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16. Abstract

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Simulation techniques were employed with animation, which gave the viewers visual perceptions directly in addition to analytic solutions. Examples of operational analysis and planning analysis were presented to demonstrate the application.

As a result of this study, it was recommended that the density criterion be utilized for defining levels of service at toll plaza areas, and that it be incorporated into a future edition of the *Highway Capacity Manual.*

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FINAL REPORT

AN INVESTIGATION OF TOLL PLAZA CAPACITY AND LEVEL OF SERVICE

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(The opinions, findings, and conclusions expressed in this report are those of the authors and not necessarily those of the sponsoring agencies.)

Virginia Transportation Research Council
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ABSTRACT

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FINAL REPORT

AN INVESTIGATION OF TOLL PLAZA CAPACITY AND LEVEL OF SERVICE

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INTRODUCTION

Toll financing has been used as a supplemental source of revenue since this nation was founded. The primary advantages of toll financing are (1) direct payment by each driver (a form of pay-as-you-go financing), (2) an assured source of revenue that facilitates highway construction and maintenance, and (3) the ability to use toll rates as a form of congestion pricing. The use of tolls to finance highway construction has changed over the years. During periods when transportation and highway needs exceed available tax revenues, officials at all levels of government must explore possible alternatives, and toll financing is one option for supplemental revenue. There are disadvantages because toll collection can cause considerable disruption to traffic flow, resulting in delays that cause annoyance and expense.

In July 1989, the Virginia Commonwealth Transportation Board approved a proposal by a private firm (Toll Road Corporation of Virginia) to build and operate a 14-mile extension of the Dulles Toll Road. This is a milestone in highway finance; it characterizes a significant change in building in the United States. The construction of toll roads has experienced a resurgence in recent years. Numerous facilities are being planned, designed, and constructed not only across the United States but in many other countries around the world. In the United States, 26 states have 4,700 miles of toll roads, bridges, and tunnels. Approximately 5,312 miles of toll highways have been built in France, Italy, and Spain.[4]

Figures collected by the International Bridge, Tunnel, and Turnpike Association show that 16 states are considering $8.5 billion worth of proposals that would add 822 miles of toll structures.[23] One of the most innovative is a 50-mile segment of the Denver metropolitan beltway. Three Colorado counties and a small city formed the "E-470 Highway Authority" in 1986 to build the highway without any federal or state funding.[4] The first segment will open to traffic at the end of 1990. Tolls are expected to cover up to 75 percent of future construction, maintenance, and operating costs, with the balance made up from taxes and development fees. A feasibility study on a privately financed 400-mile toll road from Chicago to Kansas

City is under way (*1*). Once largely an East Coast phenomenon, the toll road renaissance has spread to Sunbelt states such as Texas and California. In a paper on trends in toll financing, it was concluded that "the nation is in an up cycle in the popularity of toll facilities."[48]

In a nationwide survey conducted in November 1988 by the *Urban Transportation Monitor*, 80 percent of the respondents indicated that their metropolitan areas are either actively planning toll roads or will be doing so in the foreseeable future.[9] The respondents were transportation professionals involved in planning in their respective metropolitan areas. The recent Transportation 2020 initiative by AASHTO recommended the use of toll collection as a financing option for future highway construction. Its report, *Beyond Gridlock,* which was prepared by the Highway Users' Federation, concluded that "with many state and local agencies strapped for highway funds, recommendations [have been produced] on additional revenue sources including toll roads, bond issues, and impact fees on businesses and developers."[2] Clearly, there is an increased emphasis on toll roads as a method of financing urban freeways in the future. Tolls can be used to achieve greater efficiency in vehicle occupancy, which can be encouraged by allowing carpools to use toll roads at a discount or free of charge, and peak-period demand can be somewhat flattened by charging a higher toll during the peak times. With the ability to manage travel demand in a way that would lead to a highly efficient use of the facility, toll roads will play a more significant role than in the past by improving travel efficiency in metropolitan areas.

The basic mechanism of toll collection has remained essentially unchanged since its inception: vehicles still must stop to render payment at a collection booth. Stops at toll plazas, however, impede the smooth flow of traffic and, consequently, can reduce the level of service provided. A toll plaza can be a bottleneck on a highway if its capacity is exceeded. The public accepts the notion of a fee to pay for roads but is unwilling to wait in traffic queues to render payment. A desirable toll plaza design is one for which capacity is greater than peak-hour volume and waiting times are minimal. In view of the time involved in each toll collection transaction, any improvement that can save even a fraction of a second will represent a substantial increase in the efficiency of operation. Efforts are now underway to develop new intelligent vehicle highway system (IVHS) technologies that eliminate or reduce the delay at toll plazas. These include exact-change lanes, flash-pass lanes, and automatic vehicle identification (AVI). Nonetheless, toll facilities still continue to affect overall travel time and traffic flows by requiring each vehicle to stop. Surprisingly, the effects that toll plaza collection facilities have on the level of service and capacity have received little attention by researchers and highway design specialists.

Problem Addressed

Most roadway design features (freeway lanes, ramps, intersections, etc.) have nationally accepted level of service standards. The *Highway Capacity Manual* is silent on this subject, and no national design guidelines exist. Level of service for toll facilities should be quantified for several reasons. First, quantification of the level of service would enable designers to evaluate alternatives using accepted standards. Second, it would provide a scientifically sound basis to compare traffic operations of various facilities. Third, it would furnish a means to evaluate before-and-after conditions and thus determine the effectiveness of any improvements. Finally, quantificaton of the level of service provides the general public and legislative representatives a readily understood and yet scientifically established measure of overall performance.

Capacity is one of the factors of greatest interest in discussions relating to any toll facility. Volume-to-capacity ratio has been used in defining level of service for several highway facility types, such as basic freeway sections and rural highways. Nevertheless, the term *capacity* is not easily defined for toll facilities, and there appears to be no general agreement among traffic engineers as to its precise meaning. As the state adopts toll financing as an alternative source of revenue, guidelines and criteria for analyzing and planning toll facilities are needed.

Study Objectives

The purpose of this research is to improve the understanding of traffic characteristics at toll plazas. A further result is the development of a methodology that can be used in the analysis of traffic operations at toll plazas. The data for analysis will be gathered at selected toll plazas in Virginia; consequently, the study will produce travel characteristics for Virginia. The specific objectives of this study are:

- to develop a methodology for evaluating the capacity of toll plazas
- to establish level of service criteria for toll area traffic
- to develop a procedure for the analysis and planning of toll collection plazas.

Issues to be addressed are capacity, level of service, and operation strategies at toll areas. The primary benefits of the study will be improvements in toll plaza planning and design, which, if applied, could result in reduced delays and could lower the cost of toll collection, and an increased level of service and safety at toll collection facilities. Criteria developed in this study for level of service and guidelines for facility design should be useful for procedures used to evaluate capacity.

Definitions

The following terms are used throughout the text:

- *Toll booth*: A booth at which vehicles stop to pay tolls.
- *Toll plaza*: One or more toll booths.

- *General Toll Booth*: A toll booth in which a toll collector is present.
- *Exact Change Toll Booth*: A toll collection device that collects exact change and is regulated by a movable barrier.
- *Toll plaza area*: A specific section of highway that begins with vehicle convergence into the toll plaza and ends with vehicles reconverging into the highway traffic stream.
- *Toll plaza capacity*: The maximum hourly rate of flow (vehicles per hour) at which traffic can be handled by a toll plaza.
- *Service time*: The time taken for a vehicle to stop, pay a toll, and clear the area so that the next vehicle in the queue is positioned to pay the toll.
- *Travel ratio*: The theoretical travel time for a vehicle traversing a toll plaza area without any impedance divided by the actual travel time per vehicle required to make the same trip. The travel ratio has a maximum value of 1.0 when there are no toll effects.
- *Density*: The number of vehicles per unit area. Since vehicles are directionally guided rather than randomly spread, the unit of area used in the text is *mile-lane*.

Research Design

The research methodology includes the following tasks:

- Review available literature dealing with capacity and level of service for toll facilities.
- Develop appropriate traffic and delay models.
- Collect and analyze data.
- Simulate the system.
- Demonstrate application of capacity procedures.
- Develop findings and recommendations.

LITERATURE REVIEW

A literature survey was conducted using the library facilities of the Virginia Transportation Research Council and computerized searches of the TRB Transportation Research Information Service. The literature review indicated that few studies of toll plaza capacity and level of service have been completed. The present state of the art is described in the following sections under two categories: capacity and level of service.

Capacity

Wood and Hamilton reported results of toll lane capacities observed in the early 1950s.[54] Toll lane performance on the San Francisco-Oakland Bay Bridge showed substantial variations in the number of vehicles handled per hour through adjacent lanes under similar conditions. To determine basic capacities, the performance statistics of lanes with ideal alignment were selected when the lane was manned by a superior collector and heavy traffic pressure prevailed. Since the values for basic capacity were determined for favorably located lanes under conditions of congestion that would not normally be tolerable and excellence of collector and patron performance and cooperation that could not be insured, it was decided that other factors be considered that would result in more realistic values. Basic capacities and average performance, as reported by Wood *et al.* are summarized in Table 1 where the terms *onside* and *offside* refer to the side on which the driver pays toll with respect to his position in the vehicle. The auto toll was 25 cents per car, and 90 percent of passenger car transactions were made by cash at the Bay Bridge. Others used credit vouchers.

Table 1

BASIC CAPACITIES AND AVERAGE PERFORMANCE

Reported by Wood and Hamilton (vehicles/hour per lane)

	Capacity	
Type of Lanes	Basic	Practical
Onside Passenger Car	700	580
Offside Passenger Car	630	525
Bus	400	360
Truck (cash transaction)	223	200
Truck (credit transaction)	223	150

Design criteria for toll facilities including cross sections, mainlines, toll collection, and toll plaza sizing were utilized in the design of the E-470 Beltway in Denver. Generalized booth capacities were assumed for estimating the mix and number of booths.[30] These were:

- manual lanes—350 vehicles/hour
- automatic lanes—650 vehicles/hour
- AVI—1000 vehicles/hour.

By means of a one-second time lapse film taken from a vantage point, Bald *et al.*[13] took traffic data of a toll bridge in the city of Dundee, Great Britain. The interval between successive vehicles leaving the booth was defined as processing time. The average processing time was found to be 6.4 seconds (the median value was 5.2 seconds). The capacity of a single toll booth (550 vehicles per hour) was obtained by rounding the following fraction to the nearest 50 vehicles per hour:

$$\frac{3600(\text{sec/hour})}{6.4(\text{sec/veh})} = 562.5 \text{ (veh/hour)}$$

A study of the Severn Bridge in London by Griffiths *et al.*[28] defined the "practical" capacity of a bridge toll plaza as that flow rate that corresponds to a "reasonable" queue in terms of vehicle number. The "practical" capacity defined in this way is virtually independent of the length of any 'reasonable' delay greater than about 20 seconds. It was determined that the practical capacity of the 4-booth plaza on the Severn Bridge was about 2100 vehicles per hour.

A bottleneck is a section of roadway with a capacity lower than the adjacent upstream section. Thus, the volume input can exceed the capacity of the bottleneck, and the roadway upstream becomes a storage area whose level of service and rate of flow are governed by the capacity and operating conditions through the bottleneck. In a paper discussing freeway level of service, Drew and Keese[21] pointed out that if the traffic backed up at a bottleneck is required to stop, the capacity of the bottleneck becomes a function of vehicular departure headway from a stopped condition.

Level of Service

The literature describing nationally accepted design standards for toll facilities based on defined level of service is essentially nonexistent. This void limits the application of a consistent nationwide design process.

The first edition of the *Highway Capacity Manual* (*HCM*) appeared in 1950[6] and defined service in terms of "possible" and "practical" capacity. Practical capacity was the maximum traffic volume that could be accommodated under prevailing roadway and traffic conditions while maintaining an acceptable quality of service. The concept of *level of service* was formally introduced in the 1965 *HCM*[7] and was defined in terms of two parameters: operating speed and volume-to-capacity ratio (v/c). The 1985 *HCM*[8] defines levels of service for each type of facility based on one or more operational parameters that best describe operating quality for the subject facility type. The parameters selected are called measures of effectiveness. The measures of effectiveness used in the *HCMs* from 1965 and 1985 to define levels of service for each facility type are compared in Table 2.

Table 2

MEASURES OF EFFECTIVENESS ADOPTED FROM
HIGHWAY CAPACITY MANUAL[7,8]

Facility Type	1965 HCM	1985 HCM
Freeways:		
Basic Sections	speed, V/C	density, speed, V/C
Weaving Sections	volume, speed	speed
Ramps	volume	volume
Rural Highways:		
Multilane	speed, V/C	density, speed, V/C
Two-lane	speed, V/C	percent time delayed, speed, V/C
Intersections:		
Signalized	load factor	stopped delay
Unsignalized	N/A	reserve (unused capacity)
Urban Highways:		
Arterials	speed	speed
Transit	N/A	load factor (passengers/seat)
Pedestrians	N/A	space (sq ft/ped)

Leslie C. Edie completed a study in 1954 on traffic delays at toll booths operated by the Port of New York.[22] The study provided methods for determining the relationship between traffic volumes, number of toll booths, and level of service that was expressed in terms of average delay and maximum backup. With this knowledge, the number of toll booths required at any time of day could be specified in advance. However, the concept of *level of service* was utilized only to compare situations using different values of average delay and maximum backup. There were no standards provided for defining levels of service for any specific situation.

Wood and Hamilton presented observations on the design of toll plazas based on their experience with toll bridges operated by the California Division of Highways.[54] Traffic data, toll schedules and their effects, toll collection equipment, toll lane performance, transition areas, layout of the plaza, public relations, and economics were discussed. Although their paper has value to other engineers, it is necessarily limited to experience with specific facilities.

Henk *et al.* considered level of service “C” to be correlated with an arterial volume/capacity (v/c) range of 0.70 to 0.80,[30] which was adopted for designing E-470 in Denver. This measure yields average queue lengths in the range of 2 to 3 vehicles and an average service time of 51 seconds for manual booths and 18 seconds for AVI booths. However, this measure could not be utilized because the capacity of a toll facility was not defined.

Congestion has been consistently proposed as a measure of the quality of traffic service. Congestion is easily understood by the general public, and motorists measure trip length in terms of time traveled instead of miles driven. In an analysis of urban travel times and traffic volume characteristics, Hixon[31] concluded that travel time provides a good measure of the level of traffic service afforded by a street.

The effectiveness of travel time as a measure of congestion and quality of urban traffic service was discussed in a San Diego Metropolitan Area Transportation Study.[29] The vehicle-minutes of delay per mile during the peak hour for a street section were obtained by multiplying the peak-hour volume by the difference between the actual overall travel time and the assigned level of service speed. The level of service speed assigned to each street section is that speed preset by functional classification. It concluded that overall travel time and delay are important elements in a transportation priority system.

Literature Gap

Neither the 1985 HCM nor the 1965 HCM considers traffic characteristics at highway toll plazas. Freeway toll plaza capacity and level of service have, however, been recognized as a research need as reported by the Transportation Research Board in 1987.[5] Several reports have examined the issue of toll road financing, but few, if any, investigations of traffic characteristics at toll plazas are available. Toll plaza capacities have been established by performance observation or by assumption. Considerable variation was found among individual results. A sound theoretical basis for capacity and level of service does not exist. Level of service for toll plaza performance has been used infrequently. The Denver E-470 study was the sole study in which this concept was used. Thus review of the literature indicates that there has not been any criterion proposed as a measure of effectiveness for determining level of service for toll facilities.

MODEL DEVELOPMENT THEORY

Capacity

A principal objective of capacity analysis is to estimate the maximum amount of traffic that can be accommodated by a given facility. Capacity analysis is also intended to estimate the service flow rate, which is the maximum amount of traffic that can be accommodated by a facility while maintaining prescribed operational qualities. The 1985 *HCM* defines the capacity of a facility as the maximum hourly rate at which vehicles can reasonably be expected to traverse a point or uniform section of a roadway during a given time period under prevailing roadway, traffic, and control conditions.[8] Service flow rate is defined for each level of service.

A toll booth may operate at full capacity when a queue is built up and the toll collector is busy at all times. When traffic is light, there is lag time between each toll collection, which means the toll collector is not fully occupied. The service time under conditions in which there is no waiting is sometimes intuitively mistaken to be shorter than it really is. With light traffic, toll collectors may actually consume more time than when pressured with a queue because they are able, for example, to converse with motorists or complete a transaction at a more leisurely pace. When toll collectors are under greater pressure from a growing queue they tend to process the transaction faster. Another counter intuitive result was observed at the Falling Creek Toll Plaza of the Richmond-Petersburg Turnpike: a manually operated booth for automobiles can process more vehicles than an exact-change booth with a lifting barrier because a certain amount of time is required for coins to activate the automatic machine, lift the barrier, and allow the vehicle to clear the booth.

If a queue were sufficiently long to keep a continuous backlog of traffic, capacity would be controlled by the average time required for a vehicle to complete a toll transaction. Additional lanes could be provided to ensure that demand does not exceed total capacity. However, since capacity is typically exceeded during short periods each day, the number of booths is generally based on a tolerable maximum queue length. When demand is sufficient to cause queues to form at a toll booth, each vehicle does not remain stopped in one place for some period of time and then resume its normal travel; instead, it moves up to the gate in a "stop-go" pattern of operation.

The actual service time is affected by the number of coins that must be processed. It may also be influenced by factors such as the experience of the toll collectors, the physical dimensions of toll gates, the methods of toll collection, and the presence of drivers with exact change. Manual booths with heavy truck traffic normally have lower service volumes than those that are primarily for automobiles. Traffic congestion levels also affect service time. Where queues develop, motorists have time to search for needed change prior to the transaction.

If service time when there is no waiting is determined as t_n seconds, the capacity in vehicles per hour of a toll booth would occur when the arrival rate equals $3600/t_n$. Service time under waiting conditions, t_w, determines the processing rate in vehicles per hour as $3600/t_w$. If it is assumed that $t_n \geq t_w$, then $3600/t_w \geq 3600/t_n$. However, when upstream traffic approaches $3600/t_n$, queues start to occur. This means that service time t_n is no longer valid; t_w should be used. Therefore, one of the many concerns of this study is the service time at traffic levels near capacity.

When traffic is at capacity and queues exist, an imaginary reference line can be located a short distance from the toll booth where the rear of a vehicle passes when the following vehicle just stops to pay the toll. Once this reference line is defined, the service time can be obtained by observing traffic at an actual toll booth or by analyzing video tapes of toll booth traffic. For example, the service time for the vehicle C in Figure 1 starts when it stops to pay the toll and ends when its rear end passes the reference line (as shown in (B) and (C) of the figure).

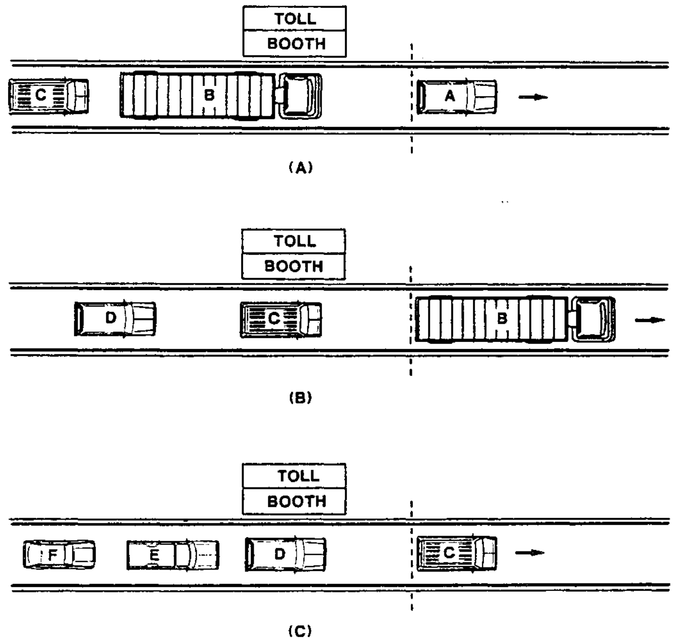


Figure 1. Vehicle movement at toll booths.

Service time can be determined for various toll collection types and geometric conditions. Assume that t_{ijk} represents the service time in seconds for vehicle type i, toll collection type j, and geometric condition k; also assume that service time for trucks, trailers, or buses may be expressed in terms of service time for automobiles, i.e.

$$t_{ijk} = \alpha_i(t_1k_j),$$

where t_1k_j is service time for automobile (type *1*), toll collection type j, and geometric condition k, and a_i is the automobile equivalent at toll areas for vehicle type i. It is apparent that vehicles' lengths and their ability to accelerate are the two major factors that affect the service time. Nevertheless, longer vehicles generally have poorer acceleration mostly as a result of the higher weight-to-power ratio. Therefore, for simplicity, vehicles were divided into two types: (1) automobiles and (2) trucks and buses. Thus, the subscript, i, can be omitted, and the service time for trucks or buses under toll collection type j and geometric condition k is

$$t_{2jk} = \alpha(t_{1jk}). \tag{1}$$

Similarly, service time for different toll collection types may be converted to a common scale based on its relationship to manual toll booths. Thus,

$$t_{ijk} = \beta_j t_{i1k}, \tag{2}$$

where t_{i1k} is service time for vehicle type i, manual toll collection (type *1*), and geometric condition k. β_j is a conversion factor for type j collection to manual toll collection, and $i = 1$ for autos and 2 for trucks or buses.

Therefore, under geometric condition k, the capacity of a toll booth with collection type j is

$$c_{jk} = \frac{3600}{t_{1jk}}. \tag{3}$$

If there are n_j booths with collection type j, the capacity of a toll plaza with geometric condition k would be

$$C_k = \sum_{j=1}^{j} n_j c_{jk} = n_1 \frac{3600}{t_{11k}} + n_2 \frac{3600}{t_{12k}} + \dots + n_j \frac{3600}{t_{1jk}} = \sum_{j=1}^{j} n_j \frac{3600}{t_{1jk}}. \tag{4}$$

Note that capacity c_{jk} and C_k are both expressed in terms of automobiles per hour.

Level of Service

Levels of service are defined as qualitative measures describing operational conditions within a traffic stream and their perception by motorists. Levels of service for interrupted flow facilities, such as toll plazas, vary widely in terms of both the user's perception of service quality and the operational variables used to describe them. Six levels of service defined for each type of facility are given letter designations from A to F in the 1985 *HCM*[8] with A representing the best operating conditions and F the worst.

A higher level of traffic service implies less travel time, lower operating costs, and greater driving comfort and convenience. The setting in which a facility is placed generally imposes limitations on the attainable level of service.

Level of service analysis has been based on the use of one or two measures that effectively evaluate the quality of traffic service. These are measures understood by the average motorist and useful to the transportation analyst and management in evaluating the relative need for specific improvements or for evaluating current operations.

The toll plaza is seen as a bottleneck where traffic is regulated at the capacity of the toll plaza. Unless the toll plaza area is so designed that its downstream section has a lower capacity than the toll plaza, which could happen if the number of available travel lanes downstream is less than that upstream, the number of vehicles passing a toll plaza will be a nondecreasing function of incoming traffic flow. This is shown in Figure 2. Before incoming traffic reaches the capacity of the toll plaza, toll booths are able to accommodate all traffic as represented in zone A of the figure. When traffic approximates the capacity of the toll booths, delays will occur. This is marked as an "unstable zone" in the figure. If traffic exceeds the capacity, the plaza can only serve at its capacity as shown in zone C.

