists, the arriving vehicle is assigned to the platoon in which the platoon range will increase by the smallest amount when the vehicle is assigned.

Dynamic Grouping and Platoon Splitting (DGPS)

The third strategy is a dynamic policy for grouping destinations that permits platoons to continue after some vehicles split off. This is accomplished by ensuring that vehicles in each platoon are sorted, front to back, in order of non-increasing destination. Thus, the same vehicle can remain as platoon leader through the platoon's lifetime, while the platoon "drops off" vehicles that have closer destinations. This also provides flexibility to group vehicles with a greater range of destinations within a single platoon, which provides flexibility in the entrance process.

Suppose there are n lanes, and let d_j be the destination index for the last vehicle in lane j. The policy is implemented through three rules, representing (1) lane assignment, (2) platoon release, and (3) platoon splitting.

Lane Assignment Upon arrival, a vehicle with destination ϕ is assigned to the lane for which: $d_j \geq \phi$, and $d_j - \phi$ is minimized. If no lane satisfies $d_j \geq \phi$, then platoon release is invoked.

Platoon Release A platoon is released when any of the following events occurs:

- The elapsed time since the first vehicle arrived equals the release time τ
- The number of vehicles in the platoon reaches the maximum N, or
- An arrival cannot be assigned to any current platoon, and the platoon has the smallest value of d_j among those waiting.

Platoon Splitting A platoon is split when reaching a distance *y* before the destination of the last vehicle in the platoon. Vehicles with more distant destinations remain in the platoon until reaching a distance *y* before their destinations.

Example Suppose, without loss in generality, that lanes are numbered according to the destination indexes: $d_1 < d_2 <\ldots< d_n$. If $\phi > d_n$, then platoon one is released, and ϕ is inserted at the end of the sequence, creating a state vector of $(d_2, d_3,\ldots,d_n, \phi)$. Otherwise, ϕ is inserted at the end of one of the platoons. For instance, if ϕ is greater than d_1, but less than or equal to d_2, the state becomes: $(d_1 , \phi ,d_3,\ldots, d_n)$.

Multistage Sorting

It is also possible to form platoons through a two (or more) staged sorting process, which can reduce the width of the entrance ramp (Figure 9). For instance, stage one could divide vehicles into three groups, and stage two could subsequently divide each group into three subgroups. Thus, three lanes would produce nine destination groups.

Suppose that the process follows a fixed cycle (length T), divided into n_1 stages (or groups). At the start of each phase, the queued vehicles in one lane are sent to stage 2, where vehicles are sorted into n_2 sub-groups. The sub-groups are released to the highway as soon as the vehicles from Stage 1 are sorted in Stage 2, and the process repeats with the next lane in the cycle. The principle drawbacks of this approach are a drop in entrance throughput (due to loss time switching between phases), along with additional entrance delay as vehicles are processed through multiple stages.

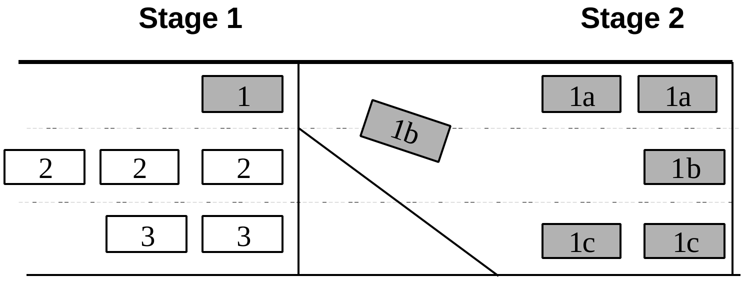


Figure 9. Multi-stage Sorting, First Grouped 1-2-3, then into subgroups a-b-c.

Multi-stage sorting is implemented differently for each strategy. For DG, the implementation is straight forward. Destinations are divided into non-intersecting sets in Stage 1, which are then divided into non-intersecting sub-sets in Stage 2. For dynamic grouping, only Stage 1 is truly dynamic. Once vehicles are sent to Stage 2, no more vehicles arrive, so the allocation can be statically optimized according to any desired criterion. For DGPS, Stage 1 is not required to maintain a strict ordering of destinations, as vehicles can be resequenced in Stage 2. The implementation is not straight-forward, and is a subject for future research.

Simulation of Entrance-only Sorting

A simulator was developed to evaluate platoon formation policies with respect to a range of performance measures. The following features were common for all policies: (1) Vehicles arrive by stationary Poisson process, (2) Platoon size is constrained not to exceed N, and (3) Vehicle waiting time was constrained not to exceed τ. In our simulation, N was set at 8 and τ was set at 180 seconds.

Performance was evaluated with respect to: Platoon Ratio, Highway Throughput, and Waiting Time. For comparison, we also evaluated a policy in which vehicles were randomly assigned to lanes. In this policy a platoon was split as soon as the first vehicle needed to exit.

The policies were evaluated for a set of scenarios, defined as follows:

Trip length was exponentially distributed, uniformly distributed or clustered. For clustered, (1) 20% of the exits accounted for 50% of demand; (2) demand was identical within each group (those with high demand and those with low demand); and (3) demand followed a repeating pattern, with four low demand exits between each pair of high demand exits.

Exit Spacing was either large (5 miles) or small (1 mile)

Number of Entrance Lanes varied from 2 to 7

Average Trip Length equaled 10 miles in all cases

Highway Length depended on the trip length distribution. For exponential, the highway was limited to 60 miles (6 x mean trip length); for uniform, the highway was limited to 20 miles (e.g., 20 exits with 1-mile spacing).

Throughput Calculation

An upper bound on highway throughput was calculated from spacing parameters and expected platoon sizes. We assume that different types of platoons are intermixed in lanes, and that throughput can be derived from the platoon ratio (which is averaged across all highway segments). In this model, spacing is defined by the time-separation between fronts of vehicles, which eliminates the need to parameterize vehicle sizes. Let:

a = intra-platoon time spacing, front-to-front (seconds)
b = inter-platoon time spacing, front-to-front (seconds)
Π = expected platoon size
μ_1 = vehicle flow per lane
μ_2 = platoon flow per lane = μ_1/Π

Then

$$a\,\mu_1 + (b-a)\,\mu_2 \leq 3600 \tag{5a}$$

or

$$\mu_1 \leq 3600/\left[a + (b-a)/\Pi\right] \tag{5b}$$

For expected platoon size, we use the platoon ratio (expected vehicle miles divided by expected platoon miles). Following Hall and Li (2000), we evaluated throughput for each case using a = .26 s and b = 1.36 s.

Dynamic Grouping Range (DYG)

For the DYG strategy, the range was adjusted to produce the maximum throughput in each situation. This was accomplished by simulating system performance for different values of r, and selecting the best quantity. For 5 miles spacing, a range of 2 was used in all cases. For 1 mile spacing, the range varied from 2 to 7, depending on the trip length distribution and number of lanes. The optimal range increased as the number of lanes increased, and was larger for exponential trip lengths than uniformly distributed or clustered trip lengths.

Simulation Results

Figures 10 to 12 provide sample results (see Hall and Chin (2002) for complete results). As a general trend, adding lanes tends to provide longer average waiting time, larger platoon ratios and larger throughput. Waiting times increase because each lane handles fewer vehicles, meaning it takes longer to form a platoon of a given size. The platoon ratio increases because platoons can serve a smaller range of destinations, and because (for some strategies) larger platoons can be formed. Throughput increases because the platoon ratio increases. However, the benefits of adding lanes diminish rapidly beyond four entrance lanes.

Among the four strategies, DG provided the largest platoon ratio and throughput in most situations. However, with a small number of lanes (2 or 3) and the uniform trip length distribution, dynamic grouping (DYG) performed better. The flexibility of dynamic grouping appears to be important when the ratio of number of lanes to number of exits is a small number. The random assignment strategy, as could be expected, produced the smallest platoon ratio and throughput in all cases. It should be noted that throughput is not a strictly increasing function of the number of lanes for DGPS. The range of destinations within a platoon can be smaller with fewer lanes, meaning that platoons remain intact over longer distances.

Average waiting time is a nearly linear function of number of lanes in most cases. When vehicles are split into more categories, it takes longer to form a platoon of a given size. And although platoon size is also a function of number of lanes, the relationship is fairly insensitive. DYG tends to produce the smallest expected waiting time, though the range among strategies is not so great as the range for platoon ratio or throughput. However, shorter waits do not seem sufficient to compensate for lower throughput (relative to DPGS and DG).

Summary of Entrance-only Findings

To maximize highway throughput, it is desirable to create platoons that are large in size, and that remain intact over long distances. Sorting vehicles by destination at the entrance is one way to accomplish this objective. Toward this end, this section evaluated a range of strategies, and determined how to optimize a dedicated assignment of vehicles to entrance groups. For the cases studied in this paper, dedicated grouping performed better than dynamic assignments with respect to platoon ratio and throughput. However, average waiting time at entrance was somewhat larger.

Integrated Sorting on Highway and Entrances

In actuality, if a platoon is split during its travel, or if a vehicle separates from its platoon, it may be desirable to form a new platoon among a different set of vehicles. Vehicles may form, and reform, repeatedly throughout their trip. One approach would be to create platoons solely from their adjacency in lanes. The drawback is that platoons would contain a random mix of vehicles, some of which may need to exit from the highway soon after the platoon is formed. Thus, the benefits of platooning are not maximized. Alternatively, platoons may be deliberately formed among vehicles with common destinations, so that the platoon remains intact for the maximum distance. The entire platoon may even be directed to exit from the highway as a unit, thus providing efficiency in the exiting process.

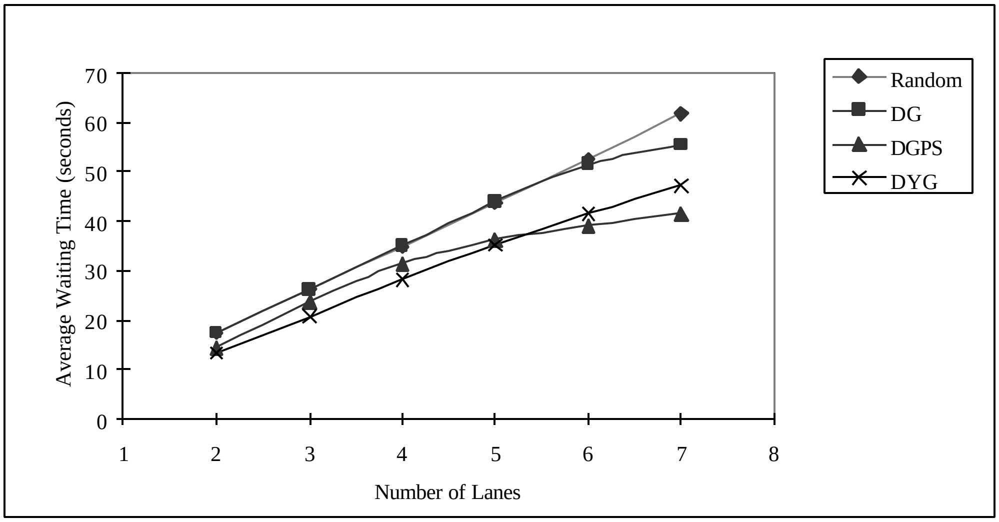


Figure 10. Average Waiting Time Versus Number of Lanes, Exponential Trip Length with 5-mile Exit Spacing

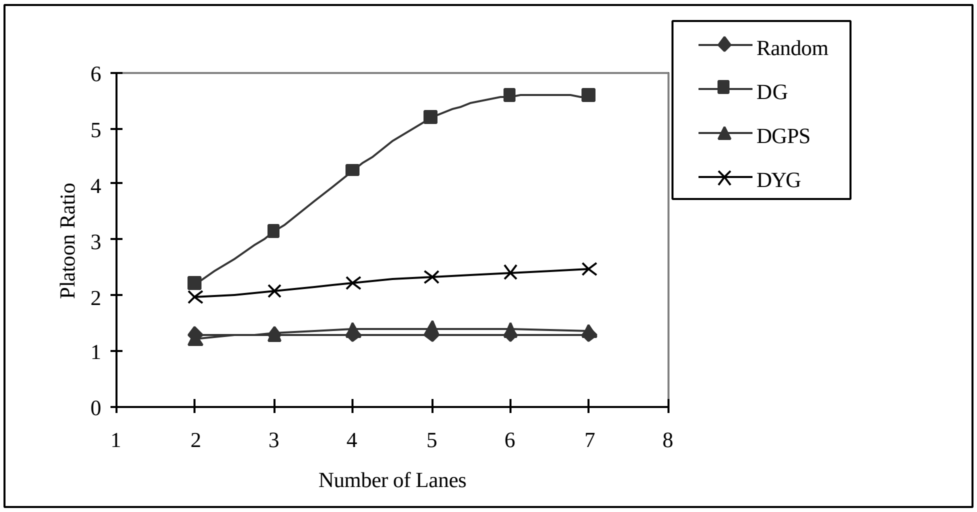


Figure 11. Platoon Ratio Versus Number of Lanes, Exponential Trip Length with 5-mile Exit Spacing

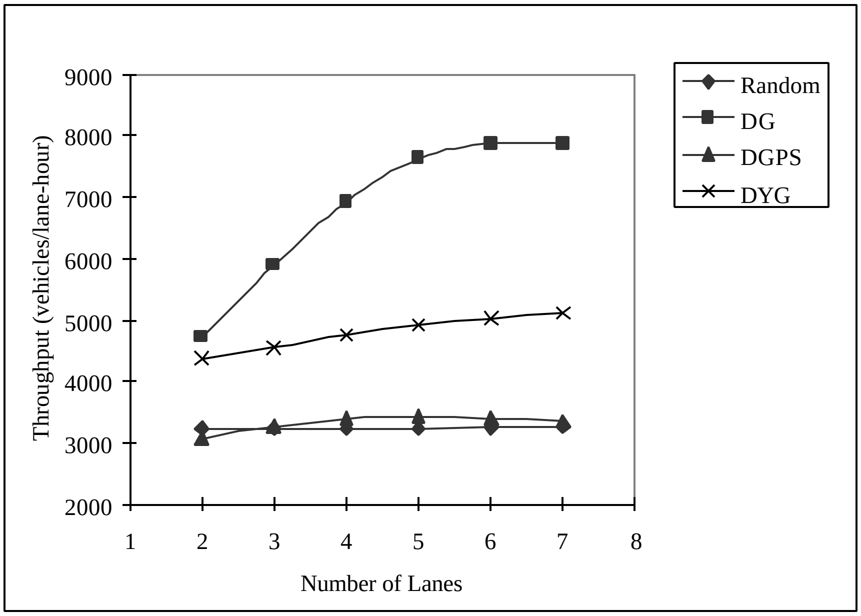


Figure 12. Highway Throughput Versus Number of Lanes, Exponential Trip Length Distribution and 5-mile Exit Spacing

In the following sections, we first describe our approach for modeling lanes changes and the progression of traffic within platoons. Each platoon is represented as a slot of fixed space and capacity. As vehicles join or leave a platoon, the platoon can vary in size, but the slot will retain a constant length. We also describe methods for assigning vehicles to lanes, based on destination, and methods for assigning vehicles to slots within a lane. Last, simulation methodology and results are provided.

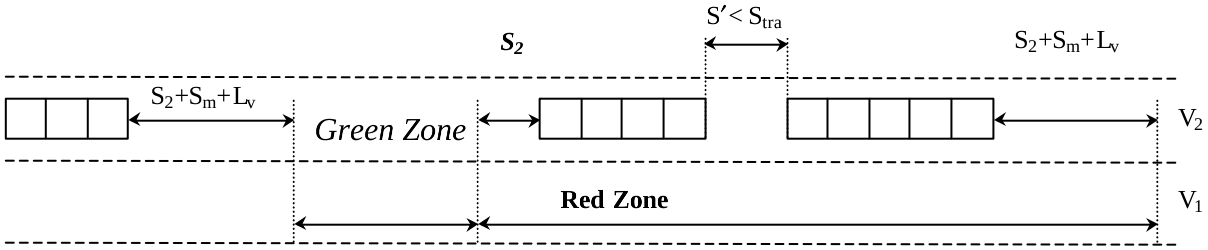
Model Description

A platoon consists of vehicles that are closely spaced. Intraplatoon distance is the minimum safety distance between vehicles, and interplatoon distance is the minimum safety distance between platoons. In practical operation, there are many situations in which the space between platoons is wasted. For example,

- The distance between adjacent platoons could be longer than the interplatoon distance, but too short to accommodate additional vehicles.
- Several consecutive platoons are not at maximum length. There is, however, no space between each pair of them. The control center has to decide either to combine two adjacent platoons or coordinate platoons to release space.
- Two adjacent platoons cannot be joined because the resulting platoon is over the maximum allowable length.

