DETERMINISTIC ASPECTS OF FREEWAY OPERATIONS AND CONTROL

by

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INTRODUCTION

The Problem

The efficient use of resources by eliminating or reducing congestion is a rather common type of investigation undertaken by researchers in industry, the military, and communications, as well as in transportation. Vehicular traffic congestion is exemplified by delay to the motorists, reduced flow of traffic, low speeds and high traffic concentrations, frequent changes in speed, and long queues.

Interest in vehicular traffic congestion is less than twenty years old. Until World War I, the primary objective of highway engineers was providing all-weather road surfaces to literally keep the road user out of the mud. After World War I, as Americans became more speed conscious, geometric design considerations became more important. Some attention was given to the elimination of hair-pin curves, narrow pavements and steep grades. It was at the end of World War II that this country discovered that it had an urban transportation problem. Because of such factors as our population growth, the steady migration of our people to urban areas, the increased ownership and use of the auto, and the decline of public transportation; the expansion of auto transportation has far exceeded the provisions for city streets.

The freeway concept represents the most vigorous attempt to eliminate traffic congestion. It is a superhighway, eliminating vehicle-to-pedestrian conflicts, eliminating delay producing traffic control devices, and reducing vehicle-to-vehicle conflicts. The freeway motorist expects to have his needs anticipated and fulfilled to a much higher degree than on conventional roads. This expectation can sometimes be fulfilled by rational geometric design and constant operational attention after construction. Still, practically all major cities are troubled with severe peak hour congestion on newly completed freeways.

The total problem is to increase the level of service on our freeways--that is to operate them as they were planned and designed to operate. Level of service, as applied to traffic operation on a particular roadway, refers to the quality of the driving conditions afforded a motorist. Factors involved are (1) speed, (2) density, (3) volume, (4) travel time, (5) traffic interruption, (6) freedom to maneuver, (7) safety, (8) driving comfort and convenience, and (9) vehicular operational costs.

The Approach

An automatic traffic surveillance and control system is to be installed on the Gulf Freeway in Houston, Texas. A traffic surveillance system should involve the continuous sampling of basic traffic characteristics for interpretation by established control parameters, in order to provide a quantitative knowledge of operating conditions necessary for immediate rational control and future design. The control logic of a surveillance system, or any system, for that matter is that combination of techniques and devices employed to regulate the operation of that system. The analysis shows what information is needed and where it will be obtained. Then and only then, can the conception and design of the processing and analyzing equipment necessary to convert data into operational decisions and design warrants be described.

The purpose of this investigation is to establish some of the control parameters necessary to provide a quantitative knowledge of freeway operations and a rational basis for future freeway surveillance and control. Traffic operations should be defined, characterized and described as particular states of traffic flow, thus affording the means of developing rational control parameters.

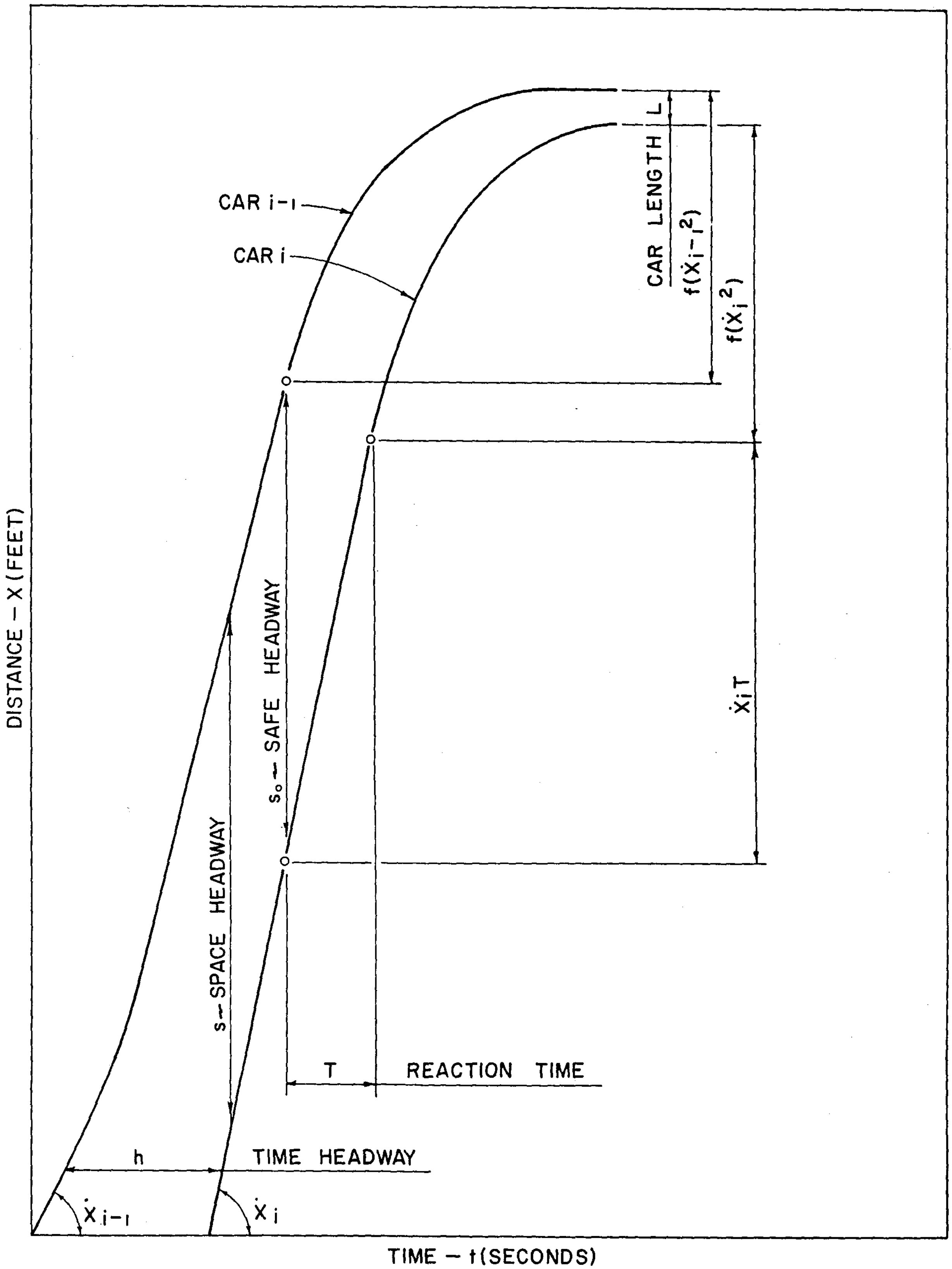
Existing theories of traffic flow may be classified as either stochastic or deterministic. The stochastic models are based on the classical subjects of queueing theory, mathematical probability and stochastic (variable) processes. The deterministic models of traffic flow are based on writing suitable descriptions of the flow of vehicular traffic in the form of differential equations, and then solving these equations for observed boundary conditions. This report deals with the deterministic aspects of traffic flow and operations.

Specific objectives of this study are to:

1. Develop deterministic control parameters through the generalization of the macroscopic and microscopic models of traffic flow.

2. Measure the primary traffic characteristics on the Gulf Freeway as a means of establishing a quantitative basis of operation on the facility, as well as testing the theoretical models formulated.

3. Suggest means of applying these concepts to freeway surveillance and control.



FUNDAMENTAL RELATIONS OF TRAFFIC IN TIME AND SPACE

FIGURE 1

DEVELOPMENT OF CONTROL PARAMETERS

Notation

Highway traffic theory is concerned with the movement of discrete objects over a two-dimensional network. The control of these objects rests both with the individual drivers and the unified system. Vehicular traffic is further distinguished from classical network theory because the relationship between cars in time and the relationship between cars in space are different.

It is convenient to show the progress of a stream of vehicles, designated as $i = 1, 2, \ldots, n$, in terms of a time-space diagram (Figure 1). The ordinate represents distance, x, and the abscissa represents time, t. The slope of the line gives the rate of change of distance with respect to time (dx/dt), or vehicular velocity, $\dot{x}_i$. A curved line means a changing slope or changing velocity designated as vehicular acceleration, $\ddot{x}_i$. The time and space intervals between successive vehicles are referred to as time headways, h_i, and space headways, s_i. Their respective units are time (usually expressed as seconds) and distance (usually expressed in feet). The concept of safe headway (s_o) is illustrated in Figure 1. It is that headway which a vehicle must maintain at an instant (t) to avoid a rear-end collision with a preceding vehicle which is in the process of braking to a stop. The reciprocals of time headways and space headways become "flow" (q), the number of vehicles per unit time passing a given stationary point on the roadway, and "concentration" (k) , the number of vehicles per unit length of roadway at some instant in time. The term "volume" refers to the flow of vehicles per hour and "density" refers to the concentration of vehicles per mile.

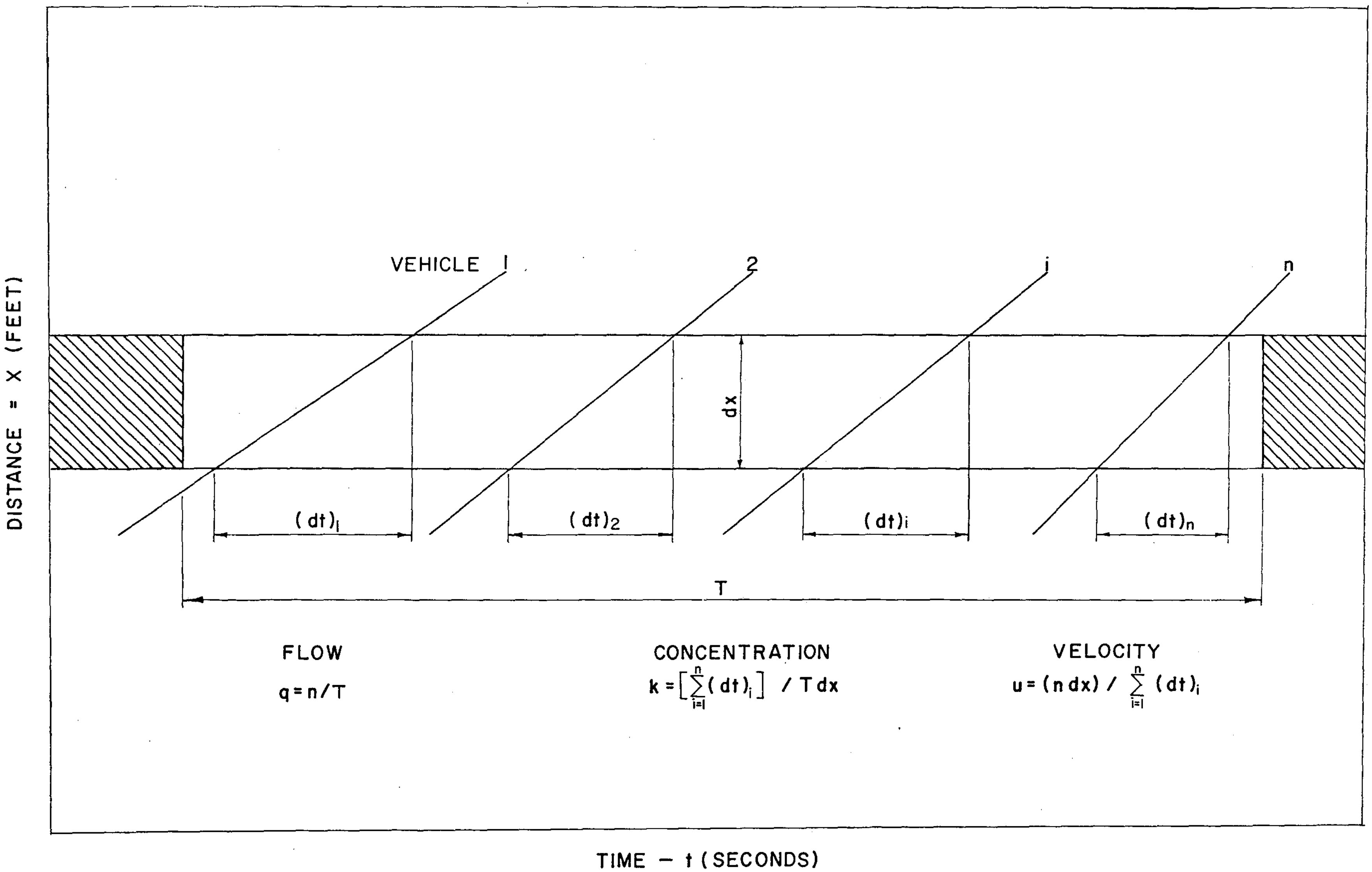
A dimensional analysis suggests that a relationship exists between vehicular velocity, space headway, and time headway,

$$\text{velocity (ft./sec.)} = \frac{\text{space hdwy.}}{\text{time hdwy.}} \quad \frac{\text{(ft.)}}{\text{(sec.)}} \;;$$

and between velocity, concentration and flow,

$$\text{velocity (ft./sec.)} = \frac{\text{flow}}{\text{concentration}} \quad \frac{(\text{sec.}^{-1})}{(\text{ft.}^{-1})} \;.$$

Actually this relationship as well as the precise definitions of flow, concentration and velocity can be seen in terms of the instructions for measuring them. Referring to Figure 2a, consider an interval of road dx located at a point X and an interval of time T at time, t. If n vehicles pass the point X in T, the traffic flow may be expressed as $q = n/T$. If the summation of travel times $(dt)_i$ is divided by T, the result represents the average number of vehicles on the increment of road at time, t, or



DEFINITIONS OF FLOW, CONCENTRATION AND VELOCITY

FIGURE 2A

TABLE 1

TRAFFIC FLOW NOTATION

Term	Symbol	Units
acceleration	$\ddot{x}$	dist./time^2
concentration (density)	k	veh./dist.
jam concentration	k_j	"
optimum concentration	k_m	"
constants of proportionality	a, c	varies
constants of integration	$C_1, C_2,$	varies
flow (volume, demand)	q	veh./time
optimum flow (capacity)	q_m	"
service rate (capacity)	Q	"
length of car	L	feet
position	x	feet
space headway	s	feet
time	t	sec.
time of reaction	T	sec.
time headway	h	sec.
velocity (speed), individual vehicle	$\dot{x}$	dist./time
velocity (speed), traffic stream	u	"
free speed	u_f	"
optimum speed	u_m	"

$$k = \left[\sum_{i=1}^{n} (dt)_i \right] / T \;\; dx. \qquad (1)$$

Since the mean velocity of the n vehicles may be expressed as

$$u = (ndx) \; / \; \sum_{i=1}^{n} (dt)_i, \qquad (2)$$

it follows that

$$q = ku \qquad (3)$$

Concentration is a better indicator of congestion than flow but, except for aerial studies, concentration is very difficult to measure directly. Therefore, in the past, many researchers have measured flow and velocities and then obtained a point density by division.