Many traffic engineers view overall speed as the most representative measure of traffic quality. Others believe that the true measure of service provided by a roadway is the volume of traffic it can handle and that a relationship between volume and capacity (in effect between demand and supply) is a measure superior to that of speed, particularly since speed is a function of volume.[46]

Traffic engineers have long been faced with the dilemma of relating capacity to level of service. Much of the difficulty can be attributed to the fact that capacity is expressed in the units of volume, whereas the level of service is highly subjective in nature. Volume is a logical measure of efficiency from the point of view of the engineer, and density and v/c ratio may be proper in addressing freedom to maneuver and proximity to other vehicles with respect to service quality, whereas motion in the form of speed and the magnitude and frequency of speed changes is an important measure of level of service from the point of view of the individual driver. However, unlike freeway operating characteristics, which include a wide range of rates

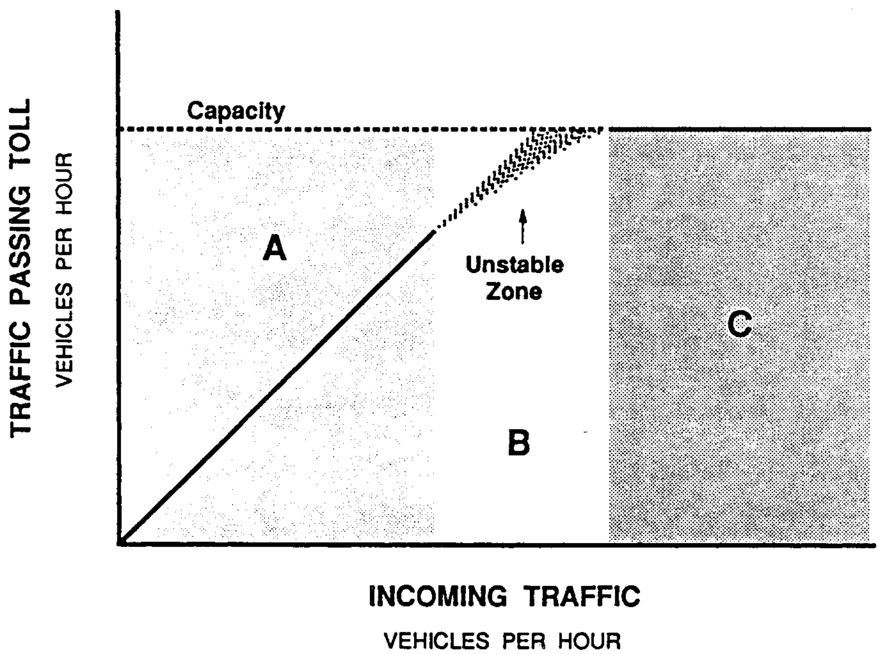


Figure 2. Traffic passing toll v. incoming traffic.

of flow over which speed is relatively constant, toll plaza area traffic occurs at a wide range of speeds even at a constant rate of flow.

Since the individual driver can perceive speed in terms of travel time, this parameter is introduced. In the past, travel time has been regarded as a highway performance rating measure for three basic reasons. First, road users rarely measure distance between two points in terms of miles, and the common measure of distance is usually minutes. Second, improvements in overall travel time is one of the main objectives of transportation planning. Third, travel time is widely accepted as one of the cost indices in transportation planning. In fact, time savings is the most important single factor inducing drivers to travel on toll roads.[19]

Travel time could be expressed in a number of forms including travel speed, travel time delay, and stop time delay. However, travel speed is not easily measured at toll plaza areas, and where it is appropriate to measure the speed is not known. Figure 3 presents the relationship between travel time and location and speed and location for a hypothetical toll plaza area. In the figure, curve I represents the ideal condition when there is no toll booth and a vehicle travels at the posted speed throughout the whole area. Curve A, which represents a case where volumes are low, has a better level of service than curve B, where volumes are higher, and as volumes further increase as in curve C, level of service is decreased. Delay is a measure of driver discomfort, frustration, fuel consumption, and lost travel time. Either travel time delay or stop time delay accounts for only part of the impedance caused by a toll plaza. For curve A in Figure 3, the extra time it takes to travel the toll plaza area incorporates both of these two elements. In the figure, d_s stands for stop time delay and d_t for travel time delay. Therefore, the total delay resulting from the presence of a toll plaza is

$$D = d_s + d_t.$$

If the posted speed limit is $\hat{V}$, the theoretical travel time along the toll plaza area without toll effects is

$$\hat{T} = \frac{L}{\hat{V}}. \tag{5}$$

Speed (V) is a function of travel distance (l) and time (t). It can be expressed as

$$V(t) = \frac{\mathrm{d}l}{\mathrm{d}t}, \quad \text{or} \quad V(t)\mathrm{d}t = \mathrm{d}l.$$

Once the length of a toll plaza area is defined as L and the overall travel time is expressed as T, then

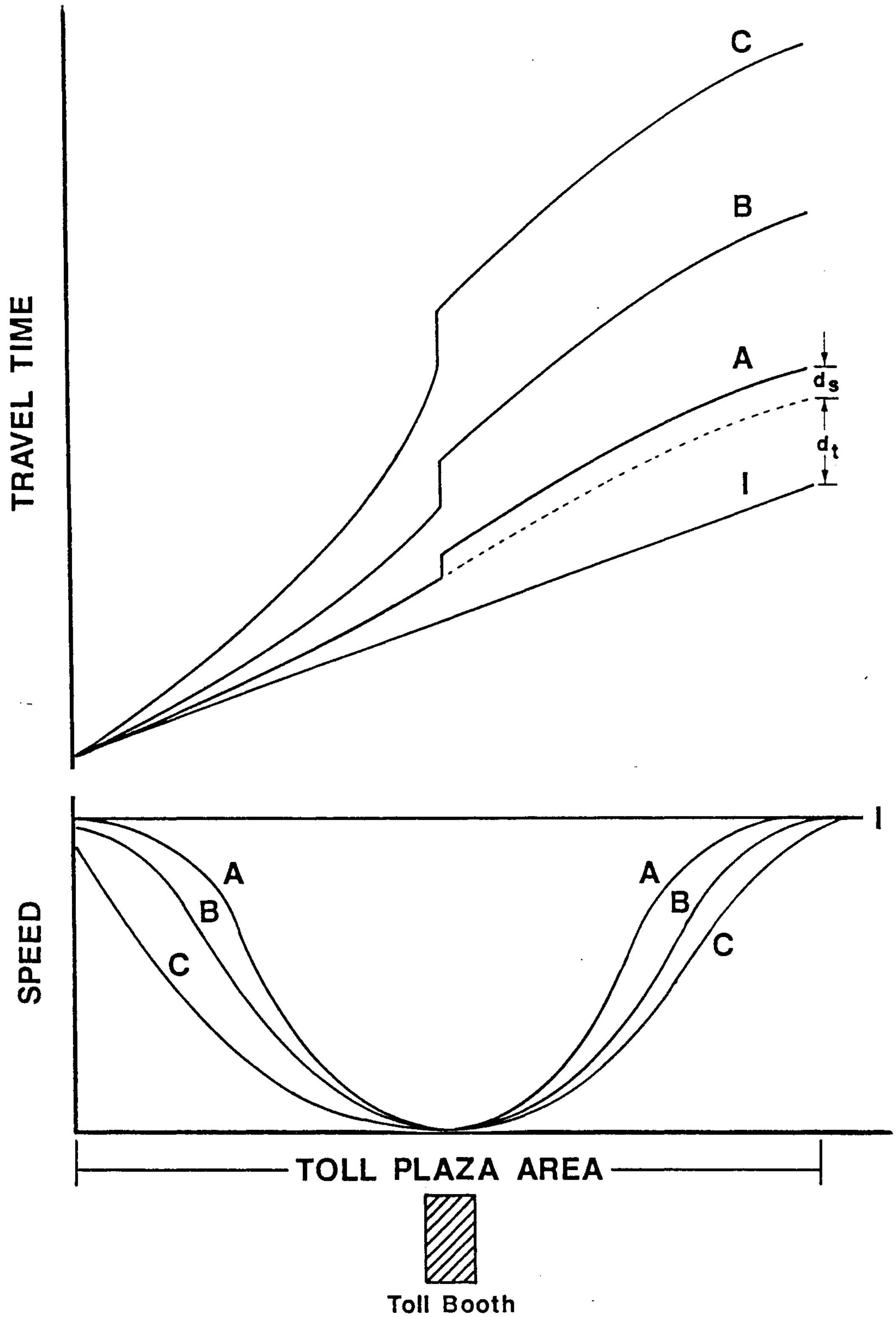


Figure 3. Travel time location and speed location in toll plaza areas.

$$\int_0^T V(t)\mathrm{d}t = \int_0^L \mathrm{d}l = L, \tag{6}$$

where $T = \hat{T} + D = \hat{T} + d_s + d_t$. Divided by T, Eq. 6 becomes

$$\frac{\int_0^T V(t)\mathrm{d}t}{T} = \frac{L}{T}. \tag{7}$$

The left side of Eq. 7 is known in traffic flow theory as space mean speed (or average running speed), $\bar{u}_s$. Thus,

$$\bar{u}_s = \frac{L}{T}, \text{ or } T = \frac{L}{\bar{u}_s}. \tag{8}$$

Average running speed is a statistical parameter that may be computed from sample observations of the traffic stream.

Since travel time through a toll plaza area is a function of the plaza length, a normalized scale should be used. The travel ratio, R, can now be expressed from Eq. 5 and Eq. 8 as

$$R = \frac{\hat{T}}{T} = \frac{L/\hat{V}}{L/\bar{u}_s} = \frac{\bar{u}_s}{\hat{V}}. \tag{9}$$

The last fraction of Eq. 9 is a relative scale of speed and is sometimes termed normalized speed. Similar to the volume-to-capacity ratio, which indicates the system utilization, the normalized speed describes the extent of speed utilization. Both are dimensionless. Either travel ratio or normalized speed is very adequate as a performance measure to address mobility as perceived by the public.

It is also interesting to note that space mean speed is the parameter that must be used in the basic traffic flow relation:

Volume (vehicles/hr) = *Density* (vehicles/mi) x *Speed* (mi/hr).

Roess *et al.* has recommended that average running speed be used to establish speed criteria for freeway levels of service despite its sensitivity to the presence of trucks.[40] Hence, the choice of overall travel time is obviously based on its adequate accountability of toll plaza effects beside the simplicity of the measure.

Although speed is a major concern of drivers with respect to service quality, freedom to maneuver and proximity to other vehicles are equally important parameters. These other qualities are directly related to the density of the traffic stream. Further, it has been shown that the rate of flow increases with increasing density throughout the full range of stable flows.

In traffic flow, density stands for number of vehicles per unit length of a travel lane. A toll plaza area is comprised of two trapezoids, as shown in Figure 4. The area is then

$$A = A_1 + A_2 = \frac{1}{2}(n_1 + n_2)L_1 + \frac{1}{2}(n_2 + n_3)L_2, \tag{10}$$

where A = total area in length-lanes

A_1 = area in length-lanes for convergence section

A_2 = area in length-lanes for reconvergence section

n_1 = number of arrival lanes

n_2 = number of departure lanes

n_3 = number of booths

L_1 = length of convergence section

L_2 = length of reconvergence section.

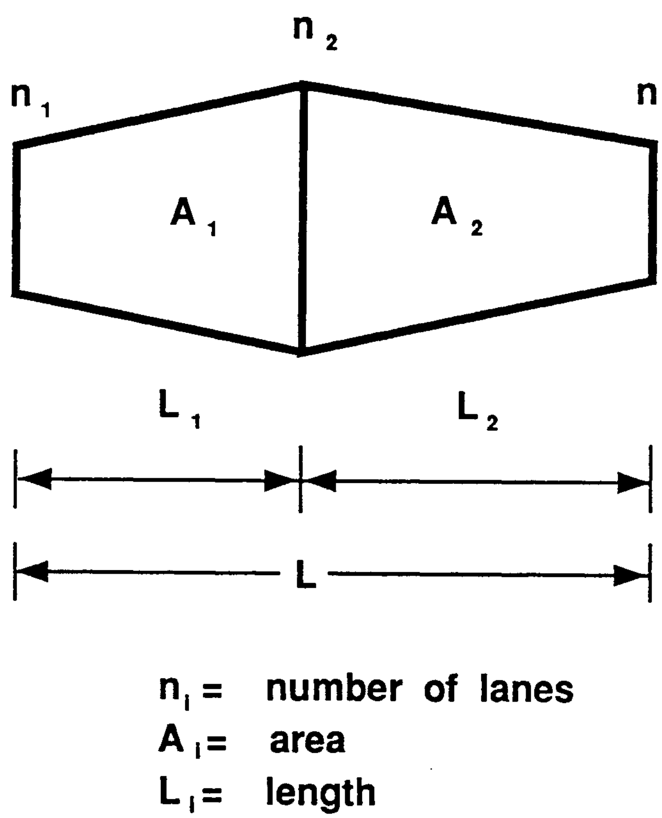


Figure 4. Area of a toll plaza.

If the average total time to travel through the toll plaza area is T, the number of vehicles appearing within this area should be the product of flow rate Q and T. If vehicles are placed into two categories, the density of a toll plaza area K can now be expressed as

$$K = \frac{\Sigma\, Q_i T_i}{A} = \frac{2(Q_a T_a + Q_t T_t)}{(n_1 + n_2)L_1 + (n_2 + n_3)L_2}, \tag{11}$$

where subscripts a and t denote types of automobiles and trucks.

STUDY SITES

For the purposes of establishing level of service and capacity evaluation procedures, it was necessary to observe traffic and collect data at selected toll plaza areas. The following sections describe the study sites and the process of data collection.

Description

There are seven toll roads in Virginia (see Table 3). The majority of these facilities are located in the Richmond area, and the study sites that were selected are from the Richmond-Petersburg Turnpike. There are eight sites, which represent a wide variety of traffic volumes, numbers of lanes, and vertical alignments (these are described in Table 4). Figure 5 illustrates a general toll plaza layout, and Figure 6 presents the lane restrictions at each toll plaza location as they existed at the time of data collection.

Table 3

TOLL ROADS IN VIRGINIA

Road	Route	No. of Plazas*
Richmond-Petersburg Turnpike	I-95	8**
Powhite Parkway	Rt. 76	4
Downtown Expressway	Rt. 195	2
Boulevard Bridge	Rt. 161	2
Virginia Beach-Norfolk Expressway	Rt. 44	2
Chesapeake Bay Tunnel Bridge	Rt. 13	2
Dulles Airport Access Road	Rt. 267	2

*These numbers are counted for both directions.
**As of July 1, 1989, there were only 6 plazas.

Table 4

STUDY SITE DESCRIPTION

Plaza & Direction	Area Distance (ft)	Grade (%) a_1	a_2	No. of Lanes n_1	n_2	n_3	1988 AADT
Belvidere:							89,070
Northbound (BDN)*	1313	1.0	1.0	3	8	3	
Southbound (BDS)	1440	-1.0	-1.0	3	8	3	
Falling Creek:							61,920
Northbound (FCN)	1460	0.5	0.5	3	6	3	
Southbound (FCS)	1250	-0.5	-0.5	3	6	3	
Colonial Heights:							57,530
Northbound (CHN)	891	0.5	0.5	3	6	3	
Southbound (CHS)	1274	-0.5	-0.5	3	6	3	
Petersburg:							26,400
Northbound (PBN)	860	-3.7	0.62	2	4	2	
Southbound (PBS)	822	-0.62	3.7	2	4	2	

*These abbreviations inside the parentheses will be used to identify these sites hereafter.

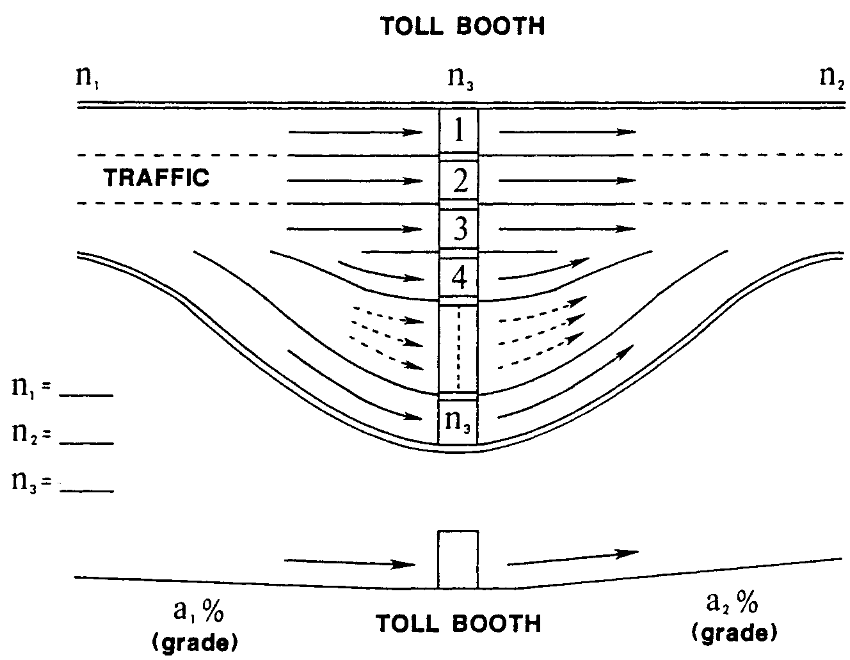


Figure 5: Illustration of toll plaza layout.

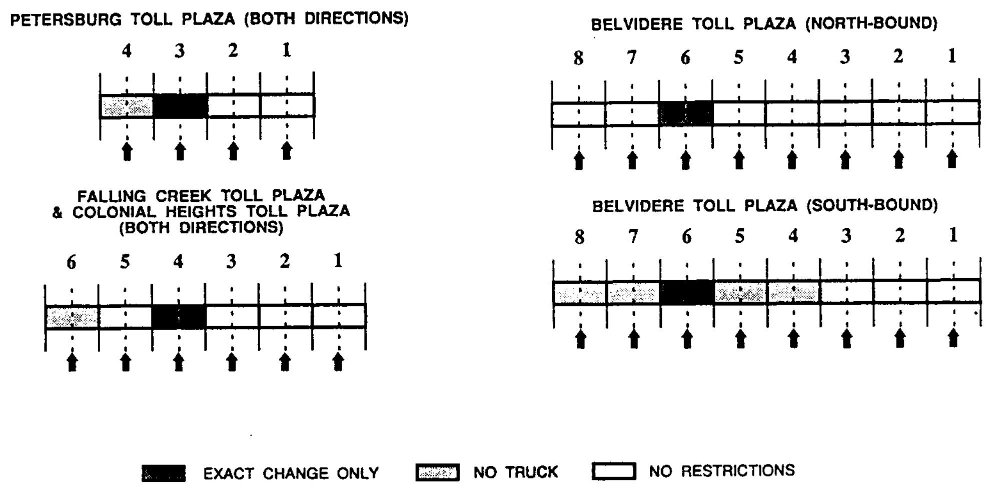


Figure 6. Lane restrictions at study sites.

Data Collection

VHS camcorders were used for data collection because they have the capability to transfer recorded information onto broadcast-quality video tapes that can be analyzed at 1/30 second precision. The camcorders were synchronously used in pairs as illustrated in Figure 7. By setting a camcorder (1) on the top of a toll plaza pointing into the upstream traffic, data on volume, traffic mix, and delay could be collected. A second camcorder (2), also set on top of the toll plaza, points downstream to determine travel time. The third camcorder (3) faces the toll booth from downstream to determine service and was placed at a vantage point on the top of a nearby toll plaza office building or a platform on top of a van. Figure 8 shows the van that was used. Each toll plaza was inspected during the summer and fall of 1989. Both ends of the toll plaza area of each site were identified and marked according to the definitions given previously. When three camcorders were used to record the traffic data for a one-hour period at each site, two persons were engaged in recording delays for the same traffic at 15-second intervals. The distance of the toll plaza area for each site was measured by a device installed in a van that traversed the area several times to produce an average value.

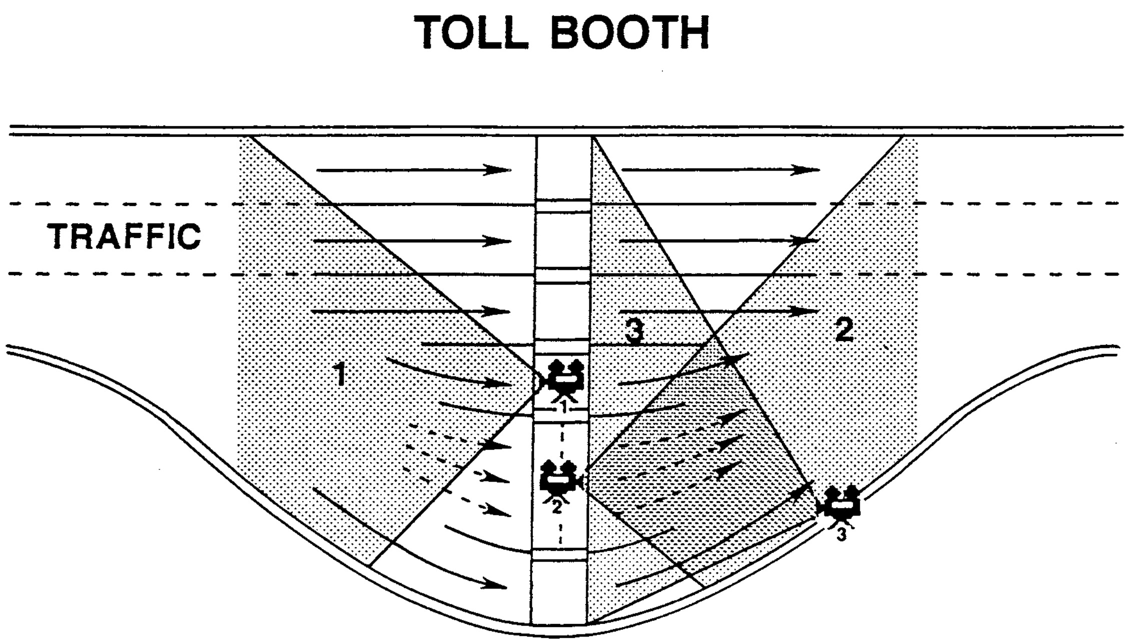


Figure 7. Layout for camcorders.

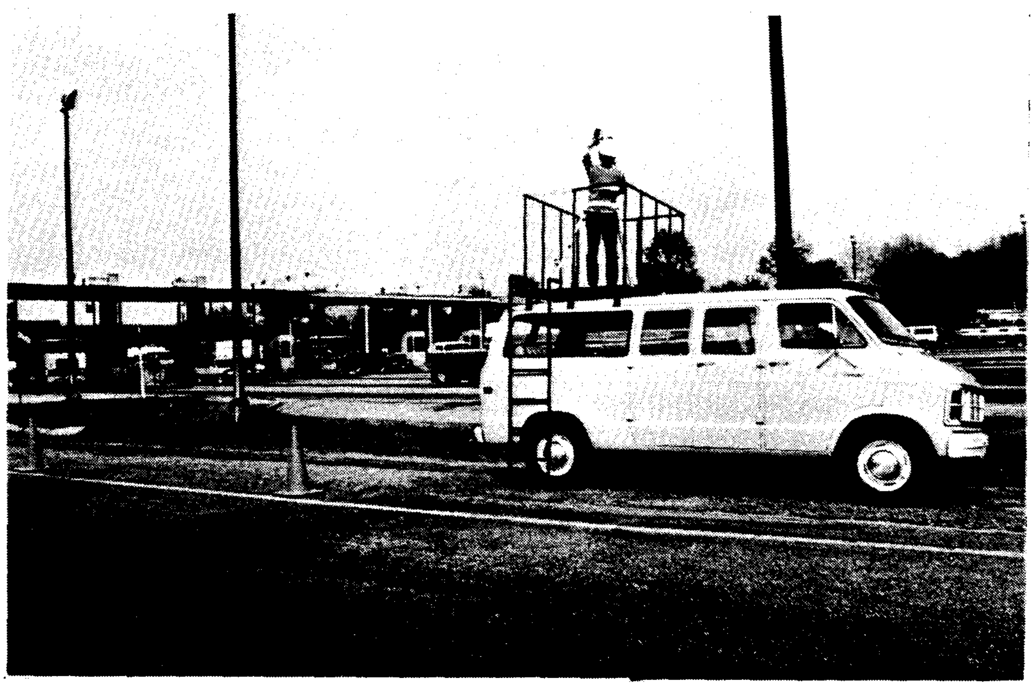


Figure 8. Van used for data collection.

Each video tape was transferred to a 3/4-in broadcast-quality video tape before evaluation and processing. These video tapes were then played back on video equipment comprised of an edit controller, a timer screen, two VCRs, and two monitors (see Figure 9). Traffic counts were made at 15-second intervals. The total number of vehicles observed was 15,746 (including 2,473 trucks). The results show that the traffic distribution is represented by the Poisson distribution, which is summarized in Appendix A.

The position of the third camcorder at the Belvidere Plaza northbound was such that it was not possible to identify data from the recorded video tape. Nevertheless, data from camcorders 1 and 2 at this site was usable. For Falling Creek Plaza northbound, camcorder 3 failed to cover the exact-change lane traffic because of an inadequate vantage point.