Figure 13 illustrates our idea for modeling lane changes. The vertical dash line coincides with the front end of the vehicle doing the lane change. For a traversing vehicle driving on the V_1-speed lane ($V_2>V_1$), an appropriate lane-change gap length should equals

$2S_2+S_m+L_v$ (=S_{tra}), which is the minimal length of the Green Zone. For a joining vehicle, the bold and italic S_2 is replaced by S_1 and the appropriate gap length will be $S_1+S_2+S_m+L_v$ (=S_{join}). It can be modified for the case $V_1>V_2$ by changing the allocation of S_{tra} and S_2 and the dash line coinciding with the rear end of the lane-change vehicle.



S_m : the distance for acceleration/deceleration (AD distance, $V_2^2=V_1^2+2aS_m$).
S_1 : the intraplatoon distance.
S_2 : the interplatoon distance.
L_v : the average vehicle length.

Figure 13. Green Zone and Red Zone for Lane Changing

When $S'< 2S_2+S_m+L_v$, the gap distance is too short for a vehicle to traverse the space into another lane. Furthermore, if $S'< S_2+S_m+L_v$, there is insufficient space for a vehicle to join a platoon. Therefore, the gap should be adjusted to make the space useful.

There is one more critical issue in the operation of the concept of platooning. When a vehicle within a platoon needs to separate, the platoon has to split to release enough space to ensure a safe maneuver. However, especially when the traffic flow is close to the lane capacity, the split of a platoon may cause another platoon to slow down or speed up to make room for a lane-changing vehicle. This increases the instability of a highway. In the moving slot concept, the mechanism of a lane change is simpler and safer, because the distance for doing a lane change is already included in each slot. When a vehicle needs to change lane, the only thing is to wait for a non-full slot on the adjacent lane and then merge This causes capacity to decline but safety to increase.

In the slot model, a slot comprises vehicles in a platoon, intraplatoon distance, interplatoon distance and acceleration/deceleration distance (*AD distance*). In this design, a platoon is included for the consideration of capacity and the AD distance is used as a safety buffer in lane changes.

Different highway lanes may have slots of different sizes due to different maximum platoon sizes and interplatoon, intraplatoon, and AD distances based on the lane speeds. The AD distance will always reside in a slot even though the slot is full (maximum platoon size attained). The advantage is that vehicles can use it as a buffer when exiting. Moreover, vehicles in a slot do not have to be closely spaced as in a platoon. They can keep at a well-coordinated distance, at least more than the intraplatoon distance, and the benefit will be the ease for vehicles to merge in. This reduces the lane change completion time.

Lane Assignment Rules

This rule regulates which lane a vehicle should use in which section of the highway from entrance to exit. We adopt approaches from Hall (1995a) and Ramaswamy (1995, 1997) and design some basic strategies in our system. Platoons can be formed at entrances and/or on highways. So, the lane assignment rules can be either entrance-based or highway-based. The entrance-based lane assignment rules mean that vehicles from different entrances form platoons based on the vehicle destination and the characteristics of entrances such as O/D demand. The highway-based lane assignment rules are to assign vehicles from different entrances based on vehicle destination and highway sections. In the project, we will examine both rules, though our proposal concentrates on highway-based rules.

Before introducing the rules, we begin with the assumption that vehicles with a further destination should be assigned to further left lanes than vehicles traveling to near destinations. If the traffic flow is very low, then all vehicles can drive on the right lane, to avoid unnecessary lane changes. With an increase in traffic flow, the capacity of the right lane has to be spared for vehicles waiting at downstream entrances. As a result, some vehicles should change to the left lanes. However, vehicles should not be in the left lanes when they have a nearby destination. This would cause too frequent lane changes on the right lane and reduce the capacity. And if vehicles with distant destinations occupied the right lane, capacity would also be reduced. Consequently, vehicles with farther destinations are assigned to left lanes when necessary. In the following, we propose three different types of highway-based lane assignment rules.

(1) The first rule (Figure 14) follows the idea that vehicles with farther destinations are assigned to the left lanes, and ranges of destinations do not intersect among lanes. The range of destination in a slot can be a sub-range of the "lane range." For example, the lane with range "8-end" can have slots of range "8-10", "11-13", and so on. We can optimize the set of lane ranges by maximizing the capacity or minimizing the total lane change times. In the example vehicles entering from the ramp in Figure 14 are assigned to the right lane if the destination is in exit 2 to 4, to the middle lane for exits 5 to 8, and the left lane for exits 9 to end.

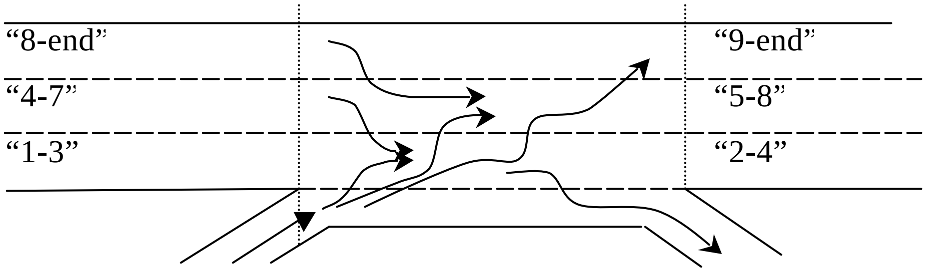


Figure 14. Destination Range Changes at Each Exit (Rule 1)

(2) Figure 15 is a modified version of rule 1 that reduces lane changes. Vehicles from entrance can all be assigned to the right lane. When the capacity on the right lane attains some specified limit, like 90% of the maximum capacity, vehicles with destinations shown in the graph will change to left lanes. The rule is practical when the traffic is low.

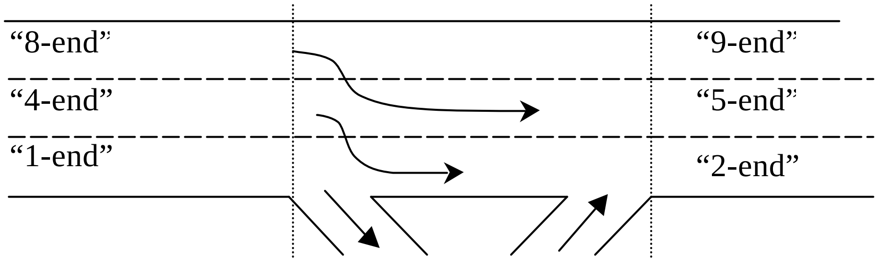


Figure 15. Each Lane Only Has Lower Bound on Destination Range

(3) The third rules is shown in Figure 16. The range of destinations on the right lane shrinks while those on the other two lanes stay the same until there are no vehicles on the right lane. At this point, vehicles in the left lanes simultaneously move right as entire platoons.

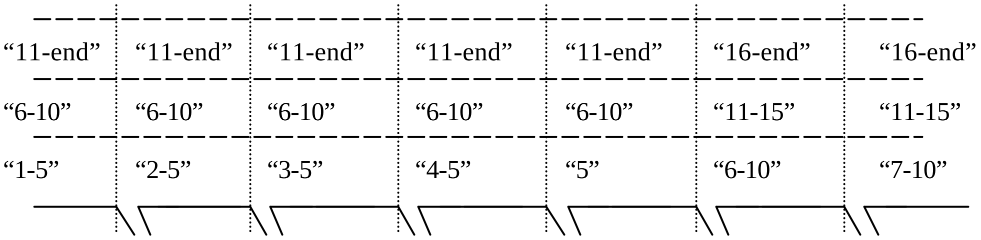


Figure 16. Vehicle Change Lane as Platoons

Slot Assignment Rule (SAR)

When the rule is appiled at entrances, sometimes we call it platoon formation rule (Hall and Chin, 2002). In the model, we focus on that vehicles are released individually and platoons are formed on highway lanes. Vehicles can also be released in platoons from entrances. However, this case will not be studied in the research.

The vehicles assigned to a lane can be further partitioned when they are assigned to slots on the lane. Thus, it is possible to assemble slots with a smaller range of destinations than those of their lanes, so as to maximize the distance over which they remain intact. Some alternatives are now described:

Random After being instructed to change lanes, a vehicle joins the first passing platoon, unless it is full. When vehicles are traveling on a lane, adjacent vehicles or platoons can be instructed to join to form a longer platoon, if the platoon has not reached maximum size. Because vehicle destination is not considered in this rule, vehicles do not need to wait for a platoon with specific serving range of destinations, so vehicles can rapidly change lanes and form platoons. However, platoons do not remain stable over long distances, causing frequent splitting and joining, with attendant loss in capacity.

Platoon Splitting (PS) A vehicle can join a passing platoon if its destination is less than or equal to that of the last vehicle in the platoon, and if the platoon is not full. For example: If the vehicle destination sequence in the passing slot is (9,6,4), vehicles with destination 4 or smaller can join the platoon, but vehicles with destination 5 or higher cannot. The PS rule has the advantage that exiting vehicles will always leave from the end of the platoon. So the entire platoon does not need to be separated. Under this situation, the space reserved for vehicle separating can be shorter than that in the "Random" rule.

Destination Grouping (DG) The range of destinations in a platoon is a subset of the range on its lane. For example, a lane with range "8-end" can have platoons serving range "8-10", "11-13", and so on. Platoon subranges can be either static or dynamic. Static means platoon serving fixed range, like "8-10" while dynamic means that a platoon can serve a range with a width of, say, 3. For example, the range could be "8-10", 9-11",or "10-12" if the range of the lane is "8-12."

A Simplified Automated Highway System

A simulation model was created to evaluate an automated highway with alternative lane assignment and slot assignment rules. Each possible combination of slot assignment and lane assignment rules was be permitted in the model. In the simulation model, a fully automated highway system is assumed. However, the configuration of a highway can be varied.

The system consists of 10 entrances and 10 exits. Exits and entrances alternate. The ramps are all separated equally by 2km. The highway has three lanes. Each entrance has its own origin/destination matrix and trip length distribution. Vehicles are assumed to have equal length of 5m. The maximum allowable number of vehicles in a slot is 10.

A simulation model has been created in terms of the system described above. In the simulation, we want to get information about the disturbance zones, stated in detail below, as well as queueing characteristics of ramps and throughput of the highway system.

The model permits two types of entry modes: "slot-searching" and "slot-assigned." The former is implemented by regular release and the released vehicles begin looking for an appropriate slot on the right lane to merge. In the latter case, vehicles are released only when there are appropriate slots approaching. In slot-searching release, the length of the ramp needs to be longer.

When platoons pass a specified position relative to their exits, vehicles change lanes toward the right. There are also two exiting modes. Figure 17 shows "step exiting," which is applicable to all three platoon assignment rules.

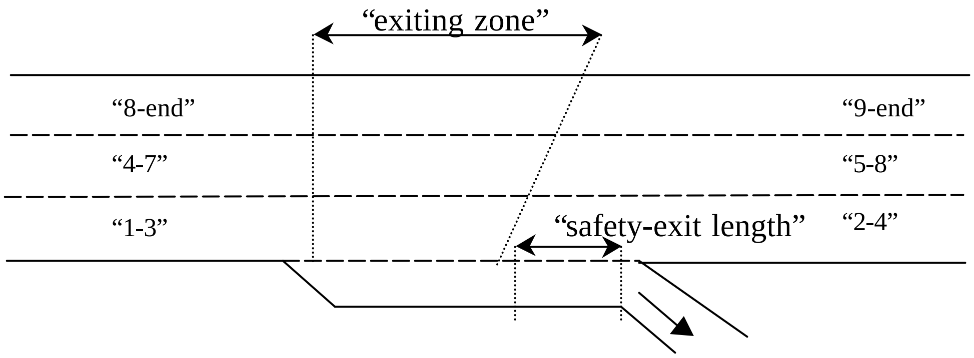


Figure 17. Step Exiting

Another exiting mode is called “continuous exiting”, illustrated in Figure 18. This means that vehicles stay in their specified lanes until their common destinations are immediately downstream. This mode may appear in Lane Assignment Rule 2. In this exiting mode, vehicles initiate exiting maneuver from target lanes until they exit. In step exiting mode, vehicles drive on the rightmost lane several ramps before their exiting ramps approach.

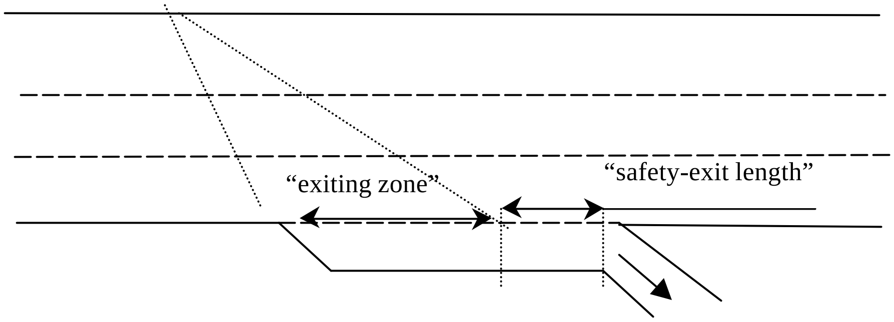


Figure 18. Continuous Exiting

Simulator Description

Figure 19 shows the flowchart of the simulation. The main processes are TableCreation, TimeDrivenUpdation, Processes, and EventDrivenUpdation. Two main tables are created. An entrance table records vehicle information, including arrival time, vehicle length, destination, release time, time to target lane, time to exit, and so on. A slot table has two sub tables: SlotEvent table and SlotState table. A slot event table stores the history of all slots while a slot state table shows only most current states of slots. The slot state table provides important data to implement real-time control such as join, separate, and lane change. The slot event table leaves us all necessary information to analyze the performance of the system, such as lane change waiting time and throughput.

The simulation is driven by time. At each time interval, all processes are executed. Therefore, the size of the time interval is a critical factor. A small value makes the simulation inefficient, while a big one loses the reality of the system. The locations of slots are updated at each interval. Slots are generated regularly since they are assumed to be continuous, one after the other, and the slot length is fixed.

Processes include arrival, release, lane change, and departure. Since there are many possible ways to model each process, assumptions are necessary. In the simulation, arrival is assumed to be a Poisson process with varied rates for different entrances. The lane change process is further divided into two processes: to target lane and to exit. The lane assignment rules specify the target lane for each vehicle based on its destination and the lane it should use in different sections of the highway. Lane Assignment Rule 1 was tested in our simulation results. The range of destinations on each lane is determined locally by the trip length distribution. The departure process is executed under the rule by inspecting vehicles in passing slots.

The occurrences from the above processes are recorded in the corresponding tables through the calling of EventDrivenUpdation procedures.

Simulation Design

The simulator is capable of analyzing a great many situations. Here, we provide results for a single highway, 20 km in length. The results are based on the following situation.

- Vehicles are released from entrances to the rightmost lane according to the passage of slots. As many vehicles as feasible are released, constrained by the available space in the slot, the number of vehicles in queue, and whether the characteristics of the passing slot match those of the vehicles at the front of the queue.
- Lane assignments are made according to the following pattern:

Segment	1	2	3	4	6	6	7	8	9	10
Lane 3	4-20	5-20	6-20	7-20	8-20	9-20	10-20	11-20	12-20	13-20
Lane 2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	1011	11-12
Lane 1	1	2	3	4	5	6	7	8	9	10

Note: exit numbers from 11 to 20 are used for assignment of vehicles with far destinations, which are considered to be beyond the terminus of the simulation. They are taken as one group that won't exit from ramps but continue their trips on the highway.