A summary of traffic flow parameters and symbols used throughout the paper is given in Table 1.

Generalization of Macroscopic Models

If vehicular traffic is assumed to behave as a one dimensional compressible fluid of concentration k, and fluid velocity, u, then the conservation of vehicles is explained by

$$\frac{\partial k}{\partial t} + \frac{\partial (ku)}{\partial x} = 0 \qquad (4)$$

Now, if it is assumed that a driver adjusts his velocity at any instant in accordance with the traffic conditions about him as expressed by $k^n \partial k / \partial x$, the acceleration of the traffic stream at a given place and time becomes,

$$\frac{du}{dt} = -c^2 k^n \frac{\partial k}{\partial x} \qquad (5)$$

Solving equations (4) and (5) for u= f(k) yields the generalized equations of state,[1]

$$u = u_f \left[1 - \left(\frac{k}{k_j} \right)^{(n+1)/2} \right], \quad n > -1 \qquad (6)$$

and

$$q = ku = ku_f \left[1 - \left(\frac{k}{k_j} \right)^{(n+1)/2} \right], \quad n > -1 \qquad (7)$$

Differentiation of (7) with respect to k, equated to zero, gives the optimum concentration, k_m, which is that concentration yielding the maximum flow of vehicles:

$$\frac{dq}{dk} = \left[1 - \frac{(n+3)\,k^{(n+1)/2}}{2\,k_j^{(n+1)/2}} \right] u_f = 0$$

$$k_m = \left[(n+3)/2 \right]^{-2/(n+1)} k_j, \quad n > -1. \qquad (8)$$

Substituting (8) in (6), one obtains the optimum velocity,

$$u_m = \frac{n+1}{n+3}\, u_f, \quad n > -1. \qquad (9)$$

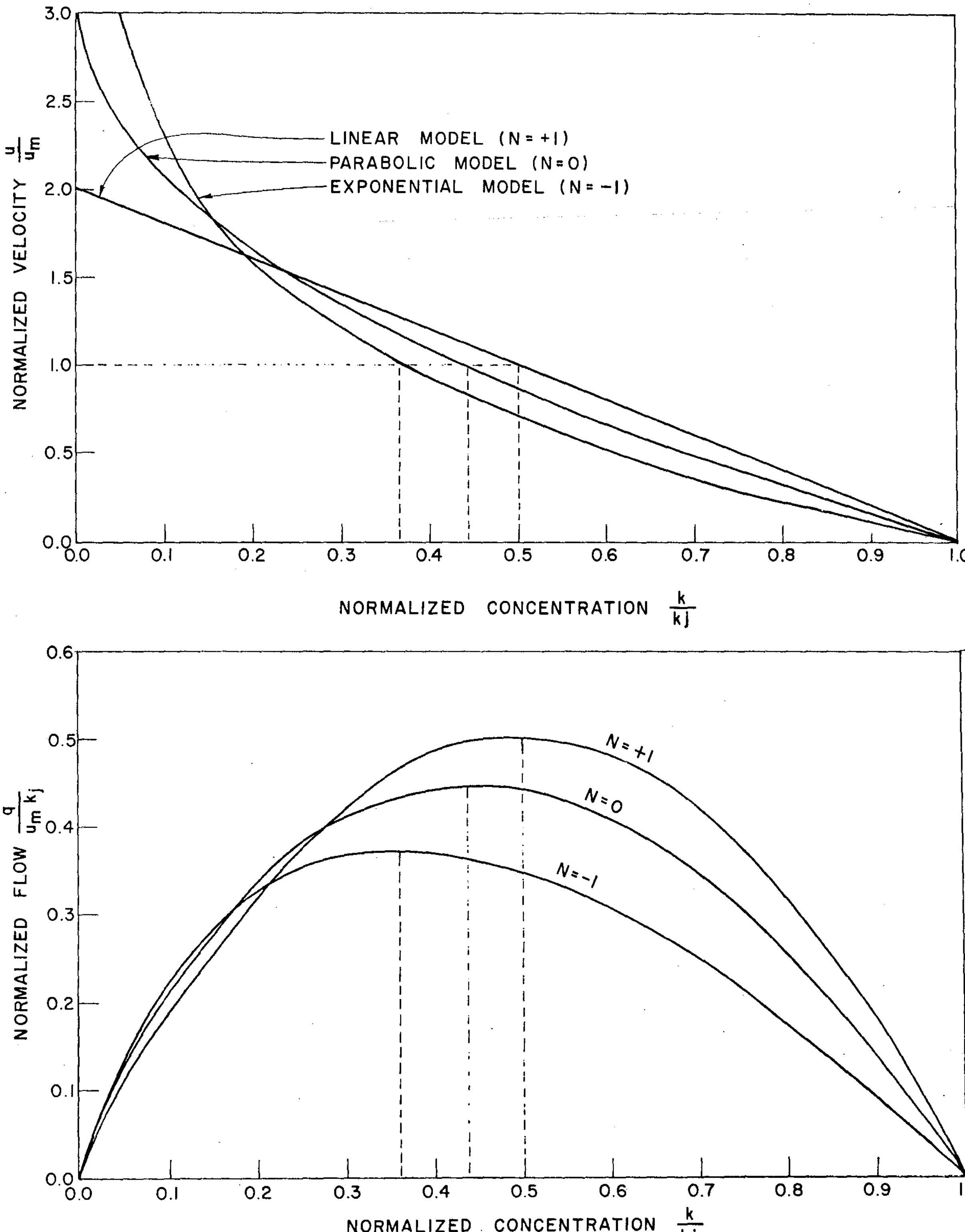
The maximum flow of vehicles of which the highway lane is capable (capacity) is obtained from the product of (8) and (9),

$$q_m = \left[\frac{(n+1)}{\left(\frac{1}{2}\right)^{(2/n+1)} (n+3)^{\left[2/(n+1)\right]}} + 1 \right] u_f k_j, \quad n > -1 \qquad (10)$$

<u>Development of Macroscopic Parameters</u>

Some special cases of the generalized macroscopic equation of motion have proven to be of significance and are summarized in Figure 2b and Table 2. Greenshields' [2] linear model and Richards' [3] model are obtainable from the generalized equations by setting n= 1. Greenberg's exponential model is the special case of the generalized equation of motion for n=-1. Since certain advantages and disadvantages are associated with both these cases, it seems logical to include in this investigation the case for n=0. This model, which plots as a parabola on the u-k graph (Figure 2b), falls between the special cases, n= 1 and n=-1. Thus, the parabolic model possesses a finite free speed higher than that of the linear model, a fact which could conceivably add more realism in the application to freeways.

Several parameters associated with the generalized model are listed in Table 2. The constant of proportionality has a physical significance dependent on the value of n chosen. For n= -1, the units of c are those of speed. For other values of n, the constant of proportionality is more difficult to interpret dimensionally. This, however, need not preclude its usefulness as a numerical index of performance. Similarly, the exponent n may hold a clue to the efficiency of a facility. Thus, on a straight, level freeway without ramps, the free speed, u_f, is not limited by the geometrics ($u_f = \infty$) and n equals -1.



SOLUTION OF GENERALIZED EQUATION OF TRAFFIC MOTION

$$\frac{du}{df} + c^2 k^n \frac{\partial k}{\partial x} = 0 , \text{ for } N = -1, 0, +1$$

FIGURE 2B

TABLE 2

COMPARISON OF MACROSCOPIC MODELS OF TRAFFIC FLOW

Element	General (n>-1)	Exponential (n=-1)	Parabolic (n=0)	Linear (n=1)
Eq. of Motion	$\frac{du}{dt} + c^2 k^n \frac{\partial k}{\partial x} = 0$	$\frac{du}{dt} + \frac{c^2}{k} \frac{\partial k}{\partial x} = 0$	$\frac{du}{dt} + c^2 \frac{\partial k}{\partial x} = 0$	$\frac{du}{dt} + c^2 k \frac{\partial k}{\partial x} = 0$
Constant of Proportionality	$c = [(n+1) u_f]/2k_j^{(n+1)/2}$	u_m	$u_f/2k_j^{1/2}$	u_f/k_j
Eq. of State	$q = ku_f \left[1 - \left(\frac{k}{k_j}\right)^{(n+1)/2}\right]$	$ku_m \ln\left(\frac{k_j}{k}\right)$	$ku_f \left[1 - \left(\frac{k}{k_j}\right)^{1/2}\right]$	$ku_f \left[1 - \frac{k}{k_j}\right]$
Optimum Concentration	$k_m = [(n+3)/2]^{-2/(n+1)} k_j$	k_j/e	$4k_j/9$	$k_j/2$
Optimum Speed	$u_m = [(n+1)/(n+3)] u_f$	c	$u_f/3$	$u_f/2$
Capacity	$q_m = \frac{(n+1) u_f k_j}{(1/2)^{2/(n+1)} (n+3)^{[2/(n+1)]+1}}$	$\frac{1}{e} u_m k_j$	$\frac{4}{27} u_f k_j$	$\frac{1}{4} u_f k_j$
Wave Vel.	$\frac{dq}{dk} = u_f \left[1 - \frac{(n+3)}{2} \left(\frac{k}{k_j}\right)^{(n+1)/2}\right]$	$u_m \left[\ln\left(\frac{k_j}{k}\right) - 1\right]$	$u_f \left[1 - \frac{3}{2}\left(\frac{k}{k_j}\right)^{1/2}\right]$	$u_f \left[1 - \frac{2k}{k_j}\right]$

The parameters just discussed, plus the other conventional parameters associated with the model such as the optimum concentration, optimum speed and optimum flow (capacity), will be evaluated under freeway conditions. An interesting assertion of the optimum flow concept, proven in the New York Port Authority tunnels, is that slight reductions in the rate of entry into bottlenecks may serve to produce heavier total flows by reducing the effect of shock waves. In this phase of the investigation, emphasis will be placed on the three special cases of the generalized macroscopic equation of motion: $n=1$, $n=0$, and $n=-1$.

Generalization of Microscopic Models

Typical of some of the car-following laws discussed in the previous section are those that express the performance of a vehicle in terms of its velocity and position with respect to the vehicle immediately preceding it,

$$\ddot{x}_i \ (t+T) = a \frac{\dot{x}_{i-1}(t) - \dot{x}_i(t)}{\left[x_{i-1}(t) - x_i(t)\right]^m} \qquad (11)$$

Equation (11) states that the acceleration of a car, $\ddot{x}_i$, at a delayed time, T, is directly proportional to the relative speed of the car, $\dot{x}_i$, with respect to the one ahead, $\dot{x}_{i-1}$; and inversely proportional to the headway of the car, $x_{i-1}-x_i$. Since the right side of (11) is of the form dy/y^m, integration of (11) yields

$$\dot{x}_i \ (t+T) = a \ \ln\left\{ L^{-1}\left[x_{i-1}(t) - x_i(t)\right]\right\}, \quad m=1 \qquad (12)$$

$$\dot{x}_i \ (t+T) = (m-1)^{-1} \ a \left\{ L^{-(m-1)} - \left[x_{i-1}(t) - x_i(t)\right]^{-(m-1)}\right\}, \quad m>1 \qquad (13)$$

Equation (12) is due to Gazis, Herman and Potts [4] who showed that the traffic equation of state could be derived from the microscopic car following law just as the gas equation of state can be derived from the microscopic law of molecular interaction. Since the space headway is the reciprocal of concentration, k, equations (12) and (13) become

$$u = a \ \ln(k_j/k) \qquad (14)$$

and

$$u = (m-1)^{-1} \ a \ (k_j^{\,m-1} - k^{\,m-1}), \quad m>1 \qquad (15)$$

The constant of proportionality is evaluated at $u=u_f$ and $k=0$ giving

$$a = \frac{(m-1)}{k_j^{\,m-1}} \ u_f, \quad m>1 \qquad (16)$$

Development of Microscopic Parameters

Some special cases of the generalized microscopic equation of motion are of interest of interest. Pipes'[5] model and the modification proposed by Chandler, Herman and Montroll[6] are obtainable from (17) by setting m=0. The "reciprocal spacing" model of Gazis, Herman and Potts[4] comes from the generalized equation with m 1. It is apparent that just as Greenberg's exponential continuous flow model and the "reciprocal spacing" car following model are related, comparable relationships exist for the linear and parabolic continuous flow models. These relationships are summarized in Table 3.

As in the continuous flow models, use can be made of the flow-concentration relationship of traffic to predict the optimum speed in order to obtain maximum flow on single lane facilities. This optimum speed is predicted by the constant of proportionality "a" for m 1. The car following law also predicts instability which can lead to rear-chain collisions.