The Statistical Analysis System (SAS) was used to analyze the relationships between travel ratio, volume-to-capacity ratio, and delay. SAS/GRAPH was used to develop the graphic displays for these relationships. The SAS System is a software system for data analysis developed by the Statistical Analysis System Institute.[10,11,12]

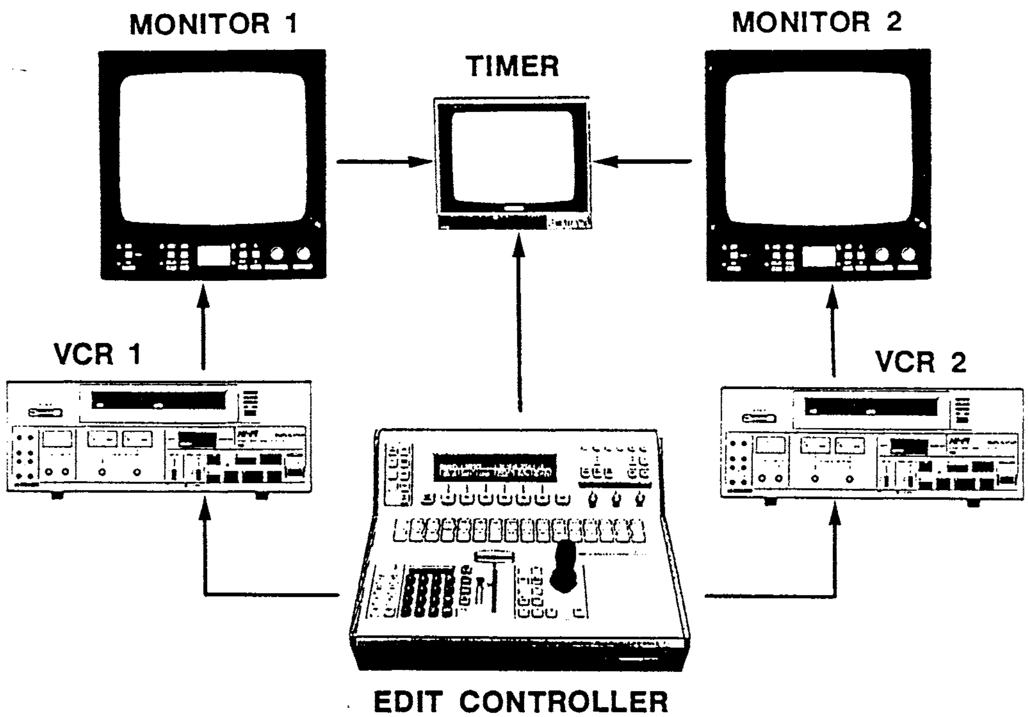


Figure 9. Video equipment used in VTRC.

Capacity

The location of the reference lines mentioned earlier can be determined by observing traffic data on the video tapes. Only those vehicles that had an immediately following vehicle were recorded for the location of the rear bumper when the vehicle following stopped to pay the toll. The data was grouped by toll collection type, and only automobiles immediately followed by a automobile were used to determine the reference lines. Cases of trucks following trucks, trucks following cars, and cars following trucks were but a small portion of the available data. Table 5 summarizes the locations of the reference lines for study sites. It shows that the reference line for a general toll booth lies about 55 feet from the toll attendant. For an exact-change booth, the reference line location was between 1 to 7 feet closer to the plaza than that of a general booth.

Table 5

LOCATIONS OF REFERENCE LINES AT STUDY SITES
(measured from where toll attendants stand, in feet)

SITE	GENERAL BOOTH	EXACT-CHANGE BOOTH
BDS	53.42	N/A*
FCN	54.28	N/A**
FCS	54.65	51.22
CHN	54.55	49.35
CHS	56.73	49.33
PBN	55.73	54.53
PBS	54.57	51.47

After the reference lines were located, the video tapes were then reviewed again to record service time for as many vehicles as available by counting the time between when a vehicle stopped to pay tolls and when its rear passed the defined reference line. Table 6 presents the results.

Comparisons of the service time between automobiles and trucks, automobiles at general booths and at exact-change booths, and automobiles at inner and outer lanes were carried out using the *t*-test for each study site. The outer lanes are those between an exact-change lane and the roadside (to the driver's right), while the inner lanes are those at the left of an exact-change lane (to the driver's left).

Table 6

SERVICE TIME FOR STUDY SITES
(in seconds)

SITE	GENERAL AUTO	GENERAL TRUCK	EXACT-CHANGE AUTO	α = truck/auto	β_j = ex-change/auto
BDS	5.47	14.40	6.53	2.63	1.19
FCN	5.17	14.43	N/A	2.79	—
FCS	5.44	14.77	5.21	2.72	0.96
CHN	5.21	14.23	5.33	2.73	1.02
CHS	5.11	14.88	4.83	2.91	0.95
PBN	5.32	14.58	5.25	2.74	0.99
PBS	5.39	12.87	5.41	2.39	1.00

The results in Table 7 indicate that at a 5 percent significance level, there is significant difference in service time between automobiles and trucks. The automobile equivalents for trucks (α) range from 2.39 to 2.91 as shown in Table 6. The mean value for α is 2.70.

At the time of data collection, there was an automatic lifting barrier at the southbound Belvidere Toll Plaza exact-change booth. The service time was, therefore, counted by measuring the time between each lifting of the barrier. The *t*-test results in Table 8 show that service time of this booth is significantly greatly than

Table 7

COMPARISON OF SERVICE TIME FOR AUTOMOBILES V. TRUCKS

SITE	AUTO		TRUCK		T	Remarks
	t*	n**	t*	n**	Value	
BDS	5.47	661	14.40	30	-8.46	Significant
FCN	5.17	473	14.43	2	-2.75#	Not Significant
FCS	5.44	482	14.77	93	-18.21	Significant
CHN	5.21	293	14.23	77	-15.04	Significant
CHS	5.11	404	14.88	179	-22.58	Significant
PBN	5.32	248	14.58	143	-23.99	Significant
PBS	5.39	238	12.87	128	-20.83	Significant

due to small sample of trucks
* mean service time in seconds
** sample number

Table 8

COMPARISON OF AUTOMOBILE SERVICE TIME FOR GENERAL BOOTHS V. EXACT-CHANGE BOOTHS

SITE	GENERAL t*	GENERAL n**	EXACT-CHANGE t*	EXACT-CHANGE n**	T Value	Remarks
BDS	5.47	661	6.53	230	-7.78	Significant
FCS	5.44	482	5.21	207	1.97	Significant
CHN	5.21	293	5.33	129	-0.98	Not Significant
CHS	5.11	404	4.83	246	2.78	Significant
PBN	5.32	248	5.25	160	0.59	Not Significant
PBS	5.39	238	5.41	90	-0.14	Not Significant

* mean service time in seconds
** sample number

that of manually operated booths. It was observed that automobiles at times had to stop and wait after placing change into the automatic collector before the barrier lifted. For all others sites, automobile service times at exact-change booths was either significantly shorter than or showed no difference from that at general booths for all other sites. Nevertheless, the conversion factors (β_j) are very close to 1.

The average automobile service time at outer lanes is greater than that at inner lanes for every site as shown in Table 9. The statistical test further indicates that automobile service times of inner lanes is either significantly shorter than or showed no difference from service time of outer lanes. The simplicity of traffic mixes at the inner lanes where trucks rarely appear is the most likely explanation.

The capacity of a toll booth and a toll plaza can be obtained from Eq. 3 and Eq. 4. Table 10 summarizes the results. It is found that the capacity ranges from

Table 9

t-TEST FOR AUTOMOBILE SERVICE TIME

SITE	INNER LANE t*	INNER LANE n**	OUTER LANE t*	OUTER LANE n**	T Value	Remarks
BDS	5.39	314	5.53	347	-0.94	Not Significant
FCS	5.17	392	6.64	90	-4.60	Significant
CHN	4.90	176	5.67	117	-3.74	Significant
CHS	5.09	357	5.25	47	-0.76	Not Significant
PBN	5.27	158	5.40	90	-0.76	Not Significant
PBS	5.33	104	5.44	134	-0.72	Not Significant

* mean service time in seconds
** sample number

Table 10

CAPACITY FOR STUDY SITES

SITE	GENERAL	EXACT-CHANGE	PLAZA TOTAL
BDS	650	551	5101
FCN	696	(691)*	4171
FCS	662	691	4001
CHN	691	675	4130
CHS	705	745	4270
PBN	677	686	2717
PBS	668	665	2669

650 to 705 automobiles per hour for a manually operated toll booth and from 665 to 745 automobiles per hour for an exact-change booth. Because of the reaction delay of the lifting barrier, the capacity of the Belvidere Plaza southbound exact-change booth was 591 automobiles per hour, which is the lowest of any booth observed.

The average automobile service time at outer lanes is greater than that at inner lanes for every site (see Table 9). The statistical test further indicates that the automobile service time of inner lanes is either significantly shorter than or showed no difference from the service time of outer lanes. The simplicity of traffic mixes at the inner lanes where trucks rarely appear is the most likely explanation.

Level of Service

The traffic and travel time data was segregated into one-minute, three-minute, and five-minute periods. The following sections describe the derivation and analysis of factors that are considered for evaluating levels of service in this study.

Volume-to-Capacity Ratio

Once the capacity of each site is determined, the volume-to-capacity (v/c) ratio can be obtained by

$$v/c = \frac{\text{Volume}}{\text{Capacity}},$$

where volume represents the flow rate in passenger cars per hour. For example, if there are 48 cars and 9 trucks/buses coming in a one-minute period, and a truck is equivalent to 2.63 a cars at the Belvidere Toll Plaza southbound direction, which has a capacity of 5101, then

$$\text{Volume} = [48 + (2.63 \times 9)] \times 60\frac{\text{min.}}{\text{hour}} = 4300\frac{\text{cars}}{\text{hour}}, \quad \text{and} \quad v/c = \frac{4300}{5101} = 0.843.$$

Travel Ratio

By playing back tapes taken by camcorder 1 and camcorder 2, the time a vehicle enters and leaves the toll plaza area can be obtained from the readings on the timer. Total travel time is the difference between the two observed values. Travel time was recorded for as many vehicles as could be identified and was separated by automobiles and trucks (including buses). Travel time for 12,737 vehicles, which represented more than 80 percent of total observed traffic, was recorded from the 8 study sites. Table 11 provides the details for each site.

Table 11

NUMBERS OF VEHICLES MEASURED FOR TRAVEL TIME AT STUDY SITES

	TRAFFIC OBSERVED			TRAVEL TIME RECORDED		
SITE	TOTAL	AUTO	TRUCK	TOTAL	AUTO	TRUCK
BDN	2,648	2,267	381	2,472 (93%)	2,122 (94%)	350 (92%)
BDS	2,808	2,313	495	2,472 (86%)	1,996 (86%)	414 (84%)
FCN	2,026	1,667	359	1,049 (52%)	812 (49%)	237 (66%)
FCS	2,724	2,371	353	1,874 (69%)	1,579 (67%)	295 (84%)
CHN	1,494	1,216	278	1,318 (88%)	1,100 (90%)	218 (78%)
CHS	2,128	1,849	279	1,970 (93%)	1,739 (94%)	231 (83%)
PBN	1,024	828	196	924 (90%)	758 (92%)	166 (85%)
PBS	912	780	132	720 (79%)	623 (80%)	97 (73%)
TOTAL	15,764	13,291	2,473	12,737(81%)	10,729 (81%)	2,003 (81%)

Because of the small size and great variation of truck travel times, only travel time for automobiles is included in this analysis. It was observed that travel time for motorcycles varies substantially. It can be extremely short but may also be very long because of the time required for a bike rider to stop and find proper change. Thus, travel time for motorcycles was also excluded.

The most obvious and generally recognized factor of service quality of traffic flow is the average or overall speed. Average speed determines the time of travel. The higher the average speed within the limit of safety, the higher the quality of travel. Travel ratio, as defined previously, takes into consideration all the effects of deceleration, delay, toll transaction, and acceleration. Since the length of a toll area and speed limit are known and travel time is measured, Eq. 9 may be expressed in the form:

$$\text{Travel Ratio}: R = \frac{L/\hat{V}}{T}. \tag{12}$$

The speed limit on the Richmond-Petersburg Turnpike is 55 miles per hour, e.g., $\hat{V} = 80.67$ feet per second. Therefore,

$$R = \frac{L}{80.67T}, \tag{13}$$

where L is the length of a toll plaza area in feet, and T is the travel time in seconds.

Density

For a standard design and for all of the study sites, the number of arrival lanes equals the number of departure lanes, i.e., $n_1 = n_3$. If $n_1 > n_3$ or $n_1 < n_3$, the one with fewer lanes must be overloaded or congested or the other one must be a slack design under design flow. Therefore, the area of a toll plaza in length-lanes is:

$$A = \frac{1}{2}(n_1 + n_2)L_1 + \frac{1}{2}(n_1 + n_2)L_2 = \frac{L}{2}(n_1 + n_2).$$

Eq. 11 becomes

$$K = \frac{Q_aT_a + Q_tT_t}{A} = \frac{2(Q_aT_a + Q_tT_t)}{(n_1 + n_2)L}. \tag{14}$$

Note that the units of Q_i and T_i in Eq. 14 should be the same (i.e., seconds). Density was calculated using Eq. 14 for all data points observed.

Delay

Average stop delay, which is used for signalized intersections, might also be used as a measurement of the level of service at a toll plaza. This can be obtained by counting the number of stopped vehicles in every 15-second period and dividing this sum by the total number of vehicles observed during a specific time period.

Analysis and Discussion

Since traffic within a toll plaza area does not operate at a relatively constant speed, and its density may not be evenly distributed along the whole area, the analysis herein considers the defined toll plaza area as a black box. Figure 10 symbolizes this representation. The toll plaza area will be treated as a whole unit.

Among the four criteria just given, travel ratio is the only one that increases with a higher level of service, whereas the other criteria decrease in value as level of service improves.

Stop delays account for only part of the impedance caused by a toll facility, and travel delay itself is not easily measured. There is no significant relationship between the average stop delay and flow rate or volume-to-capacity ratio (Figure 11). Hence, travel ratio, which includes both stop delays and travel delays, was taken into consideration in the next step.

It is an observable fact that drivers decrease their speeds as the number of cars around them increases. Because of this close interaction between density and speed, many models were explored by early investigators. From Eq. 9,

$$R = \frac{\bar{u}_s}{\hat{V}},$$

the average running speed $\bar{u}_s = R\hat{V}$, where R is the travel ratio and $\hat{V}$ is the speed limit. Among the four common speed-density models[26] tested, three were found to fit the field data. Table 12 shows the results, where R^2 is the coefficient of determination, and PROB>F is the significance probability using the F-test. If the PROB>F is 0.05 or less, the relationship between the dependent variable and the independent variable is considered significant. The 0.05 level of significance is generally accepted for most engineering work. The bell-shaped curve model seems to fit best.

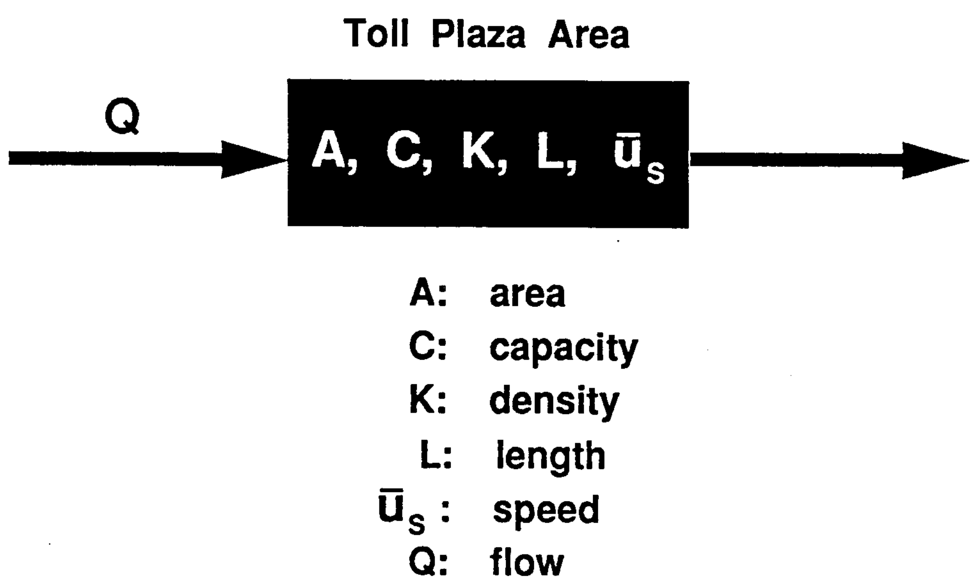


Figure 10. A black box of toll plaza area.

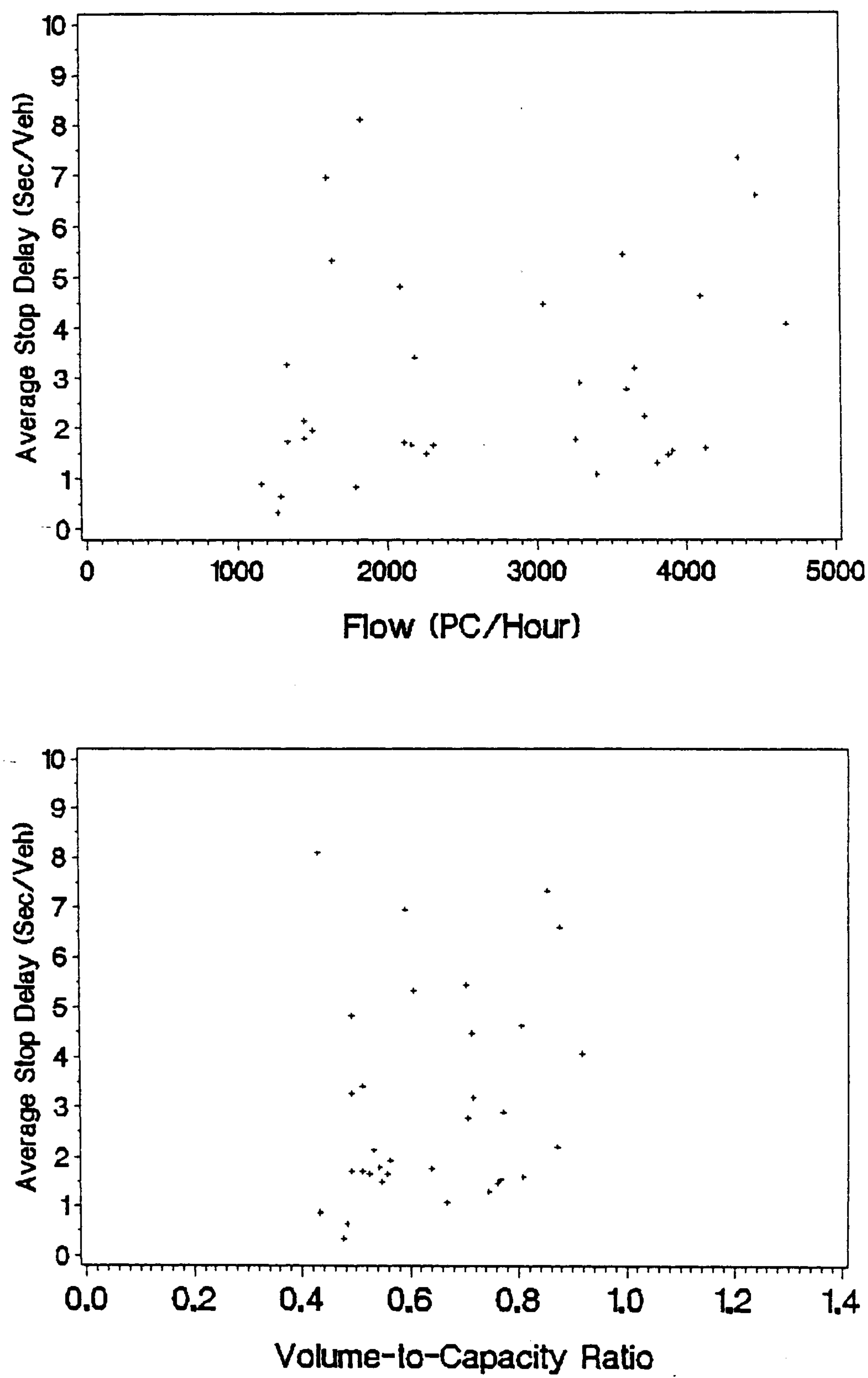


Figure 11. Diagrams of delay-flow and delay-v/c.

Table 12.
SPEED-DENSITY REGRESSION MODELS

Data Set	Model	R^2	PROB>F
1-min	$\bar{u}_s = 23.85 - 0.0973K$	0.2365	0.0001
	$\bar{u}_s = 24.50e^{-\frac{K}{183.02}}$	0.2577	0.0001
	$\bar{u}_s = 21.95e^{-\left(\frac{K}{130.37}\right)^2}$	0.2870	0.0001
3-min	$\bar{u}_s = 24.06 - 0.1082K$	0.2233	0.0001
	$\bar{u}_s = 24.87e^{-\frac{K}{164.43}}$	0.2450	0.0001
	$\bar{u}_s = 22.13e^{-\left(\frac{K}{118.21}\right)^2}$	0.2944	0.0001
5-min	$\bar{u}_s = 23.39 - 0.0936K$	0.1567	0.0001
	$\bar{u}_s = 23.91e^{-\frac{K}{193.46}}$	0.1766	0.0001
	$\bar{u}_s = 21.63e^{-\left(\frac{K}{127.92}\right)^2}$	0.2067	0.0001

The logarithmic model, which has the form

$$\bar{u}_s = a \ln\left(\frac{b}{K}\right),$$

did not satisfy the statistical test with a best $R^2 = 0.0135$ for the 5-minute data set. Figures 12, 13, and 14 display the scatter diagrams. In these diagrams, those situations with traffic characteristics appearing near the left top corner, indicating higher average speed, lower volume, and lower density, represent better service qualities at a toll plaza area. However, there is a significant amount of scattering. The diagrams reveal that average speed fluctuates significantly at a similar density or volume-to-capacity ratio. It is also true that density and volume-to-capacity ratio fluctuate at a constant average speed. The amount of scatter present masks the significance of the relationship between the variables. Nevertheless, there is a trend: average running speed decreases with increased density and volume-to-capacity ratio, as exhibited in the correlation test in Table 13.

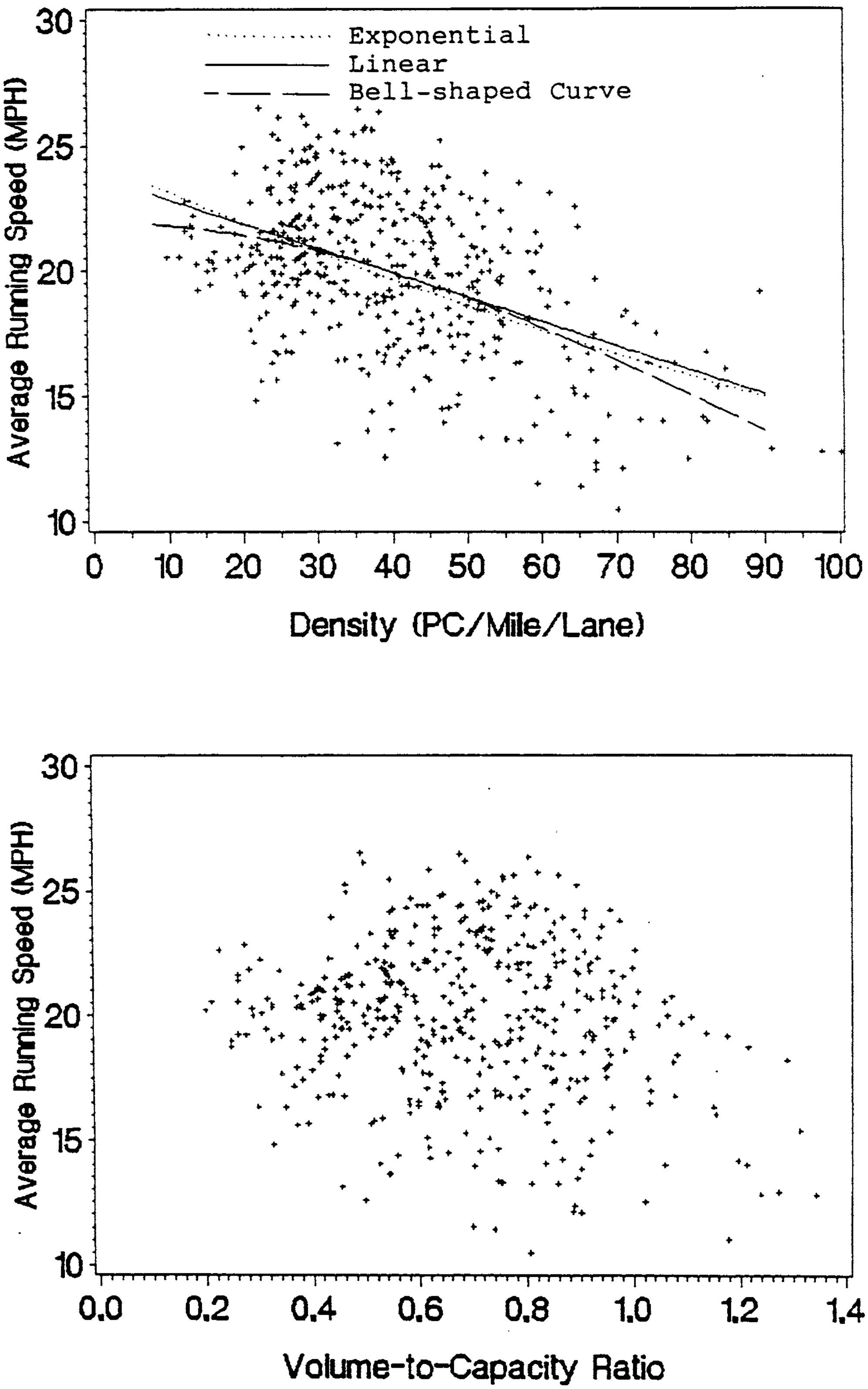


Figure 12. Speed-density and speed-v/c diagram (1-min).