- Slot assignment uses the following destination groups, preceding exit i:

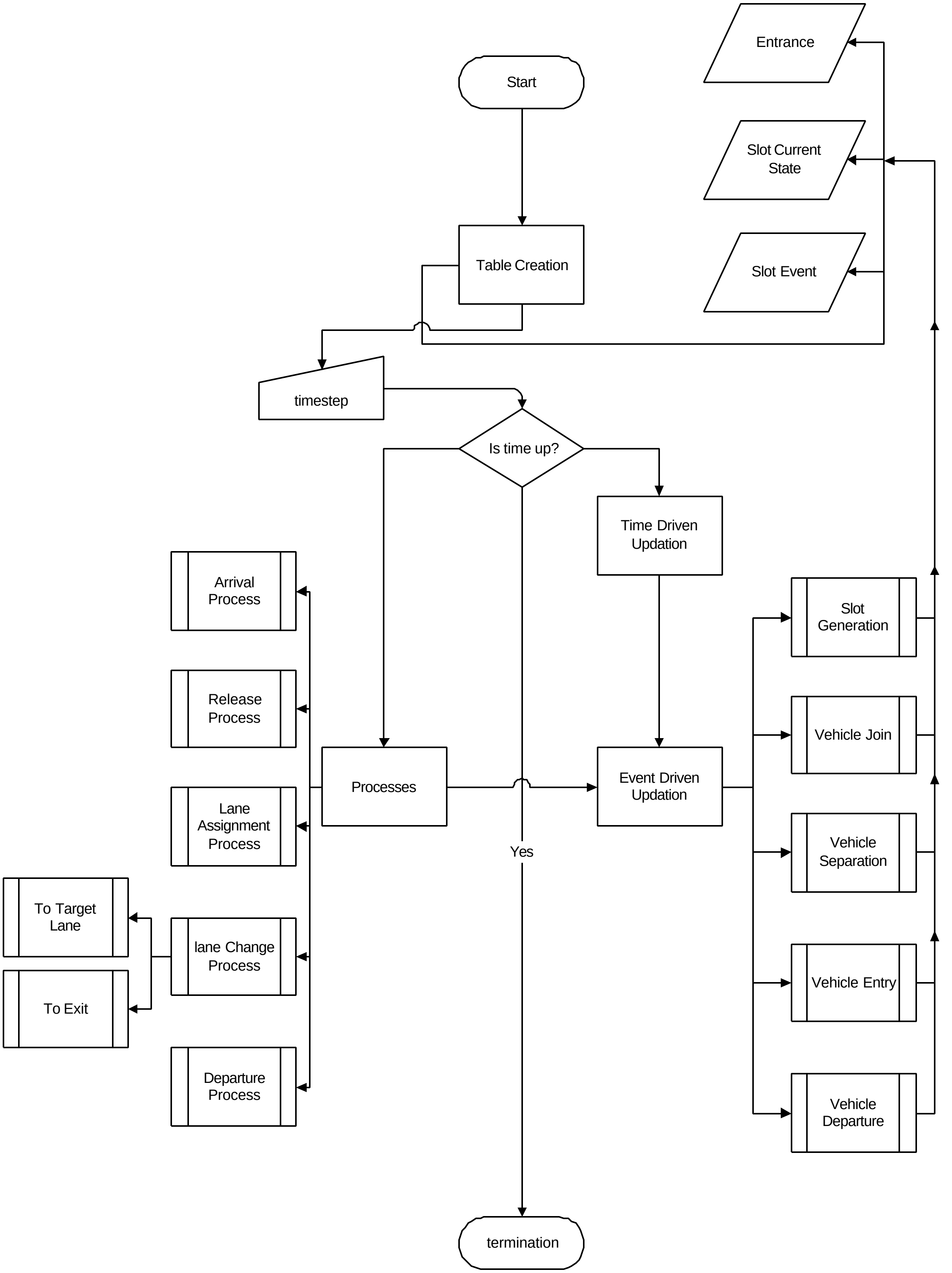


Figure 19. Flowchart of Simulation Model

DG (1):

Lane 1: one slot type for vehicles destined for exit i, and one slot type for all other destinations.

Lane 2: one slot type for exit i+1, one type for exit i+2 and one for exits i+3 and higher

Lane 3: one slot type for each exit from (i+3) to 10 and one for exits 11 and higher

DG(2):

Lane 1: same as DG1.

Lane 2: one slot for exits (i+1, i+2) combined, and one slot for exits 11 and higher.

Lane 3: one slot type for each combination (i+3,i+4), (i+5,i+6), and (i+7,i+8) and one slot type for exits 9 and higher.

DG(3):

Lane 1: same as DG1.

Lane 2: same as DG2.

Lane 3: one slot type for the combination (i+3,i+4,i+6), one slot type for the combination (i+7,i+8,i+9), and one slot type for exits 10 and higher.

The general characteristics of the simulations are summarized in Table 2.

Table 2. Summary of Simulation Characteristics

	1	2	3	4	5	6
Arrival rate (vehicles per hour per entrance)	1080	1080	1080	2160	2160	2160
Trip length distribution (mean:km)	EXPO (20)	EXPO (20)	EXPO (20)	EXPO (20)	EXPO(20)	EXPO(20)
* DG	One (DG1)	Medium	All	One (DG1)	Medium	All
Sorting at entrances	No	No	No	No	No	No
Ramp Separation (km)	2	2	2	2	2	2
Number of highway lanes	3	3	3	3	3	3
Number of exits	20	20	20	20	20	20
Maximum slot size (vehicles)	10	10	10	10	10	10
Vehicle length (m)	5	5	5	5	5	5
Interplatoon distance (m)	50	50	50	50	50	50
Intraplatoon distance (m)	1	1	1	1	1	1
Maneuver space (m)	7	7	7	7	7	7

Performance is measured with respect to:

- Failure rate in exiting (% of vehicles that were unable to exit where desired)
- Lane change frequency (number of lane changes per meter per slot)
- Release rate (% of vehicles of arriving vehicles that were served)
- Mean waiting time until release for entrances
- Mean time to complete a lane change
- Mean vehicles per slot by location

Simulation Results: Arrival Rate per Entrance of 1080 Vehicles/Hour

Results are provided for a moderate arrival rate of 1080 vehicles/hour per entrance in Tables 4-9 and Figures 20-25. In this set of experiments, strategies that did not employ sorting at entrances became saturated at downstream entrances, whereas sorting strategies did not. Sorting was needed to ensure that the proper vehicles were in place at the front of queues when each slot passed an entrance. Most vehicles were able to exit where and when desired, for all strategies, and waiting times to change lanes varied from 20 to 120 seconds, with somewhat longer waits moving right than moving left.

Table 3. Failure Rate in Exiting, Moderate Arrival Rate

	Failure Rate in Exiting
DG1	0.002017
DG1(Sorting)	0.002108
DG2	0.000937
DG2(Sorting)	0.000183
DG3	0
DG3(Sorting)	0.00088

Table 4. Lane Change Frequency: (number of lane changes per meter per slot) Moderate Arrival Rate

Lane	1	2	3
DG1	0.009082	0.002387	0.000578
DG1(sorting)	0.008167	0.002292	0.000685
DG2	0.007193	0.002714	0.000678
DG2(sorting)	0.008372	0.002915	0.000633
DG3	0.007946	0.002714	0.000666
DG3(sorting)	0.007615	0.002558	0.000784

Table 5. Vehicles Served at Entrances

	Vehicles Served
DG1	10061
DG1(Sorting)	10639
DG2	9746
DG2(Sorting)	10500
DG3	9848
DG3(Sorting)	10734

Table 6. Mean Waiting Time for Release (seconds), Moderate Arrival Rate:

Entrance	1	2	3	4	5	6	7	8	9	10
DG1	69.5	107	59.5	22.6	45.9	25.0	92.2	260	614	130
DG1(sorting)	6.8	6.6	7.0	6.8	6.8	6.7	6.9	9.7	12.9	9.0
DG2	39.0	25.7	29.6	47.8	52.8	76.9	46.4	289	512	232
DG2(sorting)	7	6.9	6.9	6.9	6.8	6.8	6.8	10	12.7	7.8
DG3	31.6	42.9	36.9	142	41.7	46.3	43.7	402	457	363
DG3(sorting)	7.1	6.7	6.8	6.6	7.0	6.7	6.9	8.2	13.0	8.4

Table 7. Mean Lane Change Time (seconds)
From/To Lane Pairs, Moving Left
Moderate Arrival Rate

Entrance	From /To	1	2	3	4	5	6	7	8	9	10
DG1	(1,2)	30	38.8	36	39.4	37.1	38.5	36.4	41.5	43	40.4
	(2,3)	112	115	118	124	121	120	119	117	82	125
DG1 (sorting)	(1,2)	32.2	36.7	35.5	38.4	38.7	43.7	39.1	42.3	43.9	38.3
	(2,3)	116	121	118	123	117	118	120	110	82.9	141
DG2	(1,2)	15.5	13.7	17.9	19.4	19.5	19	21	22.6	20	20.8
	(2,3)	66.7	68.2	69.5	73	70.7	71.9	72.3	76.4	71.9	24.9
DG2 (sorting)	(1,2)	13.9	13.7	18.1	16.8	19.4	18.6	19.8	20.2	18.6	21.7
	(2,3)	65.9	65.8	69.5	67.9	73.5	72.4	74.4	68.6	72.2	24.7
DG3	(1,2)	13.1	13.9	17.4	16.7	19.2	18.5	20.2	20.5	18.2	22.6
	(2,3)	47.1	52.5	57.8	52.5	55.1	55.8	55.8	58	56.6	36.7
DG3 (sorting)	(1,2)	14.4	13.1	16.3	17.5	15.5	16.3	18.7	18.1	18.2	21.6
	(2,3)	50.1	50.7	54.9	51.7	56.8	59.6	54.2	55.4	55.4	24

**Table 8. Mean Lane Change Time (seconds)
From/To Lane Pairs, Moving Right
Moderate Arrival Rate**

Exit	From /To	1	2	3	4	5	6	7	8	9	10
DG1	(3,2)	38.1	38.7	36.4	46	43.4	42.5	37.9	33.8	16	1.5
	(2,1)	36.3	38.8	40.6	39.5	42.8	42.2	46	45.8	38.3	4.4
DG1 (sorting)	(3,2)	36.5	41.9	40.9	44.8	44.4	45.6	40.2	38.8	25.2	3.5
	(2,1)	37.3	39.4	42.3	38	44.6	41.4	43.2	42.9	38.3	3.8
DG2	(3,2)	21.7	22	22.3	21.8	24	24.2	23.2	25.8	19.9	5
	(2,1)	32.5	35.6	35.3	40.3	36.3	36.1	37	40.9	42.4	6.1
DG2 (sorting)	(3,2)	21.5	22.4	26.3	25.4	24	25.4	27.2	25.5	19.4	4.8
	(2,1)	33.5	40	38.2	38.8	39.5	37.1	35.4	41.2	42.4	4.5
DG3	(3,2)	20	25.2	23.5	20.4	24.9	24.3	25	23.5	17.3	4.9
	(2,1)	33.5	34.5	36	35	35.4	35.8	36.2	40.4	47	9.8
DG3 (sorting)	(3,2)	23.3	25.5	23.4	24.7	24	24.1	27.9	27.6	20	6.5
	(2,1)	35.4	36.4	34	38.2	37.7	35.6	36.9	40.6	43.5	7.4

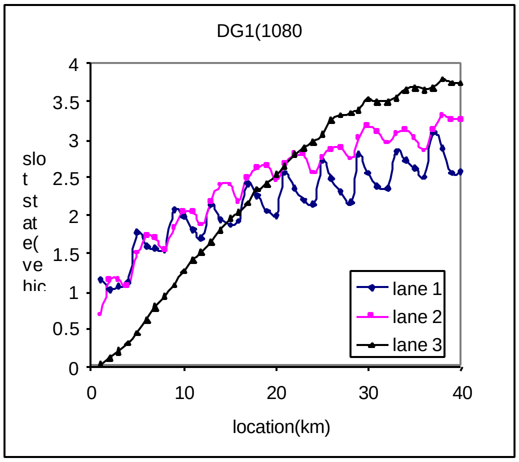


Figure 20. Mean Vehicles/Slot by Location, DG1 No Sorting

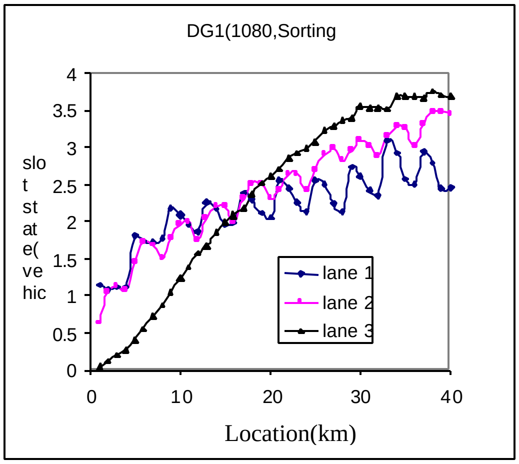


Figure 21. Mean Vehicles/Slot by Location, DG1 Sorting

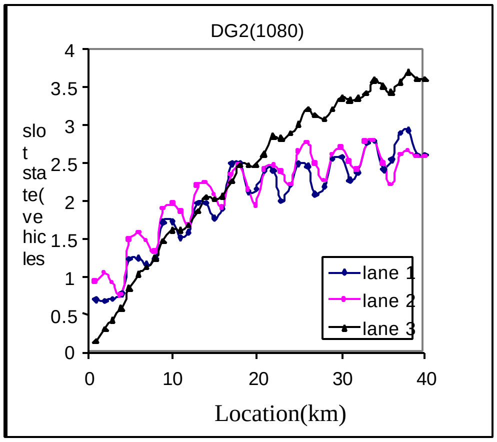


Figure 22. Mean Vehicles/Slot by Location, DG2 No Sorting

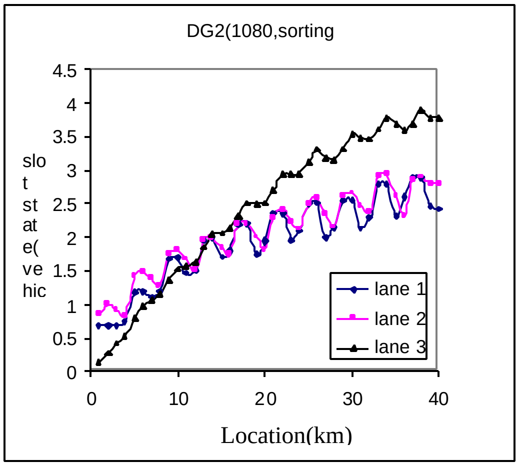


Figure 23. Mean Vehicles/Slot by Location, DG2 Sorting

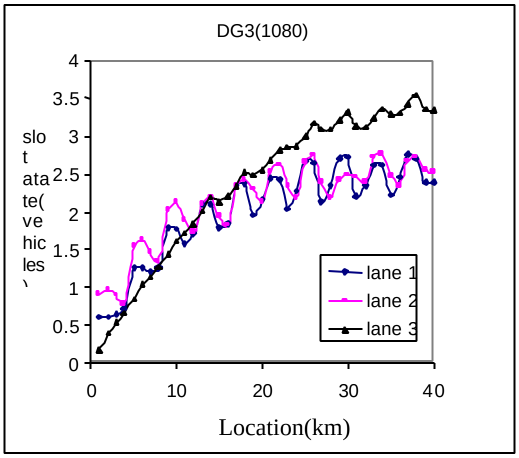


Figure 24. Mean Vehicles/Slot by Location, DG3 No Sorting

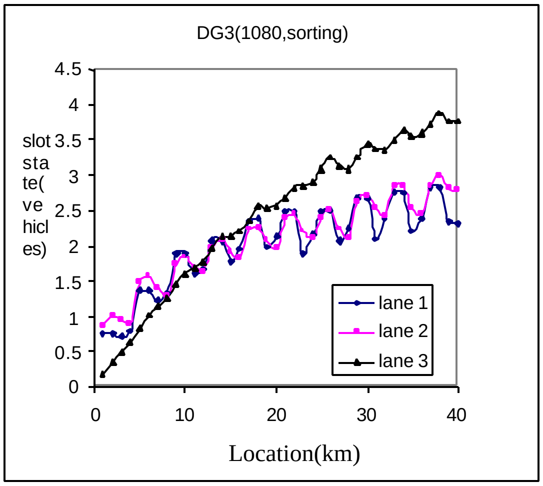


Figure 25. Mean Vehicles/Slot by Location, DG3 Sorting

Results for Arrival Rate per Entrance of 2160 Vehicles per Hour

Tables 10-15 and Figures 26-31 present results for a high arrival rate of 2160 vehicles/hour per entrance. At this arrival rate, arrival rate greatly exceeds entrance capacity for the no-sort strategies, making it is impossible to serve all arriving vehicles. While no-sort strategies perform better in exit success, this is simply the consequence of smaller traffic volumes entering the highway (because other vehicles are queued at entrances).