TABLE 3

COMPARISON OF MICROSCOPIC MODELS OF TRAFFIC FLOW

Element	General (m > 1)	m = 1	m = 3/2	m = 2
Eq. of Motion	$\ddot{x}_i = \frac{a(\dot{x}_{i-1} - \dot{x}_i)}{(x_{i-1} - x_i)^m}$	$\ddot{x}_i = \frac{a(\dot{x}_{i-1} - \dot{x}_i)}{(x_{i-1} - x_i)}$	$\ddot{x}_i = \frac{a(\dot{x}_{i-1} - \dot{x}_i)}{(x_{i-1} - x_i)^{3/2}}$	$\ddot{x}_i = \frac{a(\dot{x}_{i-1} - \dot{x}_i)}{(x_{i-1} - x_i)^2}$
Constant of Proportionality	$a = (m-1)\, u_f\, k_j^{-(m-1)}$	u_m	$u_f/2k_j^{1/2}$	u_f/k_j
Eq. of State	$q = ku_f\, [1 - \left(\frac{k}{k_j}\right)^{m-1}]$	$ku_m \ln\left(\frac{k_i}{k}\right)$	$ku_f\, [1 - \left(\frac{k}{k_j}\right)^{1/2}]$	$ku_f\, [1 - \left(\frac{k}{k_j}\right)]$
Macroscopic Counterpart (See Table 1)	$n = 2m - 3$	$n = -1$	$n = o$	$n = +1$

STUDY PROCEDURES

Study Site: The Gulf Freeway

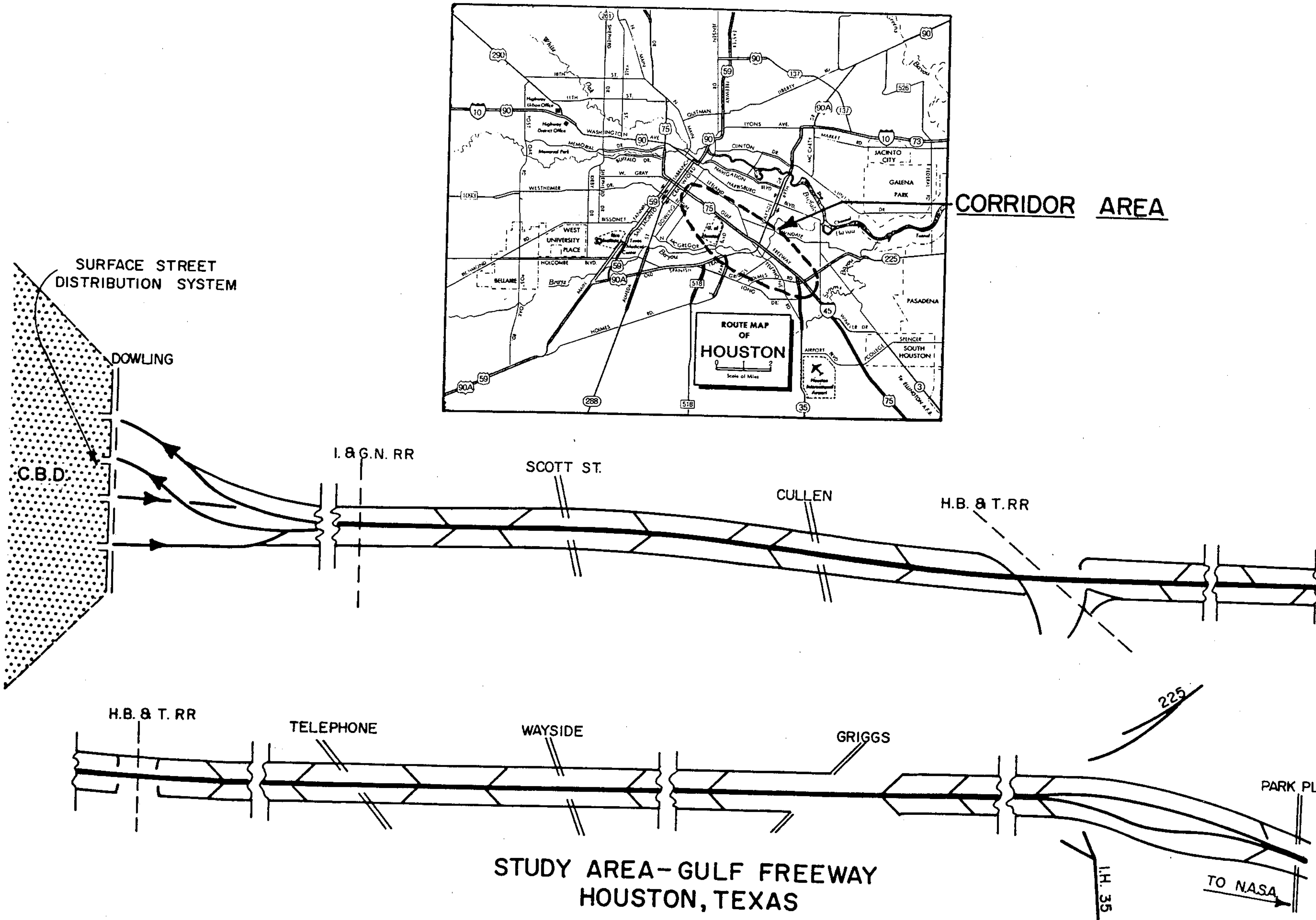
The area of study is the Gulf Freeway in Houston, Texas (Figure 3). This facility is a critical transportation link; its operation must be improved to meet new demands created by the establishment of the NASA Manned Space center to the South of the study section. Although the operation of the Gulf Freeway is typical of many freeways that are congested during the peak period; it is an older facility having several geometric deficiencies which should be eliminated.

The Gulf Freeway has three 12-foot lanes in each direction separated by 4-foot concrete median with a 6-inch barrier-type curb. The section in the study area extends from the Reveille Interchange at the intersection of Highways U.S. 75, State 225, and State 35, to the downtown distribution system at Dowling diamond interchanges or partial diamond interchanges. The Reveille Interchange and Dowling distribution systems are directional interchanges. Frontage roads are one-way, and continuous except at the three railroad crossings. The through lanes of the Gulf Freeway overpass the intersecting roadways producing a "roller-coaster" effect, as well as limiting the sight distance for the entrance ramp maneuver.

Previous Studies of the Facility

In 1956 the Texas Transportation Institute initiated a research project for the Texas Highway Department to correlate freeway operational characteristics with design features. Keese, Pinnell and McCasland[7] utilized the motion picture method in subsequent studies of the Gulf Freeway. This method facilitated the simultaneous evaluation of various operational characteristics and provided the advantage of the re-creation of traffic situations for more thorough study. Among the many conclusions, it was noted that control of freeway access during peak periods can be utilized to improve the efficiency of the over-all facility. In more recent studies,[8,9] lane-distribution factors and peaking factors were developed.

Although the motion picture technique offers advantages over such conventional studies as volume counts and spot speed measurements, it appears necessary to evaluate traffic flow characteristics by methods that do not rely on point survey data for describing flow characteristics over an area. Two methods that have been successfully utilized are television camera surveillance and aerial photography. At this time a television surveillance system is being designed for the Gulf Freeway,



STUDY AREA-GULF FREEWAY
HOUSTON, TEXAS
FIGURE 3

but will not be operational for another year. Therefore, the application of data collection by aerial photography seems to provide the best means of evaluating the critical areas of traffic congestion.

Time - Lapse Aerial Photography

In September 1963, aerial surveys of the traffic flow on the six-mile study section of the Gulf Freeway were initiated by the Texas Transportation Institute. Two types of aerial photography were investigated: (1) strip photography where two continuous pictures are taken simultaneously over the entire study section; and (2) time-lapse photography where individual overlapping pictures are taken at short intervals of time. The objectives of this were to compare the two types of aerial photography. As a result of this study, McCasland[10] concluded that time-lapse photography is more suited for density and speed measurements. Moreover, the time-lapse method can provide multiple readings of speed for each vehicle. From these several measures of speed, the acceleration of vehicles can be calculated.

The aerial surveys, from which the data for this paper were obtained, were conducted by the International Aerial Mapping Company. Flights were made according to a predetermined plan. Beginning at the south end of the study section, the crew filmed northbound, circled upon reaching Dowling Street, then filmed the study area from north to south, circled at the south extremity, and again filmed north-bound. Three such repetitions were made; or a total of nine filming runs over the area, six northbound and three southbound. A precise time measurement was furnished indicating the clock time when the plane passed over the two limits of the study area. The plane was a Cessna 195 flown at 2400 feet. A 24-inch focal length aerial camera with a 60 percent overlap was utilized. The basic information concerning the aerial study is summarized in Table 4.

Information Obtained

The traffic flow data weretaken off 18-in. by 9-in. positives with a scale of approximately 1 inch to 100 feet and a 60 percent overlap. One-hundred foot stations were located on the photographs and vehicles were located to the nearest foot (1/100 inch with engineer's scale) on each photograph. The vehicles in each lane were numbered consecutively. The information for each vehicle was put on a separate punch card. This information included the run number, lane number (numbered consecutively starting with the shoulder lane and working toward the median lane), time interval between photos for that run, vehicle classification, and the location of that vehicle on all photographs. Because of the 60 percent overlap, vehicles traveling in the same direction as the plane appear on at least three consecutive pictures, but vehicles traveling in the opposite direction appear on less than three. Since the morning or inbound (northbound) peak was

Table 4

INDEX FOR TIME-LAPSE AERIAL SURVEY

Strip No.	Direction	Exposure No.	Time of Run Start	Time of Run End	Time Lapse (Seconds)
4	Northbound	1-49	6:45:37 a.m.	6:48:20 a.m.	3.40
5	Southbound	50-106	6:50:26	6:54:02	3.95
6	Northbound	107-146	6:55:32	6:58:06	3.95
7	Northbound	1-48	7:03:44	7:06:39	3.70
8	Southbound	49-94	7:10:53	7:13:30	3.50
9	Northbound	95-141	7:15:55	7:18:34	3.45
1	Northbound	1-56	7:25:15	7:28:02	3.05
2	Southbound	57-107	7:30:25	7:33:38	3.85
3	Northbound	108-160	7:44:43	7:47:35	3.30

be studied, only data from the six northbound runs were utilized

From the several consecutive measures of position, individual vehicular ɜeds and accelerations can be calculated. Space headways are obtained taking the difference between the station positions of two vehicles in the ne lane on the same photograph. Vehicular density can be determined directly an 1800-foot section spanned by one photograph by multiplying the number vehicles on a photograph by the factor 5280/1800. Traffic volumes and time ıdways cannot be found directly, but must be calculated from the fundamental ed-concentration relationships discussed.

The speed concentration measurements taken from the photos are summarized Appendix A. The 18 station lengths designated in the first column of Appendix orrespond approximately to the length of road appearing on an individual photo. .s, the number of vehicles per lane per photo can easily be converted to density. vehicular speeds on a particular photo (18-station interval) were obtained by raging the speeds over the two successive time-lapses spanning the given otograph.

ification of Equations of State

The problem of fitting a curve to a set of points objectively is essentially the blem of estimating the true parameters of the curve. The best known method of forming the estimation of such parameters is known as the method of least ares. In applying this procedure to speed-concentration graphs, we are seek- a function u f (k) which fits the points such that the sum of the squares of the iations between the ordinates of the points and the ordinates of the curve are imized.

The additional problem of determining the accuracy of the least-squares line statistical problem. Thus the least-squares line, $y=a+bx$, is called a re- ssion line, where "a" and "b" are the intercept and slope of the regression e. The test of significance of regression is performed on the regression co- cient, b, using the t-test:

$$t=b/s_b, \quad d.f.=n-2 \qquad (17)$$

ere

$$b=\frac{\sum xy-n^{-1}\sum x \sum y}{\sum x^2-n^{-1}(\sum x)^2} \qquad (18)$$

and

$$s_b = \frac{1}{D} \left[\frac{\sum y^2 - n^{-1} (\sum y)^2 - bN}{n-2} \right]^{1/2} \qquad (19)$$

(N and D refer to the numerator and denominator of the expression for "b" in equation 18.) Inherent in the t-test is the hypothesis that B, the true regression coefficient estimated by "b", is zero and that the error in the estimate of "B" is normally distributed. If the 5% level of confidence is chosen and $t > t_{.05}$, the null hypothesis concerning B may be rejected. It then may be concluded that a cause and effect relation does exist between the variables, x and y.

In the previous section, it was indicated that the nonlinear parabolic and exponential forms of $u = f(k)$ were also used as models. Although the preceding method for finding the slope of a regression line can be generalized to find confidence limits for the regression coefficients in curvilinear and exponential regression, it is also possible by simple transformations of the variables to represent the relationships as straight lines in the transformed variates. Thus, the parabolic model may be written

$$y_2 = a_2 + b_2 x_2 \quad , \qquad (20)$$

where $y_2 = u$, $a_2 = u_f$, $b_2 = -u_f / k_j^{1/2}$, and $x_2 = k^{1/2}$. In the case of the exponential model, taking logarithms of both sides, we obtain a linear relation of the form

$$y_3 = a_3 + b_3 x_3 \quad , \qquad (21)$$

where $y_3 = \ln k$, $a_3 = \ln k_j$, $b_3 = -u_m^{-1}$, and $x_3 = u$. The linear model is simply

$$y_1 = a_1 + b_1 + x_1 \quad , \qquad (22)$$

where $y_1 = u$, $a_1 = u_f$, $b_1 = -u_f / k_j$, and $x_1 = k$. The various parameters b_1, b_2, b_3, and a_1, a_2, a_3 are obtainable by solving equation 38 and the following expression

$$a = n^{-1} (\sum y - b \sum x) \qquad (23)$$

using the speed concentration data from Appendix A.