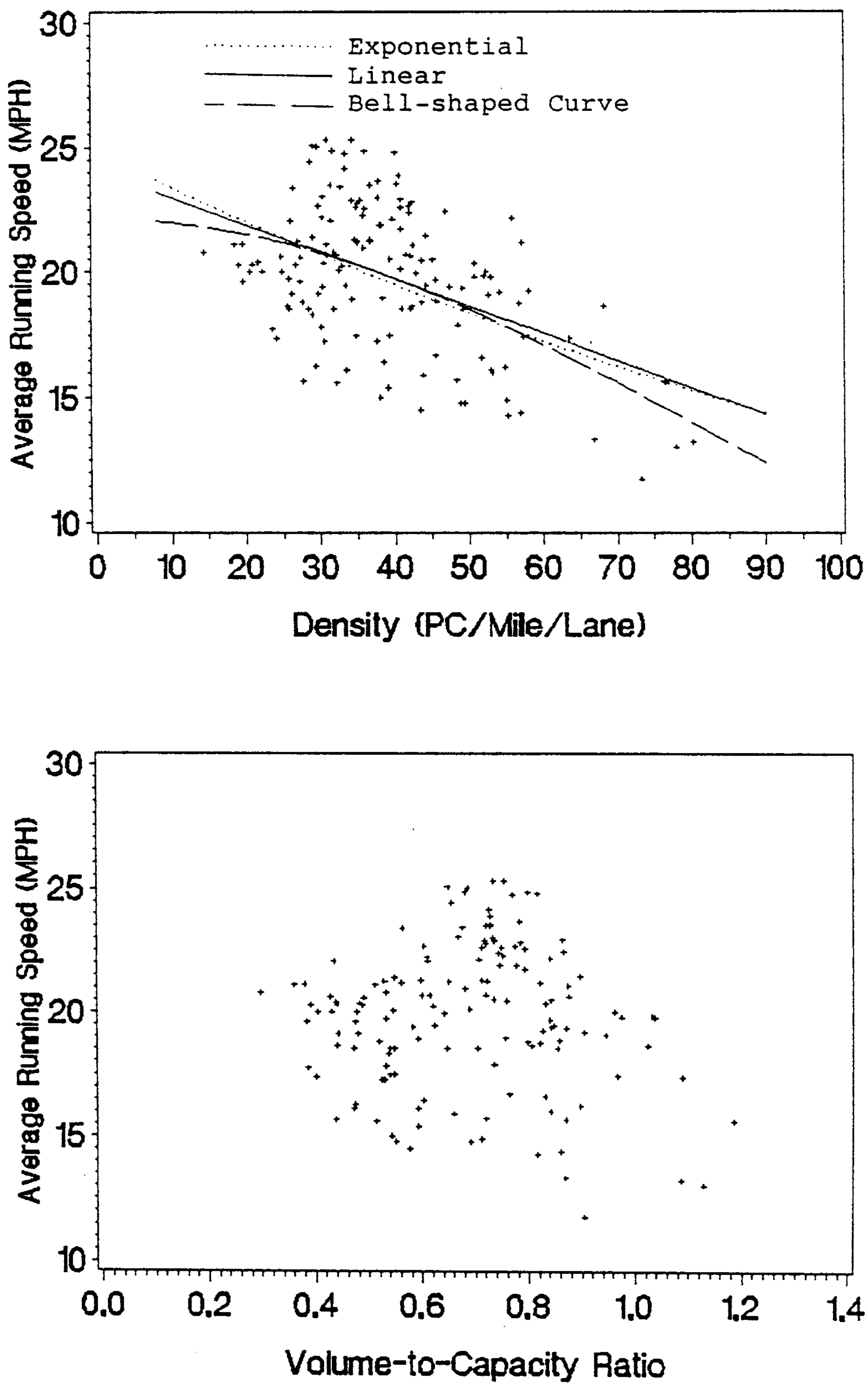
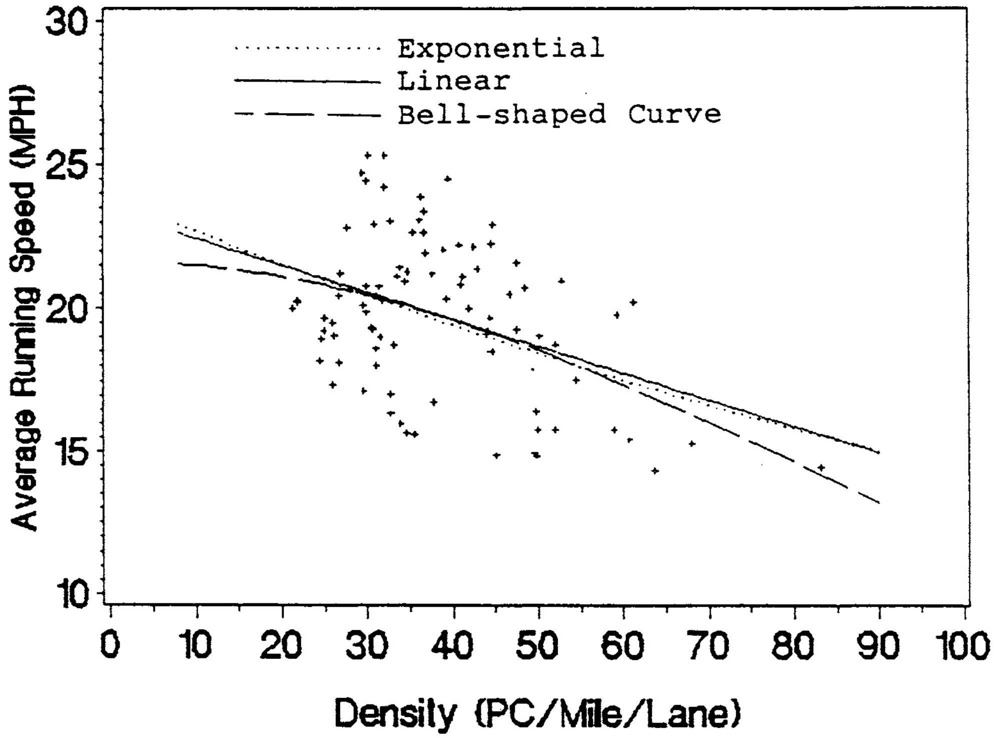


Figure 13. Speed-density and speed-v/c diagram (3-min).



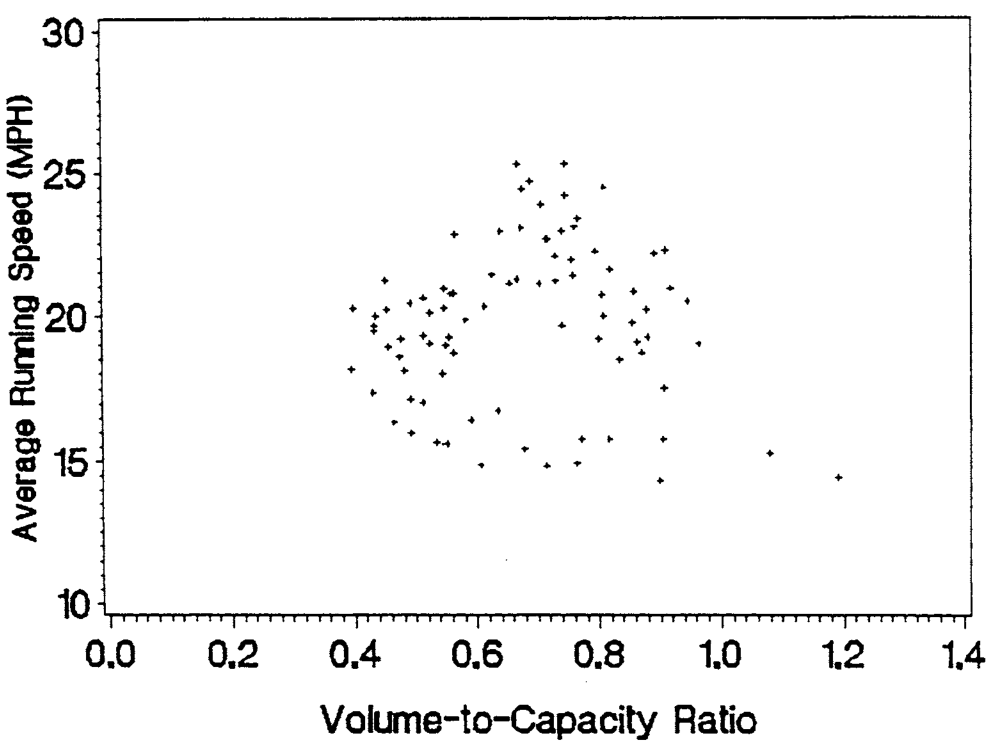


Figure 14. Speed-density and speed-v/c diagram (5-min).

Table 13

PEARSON CORRELATION COEFFICIENTS SIGNIFICANCE PROBABILITIES

1-minute Data Set (N=454)

Variables	v/c	$\bar{u}_s$	K	Q
v/c	1.0000	-0.13780	0.86771	0.89698
	0.0000	0.0033	0.0001	0.0001
$\bar{u}_s$	-0.13780	1.00000	-0.48627	0.15088
	0.0033	0.0000	0.0001	0.0013
K	0.86771	-0.48627	1.00000	0.68075
	0.0001	0.0001	0.0000	0.0001
Q	0.89698	0.15088	0.68075	1.00000
	0.0001	0.0013	0.0001	0.0000

3-minute Data Set (N=148)

Variables	v/c	$\bar{u}_s$	K	Q
v/c	1.0000	-0.06476	0.84895	0.88793
	0.0000	0.4342	0.0001	0.0001
$\bar{u}_s$	-0.06476	1.00000	-0.47254	0.26610
	0.4342	0.0000	0.0001	0.0011
K	0.84895	-0.47254	1.00000	0.64755
	0.0001	0.0001	0.0000	0.0001
Q	0.88793	0.26610	0.64775	1.00000
	0.0001	0.0011	0.0001	0.0000

5-minute Data Set (N=87)

Variables	v/c	$\bar{u}_s$	K	Q
v/c	1.0000	0.01909	0.84887	0.89145
	0.0000	0.8607	0.0001	0.0001
$\bar{u}_s$	0.01909	1.00000	-0.39587	0.34415
	0.8607	0.0000	0.0001	0.0011
K	0.84887	-0.39587	1.00000	0.65619
	0.0001	0.0001	0.0000	0.0001
Q	0.89145	0.34415	0.65619	1.00000
	0.0001	0.0011	0.0001	0.0000

The flow-density relationships were examined. It was found that quadratic curves accurately represent the flow-density relationship. Table 14 shows the regression results, and Figures 15 through 17 display the scatter diagrams.

Finally, an analysis of the relationship between volume-to-capacity ratio and density was performed. Table 15 shows the regression results, and Figures 18 through 20 display the scatter diagrams for each data set. The values of R^2 and PROB>F indicate statistical significance between these two variables and a high degree of correlation with a quadratic model. This means that volume-to-capacity ratio and density are good predictors of each other for toll plaza traffic.

It should be noted that the density criterion used for basic freeway segments and multilane rural highways is also correlated with volume-to-capacity ratio value as shown in Table 16. Figure 21 plots the models from Tables 15 and 16.

Appendix B presents the regression results of all the discussed models of speed-density, flow-density, and v/c-density for each study site.

Consider the three toll plaza areas described in Table 17 and assume that traffic flow (Q), total length (L), and average travel time (T) are all the same at these three areas. If the travel ratio is a parameter for determining level of service, these three facilities would have the same level of service, since

$$R = \frac{L}{T\hat{V}} \qquad \text{and} \qquad R_A = R_B = R_C.$$

If volume-to-capacity ratio is a parameter for determining level of service, with

$$\frac{Q}{C*} > \frac{Q}{C},$$

facilities A and B would have the same level of service, whereas facility C would have a higher level of service. However, if density is the criterion for level of service, it would be possible to differentiate the service qualities of the three facilities. From Eq. 14,

$$K_A = \frac{2QT}{6L} > K_B = \frac{2QT}{7L} > K_C = \frac{2QT}{8L}.$$

Thus, facility A has the lowest level of service, whereas facility C has the highest level of service, which reflects more precisely the reality that motorists would perceive in this case. In terms of the major parameters of stream flow used to define level of service, Roess *et al.* raised a dichotomy:[40]

1. The driver experiences speed and density.
2. The designer or analyst is most interested in the volumes that can be accommodated.

Table 14
FLOW-DENSITY REGRESSION MODELS

Data Set	Model	R^2	PROF>F
1-min	$Q = -0.670K^2 + 112.89K - 375$	0.5149	0.0001
3-min	$Q = -1.215K^2 + 163.49K - 1495$	0.4933	0.0001
5-min	$Q = -1.145K^2 + 161.74K - 1569$	0.4800	0.0001

Table 15
V/C-DENSITY REGRESSION MODELS

Data Set	Model	R^2	PROF>F
1-min	$v/c = -0.000105K^2 + 0.0216K + 0.0243$	0.7900	0.0001
3-min	$v/c = -0.000141K^2 + 0.0246K - 0.0408$	0.7560	0.0001
5-min	$v/c = -0.000122K^2 + 0.0234K - 0.0293$	0.7417	0.0001

Table 16
REGRESSION MODELS FOR PRESENT V/C-DENSITY CRITERIA

	Model	R^2	PROF>F
Freeway Segments	$v/c = -0.000221K^2 + 0.0294K - 0.0228$	0.9746	0.0001
Multilane Highways	$v/c = -0.000143K^2 + 0.0231K - 0.0891$	0.9761	0.0001

Table 17
DESCRIPTION OF EXAMPLES

Facility	Number of Arrival Lanes	Number of Booths	Number of Departure Lanes	Capacity
A	2	4	2	C^*
B	3	4	3	C^*
C	3	5	3	$C, (C > C^*)$

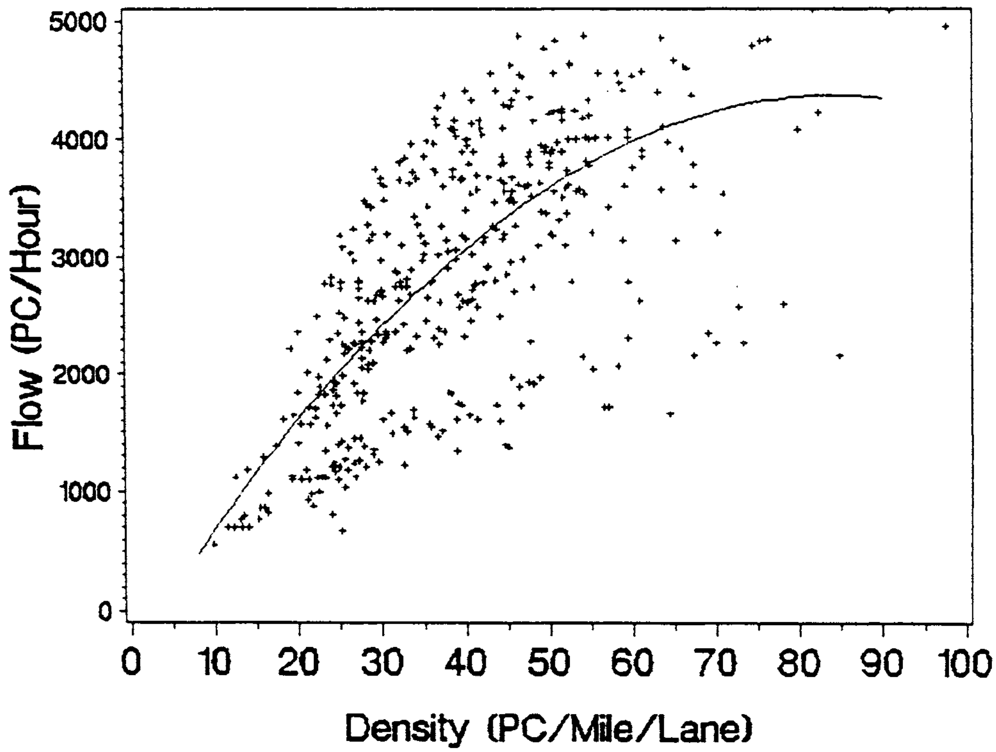


Figure 15. Flow-density diagram (1-min data set).

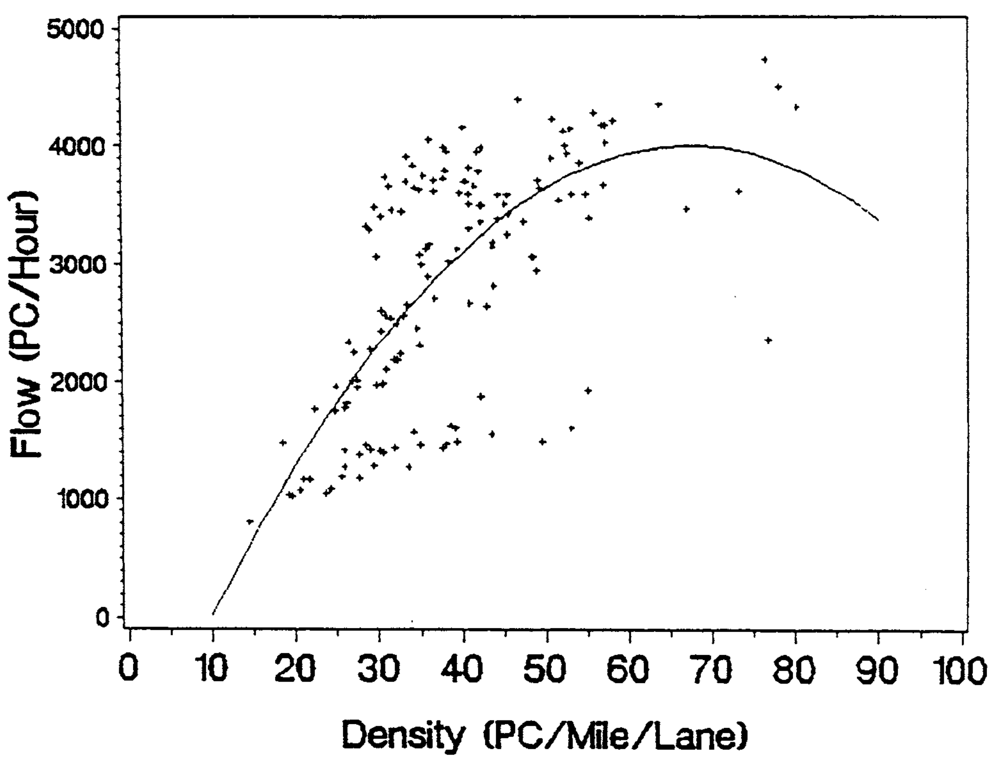


Figure 16. v/c-density diagram (3-min data set).

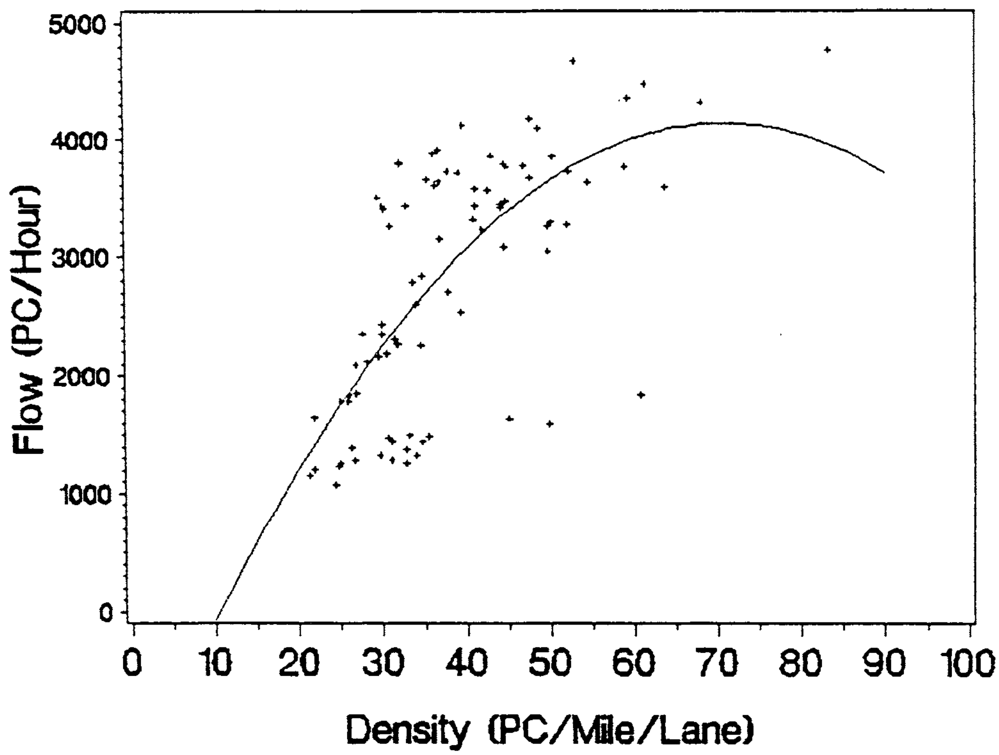


Figure 17. Flow-density diagram (5-min data set).

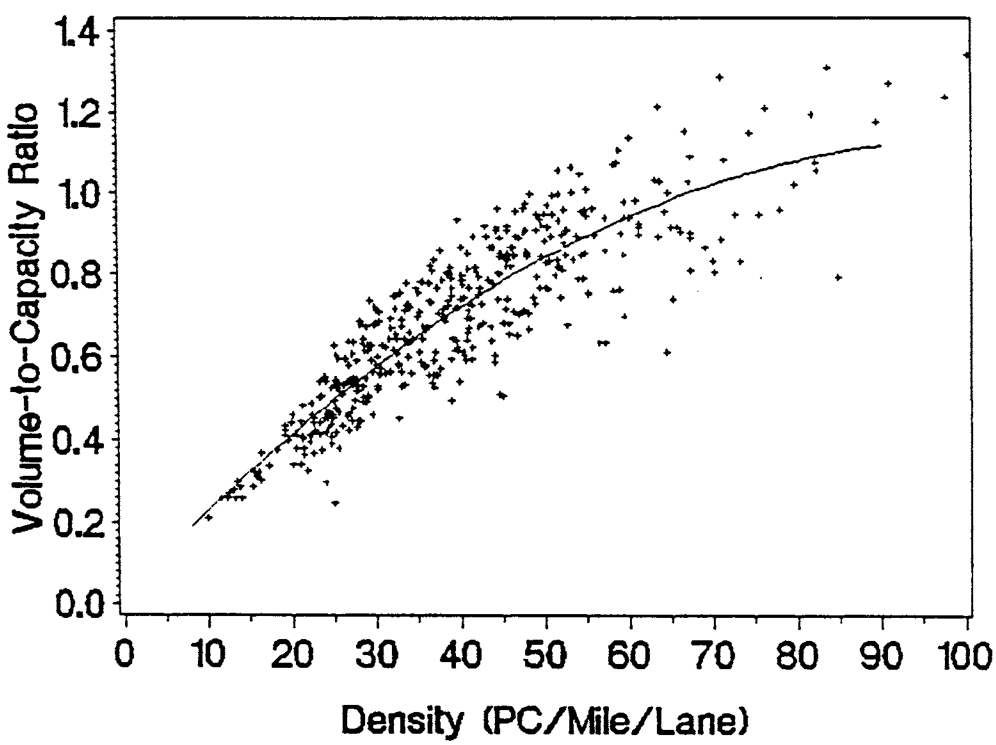


Figure 18. v/c-density diagram (1-min data set).