Compared to moderate traffic volumes, other performance measures are degraded, such as waiting time at entrance, waiting time for lane changes and failure rate in exiting. In all of the no-sort cases, failure rate in exiting is higher than acceptable, falling in the 1 to 3% range, with DG1 performing the worst. One issue revealed through the simulation is that when slots serve a narrow group of destinations, then are large number of vehicles will need to exit from a slot simultaneously. This can locally saturate the highway, compared to strategies that intersperse vehicles with different destination among different slots. To resolve this problem, a future version of the simulator will be designed to represent platoon exiting, where an entire platoon changes lane or exits simultaneously.

Overall, the simulations reveal the need for further study on assignment and exiting strategies, which will be undertaken in a follow-up project, already funded by PATH.

Table 9. Failure Rate in Exiting, High Arrival Rate

	Failure Rate in Exiting
DG1	0.005241
DG1(Sorting)	0.02973
DG2	0.001409
DG2(Sorting)	0.017256
DG3	0.002206
DG3(Sorting)	0.017875

Table 10. Lane Change Frequency, High Arrival Rate (number of lane changes per meter per slot)

Lane	1	2	3
DG1	0.00967	0.00221	0.00061
DG1(sorting)	0.00737	0.00188	0.00037
DG2	0.00999	0.00306	0.00078
DG2(sorting)	0.00920	0.00293	0.00087
DG3	0.00942	0.00349	0.00091
DG3(sorting)	0.01368	0.00401	0.00098

Table 11. Vehicles Served at Entrances, High Arrival Rate

	Vehicles Served
DG1	11199
DG1(Sorting)	21369
DG2	10870
DG2(Sorting)	21628
DG3	11239
DG3(Sorting)	21490

Table 12. Mean waiting time of vehicles for release (minutes)

Entrance	1	2	3	4	5	6	7	8	9	10
DG1	10.9	12.4	12.2	14.7	12.8	14.4	14.9	20.1	19.5	15.1
DG1(sorting)	.11	.11	.12	.11	.11	.12	.12	.21	.56	.38
DG2	13.9	13.1	14	14	14.5	15.4	16.7	18.7	19.8	16.6
DG2(sorting)	.12	.12	.12	.12	.12	.12	.14	.23	.38	.18
DG3	14.5	12.7	13.5	13.7	13.7	14	13	17.6	20.4	14.2
DG3(sorting)	.11	.12	.12	.12	.12	.12	.13	.23	.32	.17

Table 13. Mean Lane Change Time (seconds)
From/To Lane Pairs, Moving Left
High Arrival Rate

Entrance		1	2	3	4	5	6	7	8	9	10
DG1	(1,2)	27.3	36	32.3	40.3	36.9	43.8	40.2	44.3	40	38.1
	(2,3)	112	115	120	124	125	114	127	121	86	187
DG1 (sorting)	(1,2)	30.9	41.9	40.3	44.2	41.4	48.8	45.7	46.7	50	44.2
	(2,3)	112	121	117	123	127	135	128	125	102	154
DG2	(1,2)	17.1	14.8	15.3	17	19.3	19.4	18	18.9	22	23.6
	(2,3)	62.5	68.3	68.1	73.1	75.4	80.8	80.5	85.6	76	35.9
DG2 (sorting)	(1,2)	13.7	16.8	21.1	23.6	27.7	29.3	35	40	38	31.5
	(2,3)	65.4	69.7	76.1	73.8	80.4	88.5	85.9	91.3	81	33.7
DG3	(1,2)	13.2	14.8	16.1	16.3	18.9	19.8	23.2	19.8	20	23.6
	(2,3)	49.3	51.2	52.8	57.5	57.3	58.9	60.1	62.5	54.9	35.4
DG3 (sorting)	(1,2)	15.1	15.6	18	21.8	24.8	30	33.2	35.2	41.4	35
	(2,3)	49.9	53.5	57.6	64.4	69.8	76.2	77.8	70	64.1	55.7

Table 14. Mean Lane Change Time (seconds)
From/To Lane Pairs, Moving Right
High Arrival Rate

Exit		1	2	3	4	5	6	7	8	9	10
DG1	(3,2)	39.2	41.5	43.5	45.2	44.1	42.2	43.4	33	22.4	2.8
	(2,1)	37.7	42	44.4	42.2	46	46.8	48.5	47.2	40.8	3.1
DG1 (sorting)	(3,2)	42.3	50	53.2	58	59.3	60.2	53.4	43.4	17.1	6.7
	(2,1)	42.2	45.5	49.4	54	60.1	59.5	64.3	60	34.8	5
DG2	(3,2)	22.7	24.1	22.7	24.4	24.5	27.2	23.4	21.1	15.9	5.8
	(2,1)	34.7	34.8	35.4	37.5	39.3	36.3	33.1	42.6	46.2	6
DG2 (sorting)	(3,2)	27.9	31.3	37.6	41.1	42.8	46.8	49.6	37	22.6	5.3
	(2,1)	37.3	39.5	44.8	45.5	45	47	45	50.8	34	7.3
DG3	(3,2)	21.2	22.7	25.9	24.2	25.3	26.8	29	29.5	19.1	7.1
	(2,1)	31.9	34.8	34.9	34.7	35.1	34.6	37.7	42.1	43.2	6.3
DG3 (sorting)	(3,2)	31	34.6	37.9	43.2	44.4	50.2	44.8	40.6	49.2	6.6
	(2,1)	37.2	39.1	43.1	45.5	46.4	44.9	48.3	46.7	33.5	7.3

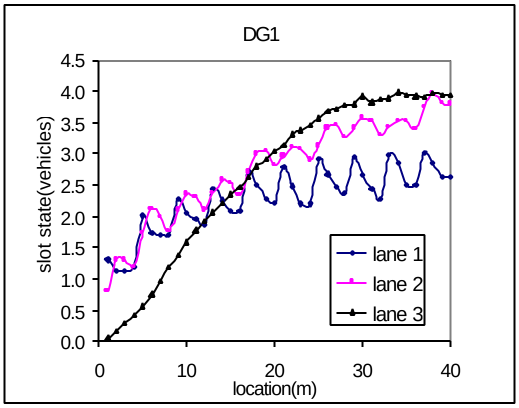


Figure 26. Mean Vehicles/Slot by Location

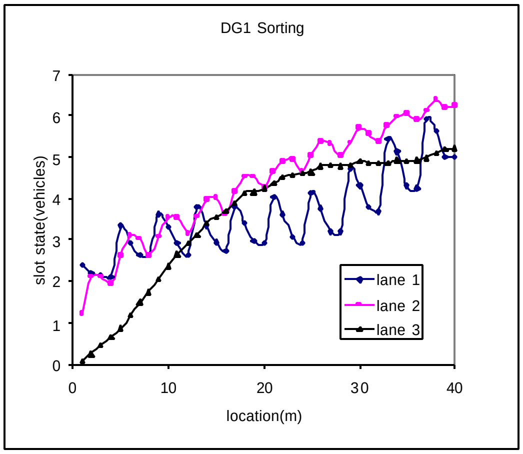


Figure 27. Mean Vehicles/Slot by Location, DG1 Sorting

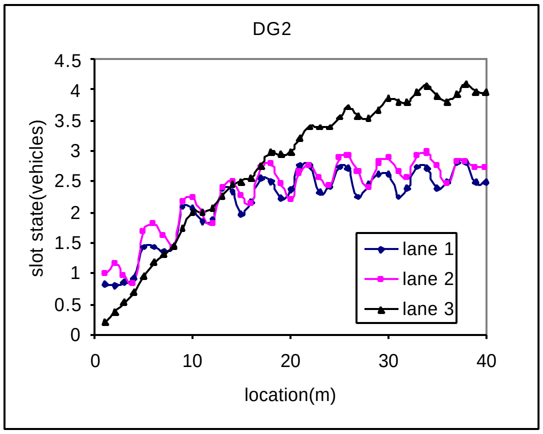


Figure 28. Mean Vehicles/Slot by Location, DG2 No Sorting

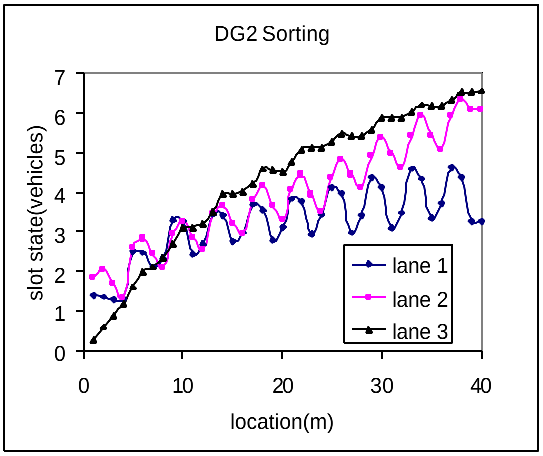


Figure 29. Mean Vehicles/Slot by Location, DG2 Sorting

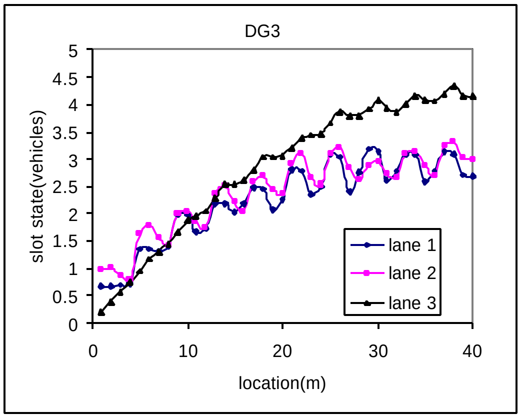


Figure 30. Mean Vehicles/Slot by Location, DG3 No Sorting

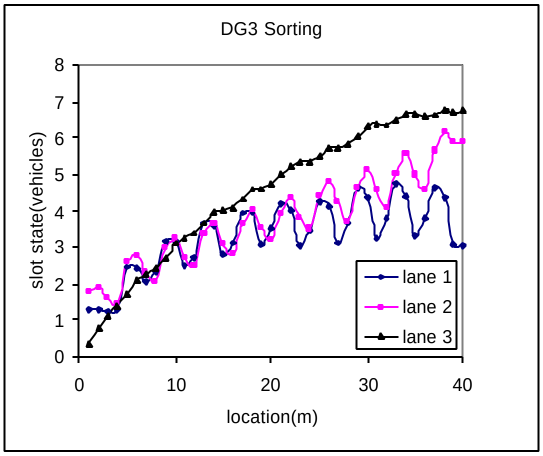


Figure 31. Mean Vehicles/Slot by Location, DG3 Sorting

4. PHYSICAL DESIGN FOR AHS ENTRANCE/EXIT

Chapter 1 presented strategic issues in the formation of AHS network interfaces. This section examines how these strategic issues translate into the physical design of the interface. The physical design is addressed from four perspectives: (1) as built physical design of the highway, (2) land uses surrounding the highway, and (3) physical requirements of the AHS entrance/exit concept. We examine these issues from the perspective of actual highways in the Los Angeles region through case studies. Our focus is on automation concepts that require specialized facilities, such as separated lanes or vehicle inspection sites, because these concepts are the most demanding with respect to physical design of AHS entrances and exits.

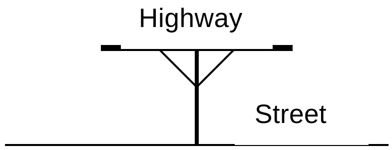
As Built Physical Design

The as built physical design represents the construction of an existing, conventional, highway, and whether that design is amenable to the addition of automated lanes and automated entrances. We consider cases in which the AHS location coincides with a conventional highway. Designs are classified according to several attributes, which constitute the space occupied by the highway. These follow.

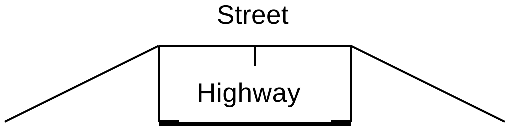
Highway Elevation

Highway elevation represents the height of the highway relative to the natural grade of the land that is being traversed. A highway may be elevated above grade level, at-grade, or submerged below grade (Figure 32). In some cases a different elevation is used for each direction of travel (e.g., one direction is constructed above another direction). A highway may also alternate between elevated, at-grade and submerged designs, possibly to provide a more level roadway than an uneven surrounding terrain.

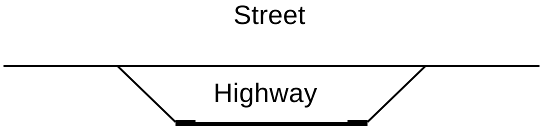
Elevated designs raise the highway above surrounding land, either structurally or through elevating the highway on fill. An elevated highway crosses above streets, which means that streets can pass under the highway without the construction of bridges. In addition, the land beneath the highway can be captured for parking, storage and other low-intensity land uses (assuming a structure is used to elevate the highway). The area underneath the highway might also be used for staging vehicles for AHS entrance or exit.



Elevated Highway



At-Grade Highway



Submerged Highway

Figure 32. Highway Elevations (cross-sections)

At-Grade places the highway at the same level as surrounding land. A disadvantage of at-grade is that each roadway that crosses the highway requires a bridge or tunnel. The advantage is that it is less expensive to construct the highway itself (as opposed to the crossings and interchanges) at grade than by other methods. At grade is the predominant technique in low density or rural areas, where few roadways need to cross the highway. When constructed in developed areas, an at-grade design can impose a barrier between communities, as the construction of highway crossings is costly.

Submerged entails digging a viaduct below the grade of surrounding land. The cost of roadway crossings for a submerged highway is less than at-grade, but more expensive than elevated. Though bridges need to be constructed at crossings, they can be constructed at a level grade, making them simpler and easier to build than on an at-grade highway. Submerged highways are also advantageous in that they are somewhat less intrusive on surrounding land uses, because noise is more contained, the highway is visually less obtrusive, and pedestrians can cross the highway with relative ease. In rare cases, an actual tunnel is constructed, which minimizes the impact of the highway on surrounding areas (once construction is completed) and permits development above the highway. However, tunnels are usually prohibitively expensive.

Median and Frontage

Buffers may be provided for traffic separation, and/or future expansion. Medians vary greatly in width, but tend to be small or virtually non-existent in urbanized areas. When the median is small, traffic barriers must be used to prevent head-on collisions. Frontage areas separate the highway from surrounding areas, and also vary greatly in width. In addition to being used for safety and future expansion, frontages also reduce the impact of the highway on surrounding areas.

Auxiliary Lanes and Shoulders

Beyond the lanes for accommodating through traffic, a highway may contain auxiliary space for stationary vehicles or vehicles entering or exiting the highway. **Shoulders** provide space for parking disabled vehicles, and may be built on one or both sides of the highway. **Transition** lanes provide an interface between the highway and surrounding streets, running in parallel to the highway. In some cases, transition lanes are provided over an extended length of highway, and serve multiple entrances and exits. Figure 33 shows a prototypical highway, with a continuous transition lane running along the right side, and shoulders on both the right and left sides of the mainline.. Both transition lanes and shoulders increase the width of the highway, but are beneficial in providing smoother traffic flows, fewer operational interruptions and greater safety. They may specifically be used to keep weaving from disrupting through traffic.