A computer program was written for these statistical calculations. Individual photographs covering 1800 feet from each of the six flight strips (Appendix A) provided on pair of u-k values. The organization of information as depicted in gure 4 suggests 196 analyses using each of the linear, parabolic and exponential odels, or a total of 588 separate equation of state regression analyses.

etermination of Car Following Variables

The solution of the generalized microscopic equation of motion for the constant proportionality depends on the evaluation of several variables. It has been stated at the sixty percent overlap in the time-lapse aerial studies provide the means of taining vehicle speeds, averaged over one time-lapse interval, and vehicle accelerations, averaged over two time-lapse intervals (see Figure 5). Since the sition trajectories, x are continuous and differentiable in the interval between and t_2, there exists a point τ in (t_1, t_2) such that

$$\dot{x}(\tau) = \frac{x(t_2) - x(t_1)}{t_2 - t_1} \quad t_1 < \tau < t_2 . \tag{24}$$

w if it is assumed that a vehicle's velocity changes at a constant rate,

$$x(t) = Ct + C_1 , \tag{25}$$

oughout the time-lapse between photos (t_1, t_2), or for about 3 seconds. Inrating (25) between the limits t_1 and t_2 yields

$$x(t_2) - x(t_1) = C(t_2^2 - t_1^2)/2 + C_1(t_2 - t_1). \tag{26}$$

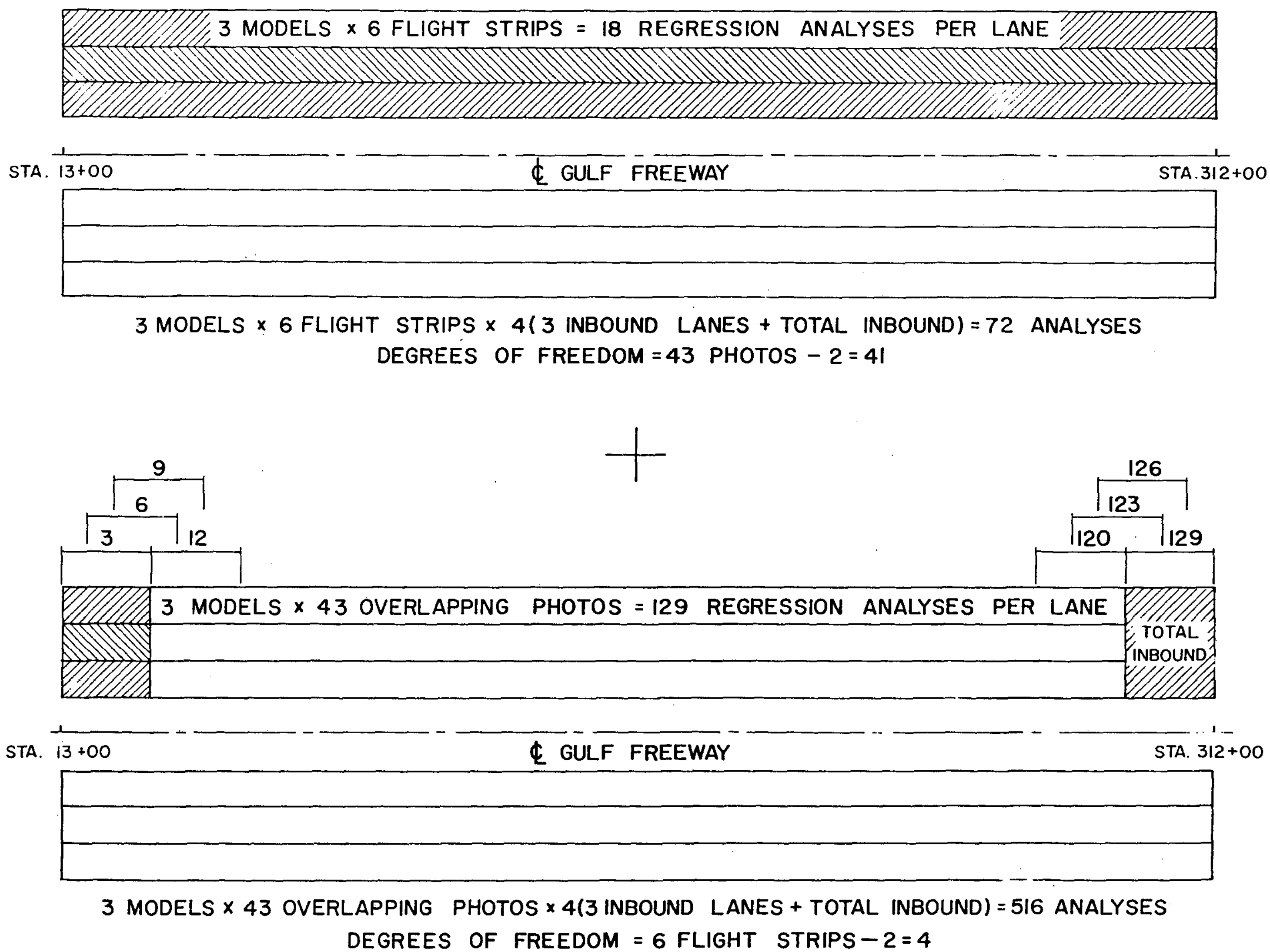
ation 44 can be solved for τ by use of (25), $x(\tau)$ $C\tau + C_1$. Then substing (26) in (24):

$$\tau = \frac{(t_2^2 - t_1^2)}{2(t_2 - t_1)} . \tag{27}$$

toring the numerator, it is apparent that for the condition assumed in (25), nust be half way between t_1 and t_2,

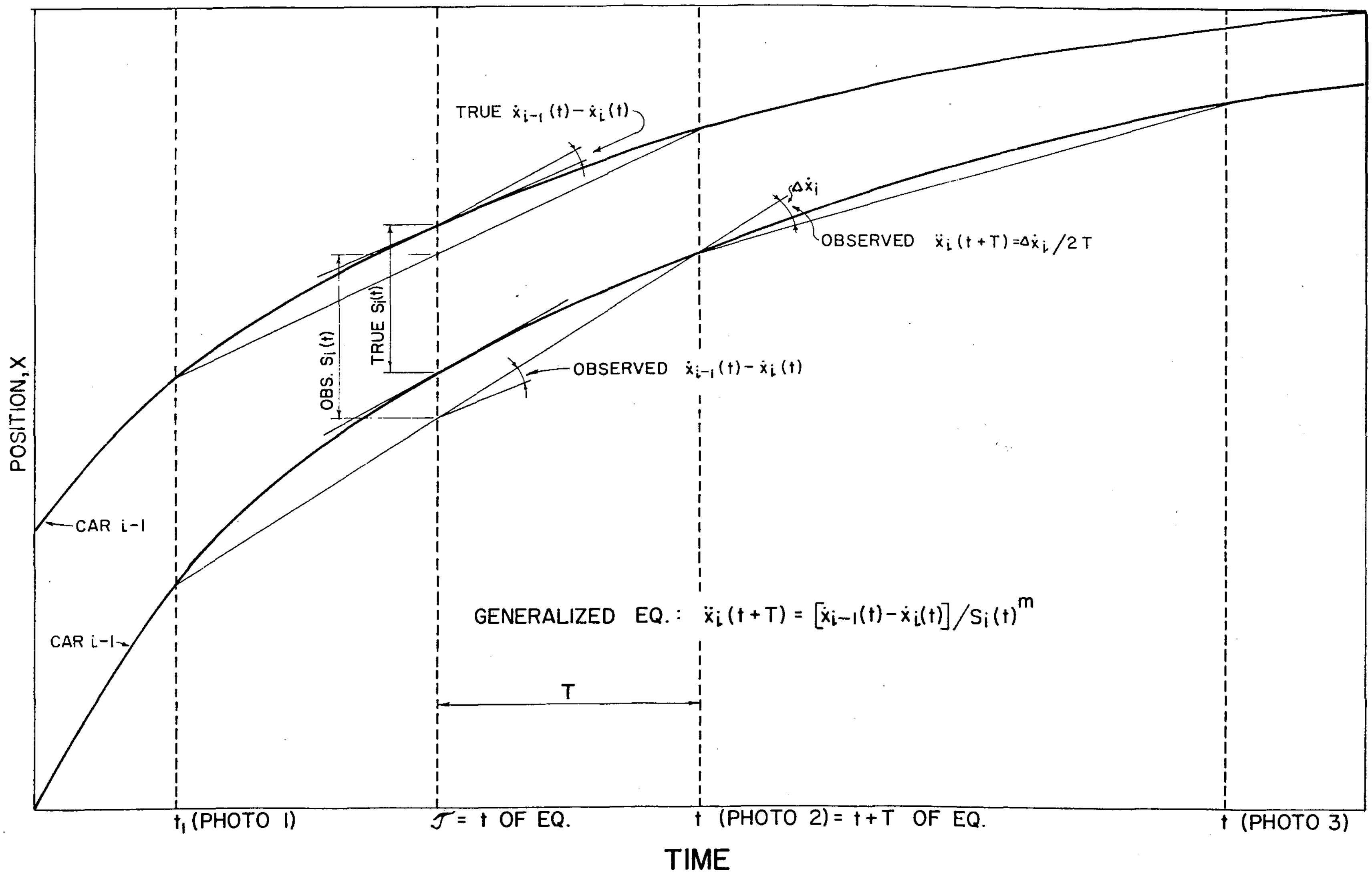
$$\tau = (t_2 + t_1)/2 \tag{28}$$

s, referring again to Figure 5, it is seen that one can obtain vehicle velocities some time τ, and vehicle accelerations at an interval, $T = t_2 - \tau$, later. This rval T is the time for the driver in the second vehicle to react. Since the aver- time-lapse between photos (Table 4) is 3.4 seconds, this implies a time lag = 1.7 seconds for the aerial car-following studies. The results of controlled following experiments in the Lincoln Tunnel [4] actually indicate a maximum cor-



SCHEMATICS SHOWING AREAS COVERED BY MACROSCOPIC REGRESSION ANALYSES

FIGURE 4



COMPARISON OF TRUE AND OBSERVED CAR-FOLLOWING VARIABLES USING TIME-LAPSE AERIAL PHOTOGRAPHY

FIGURE 5

relation for a time lag T of 1.6 seconds. Thus, use of one-half the photo time-lapse measurements for the time lag is reasonable, as well as convenient.

In order to obtain the car following variables data taken from the time-lapse photographs were subject to factors that affected the precision of measurements. Vehicle displacements were read to the nearest one-hundredth of an inch with an engineers' scale. Time intervals between photographs had an estimated accuracy of 1/10th of a second. The maximum effect of these mechanical errors on the determination of relative speed between two vehicles would be 2 ft÷3.4 sec. = ± 0.4 mph. The maximum effect on the determination of vehicle acceleration would be ± 0.5 mph/sec. at 30 mph.

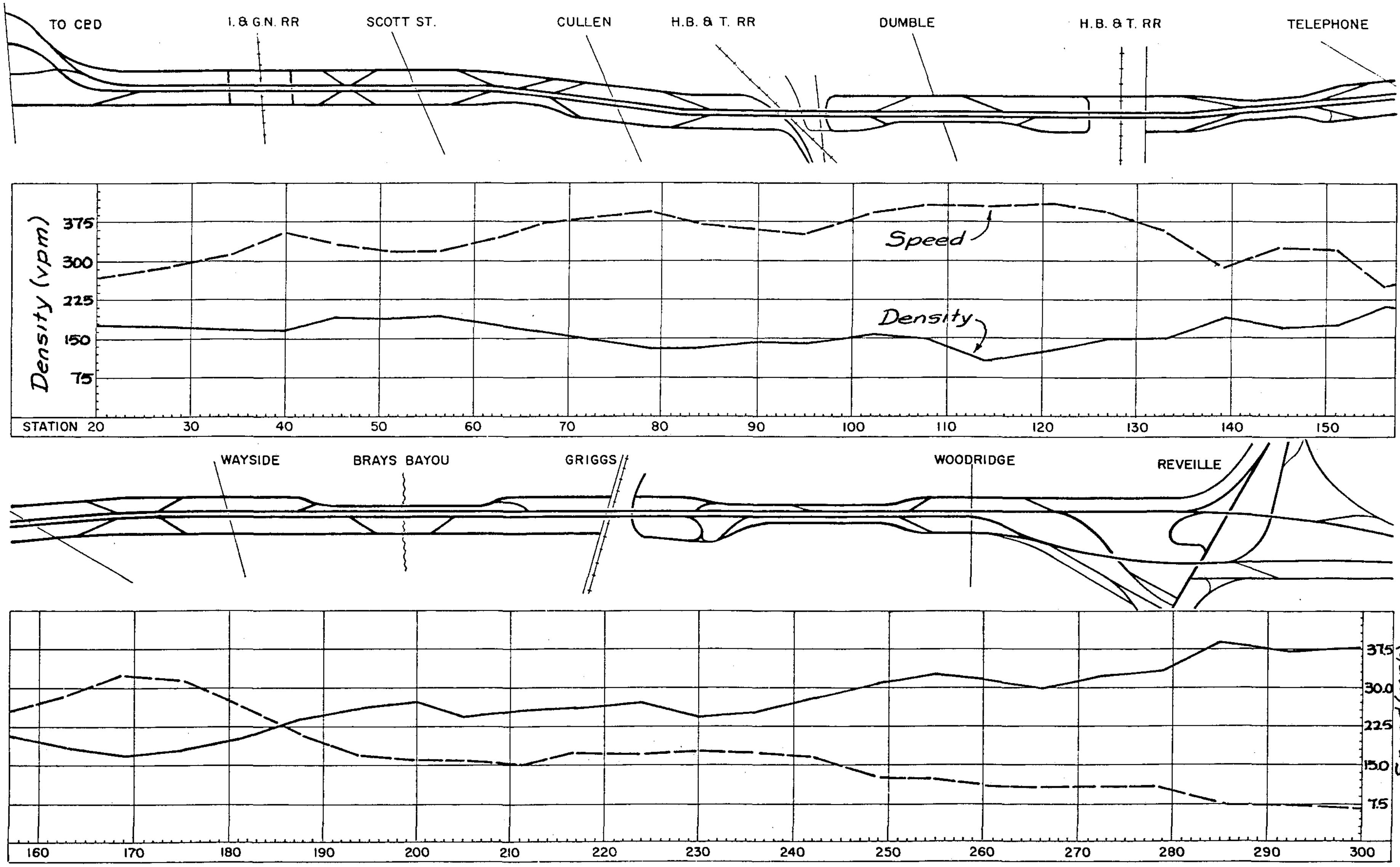
DISCUSSION OF RESULTS

Operational Characteristics

Although the two most important characteristics of traffic concern the abilities and performance of drivers and their vehicles, who together comprise the discrete unit of traffic; the primary characteristics of traffic movement are concerned with speed, density and volume. These three fundamental characteristics are dependent on the geometric design of the roadway and the operational requirements of the traffic stream. Interest in these characteristics is manifest in the need, and announced objective of this work for specific indications of impending traffic congestion, which can then be utilized in control processes intended to maintain maximum traffic flow.