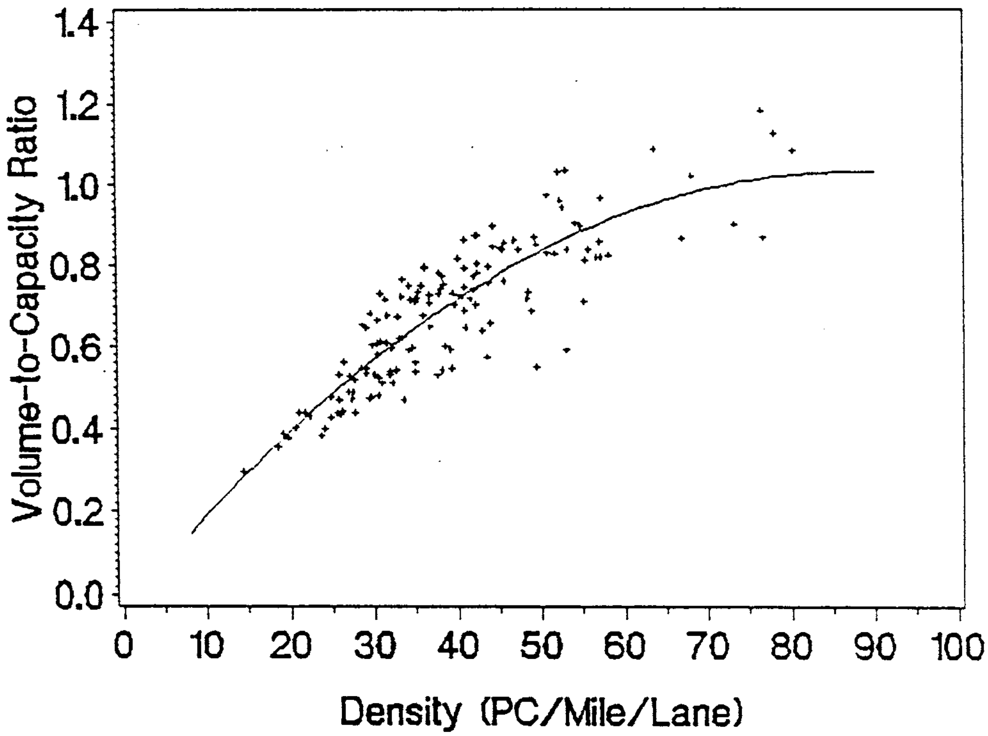


Figure 19. **v/c-density diagram (3-min data set).**

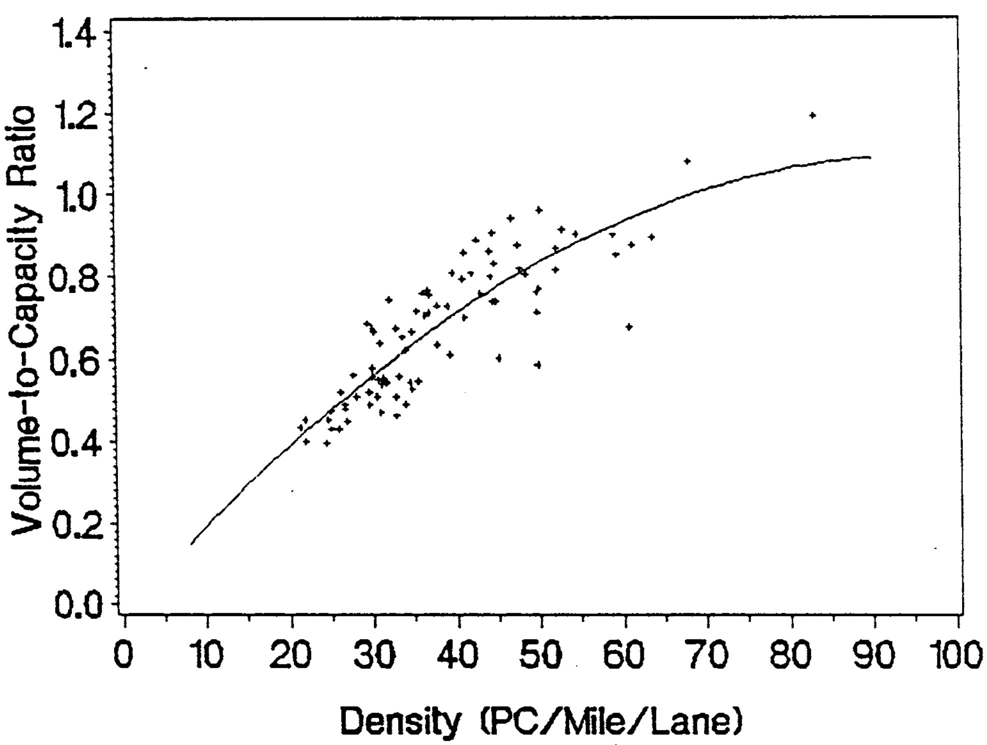


Figure 20. **v/c-density diagram (5-min data set).**

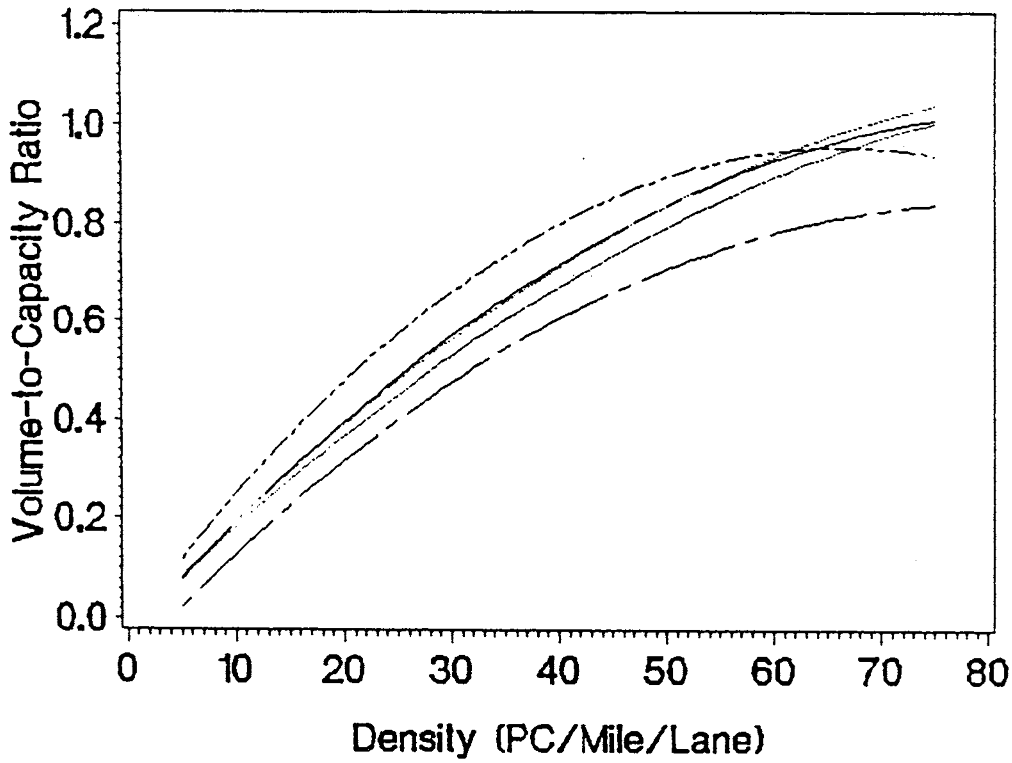


Figure 21. Plots of v/c-density models.

Roess *et al.* then recommended that level of service be defined in terms of the parameters directly experienced by drivers: speed and density. These should then be related to volumes for the use of designers, analysts, and planners.

Similar to the present level of service standards for freeway segments and multilane highways exhibited in Table 18, boundary density for level of service E at toll plaza areas is 67 pc/mi/ln, which is the density at which capacity most often occurs for stable flows. Interestingly, this critical density is found to be valid for the flow-density model and v/c-density model as reflected in Figures 15 through 20. Therefore, current boundary values of density are adopted for the various levels of service for toll plaza areas. Based on the v/c-density relationships depicted in Figures 18 through 20, the corresponding boundary values of v/c ratio are proposed as in Table 19. To be within a given level of service, the density criterion must be met. The v/c ratios indicated in the table are expected to exist for the given densities, although they may vary to some extent. Defining levels of service in this way considers parameters that drivers are directly aware of and engineers are most interested in.

The way most toll mechanisms are equipped on interstate and multilane highways, it would be a unique advantage to adopt density as the level of service criterion. This would warrant the continuance of one criterion. The major difference would lie in the decrease of average running speed, which is somewhat anticipated by all motorists who decide to use a toll road.

Table 18
LEVEL OF SERVICE CRITERIA IN CURRENT *HIGHWAY CAPACITY MANUAL*[8]

Design Speed		Freeway Sections			Multilane Highways		
		70 MPH	60 MPH	50 MPH	70 MPH	60 MPH	50 MPH
LOS	Density	v/c	v/c	v/c	v/c	v/c	v/c
A	≤ 12	0.35	—	—	0.36	0.33	—
B	≤ 20	0.54	0.49	—	0.54	0.50	0.45
C	≤ 30	0.77	0.69	0.67	0.71	0.65	0.60
D	≤ 42	0.93	0.84	0.83	0.87	0.80	0.76
E	≤ 67	1.00	1.00	1.00	1.00	1.00	1.00
F	> 67	—	—	—	—	—	—

Table 19
PROPOSED LEVEL OF SERVICE CRITERIA FOR TOLL PLAZA AREAS

LOS	Density (pc/mi/ln)	v/c
A	≤ 12	0.24
B	≤ 20	0.40
C	≤ 30	0.57
D	≤ 42	0.74
E	≤ 67	1.00
F	> 67	—

Consider a stable platoon of traffic that enters a toll plaza area. The density will tend to decrease because of the widening at the beginning of vehicle divergence; however, the evident reduction of travel speed in the toll plaza area may immediately offset this density decrease.

Note that when traffic volume and pattern are unchanged and improvement is made in the toll collection process, e.g., using AVI techniques, the capacity will increase and v/c value will decrease accordingly. Since this improvement also reduces the total travel time (from Eq. 14), the corresponding density should also decrease. Adding a new lane produces a similar situation. It increases not only the capacity but also the area (A). Hence, v/c and density decrease at the same time. Therefore, the v/c-density relationships developed here can still hold.

General operating conditions for each of the levels of service are as follows:

1. *Level of Service A* operates with very low density and delay. The operation of vehicles is virtually unaffected by the presence of other vehicles, although deceleration is necessary because of the toll plaza. The maximum average vehicle density is 12 pc/mi/ln. Most vehicles do not completely stop if change or a receipt is not required. Minor disruptions are easily absorbed. Standing queues will not form, and the general level of comfort and convenience is excellent.

2. *Level of Service B* represents a maximum average density of 20 pc/mi/ln. Vehicles start to decelerate earlier upstream than for level of service A. The presence of other vehicles in the traffic streams begins to be noticeable. However, there is a good opportunity for lane change throughout the whole area. Minor disruptions may be easily absorbed at this level, although local deterioration in level of service at individual booths is more obvious.

3. *Level of Service C* operates at a maximum average density of 30 pc/mi/ln. The number of vehicles stopping is significant. The higher delays result from the early deceleration as well as occasional complete stops for paying tolls. Minor disruptions may be expected to cause serious local deterioration in service. Queues establish at times.

4. *Level of Service D* represents the operation at a maximum average density of 42 pc/mi/ln. Vehicles have very little freedom of maneuver within the approach section to choose a toll lane. Queue length becomes significant, and stop-and-go is inevitable.

5. *Level of Service E* represents a maximum average density of 67 pc/mi/ln. Every vehicle joins a queue before arriving at a toll booth. Stop-and-go is a typical phenomenon. Maneuver within the approach section is almost impossible.

6. *Level of Service F* operates at an average density higher than 67 pc/mi/ln and v/c more than 1. This often occurs when arrival flow rates exceed the toll service rates. Queues continue to increase beyond the divergence point.

It is important to note that level of service is not a relation of volume to density in a one-to-one relation. For example, it is possible to have density at the range of level of service E while the v/c ratio is below the range of level of service E in some instances. Similarly, it is possible to have the v/c ratio at the range of level of service C while the density is below it. Nevertheless, v/c ratio and density can be a fairly reliable predictor of each other as the regression models show in Table 15.

SIMULATION

Computer simulation is one of the most powerful tools for use in the design and analysis of systems. Simulation allows the user to experiment with real and proposed systems where it would be impossible or impractical otherwise. Simulation also allows the analyst to evaluate the consequences of design and operating decisions before those decisions are made. An additional advantage of simulation is its use in training. The development and use of a simulation model allows the experimenter to see and interact with the system. This, in turn, should greatly assist him in understanding and gaining a feel for the problem.

Despite the fact that arriving customers may interact with each other before arriving at the queue, it is reasonable to assume that the arrival time of some arbitrarily numbered customer is nearly statistically independent of any other. The traffic operation in toll plaza areas involves the lane selection model which features the situation that a vehicle of type m may use any service facility of type n, where $n \leq m$ *(47)*. For example, assume that the trucks-and-buses booth is a type *1* service facility, and trucks and buses are type *1* vehicles. The toll booths for passenger cars only are a type *2* facility, and cars without exact change are type *2* vehicles. Finally, exact-change booths are type *3* facilities, and cars with exact change are type *3* vehicles. Notice that cars with exact change are permitted to use any booth, but that cars without exact change must use either type *1* or type *2* booths. It is more complex than the conventional queue model. The rule that an arriving driver decides on a queue to join is mistaken because he has few alternatives. One would expect that the type m customer tends to prefer the type m facility, and to select type n, where $n \neq m$, only when this choice represents a clear advantage, for example, when the n facility is empty. The assumption is logical if the toll lanes are reasonably designed, so that no great difference of queue length exists among toll lanes when there are queues.

CINEMA is a simulation/animation system based on the SIMAN simulation language, which was chosen to be applied in this study. The user sees a real time graphical animation of the SIMAN model with customers or jobs (vehicles, in this study) moving through the system. Animation construction is a two-step process. The first step consists of building a SIMAN model to represent the system being animated. This is followed by building an animation layout using CINEMA. The layout is a graphical representation of the SIMAN model. The SIMAN model and the animation layout are brought together to generate the real-time animation. Figure 22 shows the SIMAN simulation process diagram.

The Colonial Heights' northbound traffic data from a 30-minute period was used as input elements for the simulation:

Number of Lanes: 3-6-3

Total Length: 891 feet

Number of Automobiles: 699

Number of Trucks & Buses: 123

Service Time (in seconds):

Veh Type	Mean	σ (SD)	β	α	Travel Time
Truck	14.23	5.20	1.90021	7.48864	54.202
Auto	5.21	1.66	0.52891	9.85052	30.112
Auto(E)*	5.33	0.81	0.12309	43.29965	

*with exact change

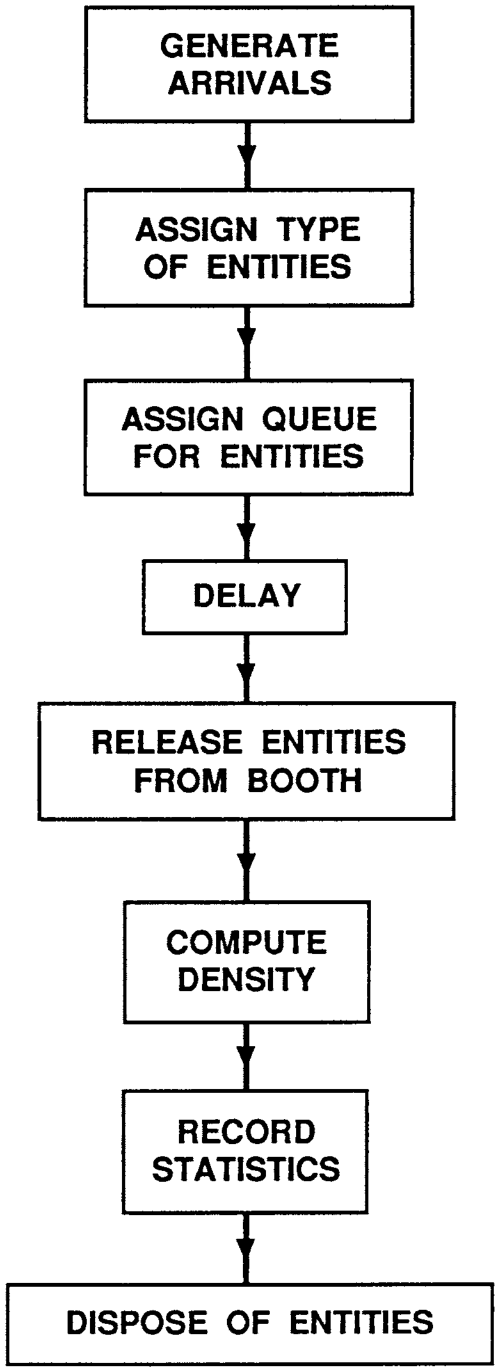


Figure 22. Simulation flowchart.

Since the number of arrivals during an interval of 15 seconds is Poisson distributed, the exponential distribution with a mean time between arrivals is used. This mean time is

$$\frac{3600}{2 \times (699 + 123)} = 2.190 \text{ seconds.}$$

The percentage of trucks is $\frac{123}{699 + 123} = 0.15$. The area is $A = \frac{1}{2}(3 + 6) \times \frac{891}{5280} =$ 0.756 mile-lane. If at any instance, there are V passenger cars traveling within the toll plaza area, the density becomes

$$K = \frac{V}{A} = 1.317V \text{ (pc/mi}-\text{ln or pc/mi/ln).} \tag{15}$$

SIMAN

Model Description

The system can be divided into four submodels. Figure 23 lists the SIMAN model. The first submodel models the arrival of entities to the system. An entity enters the system at the CREAT block and proceeds to the ASSIGN blocks. These arrivals are generated with the time between creations specified as a sample from an exponential distribution using parameter set 5 and random stream number 1. The mark modifier attached to the block assigns the creation time to attribute number 3 of each entity. This is done so that the time in system for each arrival may be recorded prior to disposing of the entity. The vehicle type is specified by the attribute number 1 using a discrete probability distribution with parameter set 4 from stream 1. Trucks are assigned a value of 1 with a probability of 0.18, automobiles are assigned as 2 with a probability of 0.62, and automobiles with exact change are assigned a value of 3 with 0.2 probability. The attribute number 2 is used to assign the service time by a Gamma distribution with parameter set depending on the vehicle type. The arrival is then counted by its vehicle type at the COUNT block and kept at the beginning of the toll plaza area set to be station 7 before it enters the second submodel.

Each arrival then enters the FINDJ block where a search is made over the index J for the value of the index J yielding the minimum value for NQ(J)+NR(J), where NQ(J) represents the number of entities residing in queue J, and NR(j) represents the number of busy units of resource J. Thus, NQ(J) + NR(J) is the number of entities in booth J. The FINDJ block automatically assigns the corresponding index value to the variable J. J will be set at the FINDJ block to the booth number having the smallest number of cars at the time when an entity is generated. Since booth 6 is designated for "EXACT-CHANGE ONLY" and booth 5 is designated for "NO TRUCKS," trucks can choose only booths between 1 and 4, whereas automo-

```
BEGIN;
;
;   ARRIVAL MODEL
;
          CREAT:EX(5,1):MARK(3);
          ASSIGN:A(1)=DP(4,1);
          ASSIGN:A(2)=GA(A(1),1);
          COUNT:A(1),1;
           BRANCH,3:
            IF, A(1) .EQ. 1, QT:
            IF, A(1) .EQ. 2, QA:
            IF, A(1) .EQ. 3, QE;
;
;   APPROACH & CHOOSE A BOOTH
;
QT        FINDJ,1,4:MIN(NQ(J)+NR(J));
          ROUTE:20.41,J;
QA        FINDJ,5,1:MIN(NQ(J)+NR(J));
          ROUTE:11.40,J;
QE        FINDJ,6,1:MIN(NQ(J)+NR(J));
          ROUTE:11.33,J;
;
;   BOOTH
;
          STATION,1-6;
          QUEUE,M;
          SEIZE:BOOTH(M);
          DELAY:A(2);
          RELEASE:BOOTH(M);
           BRANCH,3:
            IF, A(1) .EQ. 1, ET:
            IF, A(1) .EQ. 2, EA:
            IF, A(1) .EQ. 3, EE;
ET        ROUTE:13.16,7;
EA        ROUTE:7.11,7;
EE        ROUTE:7.06,7;
;
;   LEAVE THE PLAZA
;
EXIT      STATION,7;
          COUNT:A(1),-1;
          ASSIGN:X(1)=(2.7*NC(1)+NC(2)+NC(3))*1.317;
          TALLY:1,INT(3):DISPOSE;
END;
```

Figure 23. SIMAN model listing.

biles without exact change can choose only booths from 5 to 1. The arrival vehicles travel to booth J with a specified travel time depending on the vehicle type.

The third submodel represents queuing and service delay at the six toll booths. Vehicles entering the station proceed to the QUEUE block where they wait in file M to seize the indexed resource BOOTH(M). SIMAN automatically sets the station attribute, M, to the current station number of the entity when it enters a STATION block. Once a vehicle seizes a unit of BOOTH(M), it proceeds to the DELAY block where it is delayed by the time required to finish the toll transaction. The vehicle then releases BOOTH(M) and is routed to the end station 8.

The exit process is modeled by the fourth submodel. An entity enters the exit submodel at the STATION 8 block. The departure causes the counter to decrease by 1 unit. The global system variable X(1) is used to calculate the instant density for the system with Eq. 15. Finally, the time in system for each entity is recorded before the entity is disposed of.

Experiment Description

The experiment listing is shown in Figure 24. The PROJECT element is included to obtain a SIMAN Summary Report. This element specifies the project name, analyst name, and date to be used in labeling the report. The DISCRETE

```
BEGIN;
PROJECT,TOLL PLAZA,T. HUGH WOO, 3/27/90;
DISCRETE,120,3,7,8;
TALLIES:1,SYSTEM TIME;
RESOURCES:1-6,BOOTH;
DSTAT:1,NR(1),TELLER1 UTIL.:
      2,NR(2),TELLER2 UTIL.:
      3,NR(3),TELLER3 UTIL.:
      4,NR(4),TELLER4 UTIL.:
      5,NR(5),TELLER5 UTIL.:
      6,NR(6),TELLER6 UTIL.:
      7,NQ(1),BOOTH1 QUEUE:
      8,NQ(2),BOOTH2 QUEUE:
      9,NQ(3),BOOTH3 QUEUE:
     10,NQ(4),BOOTH4 QUEUE:
     11,NQ(5),BOOTH5 QUEUE:
     12,NQ(6),BOOTH6 QUEUE:
     13,X(1),DENSITY;
COUNTERS:1,TRUCK NO.:2,AUTO NO.:3,AUTOE NO.;
PARAMETERS:1,1.9,7.488:2,0.529,9.851:3,0.123,43.30:
           4,0.15,1,0.80,2,1.0,3:5,2.190;
REPLICATE,3,0,1800;
END;
```

Figure 24. SIMAN experiment listing.

element specifies a discrete model having a maximum of 120 entities concurrently in the system, with 3 attributes per entity, 6 user-defined files, and 7 stations.

The TALLIES element defines the report identifier for tally variable, SYSTEM TIME. Discrete time-persistent statistics are recorded on 14 variables using the DSTAT element. These variables include the number of busy booths and queue length and the number of trucks and automobiles concurrently in the system. Five parameter sets are used in this model. Parameter sets 1, 2, and 3 specify the β and α of a Gamma distribution for the service time of each vehicle type. Parameter set 4 specifies the cumulative probabilities of occurrence of a vehicle type. Parameter set 5 specifies the mean of an exponential distribution used in the CREAT block for generating an arrival. The REPLICATE element specifies 3 runs to start at time 0 with the length of each run being 1800 seconds.

Summary of Results

The SIMAN Summary Reports are included in Figures 25 through 27. The first section in the summary contains the observation statistics for the time spent in the system. The second section contains statistics that summarize the observations in both utilization and queue of the six toll booths. The number of trucks and automobiles is also included. The last section contains the counter values that represent the number of each vehicle type in the system at the end of the simulation run.

Comparison

The results show that, in a 30-minute run, the average density is between 24.20 and 26.83 pc/mi/ln, which indicates that the toll area is operating at level of service C using the proposed criteria in Table 19.