Specialized Lanes

Many freeways today provide lanes that are restricted to high-occupancy-vehicles; also, some locations have lanes that are designated for slow moving vehicles or trucks. Specialized lanes may only be separated from regular lanes by roadway markings, or they may be physically separated from regular traffic (sometimes at a different elevation).

Highway/Road Connectivity

Highways are connected to ordinary streets via on-ramps and off-ramps. Twelve ramps are required to completely connect two roadways, providing access from each of four directions of travel (two directions on highway and two on street) to each of three outgoing directions of travel (left, right or forward). Figure 34 provides three alternate ramp designs for executing a left-turn, and Figure 35 provides three alternate ramp designs for executing a right turn. In an indirect ramp (typical for a diamond style interchange), vehicles must slow to a stop (or near-stop) before entering or leaving the street. In addition, vehicles typically must wait for an available gap or signal phase before entering or passing through cross-traffic on the street. In a low-speed/direct ramp (typical for a cloverleaf style interchange), these delays are greatly reduced, but vehicles must still reduce speed to negotiate the ramp. In a high-speed/direct ramp (common for highway to highway interchanges), the transition from one road to another requires minimal, if any, slowing.

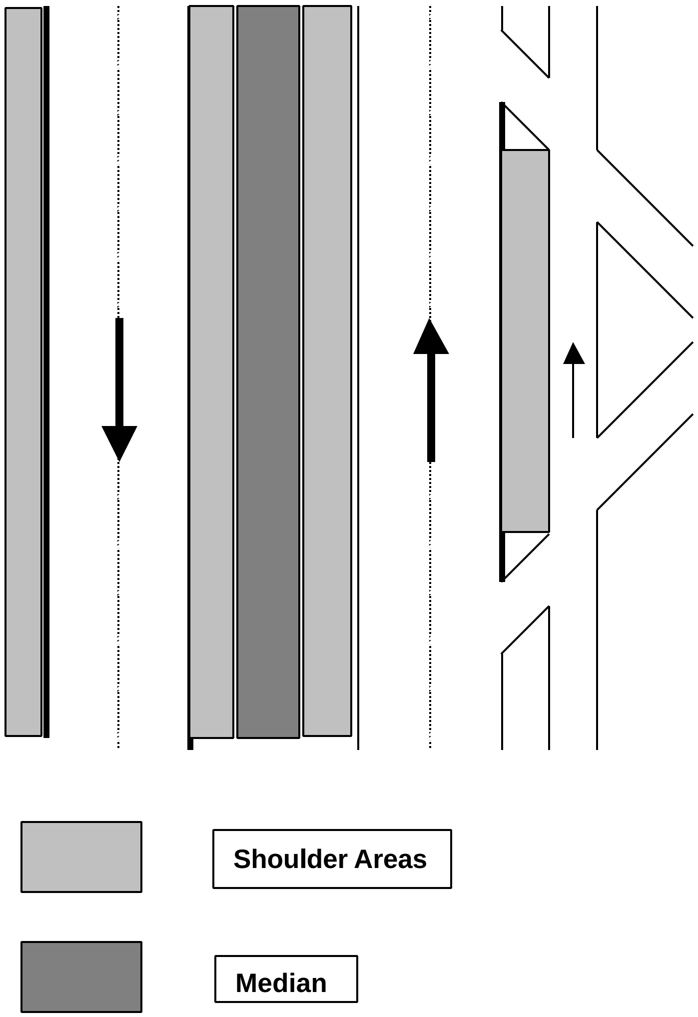


Figure 33. Highway with Auxiliary Lanes

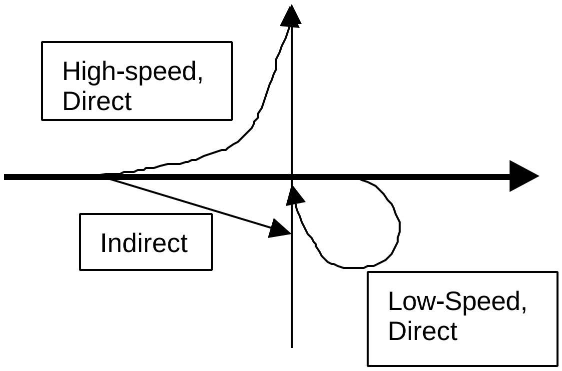


Figure 34. Three Options for Left Turn from Highway to Street. Indirect Design Delays Traffic, But is the Most Space Efficient and Least Costly.

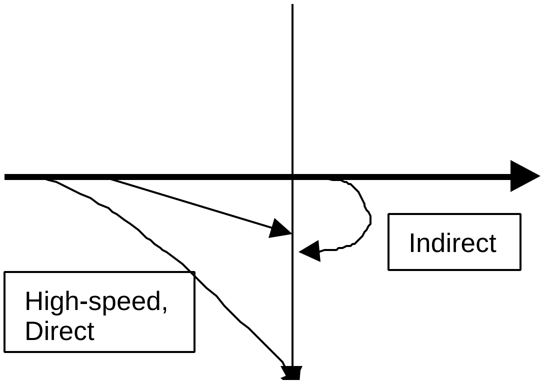


Figure 35. Three Designs for Right Turn from Highway to Street.

Indirect ramps consume the least space and are the easiest to construct, but offer the smallest capacity and the greatest delay. They often occur in urban settings, especially when ramps are closely spaced.

Interchanges become more complicated on highways that provide specialized lanes, as additional combinations of roadways may need to be connected. The Interstate 105/110 interchange in Los Angeles is especially complicated, as each highway contains separated carpool lanes; I-105 additionally has a light rail line in its median and I-110 has a bus station in its median. Direct high-speed connections are provided between carpool lanes, as well as between regular lanes.

Barriers

Barriers are frequently provided to keep highway traffic from harming surrounding areas. Examples include noise walls, physical safety barriers, and aesthetic screening. In all three examples, barriers substitute, to some degree, for the separation of medians and frontages. For instance, a highway median can be narrowed if a barrier separates two directions of travel. And a noise wall can enable highway lanes to be built in closer proximity to surrounding residences. Barriers have become an increasingly common way to enable highways to be widened without expanding the right-of-way.

A related issue is the construction of retaining walls, which also helps reduce the right-of-way requirement. For instance, in a submerged design, a retaining wall can enable the highway to be built up to the property line, rather than be separated by a sloped surface.

Surrounding Land Uses

This section is concerned with the availability of land in the vicinity of interchanges and the challenges in acquiring land in the vicinity of interchanges. Surrounding land uses constrain AHS design in two ways: (1) they may limit the amount of space available (or the cost of space) 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 may be significant at interfaces, due to the requirements of inspection, buffering, acceleration/deceleration, and extra ramps needed to inter-connect various roadways. One mile of highway lane consumes 63,360 square feet per direction of travel based on 12 foot width. A staging area, combined with an entrance or exit ramp, could potentially occupy a similar amount of space. Thus, if interchanges are spaced too frequently, and entrances and exits are not carefully designed, AHS interfaces could occupy more space than lanes themselves.

If additional space is needed at an interchange, then land needs to be acquired at prevailing market rates. If adjacent properties are highly developed (e.g., if high-rise buildings have been constructed), structures may need to be demolished, and land acquisition costs may be prohibitive. Even if additional property is not needed, negative impacts on surrounding properties, in the forms of noise and pollution, may restrict expansion options.

Surrounding land use can be characterized both by current use, and by permitted use. Changes in zoning classification alone can change the value of a property, whether or not a permitted structure has been built.

Right-of-Ways

Right-of-ways – which represent the entire size of the property owned by the highway authority -- vary greatly in size. The highway authority typically owns some amount of land adjacent to the highway, both to provide a buffer from other land uses and to provide space for future expansion. If the highway was constructed at a time when surrounding property had not yet been developed, the right-of-way would likely be larger than if the highway was constructed within an already developed area. Rights of way are frequently non-uniform, meaning that they are narrow in some places and wide in others. In some places rights-of-way are sufficient to add highway lanes, but not to enlarge interchanges.

Zoning Classifications

Each property is subject to a zoning classification, as established by its municipality or county. The zoning classifications for Los Angeles County are provided in Table 15. Each classification allows a limited set of uses, and restricts the intensity of development (e.g., the percentage of property than can be covered by a building, the square-footage of the building, or the height of a building). For instance, R-1 (residential) property may be used for the following purposes:

- Adult residential facilities, limited to six or fewer persons.
- Foster family homes.
- Group homes, children, limited to six or fewer persons.
- Residences, single-family
- Small family day care homes.
- Small family homes, children.

Table 15. Los Angeles County Zoning Classifications

Zone R-1 - Single-family residence
Zone R-2 - Two-family residence
Zone R-3-( )U - Limited multiple residence
Zone R-4-( )U - Unlimited residence
Zone R-A - Residential agriculture
Zone RPD - Residential planned development
Zone A-1 - Light agriculture
Zone A-2 - Heavy agriculture
Zone A-2-H - Heavy agriculture including hog ranches
Zone C-H - Commercial highway
Zone C-1 - Restricted business
Zone C-2 - Neighborhood commercial
Zone C-3 - Unlimited commercial
Zone C-M - Commercial manufacturing
Zone C-R - Commercial recreation
Zone CPD - Commercial planned development
Zone M-1 - Light manufacturing
Zone D-2 - Desert-Mountain
Zone IT - Institutional
Zone SP - Specific Plan
Zone M-1 1/2 - Restricted heavy manufacturing
Zone MPD - Manufacturing industrial planned development
Zone M-2 - Heavy manufacturing
Zone M-3 - Unclassified
Zone M-4 - Unlimited manufacturing
Zone M-2 1/2 - Aircraft, heavy industrial
Zone B-1 - Buffer strip
Zone B-2 - Corner buffer
Zone R-R - Resort and recreation
Zone W - Watershed
Zone P-R - Restricted parking
Zone SR-D - Scientific research and development
Zone O-S - Open space
Zone A-C - Arts and crafts
Zone MXD - Mixed use development

Property that is zoned for more intense development (e.g., commercial or multiple residence) tends to be higher valued than property that is zoned for limited development (e.g., open space). In some locations, areas surrounding highway interchanges have been zoned for intense levels of development because they are highway accessible, which consequently raises the value of the property, and the cost of land acquisition. Land along the highway itself may be cheaper to acquire than land in the vicinity of interchanges, because of prevailing land use and zoning.

The zoning regulations for a property are defined by a zoning map and zoning ordinance. The map defines the classification, which is typically applied to a group of adjacent properties surrounded by well-defined boundaries, such as streets. The ordinance defines the permitted uses and intensity for the classification (i.e., the same rules apply to all properties that have a given classification) and other regulations that are specific to the classification.

Actual Use

The actual property use depends on the zoning classification, but is not always in accordance with the classification. Zoning ordinances change over time, and a use or structure that was once permitted may no longer be permitted under the current ordinance. A property owner only needs to bring the property into compliance when further construction is proposed, when the property is sold, or possibly never. A property owner may also petition for a zoning variance, for instance to increase the square-footage beyond the amount normally allowed. On the other hand, property owners often do not build to the maximum extent permitted under the ordinance, though they may elect to expand at a future date. For all of these reasons, the properties within any given classification may exhibit wide variation in actual use.

Records of actual use are maintained by the county assessor's office. Assessor records are organized by Assessor Maps, which generally correspond to subdivision tracts. Each property on an assessor map has a lot number, and an assessor identification number. Assessor records include valuation of property and valuation of improvements (e.g., structures), date when the property last sold, transaction price for most recent sale, square footage of structures, square footage of property, and number of rooms (for residences). Assessor property valuations are generally not accurate, as inflationary increases are limited by state Proposition 13. Valuation tends to be far below actual market prices for properties that have not sold in recent years. Counties and municipalities also maintain records on building permits, which can provide more detailed information on structures, but tend not to be easily accessible.

Various private organizations sell data on real-estate transactions, including specifics on the units being sold. Dataquick, for instance, provides detailed information, derived from real-estate listings.

AHS Entrance/Exit Concept

The entrance/exit concept is dictated to a great degree by the concept for operating the automated highway as a whole, which can be characterized by such attributes as: (1) technology for detecting surrounding vehicles and obstacles, (2) technology for coordinating vehicle flows, (3) vehicle spacing and platooning, (4) intermixing of automated and manual vehicles, (5) vehicles sizes accommodated, and (6) placement of automated highway relative to a conventional highway. Our focus is on highways that utilize platoons for grouping adjacent vehicles, that do not intermix manual and automated vehicles, and that provide abilities for vehicles to communicate with the roadside. Under this scenario, the interface must enable the vehicle to transition from manual to automated control on entrance, and automated to manual control on exit. It must organize traffic to facilitate the formation of platoons on entrance, and deformation of platoons on exit. These actions can be coordinated through exchange of messages between individual vehicles and a roadside controller.

Entrance Tasks

At entrance, the following tasks may be required:

1) Verification and inspection to ensure that the vehicle is currently fit and permitted to operate on the AHS.
2) Verification and inspection to ensure that driver is permitted and fit to operate on the AHS
3) Ejection, in the event that a vehicle or driver fails verification and inspection.
4) Organization and sortation of traffic to optimize platoon characteristics.
5) Control of entry flows to coordinate with mainline flows.
6) Transition from manual to automated control
7) Control of vehicle speeds, along entrance ramps, to match mainline speeds

Task 7 is the only task that always occurs on conventional highways, and Tasks 1 to 4 and 6 do not occur at all on conventional highways. Each of these additional steps potentially requires additional space.

The space requirements depend on the time needed to complete the task, and the degree to which tasks can be parallelized. For instance, if inspections can be completed while the vehicle is accelerating to highway speed, the space requirement may be negligible, compared to creating a distinct inspection step that occurs while the vehicle is stationary.

Serial Concept Figure 36 illustrates a serial entrance concept, in which inspection and verification are distinct from organization, transition and flow control. In both steps, vehicles may need to come to a momentary rest, perhaps in a fashion similar to a metered ramp entrance. An advantage of this approach is that disallowed vehicles are more easily ejected, prior to forming platoons.

Parallel Concept Figure 37 illustrates a parallel concept, in which inspection, verification, organization, transition and flow control all occur in one step. Parallel processing greatly reduces the space requirements for the ramp, but can present operational problems if a larger portion of vehicles must be ejected.

Moving Concept Figure 38 illustrates the moving concept, in which inspection, verification, organization, transition and flow control occur in parallel with speed control. The moving concept has some space efficiency advantages, but is the most difficult to operationalize. It is much more difficult to eject a moving vehicle than a stationary vehicle, and it is also more difficult to sort vehicles, and control entry flows, if this is desired.