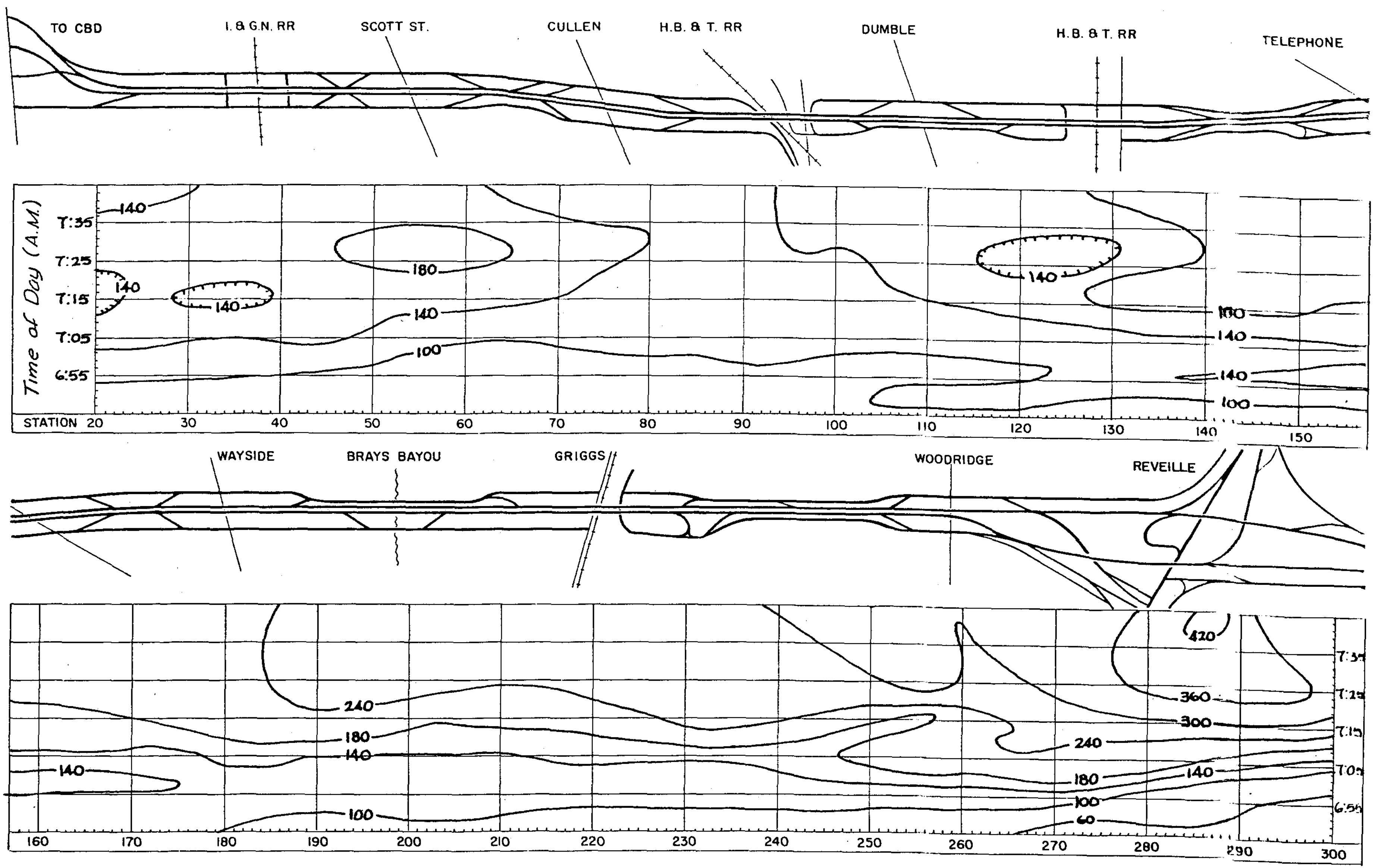
Because of the nature of the aerial photographic study procedure, speed and density were measured directly. By averaging these measurements over individual photos, values were obtained at 600 feet intervals for each lane (Appendix A) Using these values, speed and density profiles were plotted for the entire freeway. Figure 6 shows such a profile for the total inbound traffic from data taken from flight strip 1. The profiles illustrated help dramatize the inverse relationship of speed and density on the Gulf Freeway. The traffic density diminishes from a high of 375 vehicles per mile (125 vpm per lane) at Station 300 at the Reveille Interchange to a low of 110 (about 37 vpm per lane) at Station 114. Over the same distance, speeds increased from 7 miles per hour to about 40 miles per hour.

The profile method of presentation has some obvious shortcomings, namely that speed and density are functions of time, as well as distance. Thus, although the traffic characteristics are described over an area at a given time, no indication is given of variations at a point over an interval of time. Contour maps provide a means of illustrating these two-dimensional variations in the characteristics. Figures 7 and 8 illustrate density contours and speed contours, respectively, for the whole study area throughout the entire duration of the study. These maps were obtained by using time as the ordinate and distance along the freeway under the plan view as the abscissa. Since six aerial flight runs were utilized at approximately 10-minute intervals, and the speed, density characteristics were averaged at approximately 600-foot intervals, each of the contour maps were drawn from about 300 points. Just as conventional land contours connect points of equal elevation, speed contours connect points of equal speed. Thus, in Figure 7, it is apparent that at Station 285, the density doubled from 180 vpm to 360 vpm from 7:05 AM to 7:22 AM. Whereas speeds at 7:22 AM were



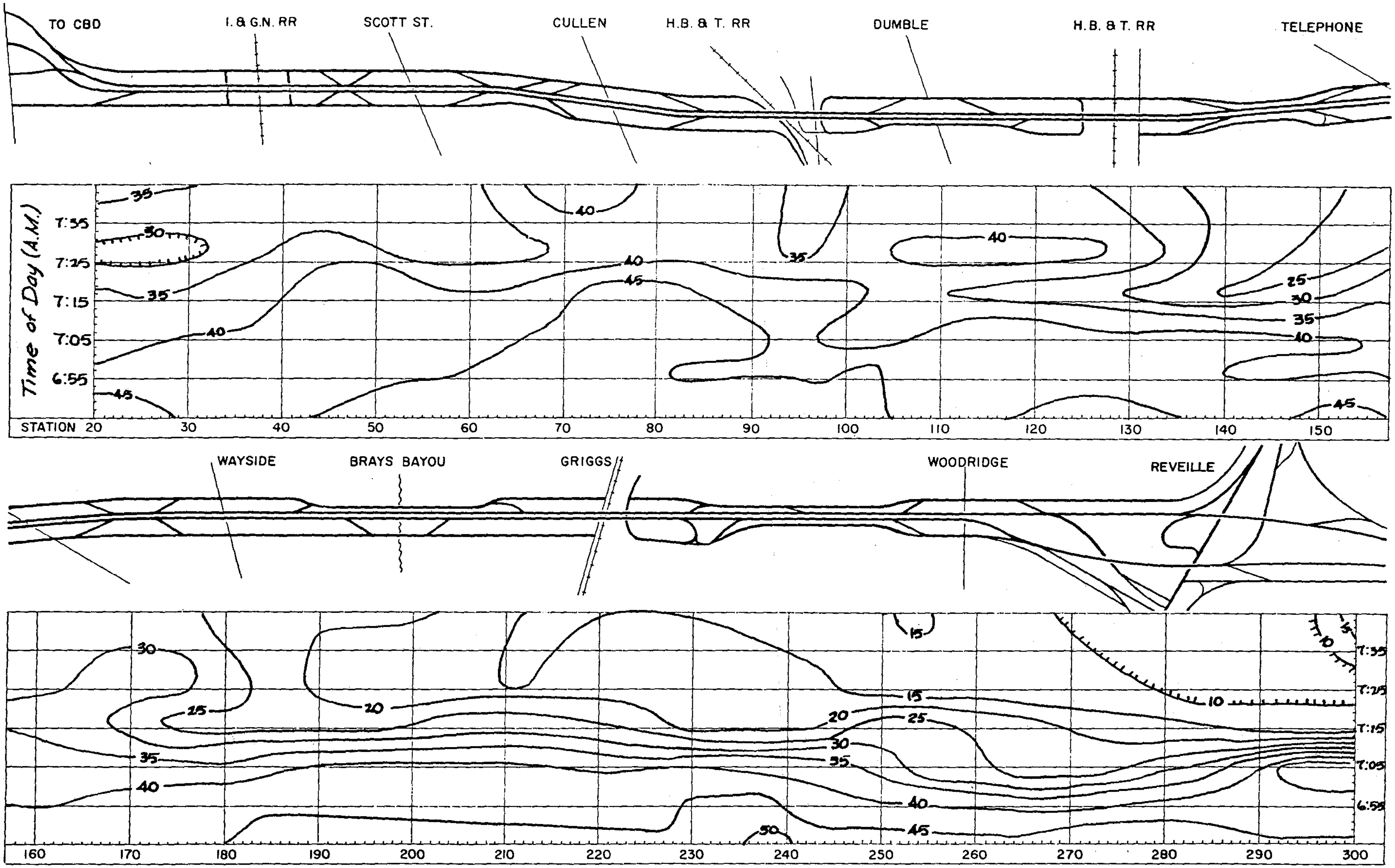
SPEED VS. DENSITY: TOTAL INBOUND TRAFFIC (7:25 A.M.)

FIGURE 6



DENSITY CONTOURS (3 LANE TOTAL)

FIGURE 7



SPEED CONTOURS (TOTAL INBOUND TRAFFIC)

FIGURE 8

less than one-third their value at 7:05 AM (Figure 8). The most important conclusion is that the portion of the freeway from Station 130 to the CBD is congestion free during the morning peak.

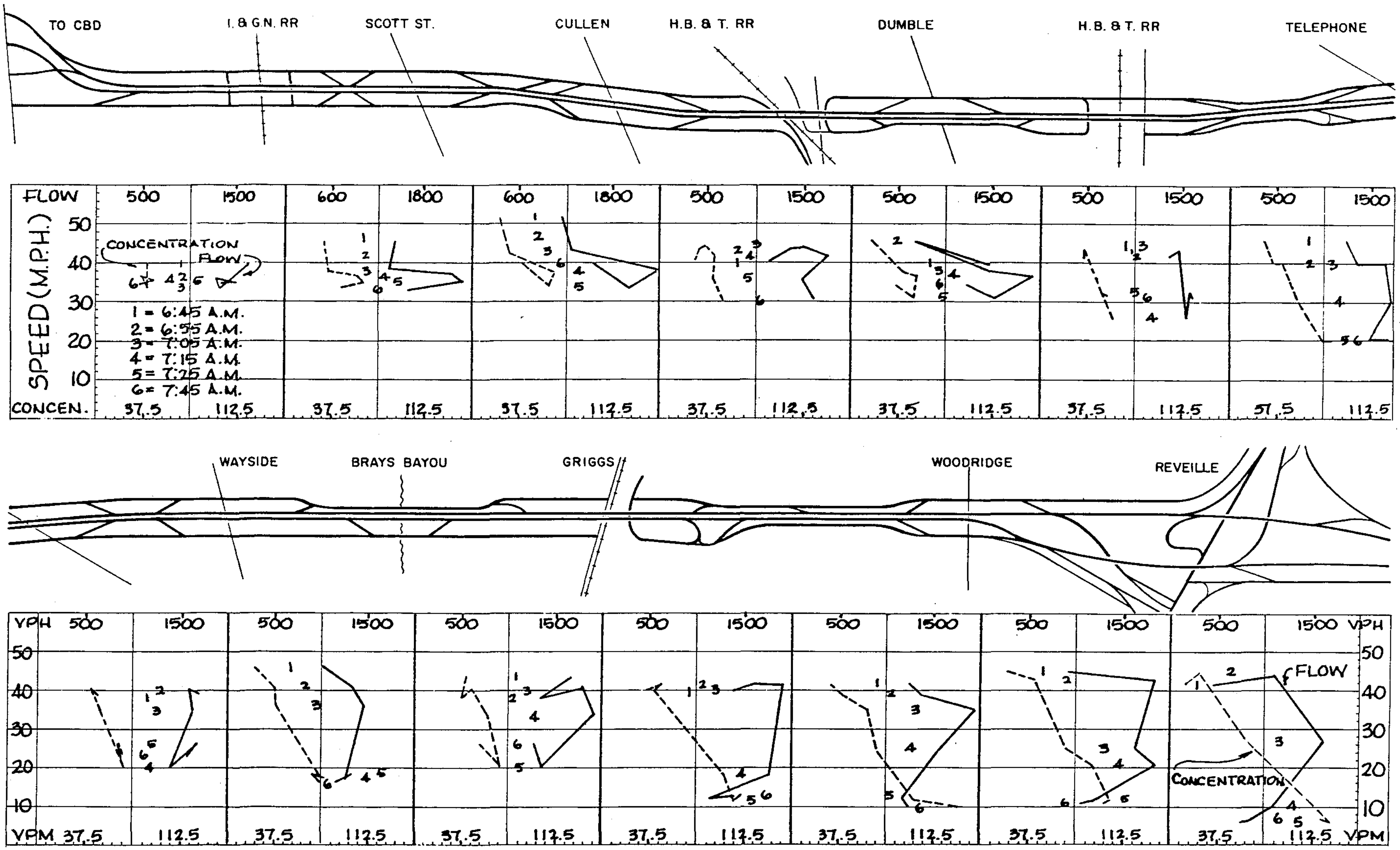
In order to illustrate the speed-density-volume relationship over shorter sections of freeway, the 14 graphs of Figure 9 were plotted for the inbound shoulder lane. Each graph represents the average conditions encountered throughout the study hour for the 200-foot length of freeway directly above the graph. The graphs' ordinate is speed in miles per hour and the upper abscissa is volume in vehicles per hour, while the lower abscissa is density in vehicles per mile. The numbers from 1 to 6 refer to the times of the six flight runs, thus giving a chronological plot of data. The speed-density relationship is shown by a dotted line; the speed-volume relationship is shown by a solid line.