The automobile equivalent for truck (α_1) is obtained from truck service time divided by automobile service time, $\frac{14.23}{5.21} = 2.7$. From the field data, v/c value is calculated as

$$\frac{2 \times (699 + 2.7 \times 123)}{4130} = 0.499.$$

Comparing this result with the proposed criteria of Table 19 indicates that the resulting level of service is *C*, which is expected to be in the range of 0.40 to 0.57 for v/c values. Since the travel times for automobiles and trucks are 30.3112 and 54.202 seconds respectively, the density can be computed using Eq. 14 as

$$K = \frac{2 \times (699 \times 30.112 + 2.7 \times 123 \times 54.202)}{(30 \times 60)(3 + 6) \times (891/5280)} = 28.57 \text{ pc/mi/ln},$$

which falls into level of service C and is very close to the values obtained from the simulation.

SIMAN Summary Report

Run Number 1 of 3

Project: TOLL PLAZA
Analyst: T. HUGH WOO
Date : 3/27/1990

Run ended at time .1800E+04

Tally Variables

Number	Identifier	Average	Standard Deviation	Minimum Value	Maximum Value	Number of Obs.
1	SYSTEM TIME	33.71355	12.30794	20.28821	103.88790	808

Discrete Change Variables

Number	Identifier	Average	Standard Deviation	Minimum Value	Maximum Value	Time Period
1	TELLER1 UTIL.	.49	.50	.00	1.00	1800.00
2	TELLER2 UTIL.	.43	.49	.00	1.00	1800.00
3	TELLER3 UTIL.	.44	.50	.00	1.00	1800.00
4	TELLER4 UTIL.	.58	.49	.00	1.00	1800.00
5	TELLER5 UTIL.	.64	.48	.00	1.00	1800.00
6	TELLER6 UTIL.	.33	.47	.00	1.00	1800.00
7	BOOTH1 QUEUE	.29	.64	.00	3.00	1800.00
8	BOOTH2 QUEUE	.32	.76	.00	4.00	1800.00
9	BOOTH3 QUEUE	.53	1.07	.00	6.00	1800.00
10	BOOTH4 QUEUE	.88	1.51	.00	9.00	1800.00
11	BOOTH5 QUEUE	.90	1.27	.00	6.00	1800.00
12	BOOTH6 QUEUE	.07	.30	.00	3.00	1800.00
13	DENSITY	26.83	9.25	.00	53.47	1800.00

Counters

Number	Identifier	Count	Limit
1	TRUCK NO.	5	Infinite
2	AUTO NO.	2	Infinite
3	AUTOE NO.	2	Infinite

Run Time : 48 Second(s)

Figure 25. SIMAN summary report (1).

SIMAN Summary Report

Run Number 2 of 3

Project: TOLL PLAZA
Analyst: T. HUGH WOO
Date : 3/27/1990

Run ended at time .1800E+04

Tally Variables

Number	Identifier	Average	Standard Deviation	Minimum Value	Maximum Value	Number of Obs.
1	SYSTEM TIME	32.80015	11.48358	20.70654	101.13550	775

Discrete Change Variables

Number	Identifier	Average	Standard Deviation	Minimum Value	Maximum Value	Time Period
1	TELLER1 UTIL.	.48	.50	.00	1.00	1800.00
2	TELLER2 UTIL.	.42	.49	.00	1.00	1800.00
3	TELLER3 UTIL.	.43	.49	.00	1.00	1800.00
4	TELLER4 UTIL.	.53	.50	.00	1.00	1800.00
5	TELLER5 UTIL.	.62	.49	.00	1.00	1800.00
6	TELLER6 UTIL.	.32	.47	.00	1.00	1800.00
7	BOOTH1 QUEUE	.26	.63	.00	4.00	1800.00
8	BOOTH2 QUEUE	.36	.94	.00	7.00	1800.00
9	BOOTH3 QUEUE	.44	.91	.00	6.00	1800.00
10	BOOTH4 QUEUE	.63	1.12	.00	6.00	1800.00
11	BOOTH5 QUEUE	.82	1.25	.00	7.00	1800.00
12	BOOTH6 QUEUE	.09	.34	.00	3.00	1800.00
13	DENSITY	24.20	7.45	.00	47.28	1800.00

Counters

Number	Identifier	Count	Limit
1	TRUCK NO.	3	Infinite
2	AUTO NO.	11	Infinite
3	AUTOE NO.	4	Infinite

Run Time : 46 Second(s)

Figure 26. SIMAN summary report (2).

SIMAN Summary Report

Run Number 3 of 3

Project: TOLL PLAZA
Analyst: T. HUGH WOO
Date : 3/27/1990

Run ended at time .1800E+04

Tally Variables

Number	Identifier	Average	Standard Deviation	Minimum Value	Maximum Value	Number of Obs.
1	SYSTEM TIME	34.11161	12.65618	21.11249	83.41150	793

Discrete Change Variables

Number	Identifier	Average	Standard Deviation	Minimum Value	Maximum Value	Time Period
1	TELLER1 UTIL.	.48	.50	.00	1.00	1800.00
2	TELLER2 UTIL.	.41	.49	.00	1.00	1800.00
3	TELLER3 UTIL.	.51	.50	.00	1.00	1800.00
4	TELLER4 UTIL.	.56	.50	.00	1.00	1800.00
5	TELLER5 UTIL.	.63	.48	.00	1.00	1800.00
6	TELLER6 UTIL.	.32	.47	.00	1.00	1800.00
7	BOOTH1 QUEUE	.29	.68	.00	4.00	1800.00
8	BOOTH2 QUEUE	.30	.73	.00	5.00	1800.00
9	BOOTH3 QUEUE	.55	1.06	.00	6.00	1800.00
10	BOOTH4 QUEUE	.81	1.49	.00	9.00	1800.00
11	BOOTH5 QUEUE	1.02	1.51	.00	7.00	1800.00
12	BOOTH6 QUEUE	.08	.32	.00	3.00	1800.00
13	DENSITY	26.47	7.58	.00	46.75	1800.00

Counters

Number	Identifier	Count	Limit
1	TRUCK NO.	5	Infinite
2	AUTO NO.	5	Infinite
3	AUTOE NO.	3	Infinite

Run Time : 47 Second(s)

Stop - Program terminated.

Figure 27. SIMAN summary report (3).

Discussion

All simulation models are so-called input-output models; that is, they yield the output of the system given the input to its interactng subsystems. Simulation models are therefore "run" in order to obtain the desired information or results. They are incapable of generating a solution on their own in the way that analytical models do. They can only serve as a tool for the analysis of the behavior of a system under conditions specified by the experimenter.

For the purpose of output analysis, traffic flows at a toll plaza area will be considered a nonterminating system that has no natural terminating event that defines the end of the simulation. Since simulation is sampling experiment, we cannot simply run a simulation for an arbitrary length of time and then interpret the results in the SIMAN summary report as the "true" system response.

In nonterminating systems, we can increase the sample size by either continuing a single run or by replicating the run. There is some debate as to the best approach. If replication is used, then a bias is introduced at the beginning of every run. The advantage is the independence between each run. If we increase sample size by continuing a single run rather than by replicating the run, we have the advantage that we waste the computer time associated with the transient period only once. The disadvantage of this approach is that the analysis of the results is complicated because the observations within a run are normally autocorrelated. The replication approach was used for this purpose in the study.

To eliminate the bias of initial conditions, the first run starts at 100 seconds rather than 0 second, and 100 replications were simulated as indicated in the REPLICATE element in Figure 28. The OUTPUT element defines variable 1 as the average of DSTAT variable 13 (density). This response variable is recorded at the end of each replication of the simulation model on output data set 10. The recorded values can then be input to the output processor for further analysis. Based on one hundred replications, a histogram of the average densities and its confidence interval were generated (see Figure 29). With a 95 percent confidence level, the average density would lie between 26.7 and 27.4 pc/mi/ln.

Different v/c values were used as inputs to experiment the SIMAN model shown in Figure 23. The only change needed is the mean time between arrivals as given in PARAMENTER set 5 of the experiment listing. Results from these simulations are illustration in Table 20. Consistency was found in level of service for all cases.

```
BEGIN;
PROJECT,TOLL PLAZA AT C,T. HUGH WOO, 5/20/90;
DISCRETE,120,3,6,7;
TALLIES:1,SYSTEM TIME;
RESOURCES:1-6,BOOTH;
DSTAT:1,NR(1),TELLER1 UTIL.:
      2,NR(2),TELLER2 UTIL.:
      3,NR(3),TELLER3 UTIL.:
      4,NR(4),TELLER4 UTIL.:
      5,NR(5),TELLER5 UTIL.:
      6,NR(6),TELLER6 UTIL.:
      7,NQ(1),BOOTH1 QUEUE:
      8,NQ(2),BOOTH2 QUEUE:
      9,NQ(3),BOOTH3 QUEUE:
     10,NQ(4),BOOTH4 QUEUE:
     11,NQ(5),BOOTH5 QUEUE:
     12,NQ(6),BOOTH6 QUEUE:
     13,X(1),DENSITY;
COUNTERS:1,TRUCK NO.:2,AUTO NO.:3,AUTOE NO.;
PARAMETERS:1,1.9,7.488:2,0.529,9.851:3,0.123,43.30:
           4,0.15,1,0.80,2,1.0,3:5,2.190;
REPLICATE,100,100,1800;
OUTPUT:1,DAVG(13),10;
END;
```

Figure 28. Experiment listing for output analysis.

Table 20

SIMULATION RESULTS WITH DIFFERENT V/C VALUES

LOS	v/c	Time*	Average Density **		
A	0.15	7.293	5.51	5.40	5.61
B	0.32	3.419	14.54	14.83	12.99
D	0.65	1.683	38.70	37.71	41.69
E	0.86	1.272	59.39	65.22	60.21

***mean time between arrivals as used in PARAMETER set 5**
****value for each of three runs in pc/mi/ln**

CINEMA

An animation layout using CINEMA was developed. The layout was so constructed that, when a booth is busy, it changes its symbol. The screen also displays instantaneous queue length for each booth and the density, which are represented by NQ(J) and X(1) in the SIMAN model. The user has an option to change the time scale, which can speed up or slow down vehicle movement on the screen. Figure 30 and 31 show two screens of the animation.

Figure 30 shows an instance about 9 minutes after the simulation starts. All booths except 2 are busy. There are 1, 1, and 3 vehicles in the queues of booth 1, 3,

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HISTOGRAM : TOLL AREA DENSITY

Cell No.	Cell Limits From	Cell Limits To	Absolute Freq. Cell	Absolute Freq. Cumul.	Relative Freq. Cell	Relative Freq. Cumul.
0	-Infinity	22.000	0	0	.0000	.0000
1	22.000	23.000	0	0	.0000	.0000
2	23.000	24.000	1	1	.0100	.0100
3	24.000	25.000	13	14	.1300	.1400
4	25.000	26.000	17	31	.1700	.3100
5	26.000	27.000	22	53	.2200	.5300
6	27.000	28.000	24	77	.2400	.7700
7	28.000	29.000	11	88	.1100	.8800
8	29.000	30.000	5	93	.0500	.9300
9	30.000	31.000	5	98	.0500	.9800
10	31.000	32.000	2	100	.0200	1.0000
11	32.000	+Infinity	0	100	.0000	1.0000

HISTOGRAM : TOLL AREA DENSITY

```
REL. FREQ.
      0.000E+00        2.500E-01        5.000E-01        7.500E-01       1.000E+00

K
CELL NUMBER
     0. C                +                +                +                +
     1. C                +                +                +                +
     2. +C               +                +                +                +
     3. +**********C     +                +                +                +
     4. +*************   +   C            +                +                +
     5. +**************** +               + C              +                +
     6. +*****************+               +                +C               +
     7. +*******         +                +                +        C       +
     8. +***             +                +                +           C    +
     9. +***             +                +                +               C+
    10. +*               +                +                +                C
    11. +                +                +                +                C
```

INTERVALS: TOLL AREA DENSITY

IDENTIFIER	AVERAGE	STANDARD DEVIATION	.950 C.I. HALF-WIDTH	MINIMUM VALUE	MAXIMUM VALUE	NUMBER OF OBS.
K	27.0	1.74	.346	23.0	31.9	100

INTERVALS : TOLL AREA DENSITY

```
              23.0                    27.0                         31.9
K              <--------------------(-X-)------------------------->
                                  26.7   27.4
```

```
| < = MINIMUM   ( = LOWER 95% CL   X = AVERAGE   ) = UPPER 95% CL   > = MAXIMUM |
```

Figure 29. Histogram and confidence interval of average densities.

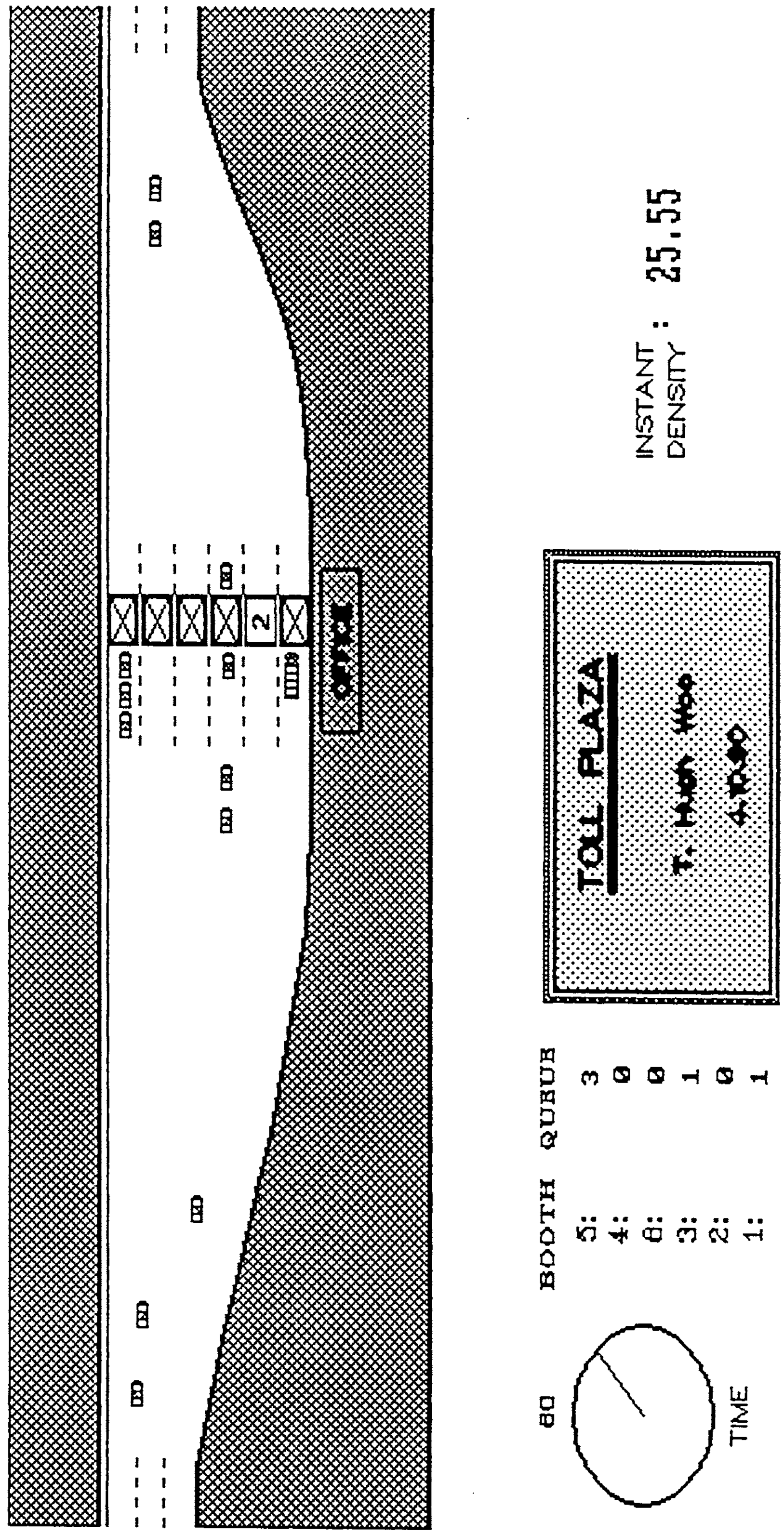

Figure 30. Display of animation (1)

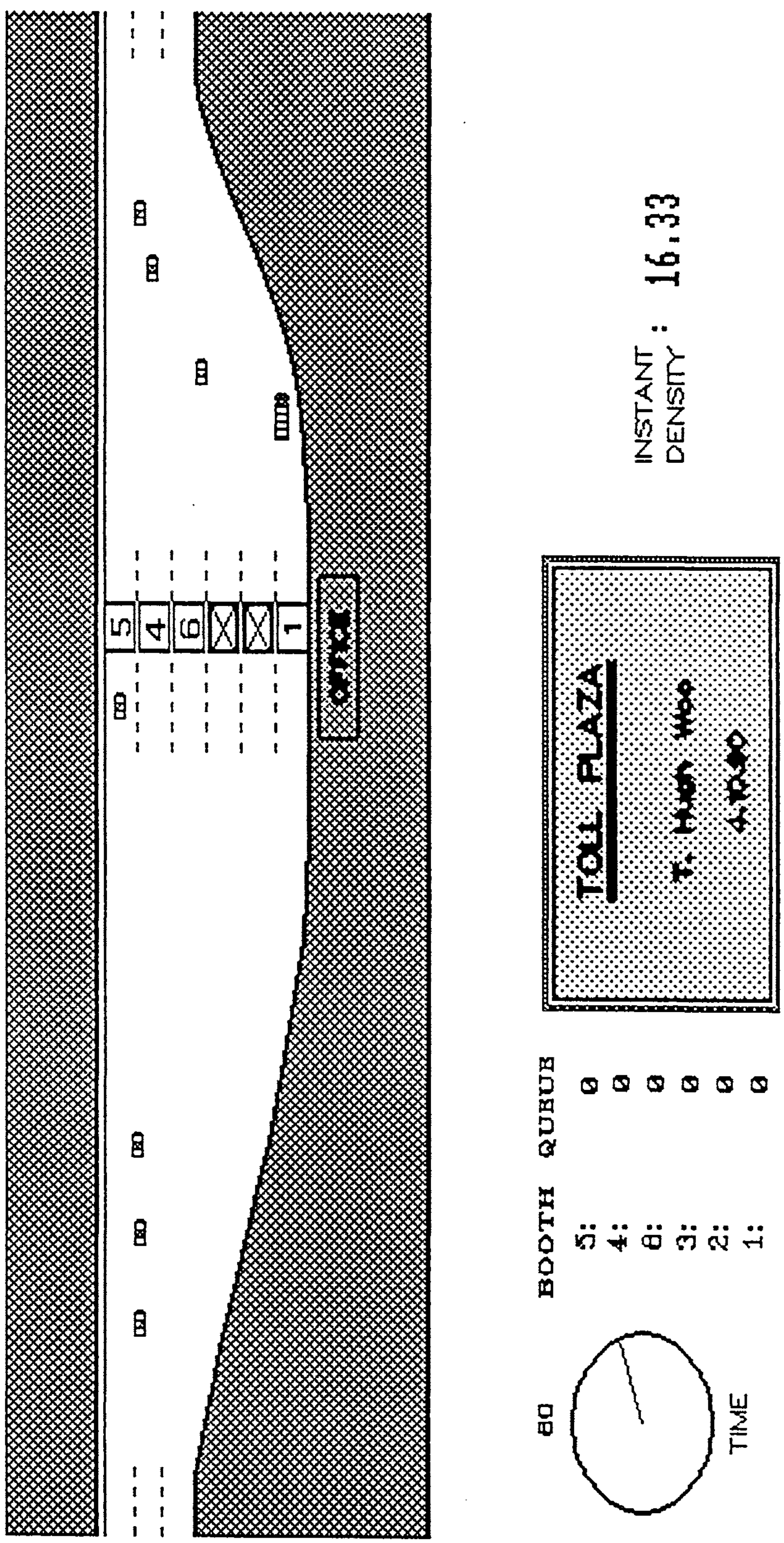

Figure 31. Display animation (2).

and 5, respectively. The circle at the left lower corner is the simulation clock that displays the time. The length of queue for each booth is also numerically shown on the screen. Instantaneous density is calculated and displayed at the right lower corner. The level of service for any instance can be determined by comparing this computed density and the boundary values proposed in Table 20.

PROCEDURES AND SAMPLES APPLICATIONS

This section presents two levels of analysis for use by traffic engineers who want to determine the level of service of a toll plaza or design a proposed toll plaza. The first is operational analysis. A second method is provided for planning analysis.

Operational Analysis

For this method, detailed information on all prevailing traffic, roadway, service time, and/or travel time must be provided. This method provides for an analysis of capacity and level of service, and can be used to evaluate alternative designs and/or types of toll collection. The operational analysis would be used in most analyses of existing toll plazas or of future situations in which traffic and other parameters are well established by projections or trial designs.

Procedures

The general procedure for performing an operational analysis is to use Eq. 3 and Eq. 4 to compute the capacity of the plaza in question. After the v/c is calculated, the respective density and the level of service can be determined with Table 19. The following steps should be used in performing these computations.

1. Convert all volumes to peak 15-minute flow rate. Let the service flow rate, SF, equal the actual peak flow rate as

$$SF = [1 + (\alpha - 1)f_t]V, \tag{16}$$

   where V = the actual hourly demand volume, α = the automobile equivalent for trucks at toll plazas, and f_t = percentage of trucks and buses.

2. Determine the plaza capacity using Eq. 3 and Eq. 4.

3. Compute the v/c ratio.

4. Use Table 19 to find the approximate density and determine the level of service.

Sample Calculation

Description

The Powhite Parkway Toll Plaza of Route 76 in the city of Richmond was selected for demonstration purposes. The Average Daily Traffic (ADT) in 1988 was 62,850. Commuters make up most of the traffic with less than 4 percent of trucks and buses. There are three approaching lanes in each direction. The grades are flat in both directions. This plaza has 14 toll booths. All booths are equipped with automatic collection machines. The use of reversible lanes allows a 9/5 split in the morning and an 8/6 split in the afternoon.

The exact-change booths are unmanned. However, it should be noted that attendants at the toll booths do not retain tolls themselves. Instead, they deposit appropriate tolls into the automatic collection machines and give the balance back to motorists.

Data was collected for the westbound traffic during an afternoon peak period. There were eight booths open for the westbound traffic, of which three were limited to automobiles with exact change of 35 cents. Figure 32 shows the arrangement of toll booths at the time of data collection. Traffic volume was found to fit the Poisson distribution as shown in Table 21.

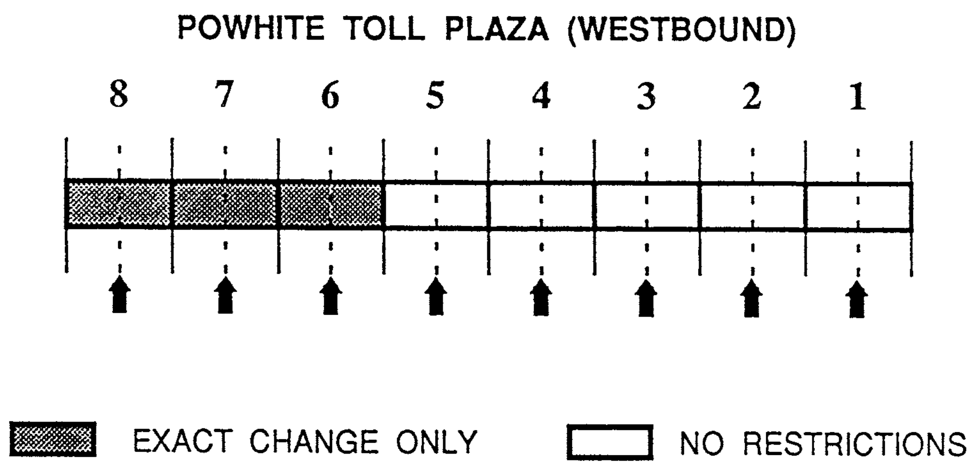

Figure 32. Lane restrictions at Powhite Parkway plaza.

Table 21
GOODNESS OF FIT (POWHITE PARKWAY)

Number of Cars per Interval	Observed Frequency(f_i)	Theoretical Frequency(F_i)		$(f_i-F_i)^2/F_i$
<5	0	0.09		
5	2	0.27		
6	3	0.69	5.53	10.117
7	3	1.53		
8	5	2.95		
9	9	5.06		3.059
10	6	7.83		0.426
11	7	10.99		1.450
12	11	14.15		0.703
13	11	16.82		2.016
14	21	18.57		0.318
15	15	19.13		0.891
16	12	18.47		2.269
17	17	16.79		0.003
18	16	14.42		0.174
19	15	11.72		0.916
20	16	9.06		5.321
21	6	6.66		0.066
22	5	4.68		0.022
23	2	3.14		
24	2	2.02	7.15	0.097
25	4	1.25		
>25	0	0.74		
TOTAL	188			27.848

$m =$ 15.452

$\chi^2 =$ 27.848*

*Accept fit at 0.01 level.