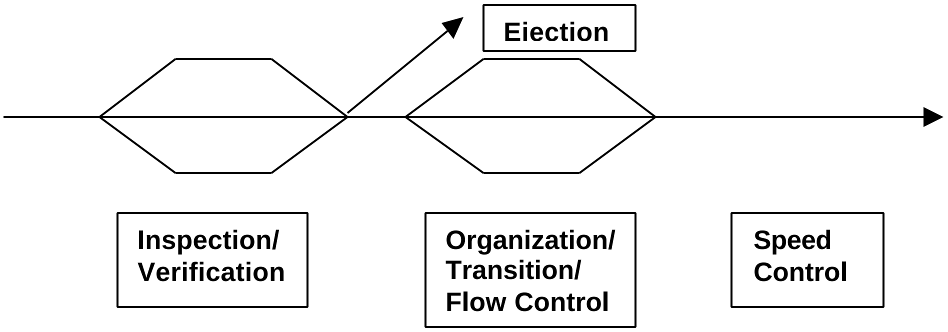


Figure 36. Serial entrance concept

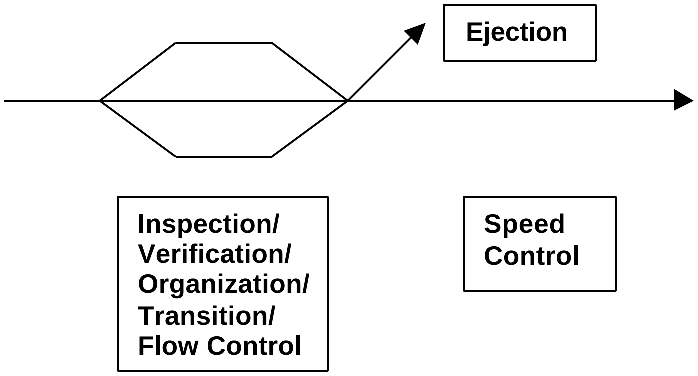


Figure 37. Parallel entrance concept

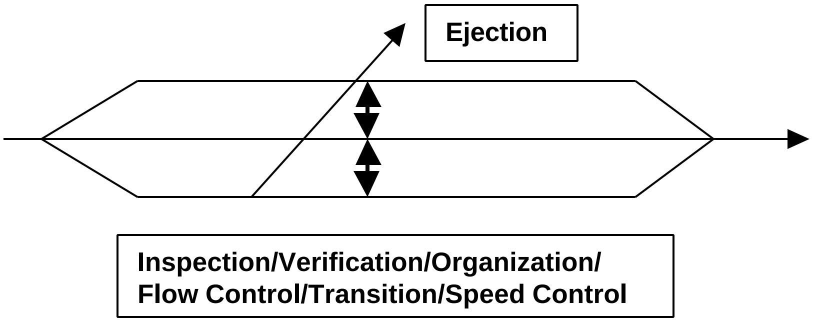


Figure 38. Moving Entrance Concept.

Exit Tasks

At exit, these steps may occur:

1) Deformation of platoon, so that each sub-platoon corresponds to exactly one vehicle.
2) Deformation of platoon, so that individual vehicles travel with safe spacing for conventional control.
3) Inspection to ensure that the vehicle is currently fit to resume manual control.

4) Inspection to ensure that driver is currently fit to resume manual control
5) Ejection, in the event that a vehicle or driver fails inspection.
6) Control of vehicle speeds along exit ramps, to match street speeds.

Similar options apply on exit as on entrance, with respect to parallel and serial tasks. It would, for instance, be feasible for whole platoons to exit from the highway and come to rest prior to inspection and transition. Alternately, these steps could occur while vehicles are in motion, with some attendant risk that drivers will be unable to resume manual control.

Situation of AHS Relative to Conventional Roadways

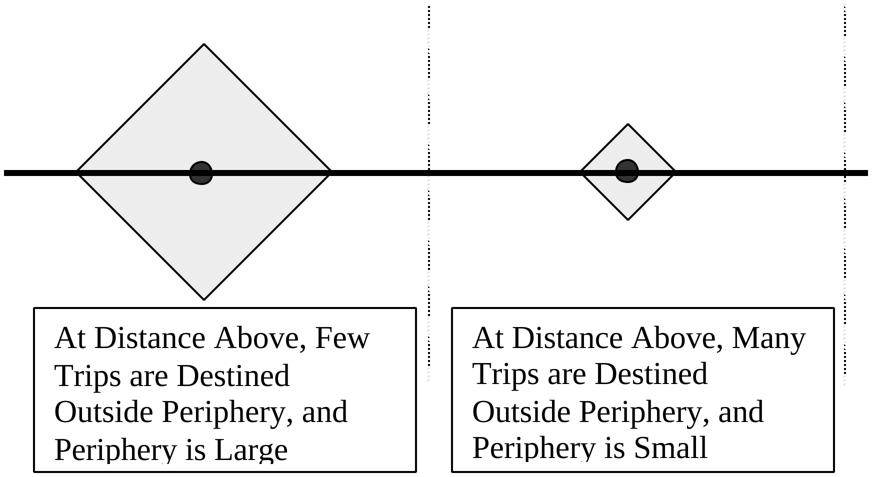
Design options include constructing the AHS to coincide with a conventional highway, or providing it with its own unique right-of-way. If the AHS does coincide with a highway, the AHS may interface with the highway or directly with the street system (e.g., their own entrance/exit ramps). For a direct interface, the AHS entrances/exits may be constructed at the same locations as conventional entrances/exits, or constructed at some alternative location.

1. Separate Right-of-Way: Interfaces Directly with Streets, with Own Entrance/Exit
2. Coincides with Conventional Highway
  2a) Interfaces with Conventional Highway
  2b) Interfaces with Streets
    2b.1) Entrances/Exits Coincide with Conventional Entrances/Exits
    2b.2) Entrances/Exits at Separate Locations

Dispersion

While an automated highway can reduce traffic on parallel streets, there is potential for increasing traffic in the immediate vicinity of entrances and exits. The effects of the highway on street traffic diminish rapidly as the distance from the highway increase for two reasons: (1) many vehicles reach their ultimate origin or destination, and thus need to travel no further, and (2) trips are spread over an increasing large periphery, meaning fewer trips traverse the periphery per unit distance (Figure 39). The effects are highly non-linear with respect to distance from the interchange, and therefore provision of infrastructure should focus on accommodating exiting/entering traffic within a fairly narrow swath around the highway.

By decreasing the spacing between interchanges (Figure 40), exiting/entering traffic is spread over more streets, and becomes more uniformly distributed among streets that are situated perpendicular to the highway. There is also less need for vehicles to travel on parallel streets, as an interchange can place vehicles closer to their origin or destination.



At Distance Above, Few Trips are Destined Outside Periphery, and Periphery is Large

At Distance Above, Many Trips are Destined Outside Periphery, and Periphery is Small

Figure 39. Traffic Dispersion Around Exits

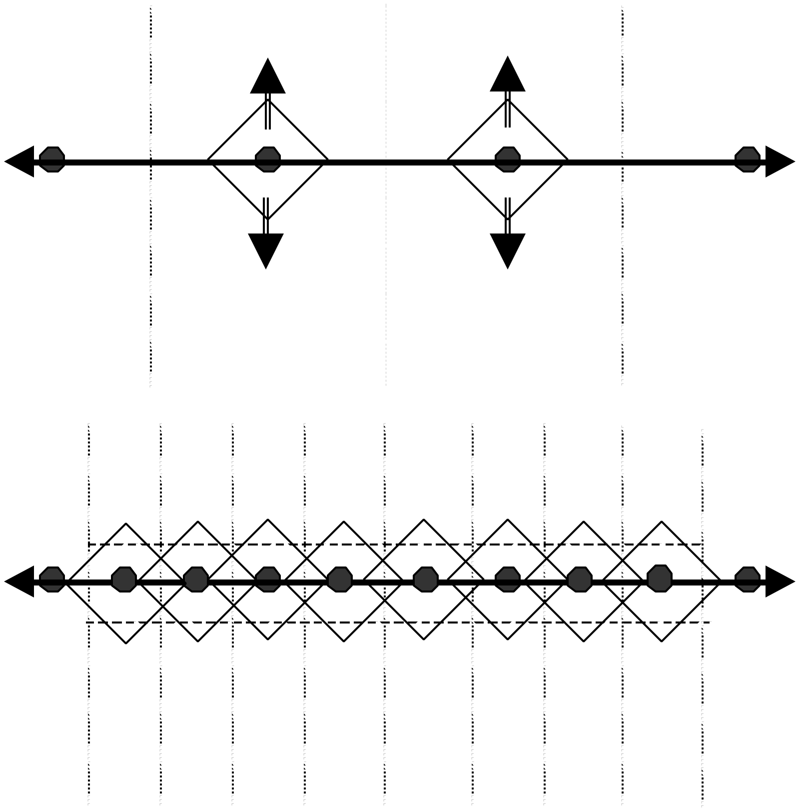


Figure 40. By Decreasing Exit Spacing, Traffic Concentration is Reduced

Traffic can be dispersed through any of several methods:

- Adding to the number of AHS entrances and exits or the number of conventional entrances and exits.
- Separating AHS entrances/exits from conventional entrances/exits
- Creating multiple street entrance/exit points for each AHS entrance or exit, possibly through the use of transition lanes or frontage road. (Figure 41)
- Constructing roadways that pass over or under the highway, so non-highway-bound traffic can bypass congested entrances and exits.
- Adding to the capacity of principal streets that access the highway, and creation of a tributary system for distributing traffic (Figure 42)

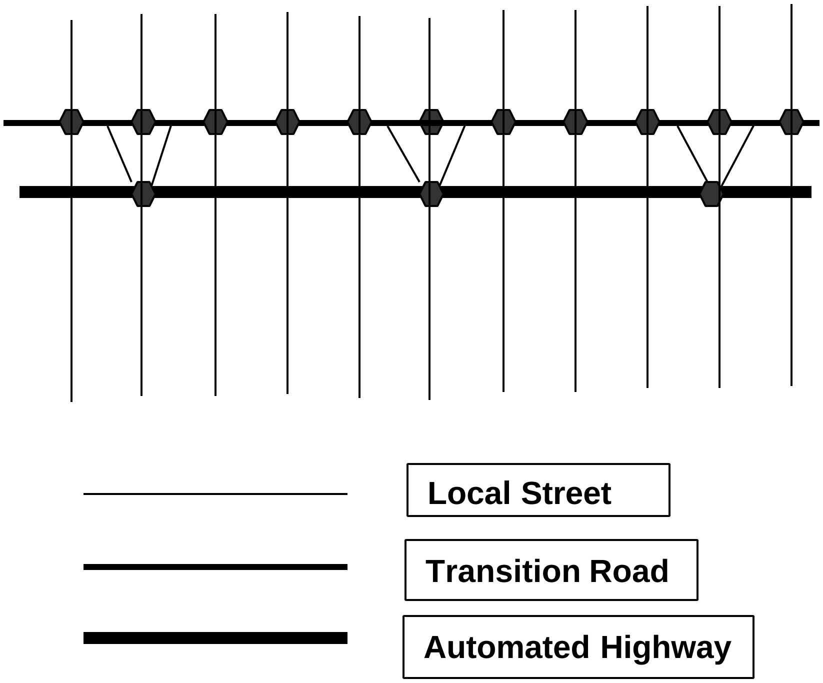


Figure 41. Dispersion of AHS Traffic Through a Transition Road

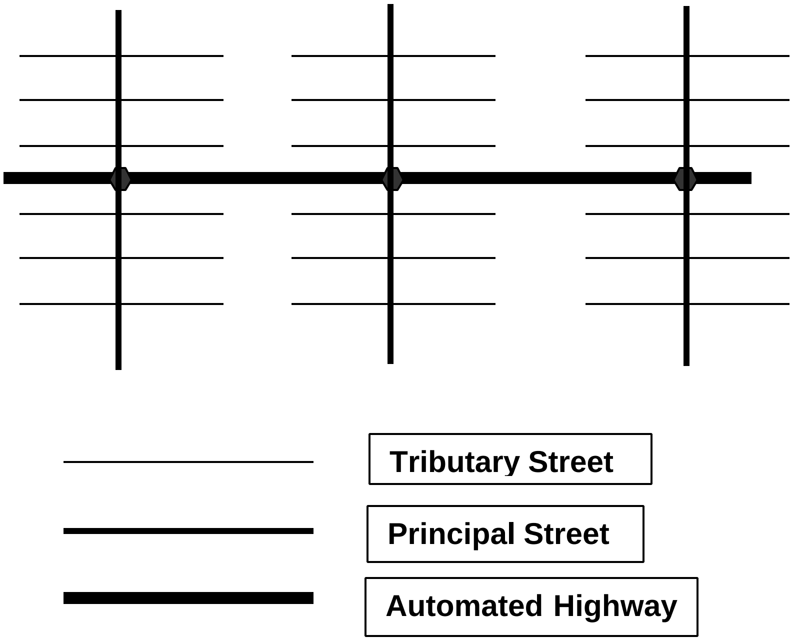


Figure 42. Traffic Distribution Through Principal and Tributary Roadways

A still different strategy would be to build more highways, at closer spacing, each with smaller capacity. This would both reduce the distance traveled on streets, and reduce the concentration of traffic in the vicinity of interchanges. However, developed cities lack suitable sites for construction of new highways, making it necessary to consider the alternative of adding capacity to existing highways instead.

In many locations, it does not seem unreasonable for local streets to absorb exiting/entering highway traffic through a combination of these methods. Let:

D = average highway trip length
F = highway traffic volume/vehicles per hour per direction
S = distance between entrances and exits on highway

Then:

V = average highway entrance/exit volume per street per direction
= S(F/D)

Some sample results are shown below

F = 20,000 vehicles per hour

	D		
S	10	15	20
.5	1,000	667	500
1	2,000	1,333	1,000
2	4,000	2,667	2,000

The combination of very high traffic volumes, short trip lengths, and long interchange spacing is problematic, as 4,000 vehicles per hour is a very high volume for city streets, even for multi-lane limited access roads. On the other hand, if traffic is dispersed among many streets, then it should be possible to accommodate exiting/entering traffic from AHS.

Case Studies

In this project, sites were visited to assess the challenges in AHS interchange construction around real highways. The work is focused 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 potential 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 10: from Downtown Los Angeles to El Monte
- Interstate 105: in Los Angeles, connecting to Los Angeles International Airport
- US 101: from Downtown Los Angeles north through San Fernando Valley

Interstate 10 contains separated carpool/bus lanes, and carries more bus traffic than any other roadway in California. Interstate 105 is the newest highway in LA County, and provides access to Los Angeles International Airport. The highway also has carpool lanes and a light rail line in its median. Interstates 5 and 101 are older and highly congested roadways. Their designs do not conform to current standards in all places. US 101, in particular, passes through a highly crowded section of Los Angeles (Hollywood , Echo Park and Downtown).

Each site was visited and photographed (Appendix A), and a street map, aerial photograph and assessor parcel map were obtained for each site (Appendix B). Location characteristics are summarized below.

Sites Along I-5

Interstate 5 is a primary north-south route spanning the Los Angeles region, continuing north to Oregon and Washington, and south to San Diego. The portion of the highway south of Downtown Los Angeles passes through older neighborhoods and industrial areas, then suburban neighborhoods. One location was visited, at the interchange with

Lakewood Street/Rosemead Blvds in Downey. The site can be characterized as suburban, with a mixture of low density housing, commercial development, park and parking lot. The interchange has a partial cloverleaf design. Due to relatively low intensity land use, and the high capacity of the intersecting street, this would be one of the easier locations to accommodate a new automated entrance.

Sites Along I-10

Interstate 10 is the major east-west artery connecting Santa Monica, West Los Angeles, Downtown Los Angeles, and points east. The segment east of downtown provides an HOV/busway facility, and the largest bus traffic in the state. Surrounding areas are predominantly commercial and residential, and become increasingly suburban in character as the highway heads east. Several locations were visited, as described below.

New Avenue (Alhambra/Monterey Park/Rosemead/San Gabriel): Suburban/Residential
This can be characterized as a compact cloveleaf design. Because the cloverleaf has been compressed into an unusually small area, turns have tight curvature, forcing vehicles to slow as they exit and enter the highway. Surrounding land is predominantly single-family residential, with a park located at the south-west corner of the interchange. Construction of a new automated entrance at this interchange would be problematic, as surrounding parcels would almost certainly need to be acquired due to the compact size of the interchange.

Rosemead Boulevard (El Monte/Rosemead): Suburban/Commercial
Like New Avenue, and many other interchanges on Interstate 10, this is also a compact cloverleaf, though not quite as compact as New Avenue. Rosemead itself is a larger and higher traffic roadway, and surrounding land uses are a mixture of commercial (north side), office (southeast side) and single-family residential (southwest side). A culvert also passes through the intersection. Due to the intensity of development, this site presents challenges, though expansion into surrounding parking lots is a possibility.

Soto Street (Los Angeles): Urban/Mixed
Soto/10 is the most complicated interchange visited, due to the width of the highway and the placement of a street intersection on a bridge above the highway. It does not follow a conventional design. Surrounding land-uses are a mixture of older residential and industrial. A new AHS entrance/exit could likely be constructed within existing space, but would require investment in elevated ramps.