It is apparent, in studying the graphs in Figure 9, that almost without exception, increases in density are accompanied by decreases in speed. For the graph covering the interval within the Reveille Interchange, the range in average speeds varies from 45 to 5 mph over the study hour. At the other end of the freeway, however, average speeds remain at from 40 mph to 35 mph during the same period. The range of average speeds plainly decreases throughout the morning peak hour as one travels toward the CBD on the facility.

The volume-speed relationship is more difficult to explain. Decreases in speed do not always accompany increases in flow. However, several of the graphs exhibit a characteristic parabolic loop resulting from the decrease of speed at excessive flows. Keese, Pinnell and McCasland[7] explain that as peak flows build up, the average speed drops and generally does not recover to the original relationship with volume until the peak flow or demand has passed. Ryan and Breuning[11] utilize the concept of critical vs. noncritical flow, with the dividing point being the maximum flow. They report that all three relations among speed, volume and density are linear within the noncritical flow region (before congestion sets in). May et. al.[12] define three zones which may be described as constant speed, constant volume and constant rate of change of volume with density. In zone 1, the speed of the vehicle is determined by the facility itself and the volume matches the demand. Zone 2 represents impending poor operations; average speed drops but the flow rates may be sustained at a high level. In zone 3 both speed and volume rates decrease, which in itself may serve as a definition of congestion.

Deterministic Model Parameters

The analysis of highway traffic is more than the making of measurements and collection of facts. Although this exploration of the true nature and characteristics of freeway traffic is the necessary beginning in providing new ways of



OBSERVED SPEED-VOLUME-DENSITY RELATIONSHIPS (LANE 1)
IN TIME AND SPACE

FIGURE 9

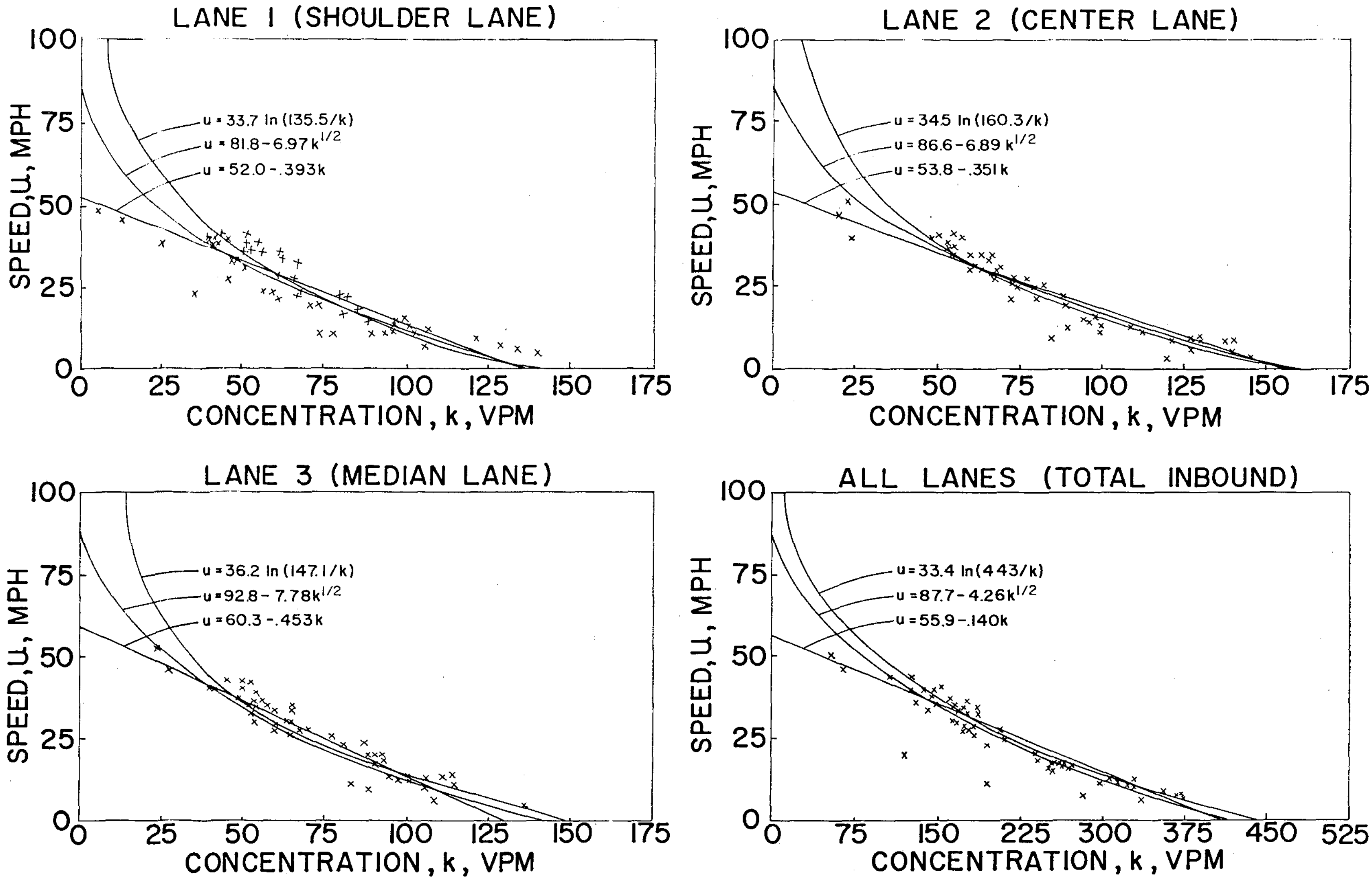
improving performance, the freeway traffic phenomena is so complex that a collection of bare data tell us little more than we already know. In the early chapters, two models were formulated: (1) the Generalized Macroscopic Model and (2) the Generalized Microscopic Model. These models yield several parameters which provide the means of organizing and interpreting the traffic characteristics summarized.

The freeway system is composed of several components; the most important of these are the freeway lanes and entrance ramp. From a knowledge of the characteristics of these two components, the operation of a given facility may be conducted on a rational basis , and the generalization of this knowledge to the design of future freeway systems becomes a reality. However, theory is the catalyst between measurement and application. Without it progress is merely placed on a trial-and-error basis.

There seems to be no end to the number of freeway operational variables that must be studied extensively before choosing one which fulfills the requirements of a practical indicator of congestion. The results of the regression analyses utilizing the linear, parabolic and exponential models derived from the Generalized Macroscopic Equation of State, provide at least three possible control parameters; optimum speed, optimum density and optimum flow. Figure 10 illustrates the results of the regression of speed on density for the individual freeway lanes and all lanes taken together. The observed points plotted refer to the average speeds and vehicular concentrations over 700-foot sections of freeway, as observed from a time-lapse aerial photography flight.

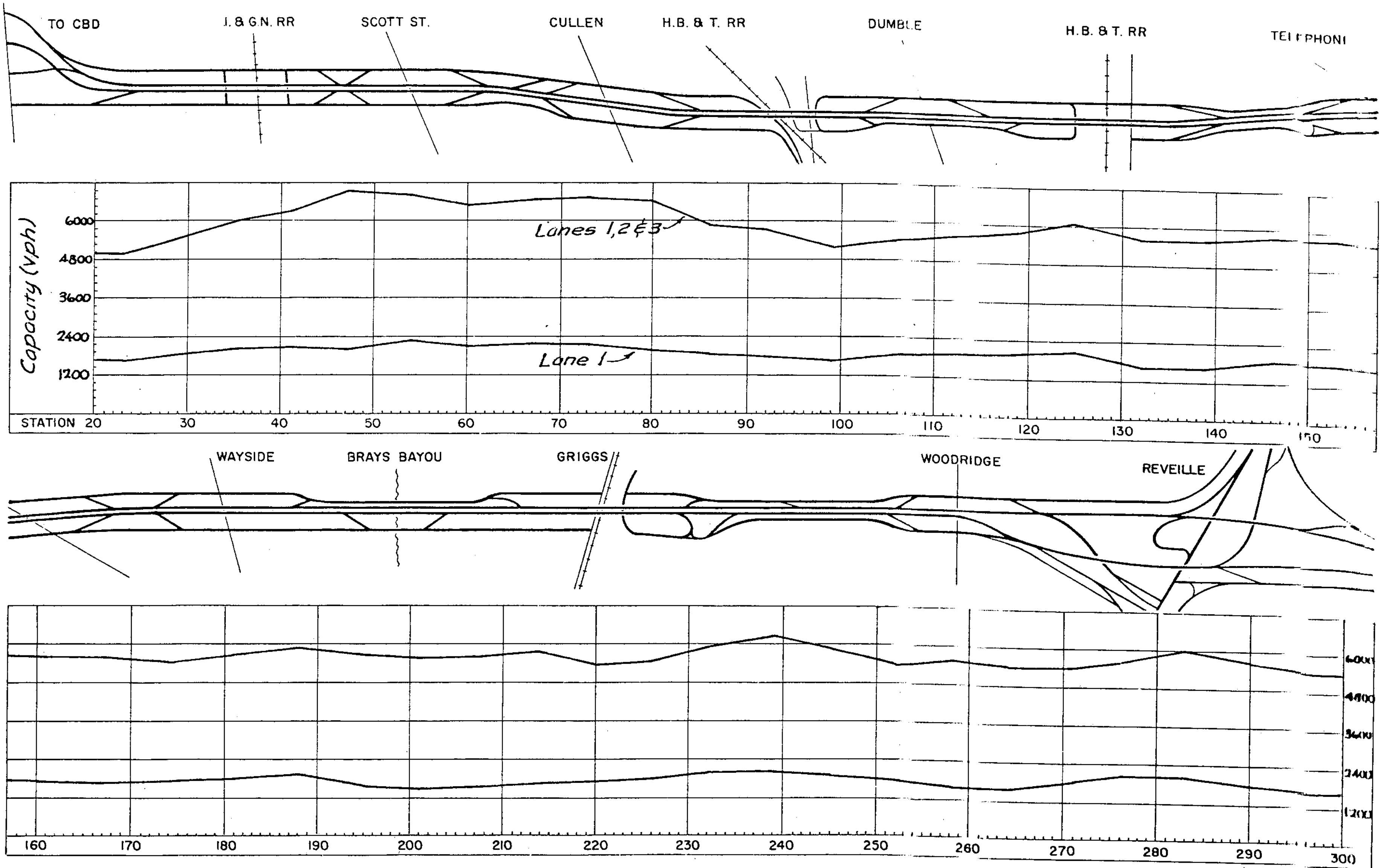
In Appendix B, 516 regressions of speed on density are summarized. In general, the regressions were highly significant for all three models on all three individual lanes, as well as for the inbound traffic taken as a whole. The model parameters (optimum density, k_m ; optimum speed, u_m; and optimum flow, q_m) were calculated from the regression parameters "b" and "a" as described.

Because of the confusion that has existed concerning the meaning of many terms used in traffic engineering practice, and because the above parameters were obtained in an unconventional, though rational, manner; it is important that they be understood. The optimum speed is the average speed at which traffic must move when the flow is at a maximum on a given roadway. An average speed higher or lower than the optimum will result in a reduction of flow. The counterpart to optimum speed is optimum density, sometimes called the critical density. This is the density when the traffic volume is at the possible capacity on a given roadway, and it too occurs when traffic is moving at the optimum speed. However since q_m, in its derivation, is simply the product of u_m and k_m, it follows from the above definitions that q_m is possible capacity, the maximum number of vehicles that can pass a given point on a lane during one hour.