Solution

The traffic flow was measured for 780 vehicles in a 15-minute period, including 19 trucks and buses. Assume $\alpha = 2.7$. Percentage of trucks and buses is then $\frac{19}{780} \approx 2.5\%$. The hourly volume is then 780 x 4 = 3120 (veh/hr).

From Eq. 16,

$$SF = [1 + (2.7 - 1) \times 0.025] \times 3120 = 3253 \text{ pc/hr.}$$

There was a signal light at each booth. Because vehicles at either unmanned booths or attended booths have to obey the signal light that is activated by the coins deposited, locations of the reference lines for both types of booths were found to be about the same distance downstream (46 ft) from where the toll attendants stood. Consequently, service time and capacity of a booth were determined as shown in Table 22.

Table 22

POWHITE PARKWAY PLAZA (WESTBOUND)

Type of Booth	Service Time (seconds)	Capacity (pc/hour)
Unmanned Booths	4.82	747
Attended Booths	5.01	719

Since there are five general booths and three unmanned booths, the total capacity of this plaza can be computed from Eq. 4:

$$C = 5 \times 719 + 3 \times 747 = 5836 \text{ pc/hr.}$$

Then v/c = 3253/5836 = 0.557. Comparing this result with the proposed criteria of Table 19 indicates that the resulting level of service is C, which is expected to occur for v/c values in the range of 0.40 to 0.57.

Because actual field data on travel time were collected in this example, the level of service could be found directly from the density. Travel time is 33.26 seconds for automobiles and 47.27 seconds for trucks. The total length of this toll plaza area is 1,123 feet. The number of lanes is $n_1 = 3$ and $n_3 = 8$. Thus, density was computed using Eq. 14,

$$K = \frac{2 \times 3120[(2.7 \times 0.025 \times 47.27) + (0.975 \times 33.26)]}{(3 + 8) \times (1123/5280) \times (60 \times 60)} = 26.39 \text{ pc/mi/ln.}$$

Comparing the density of 26.39 pc/mi/ln with the level of service criteria of Table 19 shows that the result is consistent with the earlier determination of level of service C from the v/c value.

Design Analysis

In design, a forecast demand volume is used in conjunction with known design standards for geometric features and a desired level of service to compute the number and composition of booths required for the toll plaza in question. Lane widths of 10 feet for an auto-only booth and 12 feet for a general booth are prevalent. If the lane is too wide, the driver tends to stand out from the toll booth, thus forcing the collector to reach out to collect the toll. Both collector fatique and time lost in the unnecessary motion reduce the capacity of the lane. Whereas, if a lane is too narrow, drivers may be overcautious in entering the lane, thus slowing down traffic unduly. When it is possible, a toll plaza should be constructed on a level section of the road or a section with a minimal grade available. Horizontal curvature should also be at a minimum to provide safety and eliminate excessive impedance beside toll effects.

Procedures

Design analysis requires the selection of a design level of service, which determines the design value of v/c. Information concerning the projected directional design hourly volume (DDHV) and traffic characteristics is required. Design speed limit must be specified. The basic analytic procedure for design purposes is to solve for the number and composition of toll lanes needed at a plaza. The following steps are used.

1. Convert the DDHV to an equivalent peak flow rate, which is set equal to the service flow rate,

$$SF = [1 + (\alpha - 1)f_t](DDHV). \tag{17}$$

2. Select a design v/c ratio from Table 19.

3. Solve for the required capacity.

4. Determine the number of lanes and verify the lane composition.

Vehicles such as trucks have fewer choices of a toll booth to go through. Therefore, it should be assured in a design analysis that they secure enough booths so as not to locally increase delays and deteriorate the service quality. The following formula can be used for this practice:

$$\frac{\alpha V_T}{n_T C_A} \le \frac{\alpha V_T + V_A}{(n_T + n_A) C_A} \le \frac{V_E}{n_E C_E}, \tag{18}$$

where α = truck equivalent

V_T = design hourly volume of trucks

V_A = design hourly volume of automobiles

V_E = design hourly volume of automobiles with exact-change

n_T = number of general booths where trucks are allowed

n_A = number of booths for automobiles only

n_E = number of booths for automobiles with exact-change only

C_A = capacity of a general booth

C_E = capacity of an exact-change booth.

If the first fraction in this formula is greater than the second fraction, there would be extra trucks to be served and the general booths where trucks are allowed would have a much lower level of service than other booths. However, excessive traffic of other types, such as V_E or V_A, can choose the lower type of booths, such as those in n_A and n_T.

Sample Calculation

With the modern tools available, the designer should have at his hand an accurate estimate of traffic demand for the planned system. Engineering and management must be coupled in the selection of the design volume and a level of service for design that is best adapted to the specific need.

Description

A new toll plaza on an interstate highway is to be designed for level of service B. The DDHV is 2000 for its northbound traffic, including 6 percent trucks and buses. The capacities of available toll mechanisms are 710 pc/hr (C_1) for a general booth and 760 pc/hr (C_2) for an exact-change booth. How many lanes of each type will be required for this northbound plaza? Assume that 15 percent of the total traffic is automobiles with exact change.

Solution

From Eq. 17, the service flow rate is computed

$$SF = [1 + (2.7 - 1) \times 0.06] \times 2000 = 2204 \text{ pc/hr.}$$

From Table 19, a design value of 0.40 will be used for v/c, the maximum permissible value for level of service B. The capacity needed to provided this v/c level is

$$C = \frac{SF}{v/c} = \frac{2204}{0.40} = 5510 \text{ pc/hr.}$$

$$\left.\begin{aligned} 5510/710 &= 7.76 \text{ max} \\ 5510/760 &= 7.25 \text{ min} \end{aligned}\right\} \blacktriangleright \text{ use 8 lanes.}$$

If x general booths and y exact-change booths are needed, the following equations must hold:

$$x + y = 8 \quad \text{and} \quad xC_1 + yC_2 \geq C = 5785 \text{ pc/hr.} \tag{19}$$

It can be found that there are several sets of solutions that satisfy conditions in Eq. 19. Try $x = 7$ and $y = 1$, where $x = n_T + n_A$ and $y = n_E$. By trial, $n_T \geq 2$ will meet the requirement of Formula 18. Therefore, the plaza should have eight booths consisting of one for automobiles with exact change only, five for automobiles only, and two allowing trucks and any other vehicles.

$$\left.\begin{aligned} &\frac{2.7 \times 2000 \times 0.06}{2 \times 700} = 0.228 \\ &\frac{2.7 \times 2000 \times 0.06 \times 91 - 0.06 - 0.15)}{7 \times 710} = 0.383 \\ &\frac{2000 \times 0.15}{1 \times 760} = 0.395 \end{aligned}\right\} \blacktriangleright 0.228 < 0.383 < 0.395.$$

Figure 33 shows the possible design composition.

CONCLUSIONS

1. Service Time. For purposes of determining service time for a toll booth, an imaginary reference line was developed, where the rear of a vehicle passes when the following vehicle just stops to pay the toll. This reference line can be located 55 feet from where the toll attendant stands for a general toll booth and about 50 feet for an exact-change booth.

Service times at toll booths for trucks range from 12.87 seconds to 14.88 seconds and from 5.11 seconds to 5.47 seconds for automobiles. Automobile service times at exact-change booths is shorter or exhibits little or no difference from that at general booths. Automobile service time for inner lanes is either shorter than or no different from automobile service time for outer lanes.

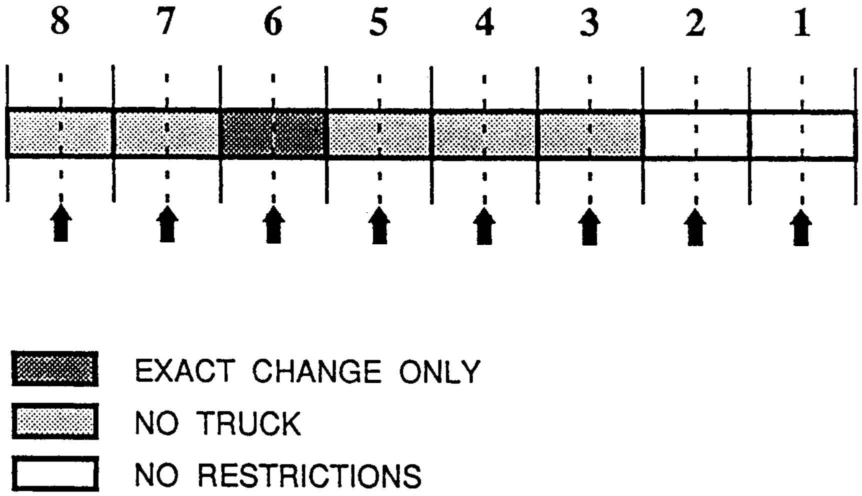

Figure 33. Design example.

2. Capacity. The capacity of a general booth is found to range from 650 to 705 passenger cars per hour. The capacity of an exact-change toll booth without a lifting barrier is between 665 to 745 passenger cars per hour. An exact-change toll booth with a lifting barrier has a capacity of 600 passenger cars per hour, which is lower than other arrangements because of delay inherent in the automatic collection machines.

3. Stopped Delay. Stop delay is not a good indicator for describing level of service at toll plaza areas. A comparison between field data and simulation results revealed that motorists do not always obey the simple assumption of queuing theory that they will join the shortest queue available. Occasional incidents also disrupt traffic flow and consequently increase the local delay.

4. Travel Time and Travel Ratio. Travel time and travel ratio are not the best criteria to use in determining level of service at toll plaza areas. Travel ratio alone can not be used as a level of service criterion partly because of its low correlation to v/c ratio. Nevertheless, there is a trend that travel ratio decreases with increases of v/c.

5. Density. Density is the most suitable variable for use in determining level of service for toll plaza areas. Density is a good indication of the degree of freedom available to drivers and the operating speeds that can be achieved. Since vehicles are not evenly distributed throughout a toll plaza area, an average value is the most appropriate. The average density for the toll plaza area in Figure 34 is

$$K = \frac{2\Sigma Q_i T_i}{(n_1 + n_2)L_1 + (n_2 + n_3)L_2},$$

where K = density in passenger cars per mile-lane or pc/mi/ln
Q_i = flow rate in passenger cars per hour for vehicle type i
T_i = average time in hours for vehicle type i to travel the area
n_1 = number of arrival lanes
n_2 = number of departure lanes
n_3 = number of booths
L_1 = length of convergence area in miles
L_2 = length of reconvergence area in miles.

The flow/density relationships were examined; quadratic curves represent these relationships.

Densities of toll plazas were found to be highly correlated to the corresponding v/c values with a quadratic model. Therefore, if density is used as the parameter for defining level of service of a toll plaza area, the volume can be used as a measurement. Based on this finding and current standards, level of service criteria were proposed for toll plaza areas in terms of density (see Table 19).

6. Simulation and Validation. The simulations using SIMAN show consistent agreement with the results that are computed from the field data. Different

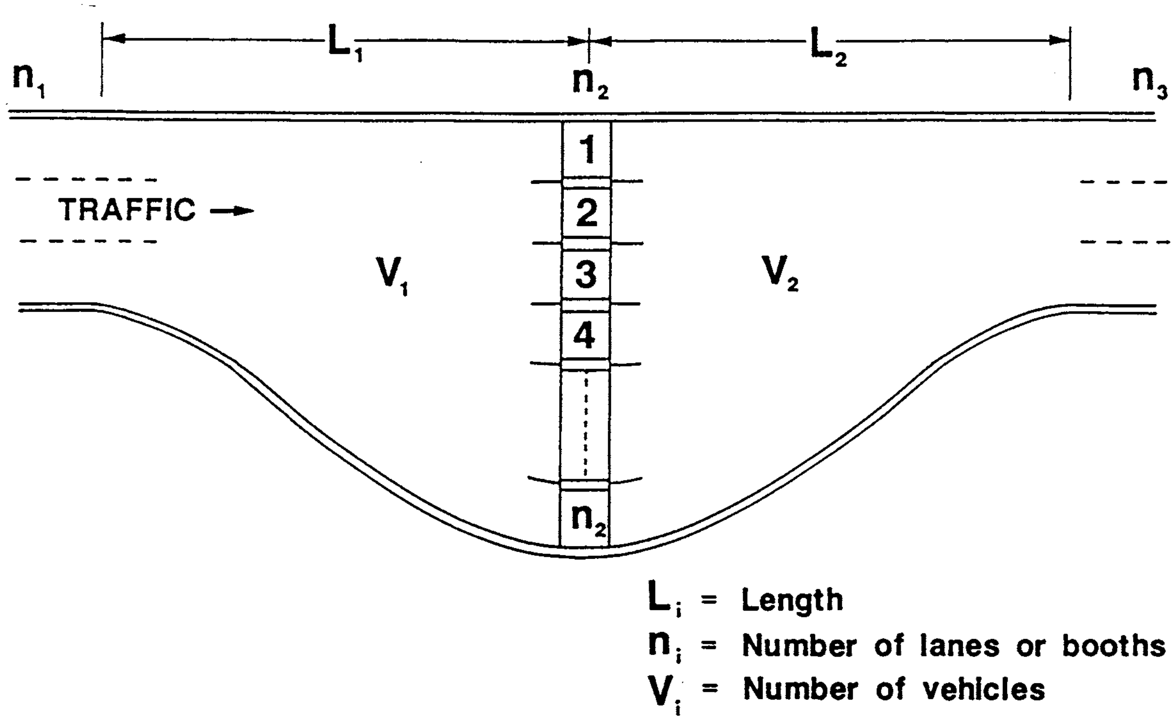

Figure 34. Toll plaza area density.

inputs of traffic flows were used to test the model developed, and consistency was also found in determining level of service.

There is a better appreciation of traffic flow in toll plazas by using graphical animation than by using numerical results. The visual display helps users to have a realistic perception of actual conditions. Although graphical animation cannot be presented in this report, two screens from the animation were printed to show the layout and results.

7. Applications. The density criteria were used in applications to analyze an example of an existing toll plaza. The results showed that levels of service determined by density and v/c value were consistent. A design example was also demonstrated in which the number of toll booths and their composition were determined with given design traffic and desired level of service.

Based on the availability of field data in this study, limitations should apply in the following areas:

- *Geometric Conditions.* Due to geometric restrictions, on-ramps or off-ramps may be placed next to toll plazas, which is not the case for any of the study sites. These types of configuration produce more traffic weaving and conflicts, thereby affecting capacity and increasing travel times. Other adverse geometric conditions such as sharp horizontal or vertical curves also affect travel times and densities.
- *Vehicle Category.* Vehicles were divided into only two categories: (1) automobiles and (2) trucks and buses. If traffic consists of vehicles that can be clearly separated into more than two categories (for example, (1) automobiles, (2) single-unit trucks, and (3) truck trailers), the analysis should be made taking this into account.
- *Toll Collection Method.* The Richmond-Petersburg Turnpike does not have any advanced toll collection equipment. Toll facilities with advanced electronic or optical collection mechanisms cannot adopt the results directly from this study without modification.

These limitations provide information for making several specific recommendations regarding further study as described in the following section.

RECOMMENDATIONS

1. On July 1, 1989, the tolls in the Richmond-Petersburg Turnpike were increased from 25 cents to 50 cents for passenger cars, and the Petersburg Toll Plaza was removed permanently. Numbers of coins collected affect service time. Collection and analysis of traffic data of the existing toll plazas in the turnpike may reveal the effects of toll increases.

2. As required by legislation, the state will take tolls off the Richmond-Petersburg Turnpike in 1992 when its parallel beltway I-295 is completed. There will definitely be some impact of the lifting of tolls. This may well deserve a close investigation for future planning purposes.

3. Further studies should be conducted using the approach developed in this study to determine the locations of reference lines for various types of toll booths that are not presented in this study. Once these reference lines are located, the capacities can be easily determined. For nonstop AVI toll booths, the reference lines may be treated as being where a vehicle's rear passes when the following vehicle is passing the toll transaction mechanism.

4. Although twin trailer trucks comprise a very small portion of total traffic at the study sites, it may well be necessary to consider the service times and travel times of twin trailer trucks and/or triple trailers separately for toll facilities where these longer vehicles constitute a moderately large portion of traffic.

5. Because of the small number of study sites and the similarity among these sites, the geometric parameter k in Eqs. 1 through 4 was not included in the analyses. Therefore, it is suggested that future research be conducted to determine the effects of geometric conditions.

6. Because of periodic severe delays, toll booths at highway ramps in urban areas have received increasing attention. Although the model developed in this study could basically be applied to these ramp toll booths, minor distinctions may be identified that differentiate the application. For example, the ramp capacity is also limited by the number of gaps that are greater than the critical gap for acceptance in the shoulder lane to which the ramp traffic leads.

7. With the rapid development of advanced toll collection methods, such as AVI, toll plazas could enjoy higher capacities under the same geometric restrictions. Continuing research in the area of toll collection technology is integral to the enhancement of toll financing as a viable transportation funding alternative.

8. Simulation techniques have been widely used in traffic operations to gain timely possible outcomes in design and analysis. However, the animation used in this study has improved the understanding of a scenario for viewers. Since the major subjects that traffic engineers deal with are moving vehicles, it would be very beneficial if the animation techniques could be applied in many other subjects within traffic engineering.

BIBLIOGRAPHY

1. "New Toll Road Models," *AASHTO International Transportation Observer*, p.1, October (1988).
2. Beyond Gridlock. p. 72, Highway Users Federation: Washington, D.C. (1988).
3. "OECD Lists Pros and Cons of Toll Roads," *World Highways* XXXVIII:5, International Road Federation (1987).
4. "IRF Reviews Topics of World Interest," *World Highway* XLI:1, International Road Federation (1990).
5. "Research Problem Statements: Highway Capacity," p.11, Transportation Research Board: Washington, D.C., June (1987).
6. *Highway Capacity Manual*. Bureau of Public Roads: Washington, D.C. (1950).
7. *Highway Capacity Manual*, Special Report 87. Highway Research Board: Washington D.C. (1965).
8. *Highway Capacity Manual*, Special Report 209. Transportation Research Board: Washington, D.C. (1985).
9. Editorial, *The Urban Transportation Monitor* 2:24, p. 8 (1988).
10. *SAS/GRAPH User's Guide*, Version 5 Edition. SAS Institute Inc., Cary, N.C. (1985).
11. *SAS User's Guide: Statistics*, Version 5 Edition. SAS Institute Inc., Cary, N.C. (1985).
12. *SAS User's Guide: Basics*, Version 5 Edition. SAS Institute Inc., Cary, N.C. (1985).
13. W. G. Bald and J.R. Underwood. "An Investigation into the Effect of Toll-Booths on Morning Peak Traffic Flow," *Chartered Municipal Engineer* 104:11, pp. 205-208 (1977).
14. J.H. Banks. "Performance Measurement for a Metered Freeway System," *Transportation Research Record* 1173, pp. 30-32 (1988).
15. D. S. Berry. "Using Volume-to-Capacity Ratios to Supplement Delay as Criteria for Levels of Service at Traffic Signals," *Transportation Research Record* 1112, pp. 23-28 (1987).
16. D. Bowman, C. Miller, and B. Deuser. "Operations and Design Guidelines for Facilities for Highway-Occupancy Vehicles," *Transportation Research Record* 757, pp. 45-54 (1980).
17. R. Brenner, E.T. Telford and D. Frischer. "A Quantitative Evaluation of Traffic in A Complex Freeway Network," *Highway Research Board Bulletin* 291, pp. 163-206 (1961).

18. J. L. Byrne and R. B. Potts. "Scheduling of Toll Collectors," *Transportation Science* 7:3, pp. 224-245 (1973).

19. P. J. Claffey. "Characteristics of Passenger Car Travel on Toll Roads and Comparable Free Roads," *Highway Research Board Bulletin* 306, pp. 1-19 (1961).

20. F. M. Croft, Jr. and J. E. Clark. "Quantitative Measure of Levels of Service," *Transportation Research Record* 1005, pp. 11-19 (1985).

21. D. R. Drew and C. J. Keese. "Freeway Level of Service as Influenced by Volume and Capacity Characteristics," *Highway Research Record* 99, pp. 1-39 (1965).

22. Leslie D. Edie. "Traffic Delays At Toll Booths," *Journal of the Operations Research Society of America* 2, pp. 107-138 (1954).

23. S. C. Fehr. "Toll Roads Gain in Popularity From Coast to Coast," *Washington Post*, September 20, p. A3 (1989).

24. R. S. Foote. "Collection Problems and the Promise of Automatic Vehicle Identification," *Transportation Research Record* 494, pp. 15-20 (1974).

25. R. S. Foote. "Prospects For Non-Stop Toll Collection Using Automatic Vehicle Identification," *Traffic Quarterly* 35:3, pp. 445-460 (1981).

26. D. L. Gerlough and M. J. Huber. *Traffic Flow Theory - A Monograph*, Special Report 165, pp. 49-54. Transportation Research Board: Washington, D.C. (1975).

27. B. D. Greenshields, H. P. George, N.S. Guerin, M.R. Palmer, and R.T. Underwood. *Quality and Theory of Traffic Flow*, Bureau of Highway Traffic, Yale University. (1961).

28. J. D. Griffiths and J. E. Williams. "Traffic Studies on the Severn Bridge," *Traffic Engineering and Control*, pp. 268-274, May (1984).

29. E. M. Hall and S. George, Jr. "Travel Time: An Effective Measure of Congestion and Level of Service," *Highway Research Board Proceedings* 38, pp. 511-529 (1959).

30. G. G. Henk, E. C. Pahlke, and M. C. Schaefer. "Toll Road Facility Design Issues--Planning for Flexibility," Paper read at the Conference on National Perspectives on Toll Road Development at Irvine Hilton and Tower, Irvine, California, November 13-15 (1988).

31. C. D. Hixon. "An Analysis of Urban Travel Times and Traffic Volume Characteristics," *Highway Research Board Bulletin* 303, pp. 103-116 (1961).

32. C. E. Lee and V. S. Savur. "Analysis of Intersection Capacity and Level of Service by Simulation," *Transportation Research Record* 699, pp. 34-41 (1979).

33. C. E. Lee and F. Lee. "Simulation of Traffic Performance, Vehicle Emissions, and Fuel Consumption at Intersections: The Texas-II Model," *Transportation Research Record* 971, pp. 133-140 (1984).

34. H. S. Mahmassani and Y. G. Kim. "Effect of Traffic Mix, Volume, and Geometrics on the Trip Time of Passenger Cars and Trucks on Urban Freeways," *Transportation Research Record* 1112, pp. 98-106 (1987).

35. A. D. May, Jr. "A Friction Concept of Traffic Flow," *Highway Research Board Proceedings* 38, pp. 493-510 (1959).

36. S. Myers. "Collection Problems and the Promise of Self-Canceling Tickets," Transportation Research Record 494, pp. 21-24 (1974).

37. A. Polus, J. Craus, and I. Grinberg. "Applying the Level-of-Service Concept to Climbing Lanes," *Transportation Research Record* 806, pp. 28-33 (1981).

38. A. E. Radwan and S. A. F. Kalevela. "Investigation of the Effect of Change in Vehicular Characteristics on Highway Capacity and Level of Service," *Transportation Research Record* 1005, pp. 65-71 (1985).

39. A. J. Richardson. "Measurement of the Performance of Signalized Intersections," *Transportation Research Record* 699, pp. 49-58 (1979).

40. R. P. Roess, W. R. McShane, and L. J. Pignataro. "Freeway Level of Service: A Revised Approach," *Transportation Research Record* 699 pp. 7-16 (1979).

41. R. P. Roess, W. R. McShane, E. M. Linzer, and L.J. Pignataro. "Freeway Capacity Analysis Procedures," *ITE Journal*, pp. 16-21, December (1980).

42. R. P. Roess. "Level of Service Concepts: Development, Philosophies, and Implications," *Transportation Research Record* 971, pp. 1-6 (1984).

43. R. P. Roess. "Development of Weaving Area Analysis Procedures for the 1985 *Highway Capacity Manual*," *Transportation Research Record* 111}, pp. 17-22 (1987).

44. R. P. Roess and W. R. McShane. "Changing Concepts of Level of Service in the 1985 *Highway Capacity Manual*: Some Examples," *ITE Journal*, pp. 27-31, May (1987).

45. L. D. Rubenstein. "Tandem Toll Collection Systems," *Transportation Research Record* 905, pp. 14-16 (1983).

46. J. F. Schwar. "Quality of Traffic Service," *Traffic Quarterly* XX:1, pp. 136-146 (1966).

47. B. L. Schwartz. "Queuing Models With Lane Selection: A New Class of Problems," *Operations Research* 22, pp. 331-339, March (1974).