Sites Along I-105

Interstate 105 is a new highway, opened in the 1990s, connecting Los Angeles International Airport to points east. It provides HOV lanes, with direct connections at highway interchanges, as well as a light rail line, in the median. In the vicinity of the airport, the highway was constructed at a high elevation; further east the highway is below grade.

Aviation Boulevard (El Segundo/Los Angeles): Suburban/Industrial

I-105 is an elevated highway in the vicinity of LAX, constructed well above (perhaps 50 feet) surrounding streets, and directly over Imperial Highway. The interchange does not follow a conventional design. Surrounding land uses include industrial/airport property to the north, office to the southwest and single-family residential to the southeast. A light rail line station is also situated below the highway. Because a large section of property is already in public ownership surrounding the interchange, land acquisition is unlikely to be a major issue at this site. However, the height of the highway, and building around streets that pass below the highway, would complicate challenges.

Vermont Avenue (Los Angeles): Suburban/Residential

The Vermont/105 interchange has a conventional diamond design, modified where one entrance is placed on a separate street, and modified slightly due to the presence of carpool lanes and a light-rail line in the highway median, as well as a light-rail station. Surrounding land-uses are predominantly residential, with a mixture of single-family units and smaller apartment buildings. Union Pacific tracks parallel the highway on the south side. This site is fairly conducive to adding an AHS exit/entrance, due to the relative simplicity of the interchange and availability of surrounding properties.

Sites Along US-101

US-101 is one of the oldest highways in the region, predating the Interstate system. The interchanges investigated are all located in the vicinity of the Downtown, and are both older in character and relatively dense.

Alvarado Blvd. (Los Angeles): Urban/Mixed

The Alvarado/101 interchange has a compact diamond design, modified slightly to permit bus boarding/alighting from the highway. Surrounding land includes high-density residential, commercial properties, and some amount of vacant land to the northeast. The intersection is typical of sites along the Hollywood (101) freeway, which cuts through one of the oldest and most densely developed sections of the city. The city presents two basic challenges: (1) shortage of land for expansion, and (2) Alvarado Blvd. is already highly congested, making it difficult to absorb additional access/egress traffic.

Broadway/Spring Street (Los Angeles): Urban/Office

Broadway/Spring Street interchange is situated at the north side of the Downtown of Los Angeles, in the vicinity of office, commercial and institutional development, as well as some parking. The highway runs below grade at and around the interchange, and the interchange design is non-standard, providing access and egress to multiple streets in a multiple of ways. The narrow width of the highway, which is surrounded by large retaining walls, along with the high density of surrounding development, creates challenges. However, there may be opportunity to provide access and egress on the north side, in place of existing parking lots.

1st Street (Los Angeles): Urban/Mixed

1st Street has a partial diamond interchange, missing one of the typical four access/egress ramps. The surrounding land uses are older and highly mixed, including residential, commercial, industrial, park and some vacant property. The site is also characterized by a change in land elevation between the west and east sides of the highway. Overall, this would be one of the easier sites for adding AHS entrances and exits, due to the existence of vacant parcels in the vicinity of the highway and the relatively simple interchange design.

7th Street/Whittier Blvd. (Los Angeles): Urban/Mixed

This is one of the more complicated interchanges for two reasons: (1) the street interchange coincides with the interchange of two highways (101 and I-5), and (2) a large elevation change occurs between the west and east side of the highway. The current design is non-standard for these reasons. Surrounding land uses are industrial to the west (the lower side), and largely commercial and residential to the east. It would be a challenge to construct additional AHS entrances and exits, because they would need to be weaved among the many highway structures that already exist. However, the intersecting street appears to have excess capacity, and a large amount of land is already in public ownership surrounding the highways.

Summary

Table 16 summarizes the characteristics of the visited sites, along with the site challenges. Site challenges fall into the following general classes:

Available space: The existing publicly owned property used for highways and streets is too small to accommodate construction of new facilities. This is most common along older highways that were constructed after surrounding areas were developed (e.g., 10/New Avenue, 101/Alvarado, 101/Spring/Broadway).

Surrounding Land Uses: Surrounding properties have been developed with high intensity, making it difficult to acquire additional property to expand an interchange (e.g., 101/Alvarado and 101/Spring/Broadway).

Structures: The specific design of the existing highway or interchanges necessitates construction of more complicated structures to permit highway egress/access (e.g., 10/Soto, 101/Whittier and 105/Aviation)

Street Capacity: The intersecting street is already congested, and surrounding land-uses make the street difficult to expand (e.g., 101/Alvarado, 101/Broadway/Spring).

While none of these problems is insurmountable through sufficient investment in property acquisition and construction, they do add to the potential cost of AHS construction, especially in more urbanized areas. Specific challenges can be mitigated through these approaches:

- Creating AHS entrances and exits in locations that can more easily accommodate construction and additional street traffic. While sites immediately adjacent to downtown Los Angeles are challenging, other nearby sites seem to have both space and capacity to accommodate growth.
- Foregoing entrances and exits along highway segments that are most challenging (serving through traffic only),
- Designing entrances and exits so that connections are made to multiple streets, rather than pushing all traffic on to a single congested roadway.

Table 16. Characteristics of Sites Visited

Highway	Intersection	Elevation	Type	HOV	Community	Challenges
5	Lakewood	Elevated	Partial Clover	No	Suburban Res/Com	
10	New	At Grade	Compact Clover	Yes	Suburban Residential	Lack of Space
10	Soto	Below Grade	Custom	Yes	Mixed/Low Income	Highway Width/Structures
10	Rosemead	At Grade	Compact Clover	Yes	Suburban Commercial	Lack of Space
101	1st	Elevated	Partial Diamond	No	Mixed/Low Income	
101	Alvarado	Elevated	Diamond	No	Mixed/Low Income	Lack of Space/Surrounding Uses/Congested Street
101	Spring	Below Grade	Custom	No	High Density Commercial	Lack of Space/ High Intensity Uses
101	Whittier	At/Below Grade	Custom	No	Industrial/Residential	Uneven Terrain/ Nearby Highway Interchange
105	Aviation	Elevated	Custom	Yes	Industrial/Residential	Roads Below Highway, Height
105	Vermont	Below Grade	Diamond	Yes	Residential-Low Income	

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APPENDIX A. SITE PHOTOGRAPHS

5/Lakewood Interchange

Interstate 10 and New Avenue

Interstate 10 and Rosemead Blvd

Interstate 10 and N Soto Street

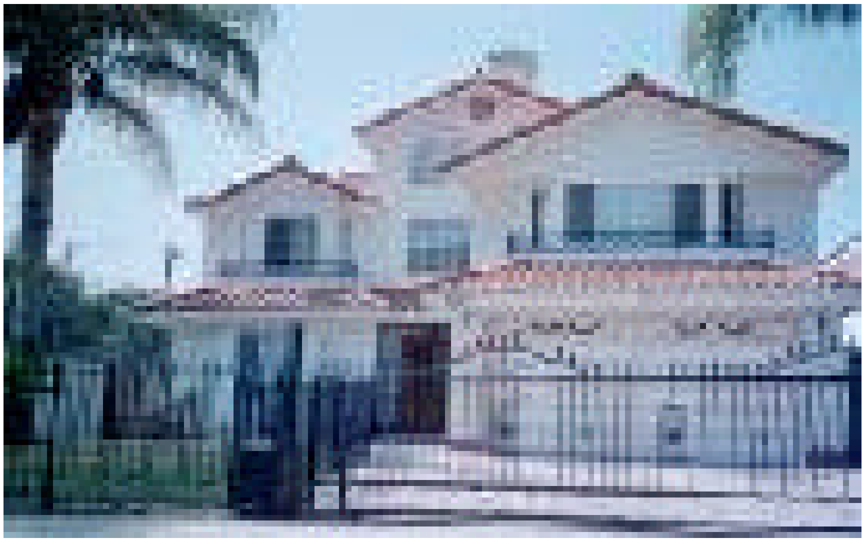
101 and N Alvarado

101 and 1st Street

101/ /Spring/Broadway Street

101 and Whittier Blvd.

Interstate 105 and Aviation Blvd.



105/Vermont Interchange

APENDIX B. MAPS AND INTERCHANGE DESIGNS

For Each Interchange, Street Map, Aerial Photo and Parcel Map are Shown in Order

Interstate 5 and Lakewood Blvd.

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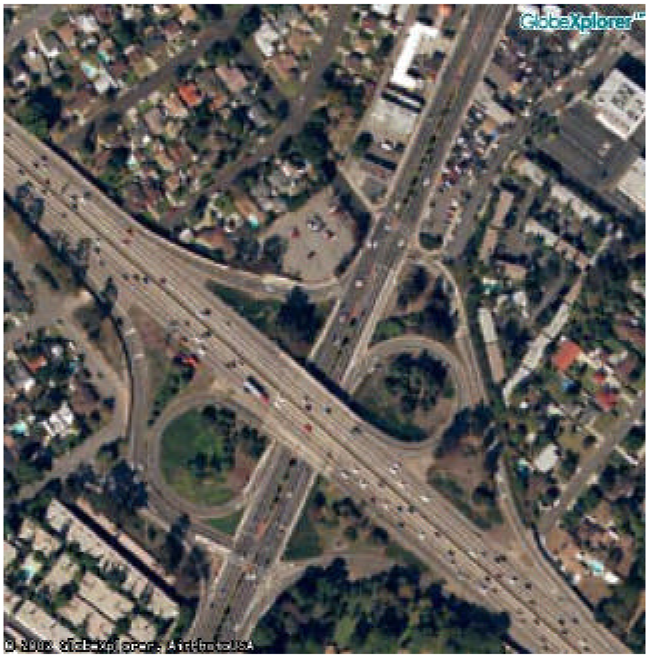

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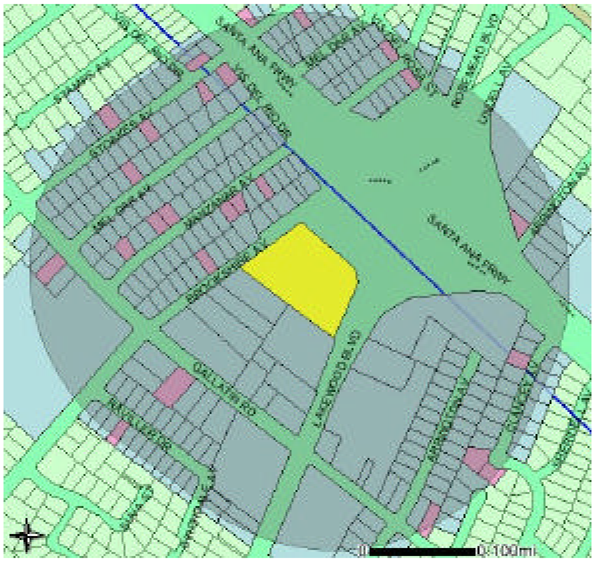
SANTA ANA FRWY
ROSEMEAD BLVD
SANTA ANA FRWY
GALLATIN RD
LAKEWOOD BLVD
0
0.100mi

Interstate 10 and New Avenue

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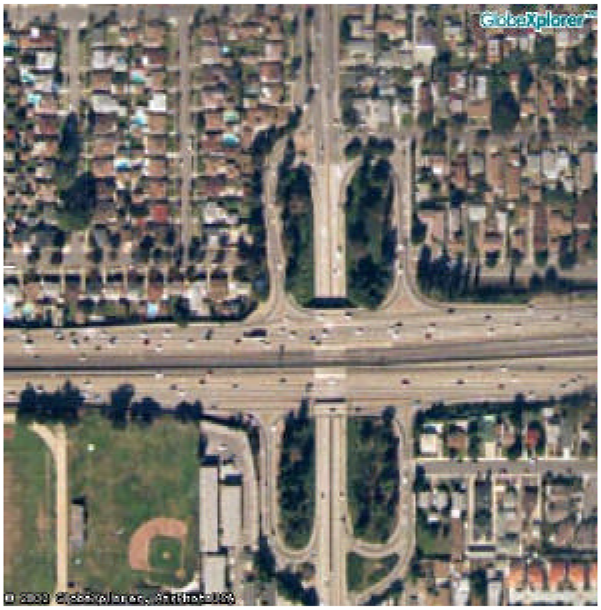

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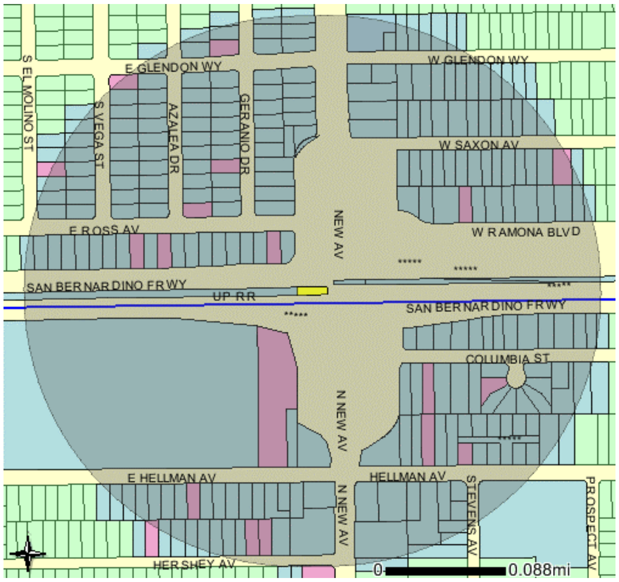
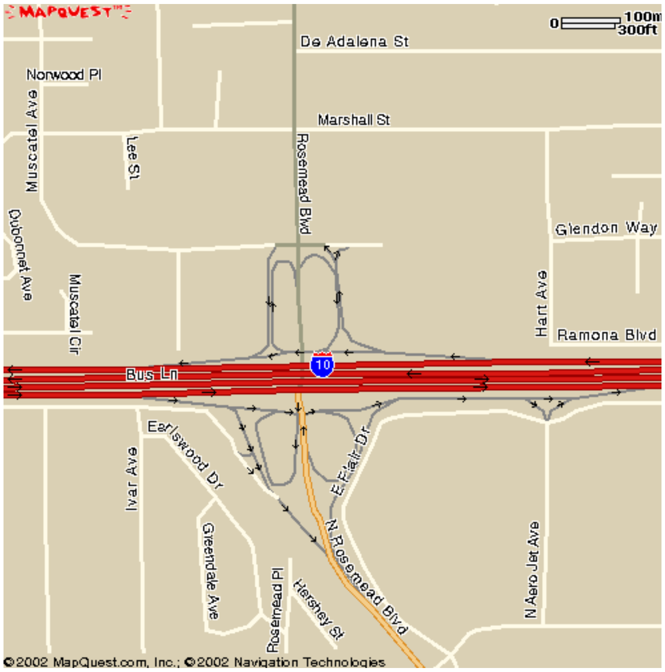

S EL MOLINO ST
E GLENDON WY
S VEGA ST
AZALEA DR
GERANIO DR
W GLENDON WY
W SAXON AV
NEW AV
W RAMONA BLVD
E ROSS AV
SAN BERNARDINO FRWY
UP RR
SAN BERNARDINO FRWY
COLUMBIA ST
N NEW AV
E HELLMAN AV
HELLMAN AV
STEVENS AV
PROSPECT AV
N NEW AV
HERSHEY AV
0
0.088mi

Interstate 10 and Rosemead Blvd.