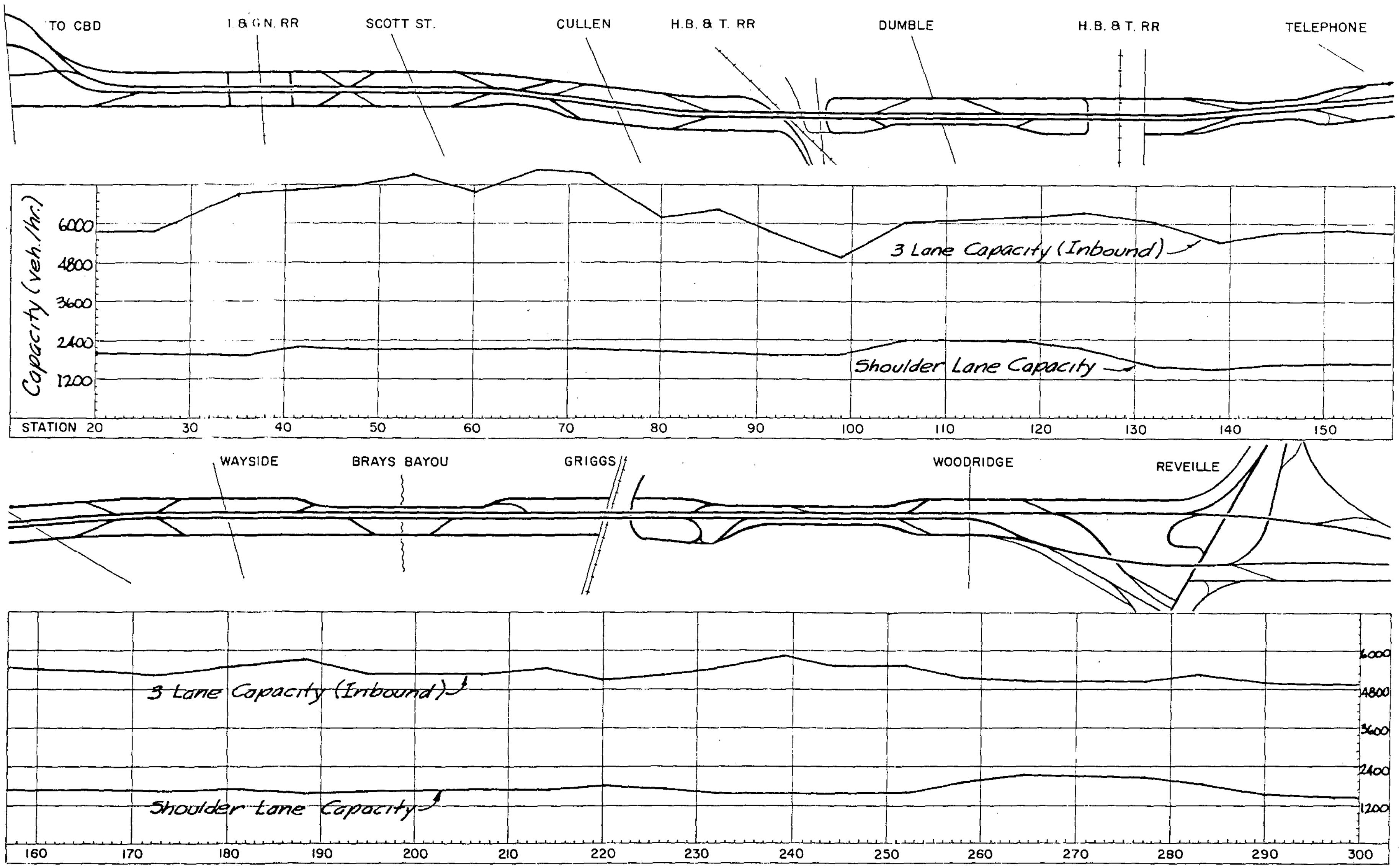
REGRESSION CURVES OF MACROSCOPIC EQUATIONS OF STATE

FIGURE 10



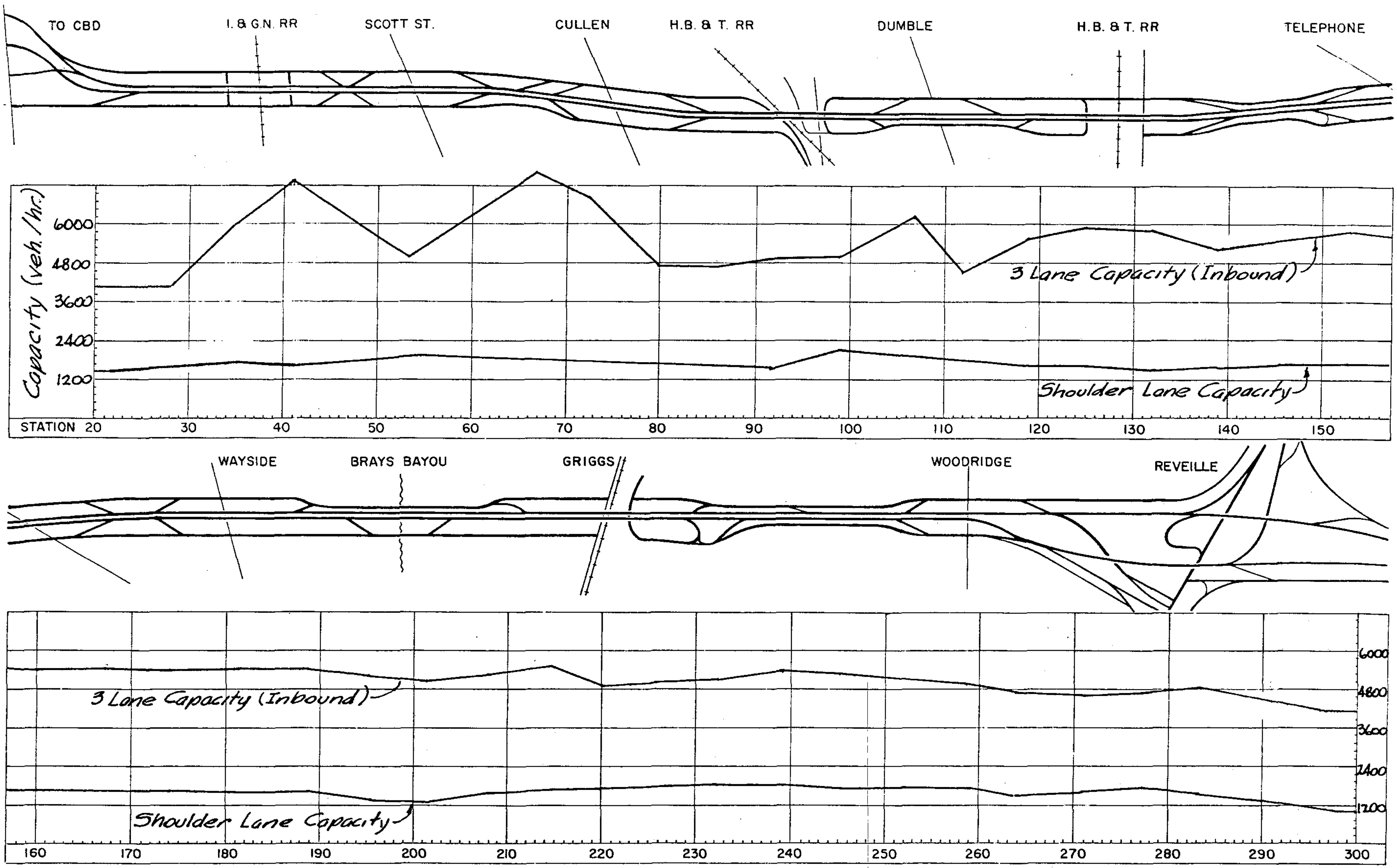
CAPACITY PROFILES (LINEAR MODEL)

FIGURE 11



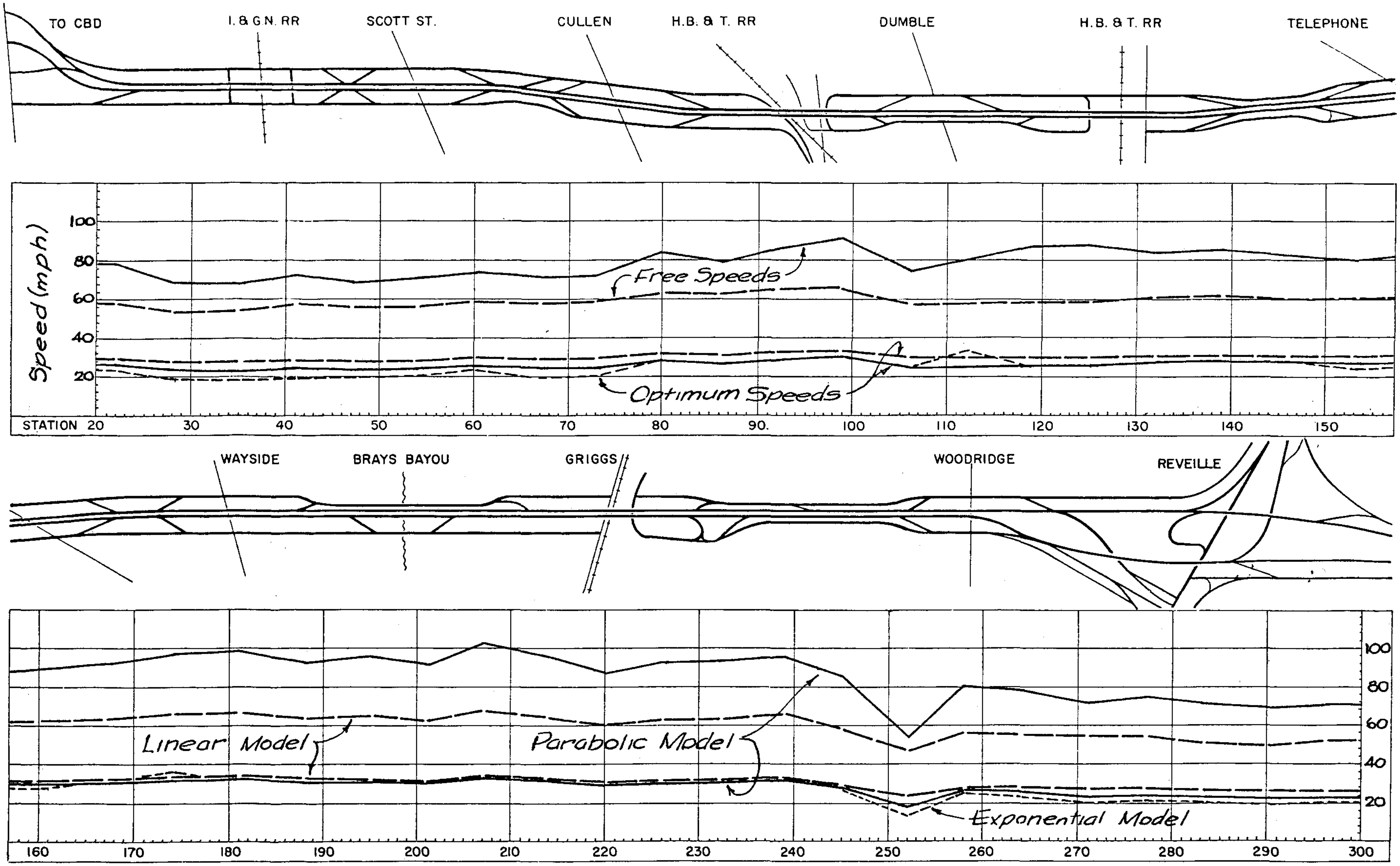
CAPACITY PROFILES (PARABOLIC MODEL)

FIGURE 12



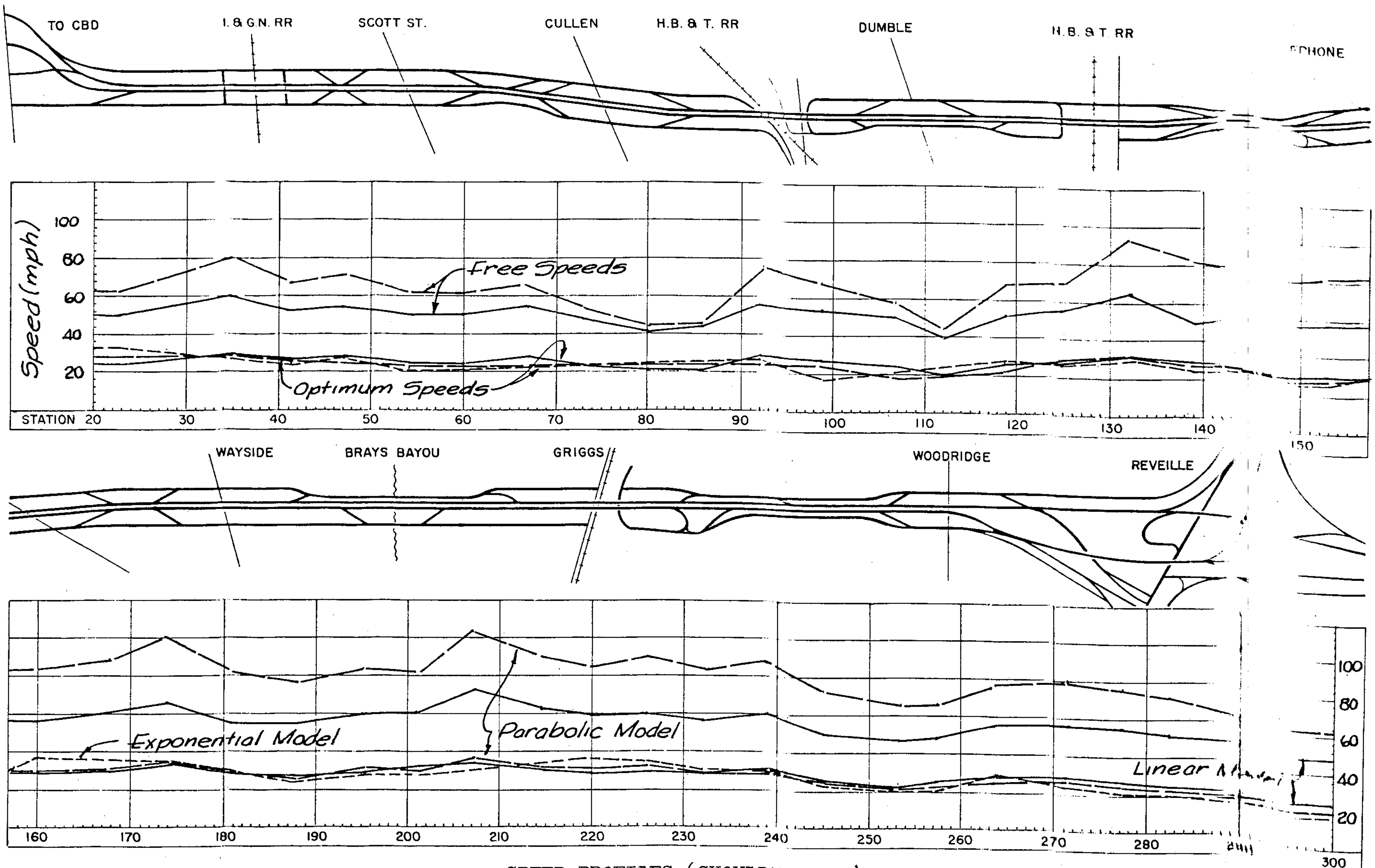
CAPACITY PROFILES (EXPONENTIAL MODEL)