48. W. S. Smith and N. H. Wuestefeld. "Current Trends in Toll Financing," *Transportation Research Record* 900, pp. 63-69 (1983).

49. R. R. Souleyrette II, C. M. Walton, and H. S. Mahmassani. *Identification of Candidate Toll Roads In Current and Future Highway Development*, University of Texas: Austin (1986).

50. M. S. Swati. *Quality of Traffic Service Measurement*, Master's Thesis, Ohio State University: Columbus (1968).

51. M. Van Aerde and S. Yagar. "Capacity, Speed, and Platooning Vehicle Equivalents for Two-Lane Rural Highways," *Transportation Research Record* 971, pp. 58-65 (1984).

52. P. M. Wechesser and J. Kraft. "New Jersey Turnpike Automatic Traffic Surveillance and Control System Performance Observation," *Transportation Research Record* 816, pp. 90-94 (1981).

53. A. Werner and T. Wills. "Cost-Effective Level of Service and Design Criteria," *Transportation Research Record* 699, pp. 1-7 (1979).

54. H. C. Wood and C. S. Hamilton. "Design of Toll Plazas from the Operator's Viewpoint," *Highway Research Board Proceedings* 34, pp. 127-139 (1955).

APPENDIX A

TRAFFIC PATTERN FITTINGS FOR STUDY SITES

The appropriate distribution for describing the truly random occurrence of discrete events is the Poisson distribution. It may be stated:

$$P(x) = \frac{m^x e^{-m}}{x!}, \quad x = 0, 1, 2, \ldots \tag{A.1}$$

where $P(x)$ = probability that x vehicles will arrive during accounting period;
m = average number of vehicles arriving during a period of duration; and
e = natural base of logarithms.

The best known test of goodness–of–fit is the chi–square (X^2) test:

$$X^2 = \sum_{i=1}^{j} \frac{(f_i - F_i)^2}{F_i} \tag{A.2}$$

where f = observed frequency for any group or interval,
F = computed or theoretical frequency for the same group, and
j = the number of groups.

For Eq. A.2 to be valid, it is necessary that the theoretical number of occurrences in any group be at least 5. When the number of theoretical occurrences in any group is less than 5, the group interval should be increased. For the lowest and highest groups, this may be accomplished by making these groups "all less than" and "all greater than," respectively.

The following tables demonstrate the computations of the X^2 test for each study site for 15–second intervals.

Table A-1

BELVIDERE - NORTHBOUND

Number of Cars per Interval	Observed Frequency(f_i)	Theoretical Frequency(F_i)		$(f_i-F_i)^2/F_i$
<3	0	0.27		
3	2	0.84		
4	2	2.33	8.60	0.018
5	5	5.16		
6	16	9.53		4.391
7	14	15.08		0.077
8	18	20.88		0.395
9	24	25.69		0.111
10	34	31.58		0.185
11	16	28.64		5.581
12	22	26.44		0.744
13	32	22.52		3.989
14	19	17.82		0.079
15	6	13.15		3.890
16	13	9.10		1.666
17	5	5.93		0.146
18	9	3.65		
19	2	2.13	7.89	2.142
20	1	1.18		
>20	0	0.93		
TOTAL	240			23.414

$m=11.075$

$\chi^2=23.414$*

*Accept fit at 0.01 level.

Table A-2

BELVIDERE - SOUTHBOUND

Number of Cars per Interval	Observed Frequency(f_i)	Theoretical Frequency(F_i)		$(f_i-F_i)^2/F_i$
0	0	0		
1	1	0.03		
2	1	0.20		
3	1	0.76	7.93	1.176
4	4	2.13		
5	4	4.81		
6	13	9.05		1.721
7	14	14.59		0.024
8	13	20.58		2.791
9	33	25.80		2.010
10	22	32.31		3.292
11	25	29.86		0.790
12	28	28.07		0.000
13	19	24.36		1.181
14	28	19.64		3.563
15	15	14.77		0.004
16	10	10.42		0.017
17	8	6.91		0.171
18	8	4.33		
19	2	2.57	9.53	0.636
20	2	1.45		
>20	0	1.18		
TOTAL	251			17.376

$m =$ 11.283

$\chi^2 =$ 17.376*

*Accept fit at 0.01 level.

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Table A-3

FALLING CREEK - NORTHBOUND

Number of Cars per Interval	Observed Frequency(f_i)	Theoretical Frequency(F_i)		$(f_i-F_i)^2/F_i$
0	0	0.04		
1	1	0.37		
2	3	1.62	6.71	0.246
3	4	4.68		
4	12	10.12		0.347
5	25	17.53		3.179
6	29	25.30		0.540
7	27	31.30		0.590
8	23	33.87		3.491
9	39	32.59		1.261
10	18	31.33		5.669
11	12	22.21		4.695
12	24	16.03		3.966
13	12	10.67		0.164
14	7	6.60		0.024
15	5	3.81		
16	5	2.06		
17	0	1.05		
18	2	0.51	7.82	3.438
19	0	0.23		
20	0	0.10		
21	1	0.04		
>21	0	0.02		
TOTAL	249			27.610

$m = 8.659$

$\chi^2 = 27.610$*

*Reject fit at 0.01 level ($\chi^2_{0.01}=24.7$) .

Table A-4

FALLING CREEK - SOUTHBOUND

Number of Cars per Interval	Observed Frequency(f_i)	Theoretical Frequency(F_i)		$(f_i\text{-}F_i)^2 / F_i$
<3	0	0.18		
3	1	0.59		
4	7	1.70	6.40	6.803
5	5	3.93		
6	12	7.57		2.592
7	11	12.50		0.179
8	23	18.05		1.355
9	21	23.18		0.205
10	19	29.74		3.879
11	23	28.14		0.941
12	18	27.11		3.059
13	22	24.09		0.182
14	20	19.89		0.001
15	13	15.32		0.352
16	16	11.07		2.198
17	10	7.52		0.815
18	9	4.83		
19	5	2.94		
20	3	1.70	10.89	4.639
21	1	0.93		
>21	0	0.49		
TOTAL	239			27.200

$m =$ 11.556

$\chi^2 =$ 27.200*

*Reject fit at 0.01 level ($\chi^2_{0.01}$=26.2).

Table A-5

COLONIAL HEIGHTS - NORTHBOUND

Number of Cars per Interval	Observed Frequency(f_i)	Theoretical Frequency(F_i)		$(f_i-F_i)^2/F_i$
0	1	0.84	5.63	1.005
1	7	4.79		
2	15	13.75		0.114
3	22	26.32		0.708
4	33	37.78		0.605
5	36	43.39		1.258
6	52	41.52		2.642
7	39	34.06		0.715
8	31	24.45		1.754
9	11	15.60		1.357
10	5	9.94		2.459
11	2	4.68		
12	4	2.24	8.55	0.035
13	2	0.99		
>13	0	0.64		
TOTAL	260			12.652

$m = 5.742$

$\chi^2 = 12.652$*

*Accept fit at 0.01 level.

Table A-6

COLONIAL HEIGHTS - SOUTHBOUND

Number of Cars per Interval	Observed Frequency(f_i)	Theoretical Frequency(F_i)		$(f_i-F_i)^2/F_i$
<2	0	0.18		
2	2	0.77		
3	7	2.43	9.15	6.734
4	8	5.77		
5	17	10.95		3.337
6	20	17.33		0.412
7	20	23.49		0.520
8	24	27.87		0.538
9	22	29.39		1.860
10	17	30.97		6.302
11	25	24.07		0.036
12	14	19.04		1.334
13	19	13.90		1.871
14	8	9.42		0.215
15	7	5.96		0.180
16	5	3.54		
17	5	1.97		
18	5	1.04		
19	0	0.52	7.48	9.706
20	0	0.25		
21	1	0.11		
>21	0	0.05		
TOTAL	226			33.045

$m = 9.491$

$\chi^2 = 33.045$*

*Reject fit at 0.01 level ($\chi^2_{0.01}=24.7$).

Table A-7

PETERSBURG - NORTHBOUND

Number of Cars per Interval	Observed Frequency(f_i)	Theoretical Frequency(F_i)		$(f_i - F_i)^2 / F_i$
0	7	5.91		0.202
1	24	22.58		0.089
2	49	43.15		0.793
3	52	54.98		0.161
4	49	52.53		0.238
5	34	40.16		0.945
6	26	25.58		0.007
7	15	13.97		0.076
8	6	6.67		
9	4	2.83		
10	2	1.20	11.25	0.669
11	1	0.38		
12	1	0.12		
>12	0	0.05		
TOTAL	270			3.180

$m =$ 3.822

$\chi^2 =$ 3.180*

*Accept fit at 0.01 level.

Table A-8

PETERSBURG - SOUTHBOUND

Number of Cars per Interval	Observed Frequency(f_i)	Theoretical Frequency(F_i)		$(f_i-F_i)^2/F_i$
0	4	3.45		0.086
1	15	14.37		0.028
2	35	29.87		0.881
3	34	41.41		1.324
4	44	43.04		0.021
5	37	35.80		0.040
6	23	24.81		0.132
7	13	14.74		0.205
8	7	7.66		0.057
9	6	3.54		
10	1	1.63	6.01	1.487
11	2	0.56		
>11	0	0.28		
TOTAL	221			4.261

$m = 4.158$

$\chi^2 = 4.261$*

*Accept fit at 0.01 level.

APPENDIX B

REGRESSION MODELS

The following models were tested in this study. This appendix includes the results of regression analyses for each study site. Different data groups by time duration are separated. R^2 is the coefficient of determinaton. PROB>F is the probability of getting a greater F statistic than that observed if the hypothesis that all parameters are zero is true.

Linear Model	$\bar{u}_s = a + bK$
Exponential Model	$\bar{u}_s = ae^{-\frac{K}{b}}$
Bell-shaped Curve Model	$\bar{u}_s = ae^{-(\frac{K}{b})^2}$
Quadratic Model	$Q = aK^2 + bK + c$
Quadratic Model	$\mathrm{v/c} = ak^2 + bk + c$

Where $\bar{u}_s$ = average running speed in miles per hour

K = density in passenger cars per mile per lane

Q = traffic flow in passenger cars per hour

v/c = volume-to-capacity ratio

a,b,c = constants

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Table B-1

Speed-Density Linear Model (1-minute Data Sets)

Site	Model	R^2	PROB>F
BDN	$\bar{u}_s = 26.62 - 0.0798K$	0.1735	0.0011
BDS	$\bar{u}_s = 26.06 - 0.0930K$	0.3462	0.0001
FCN	$\bar{u}_s = 24.38 - 0.1008K$	0.2870	0.0001
FCS	$\bar{u}_s = 26.29 - 0.1522K$	0.6006	0.0001
CHN	$\bar{u}_s = 21.34 - 0.0294K$	0.0603	0.0708
CHS	$\bar{u}_s = 23.57 - 0.1152K$	0.2695	0.0001
PBN	$\bar{u}_s = 19.48 - 0.0637K$	0.2876	0.0001
PBS	$\bar{u}_s = 22.71 - 0.1241K$	0.6205	0.0001

Table B-2

Speed-Density Linear Model (3-minute Data Sets)

Site	Model	R^2	PROB>F
BDN	$\bar{u}_s = 26.60 - 0.0795K$	0.0639	0.2966
BDS	$\bar{u}_s = 27.24 - 0.1227K$	0.4992	0.0005
FCN	$\bar{u}_s = 27.06 - 0.1664K$	0.5055	0.0006
FCS	$\bar{u}_s = 28.84 - 0.2001K$	0.8028	0.0001
CHN	$\bar{u}_s = 21.33 - 0.0341K$	0.0579	0.3211
CHS	$\bar{u}_s = 25.66 - 0.1719K$	0.3835	0.0061
PBN	$\bar{u}_s = 20.02 - 0.0870K$	0.4563	0.0011
PBS	$\bar{u}_s = 21.99 - 0.1073K$	0.4965	0.0049

Table B-3

Speed-Density Linear Model (5-minute Data Sets)

Site	Model	R^2	PROB>F
BDN	$\bar{u}_s = 27.81 - 0.1158K$	0.1616	0.2205
BDS	$\bar{u}_s = 26.16 - 0.1011K$	0.5673	0.0047
FCN	$\bar{u}_s = 26.69 - 0.1568K$	0.4978	0.0153
FCS	$\bar{u}_s = 27.69 - 0.1795K$	0.7370	0.0007
CHN	$\bar{u}_s = 19.67 - 0.0197K$	0.0209	0.6716
CHS	$\bar{u}_s = 23.71 - 0.1400K$	0.3429	0.0584
PBN	$\bar{u}_s = 19.72 - 0.0836K$	0.4520	0.0166
PBS	$\bar{u}_s = 22.51 - 0.1266K$	0.4952	0.0514

Table B-4

Speed-Density Exponential Model (1-minute Data Sets)

Site	Model	R^2	PROB>F
BDN	$\bar{u}_s = 26.94e^{-\frac{K}{279.06}}$	0.1836	0.0008
BDS	$\bar{u}_s = 26.57e^{-\frac{K}{225.56}}$	0.3545	0.0001
FCN	$\bar{u}_s = 24.85e^{-\frac{K}{192.94}}$	0.2764	0.0001
FCS	$\bar{u}_s = 29.16e^{-\frac{K}{108.33}}$	0.6025	0.0001
CHN	$\bar{u}_s = 21.37e^{-\frac{K}{153.91}}$	0.0640	0.0625
CHS	$\bar{u}_s = 24.49e^{-\frac{K}{149.51}}$	0.2749	0.0001
PBN	$\bar{u}_s = 19.41e^{-\frac{K}{276.98}}$	0.2686	0.0001
PBS	$\bar{u}_s = 23.28e^{-\frac{K}{143.18}}$	0.6220	0.0001

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Table B-5

Speed-Density Exponential Model (3-minute Data Sets)

Site	Model	R^2	PROB>F
BDN	$\bar{u}_s = 26.77e^{-\frac{K}{296.76}}$	0.0648	0.2930
BDS	$\bar{u}_s = 28.23e^{-\frac{K}{170.08}}$	0.5109	0.0004
FCN	$\bar{u}_s = 28.74e^{-\frac{K}{114.73}}$	0.4957	0.0008
FCS	$\bar{u}_s = 33.98e^{-\frac{K}{83.08}}$	0.7959	0.0001
CHN	$\bar{u}_s = 21.37e^{-\frac{K}{580.45}}$	0.0602	0.3112
CHS	$\bar{u}_s = 27.03e^{-\frac{K}{107.21}}$	0.3657	0.0078
PBN	$\bar{u}_s = 20.11e^{-\frac{K}{200.36}}$	0.4588	0.0010
PBS	$\bar{u}_s = 22.18e^{-\frac{K}{178.94}}$	0.4845	0.0057

Table B-6

Speed-Density Exponential Model (5-minute Data Sets)

Site	Model	R^2	PROB>F
BDN	$\bar{u}_s = 28.10e^{-\frac{K}{207.70}}$	0.1606	0.2219
BDS	$\bar{u}_s = 26.68e^{-\frac{K}{212.31}}$	0.5830	0.0039
FCN	$\bar{u}_s = 28.31e^{-\frac{K}{120.48}}$	0.5188	0.0124
FCS	$\bar{u}_s = 31.01e^{-\frac{K}{97.18}}$	0.7574	0.0005
CHN	$\bar{u}_s = 19.67e^{\frac{K}{1023.1}}$	0.0207	0.6729
CHS	$\bar{u}_s = 24.67e^{-\frac{K}{126.08}}$	0.3508	0.0549
PBN	$\bar{u}_s = 19.93e^{-\frac{K}{201.19}}$	0.4566	0.0159
PBS	$\bar{u}_s = 22.79e^{-\frac{K}{152.23}}$	0.4863	0.0545

Table B-7

Speed-Density Bell-Shaped Curve Model (1-minute Data Sets)

Site	Model	R^2	PROB>F
BDN	$\bar{u}_s = 25.54e^{-\left(\frac{K}{133.40}\right)^2}$	0.2292	0.0001
BDS	$\bar{u}_s = 23.82e^{-\left(\frac{K}{156.27}\right)^2}$	0.3480	0.0001
FCN	$\bar{u}_s = 22.43e^{-\left(\frac{K}{129.31}\right)^2}$	0.2701	0.0001
FCS	$\bar{u}_s = 22.11e^{-\left(\frac{K}{120.22}\right)^2}$	0.5655	0.0001
CHN	$\bar{u}_s = 20.85e^{-\left(\frac{K}{220.27}\right)^2}$	0.0570	0.0793
CHS	$\bar{u}_s = 21.21e^{-\left(\frac{K}{118.52}\right)^2}$	0.2804	0.0001
PBN	$\bar{u}_s = 17.93e^{-\left(\frac{K}{175.07}\right)^2}$	0.1798	0.0013
PBS	$\bar{u}_s = 20.77e^{-\left(\frac{K}{105.23}\right)^2}$	0.5830	0.0001

Table B-8

Speed-Density Bell-Shaped Curve Model (3-minute Data Sets)

Site	Model	R^2	PROB>F
BDN	$\bar{u}_s = 25.26e^{-\left(\frac{K}{143.66}\right)^2}$	0.0619	0.3043
BDS	$\bar{u}_s = 24.53e^{-\left(\frac{K}{130.06}\right)^2}$	0.5213	0.0003
FCN	$\bar{u}_s = 24.31e^{-\left(\frac{K}{96.46}\right)^2}$	0.5322	0.0004
FCS	$\bar{u}_s = 24.35e^{-\left(\frac{K}{99.01}\right)^2}$	0.7970	0.0001
CHN	$\bar{u}_s = 20.85e^{-\left(\frac{K}{185.42}\right)^2}$	0.0674	0.2832
CHS	$\bar{u}_s = 22.42e^{-\left(\frac{K}{94.93}\right)^2}$	0.3670	0.0077
PBN	$\bar{u}_s = 17.96e^{-\left(\frac{K}{148.81}\right)^2}$	0.3004	0.0124
PBS	$\bar{u}_s = 20.37e^{-\left(\frac{K}{107.88}\right)^2}$	0.3965	0.0158

Table B-9

Speed-Density Bell-Shaped Curve Model (5-minute Data Sets)

Site	Model	R^2	PROB>F
BDN	$\bar{u}_s = 25.81e^{-\left(\frac{K}{122.12}\right)^2}$	0.1458	0.2465
BDS	$\bar{u}_s = 23.88e^{-\left(\frac{K}{143.55}\right)^2}$	0.5758	0.0042
FCN	$\bar{u}_s = 24.22e^{-\left(\frac{K}{97.66}\right)^2}$	0.5912	0.0057
FCS	$\bar{u}_s = 22.85e^{-\left(\frac{K}{111.08}\right)^2}$	0.6940	0.0015
CHN	$\bar{u}_s = 19.96e^{\left(\frac{K}{250.44}\right)^2}$	0.0208	0.6725
CHS	$\bar{u}_s = 21.39e^{-\left(\frac{K}{98.38}\right)^2}$	0.3720	0.0463
PBN	$\bar{u}_s = 17.94e^{-\left(\frac{K}{137.53}\right)^2}$	0.3706	0.0357
PBS	$\bar{u}_s = 20.81e^{-\left(\frac{K}{92.83}\right)^2}$	0.4476	0.0696

Table B-10

Flow-Density Quadratic Model (1-minute Data Sets)

Site	Model	R^2	PROB>F
BDN	$Q = -1.58K^2 + 188.81K - 799$	0.9169	0.0001
BDS	$Q = -0.39K^2 + 90.49K + 727$	0.8288	0.0001
FCN	$Q = -0.24K^2 + 74.60K + 467$	0.8312	0.0001
FCS	$Q = -0.28K^2 + 68.19K + 946$	0.6677	0.0001
CHN	$Q = -0.74K^2 + 95.99K - 37$	0.9005	0.0001
CHS	$Q = -0.37K^2 + 84.05K + 268$	0.7939	0.0001
PBN	$Q = -0.19K^2 + 43.15K + 164$	0.8885	0.0001
PBS	$Q = -0.36K^2 + 58.69K + 53$	0.9172	0.0001

Table B-11

Flow-Density Quadratic Model (3-minute Data Sets)

Site	Model	R^2	PROB>F
BDN	$Q = -2.54K^2 + 239.27K - 1475$	0.6648	0.0002
BDS	$Q = 1.04K^2 - 66.37K + 4763$	0.7915	0.0001
FCN	$Q = -1.08K^2 + 144.34K - 868$	0.8263	0.0001
FCS	$Q = -0.38K^2 + 71.10K + 1055$	0.6044	0.0006
CHN	$Q = -0.36K^2 + 73.06K + 247$	0.8900	0.0001
CHS	$Q = -0.45K^2 + 86.38K + 281$	0.7558	0.0001
PBN	$Q = -0.036K^2 + 25.97K + 521$	0.9195	0.0001
PBS	$Q = -0.15K^2 + 43.75K + 275$	0.9445	0.0001

Table B-12

Flow-Density Quadratic Model (5-minute Data Sets)

Site	Model	R^2	PROB>F
BDN	$Q = 1.73K^2 - 55.83K + 3575$	0.6284	0.0191
BDS	$Q = -0.56K^2 + 91.92K + 980$	0.8042	0.0007
FCN	$Q = -1.68K^2 + 195.88K - 1919$	0.8965	0.0001
FCS	$Q = 0.61K^2 - 44.78K + 4257$	0.7676	0.0029
CHN	$Q = -1.71K^2 + 159.17K - 1088$	0.9285	0.0001
CHS	$Q = -1.90K^2 + 204.84K - 2121$	0.8878	0.0002
PBN	$Q = -0.21K^2 + 36.43K + 394$	0.9078	0.0001
PBS	$Q = -0.62K^2 + 62.07K + 128$	0.9181	0.0019

Table B-13

v/c-Density Quadratic Model (1-minute Data Sets)

Site	Model	R^2	PROB>F
BDN	$v/c = -0.000309K^2 + 0.0370K - 0.157$	0.9169	0.0001
BDS	$v/c = -0.000076K^2 + 0.0177K + 0.143$	0.8288	0.0001
FCN	$v/c = -0.000057K^2 + 0.0179K + 0.112$	0.8312	0.0001
FCS	$v/c = -0.000071K^2 + 0.0170K + 0.236$	0.6677	0.0001
CHN	$v/c = -0.000179K^2 + 0.0232K - 0.089$	0.9005	0.0001
CHS	$v/c = -0.0000869^2 + 0.0197K + 0.063$	0.7939	0.0001
PBN	$v/c = -0.000071K^2 + 0.0159K + 0.060$	0.8885	0.0001
PBS	$v/c = -0.000135K^2 + 0.0220K + 0.020$	0.9172	0.0001

Table B-14

v/c-Density Quadratic Model (3-minute Data Sets)

Site	Model	R^2	PROB>F
BDN	$v/c = -0.000498K^2 + 0.0469K - 0.289$	0.6648	0.0002
BDS	$v/c = 0.000204K^2 - 0.0130K + 0.934$	0.7915	0.0001
FCN	$v/c = -0.000260K^2 + 0.0346K - 0.208$	0.8263	0.0001
FCS	$v/c = -0.000094K^2 + 0.0178K + 0.264$	0.6044	0.0006
CHN	$v/c = -0.000087K^2 + 0.0177K + 0.060$	0.8900	0.0001
CHS	$v/c = -0.000106K^2 + 0.0202K + 0.066$	0.7558	0.0003
PBN	$v/c = -0.000013K^2 + 0.0096K + 0.192$	0.9195	0.0001
PBS	$v/c = -0.000057K^2 + 0.0164K + 0.103$	0.9445	0.0001

Table B-15

v/c-Density Quadratic Model (5-minute Data Sets)

Site	Model	R^2	PROB>F
BDN	$v/c = 0.000339K^2 - 0.0180K + 0.701$	0.6284	0.0191
BDS	$v/c = -0.000109K^2 + 0.0180K + 1.192$	0.8042	0.0007
FCN	$v/c = -0.000403K^2 + 0.0470K - 0.460$	0.8965	0.0001
FCS	$v/c = 0.000153K^2 - 0.0112K + 1.064$	0.7676	0.0029
CHN	$v/c = -0.000415K^2 + 0.0385K - 0.263$	0.9285	0.0001
CHS	$v/c = -0.000445K^2 + 0.0480K - 0.497$	0.8878	0.0002
PBN	$v/c = -0.000078K^2 + 0.0134K + 0.145$	0.9078	0.0001
PBS	$v/c = -0.000232K^2 + 0.0233K + 0.048$	0.9198	0.0019