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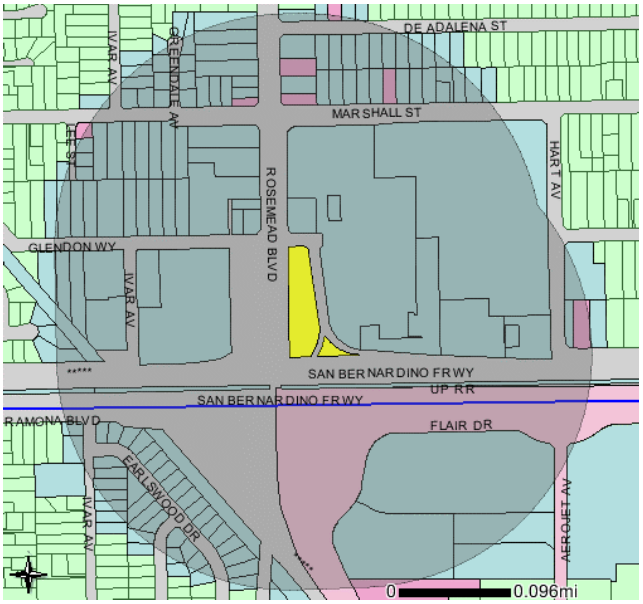
DE ADALENA ST
IVAR AV
GREENDALE AV
MARSHALL ST
LEE ST
ROSEMEAD BLVD
HART AV
GLENDON WY
IVAR AV
SAN BERNARDINO FRWY
UP RR
SAN BERNARDINO FRWY
RAMONA BLVD
FLAIR DR
EARLSWOOD DR
IVAR AV
AEROJET AV
0
0.096mi

Interstate 10 and North Soto Street

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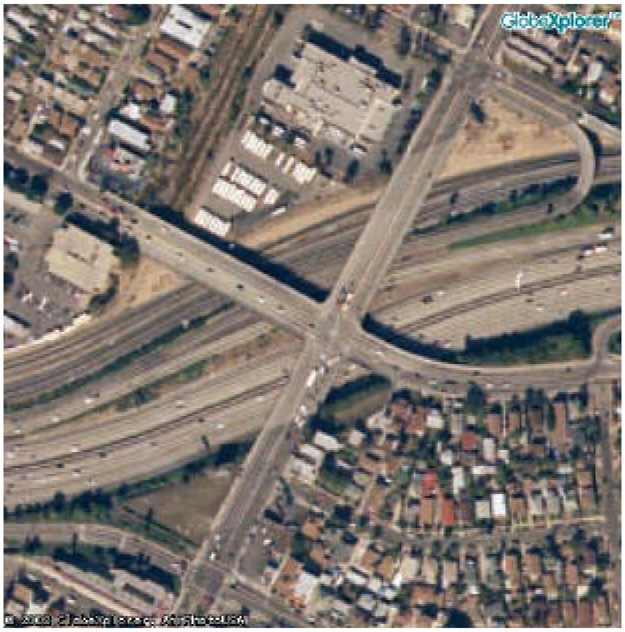

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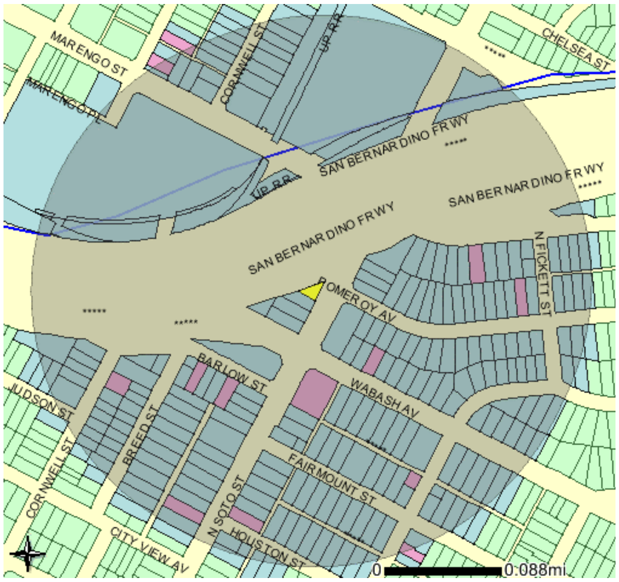
MARENGO ST
MARENGO PL
CORNWELL ST
UP RR
CHELSEA ST
SAN BERNARDINO FRWY
SAN BERNARDINO FRWY
UP RR
SAN BERNARDINO FRWY
N FICKETT ST
POMEROY AV
BARLOW ST
WABASH AV
JUDSON ST
BREED ST
CORNWELL ST
FAIRMOUNT ST
N SOTO ST
HOUSTON ST
CITY VIEW AV
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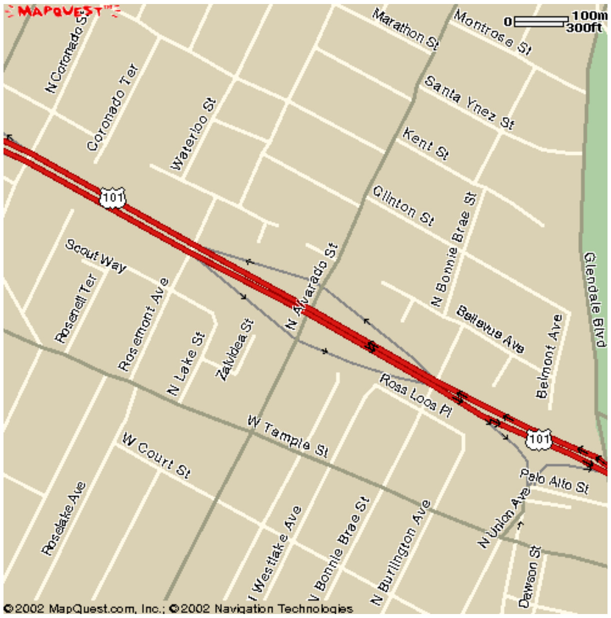
Highway 101 and N. Alvarado



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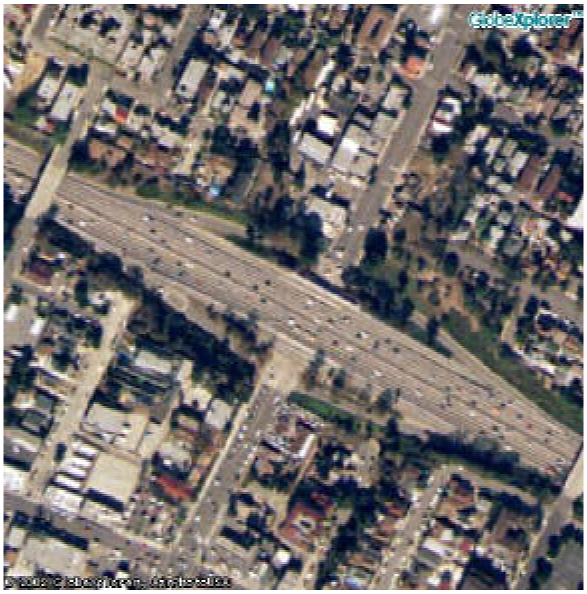
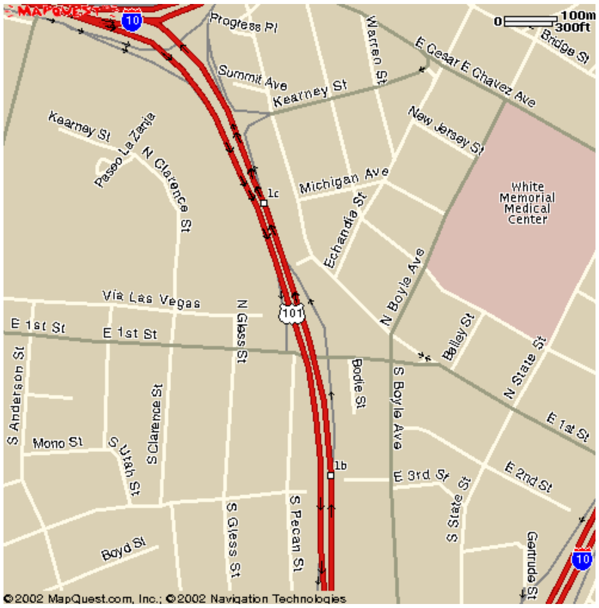


Interstate 101 and 1st Street



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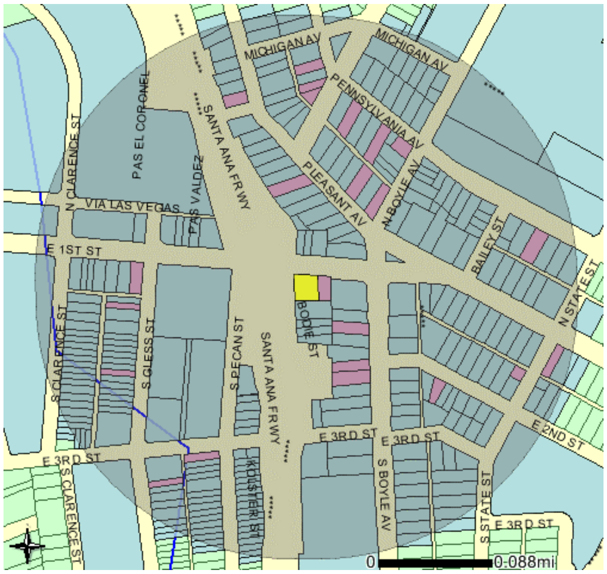
MICHIGAN AV
MICHIGAN AV
PAS EL CORONEL
N CLARENCE ST
SANTA ANA FRWY
PAS VALDEZ
PENNSYLVANIA AV
PLEASANT AV
N BOYLE AV
VIA LAS VEGAS
E 1ST ST
BAILEY ST
N STATE ST
BODIE ST
S CLARENCE ST
S GLESS ST
S PECAN ST
SANTA ANA FRWY
E 2ND ST
E 3RD ST
E 3RD ST
E 3RD ST
S CLARENCE ST
KOLSTER ST
S BOYLE AV
S STATE ST
E 3RD ST
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Interstate 101/Spring/Broadway

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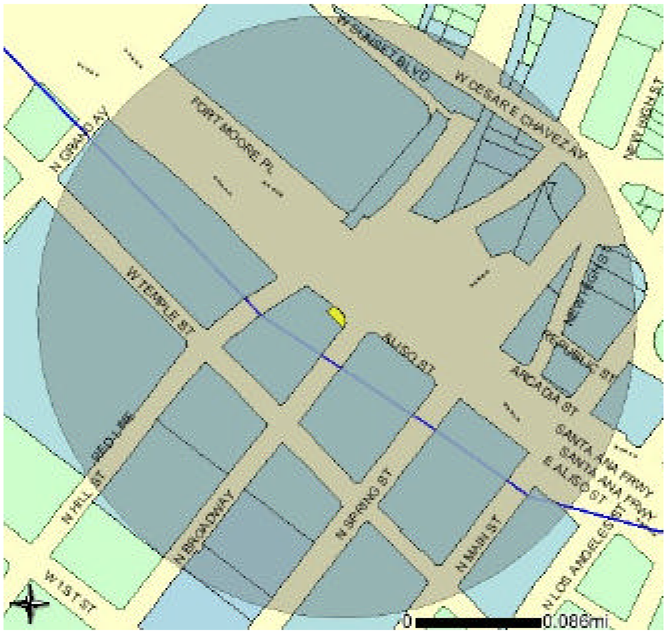
W SUNSET BLVD
W CESAR E CHAVEZ AV
NEW HIGH ST
N GRAND AV
FORT MOORE PL
W TEMPLE ST
ALISO ST
REPUBLIC ST
ARCADIA ST
SANTA ANA FRWY
SANTA ANA FRWY
E ALISO ST
N HILL ST
N BROADWAY
N SPRING ST
N MAIN ST
N LOS ANGELES ST
W 1ST ST
0
0.086mi

Interstate 101 and Whittier

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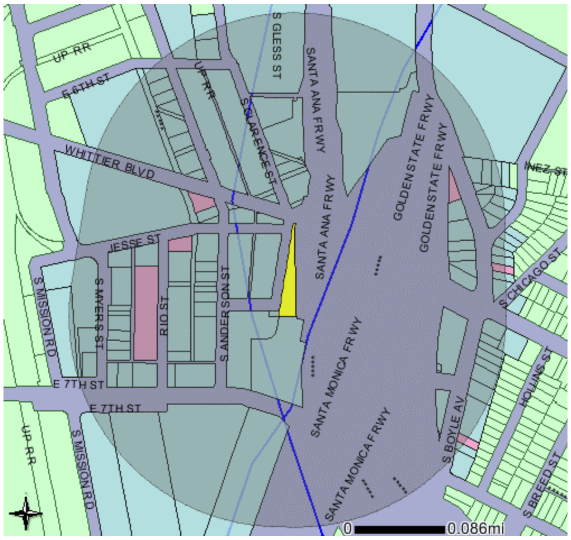
UP RR
E 6TH ST
S GLESS ST
SANTA ANA FRWY
UP RR
S CLARENCE ST
GOLDEN STATE FRWY
GOLDEN STATE FRWY
INEZ ST
WHITTIER BLVD
SANTA ANA FRWY
JESSE ST
S CHICAGO ST
S MISSION RD
S MYERS ST
RIO ST
S ANDERSON ST
SANTA MONICA FRWY
HOLLINS ST
E 7TH ST
E 7TH ST
SANTA MONICA FRWY
S BOYLE AV
UP RR
S MISSION RD
SANTA MONICA FRWY
S BREED ST
0
0.086mi

Interstate 105 and Aviation Blvd.

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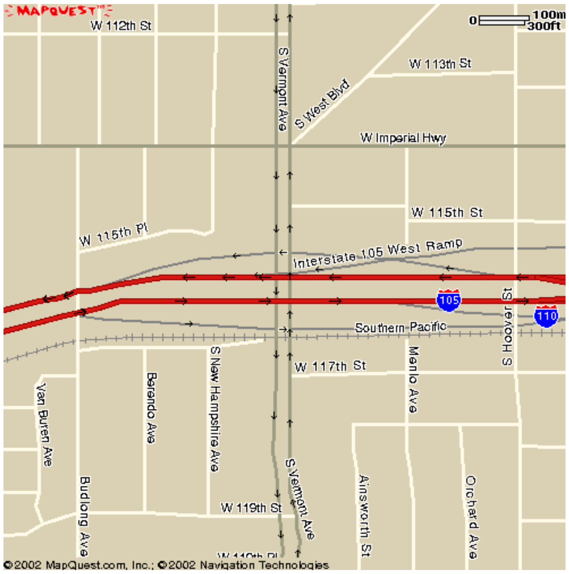
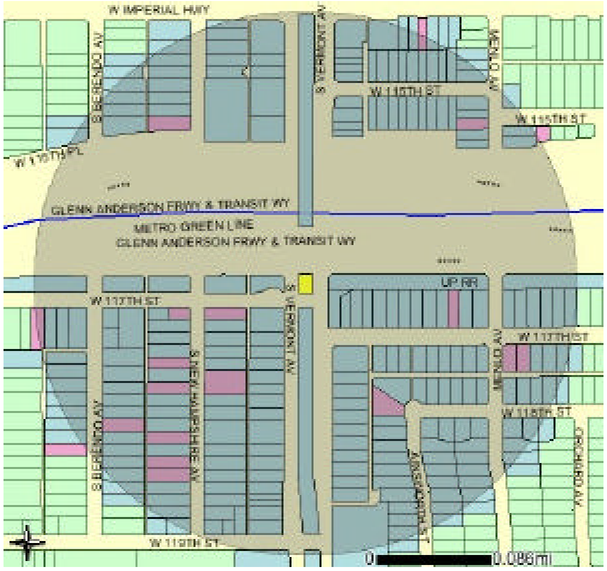
SERVICE RD
AVIATION BLVD
BNSF RR
W 111TH ST
E IMPERIAL HWY
W IMPERIAL HWY
GLENN ANDERSON FRWY & TRANSIT WY
GLENN ANDERSON FRWY & TRANSIT WY
METRO GREEN LINE
W 116TH ST
W 117TH ST
0
0.13mi

Interstate 105 and Vermont Ave.




W IMPERIAL HWY
S BERENDO AV
S VERMONT AV
MENLO AV
W 115TH ST
W 115TH ST
W 116TH PL
GLENN ANDERSON FRWY & TRANSIT WY
METRO GREEN LINE
GLENN ANDERSON FRWY & TRANSIT WY
UP RR
W 117TH ST
S VERMONT AV
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S NEW HAMPSHIRE AV
MENLO AV
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ORCHARD AV
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