FIGURE 13



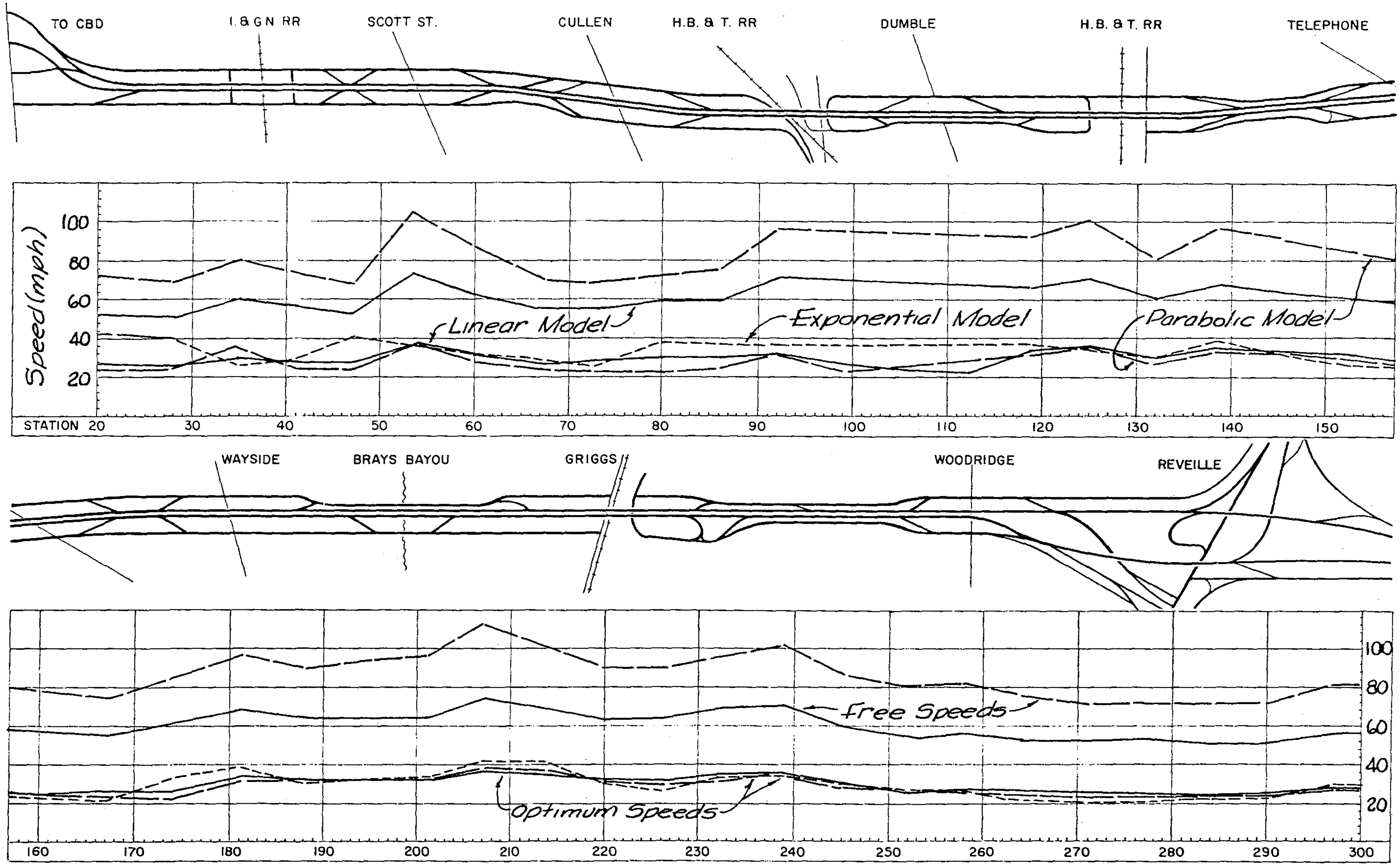
SPEED PROFILES (TOTAL INBOUND TRAFFIC)

FIGURE 14



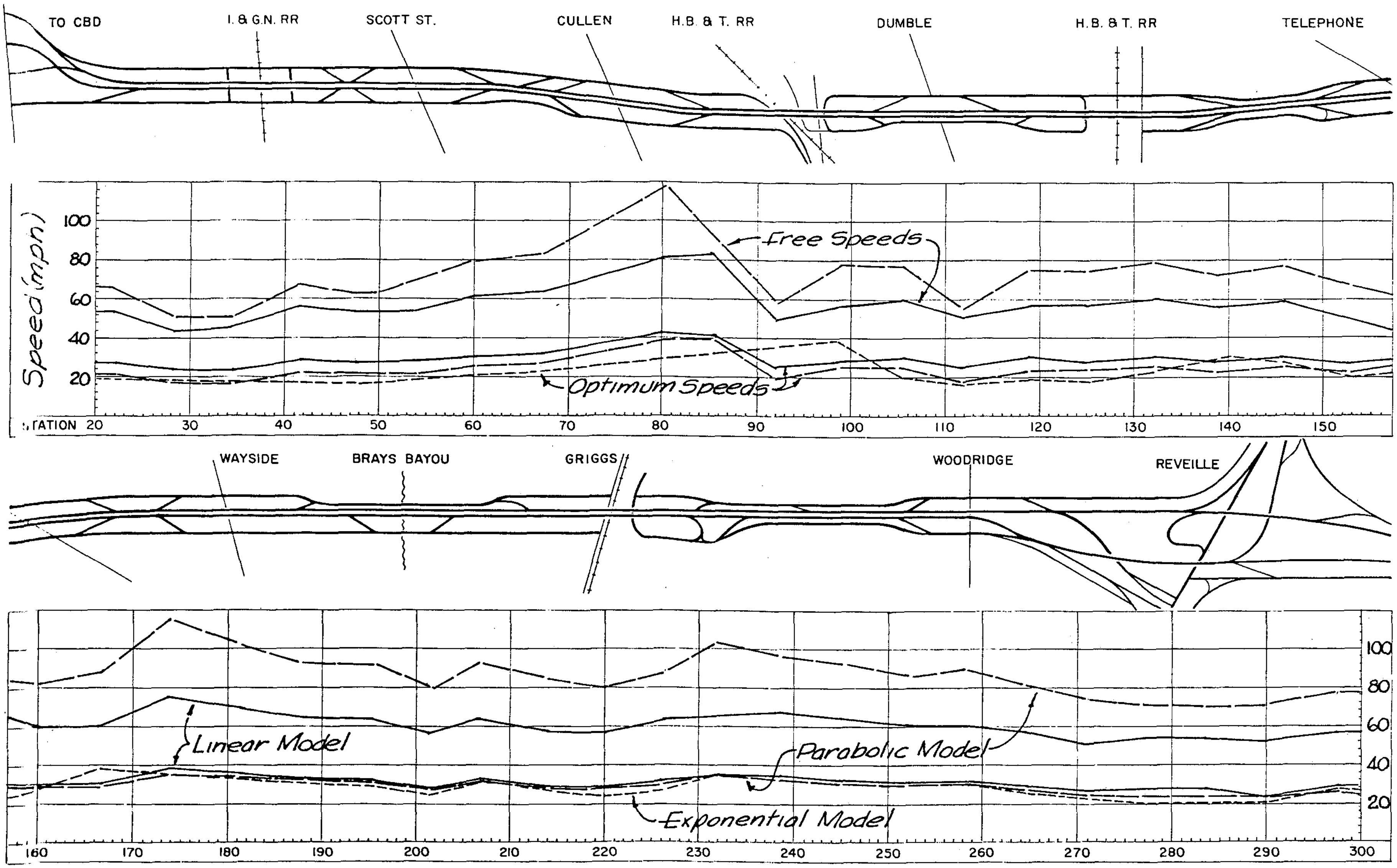
SPEED PROFILES (SHOULDER LANE)

FIGURE 15



SPEED PROFILES (CENTER LANE)

FIGURE 16



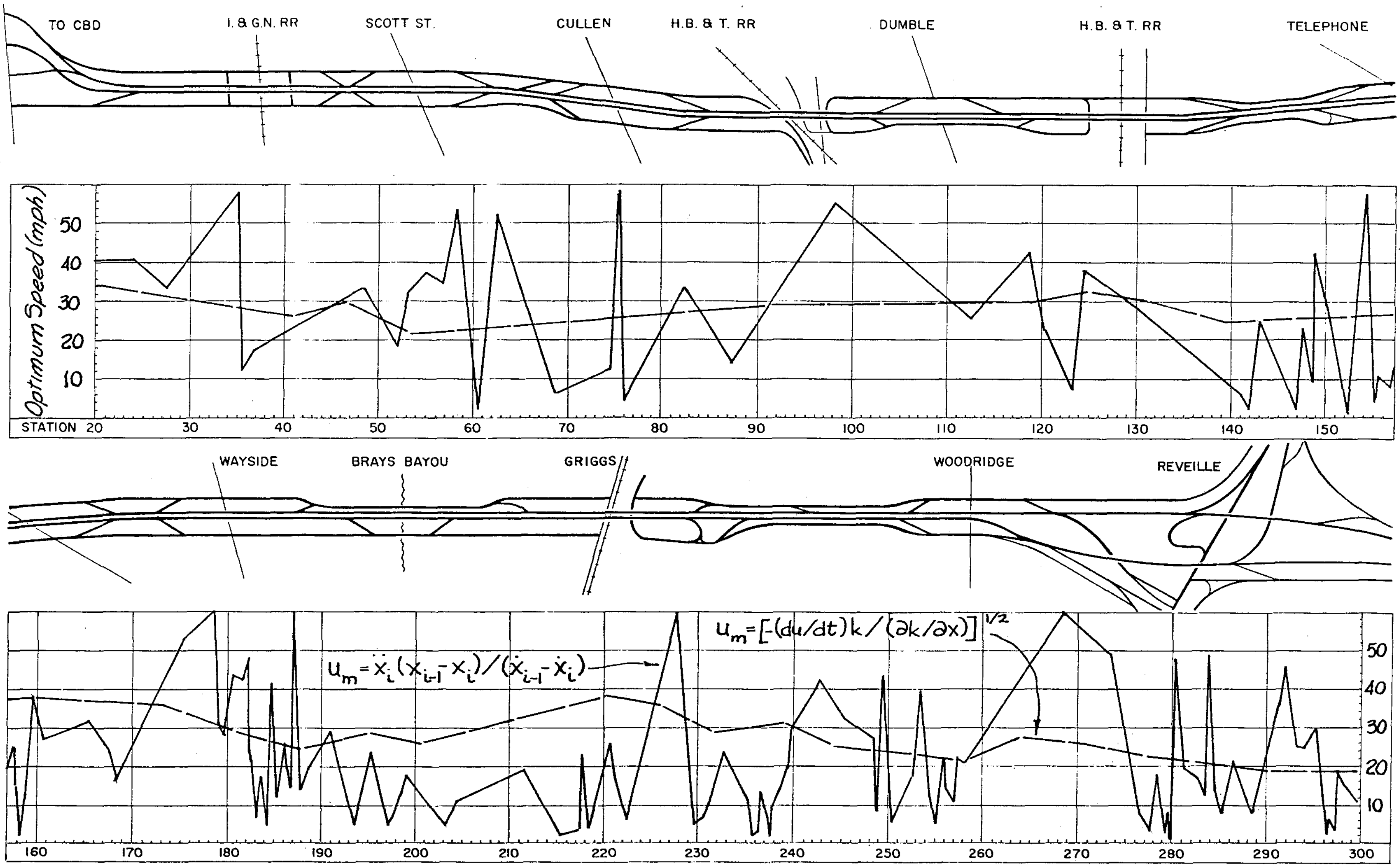
SPEED PROFILES (MEDIAN LANE)

FIGURE 17

Figures 11, 12, and 13 show capacity profiles for the shoulder lane (lane 1) and all three inbound lanes, based on the linear, parabolic and exponential models. The capacities were plotted from the data in Appendix B, and seem to be both logical and consistent between Stations 300 and 130. In this area the statistical analyses were highly conclusive. In the area between Stations 130 and 20, it must be remembered that speeds and densities were almost constant during the study hour (see Figure 9), providing a poorer basis for curve fitting.

In order to illustrate the speed parameters, optimum speeds and free speeds, speed profiles were plotted for the total inbound traffic and for each lane (Figures 14, 15, 16, and 17). For the estimation of optimum speeds at points along the freeway, the linear, parabolic and exponential models provided remarkable agreement. The free speeds, however, were quite different. The parabolic model predicts speed averaging about 20 mph greater than those predicted by the linear model. This, of course, is not surprising due to the properties of the curves (see Figure 10).

The solutions of the generalized microscopic equation of motion proved unrewarding. Theoretically, the optimum speeds determined from the car-following models are equal to those obtained from the solutions obtained from regression analyses of the generalized equation of state. However, the constants of proportionality obtained from the three car-following models were extremely erratic; a considerable percentage were negative indicating that in many situations a driver does not react solely to the performance of the car in front of him. Figure 18 illustrates a comparison of the macroscopic and microscopic optimum speeds, showing the extreme variability in the latter. It is apparent that the search for deterministic control parameters must be limited to equation of state rather than equations of motion, except in cases where the parameters are obtained from carefully controlled studies based on few vehicles.



COMPARISON OF OPTIMUM SPEEDS USING

THE CAR FOLLOWING AND CONTINUOUS FLOW MODELS

FIGURE 18

APPLICATION

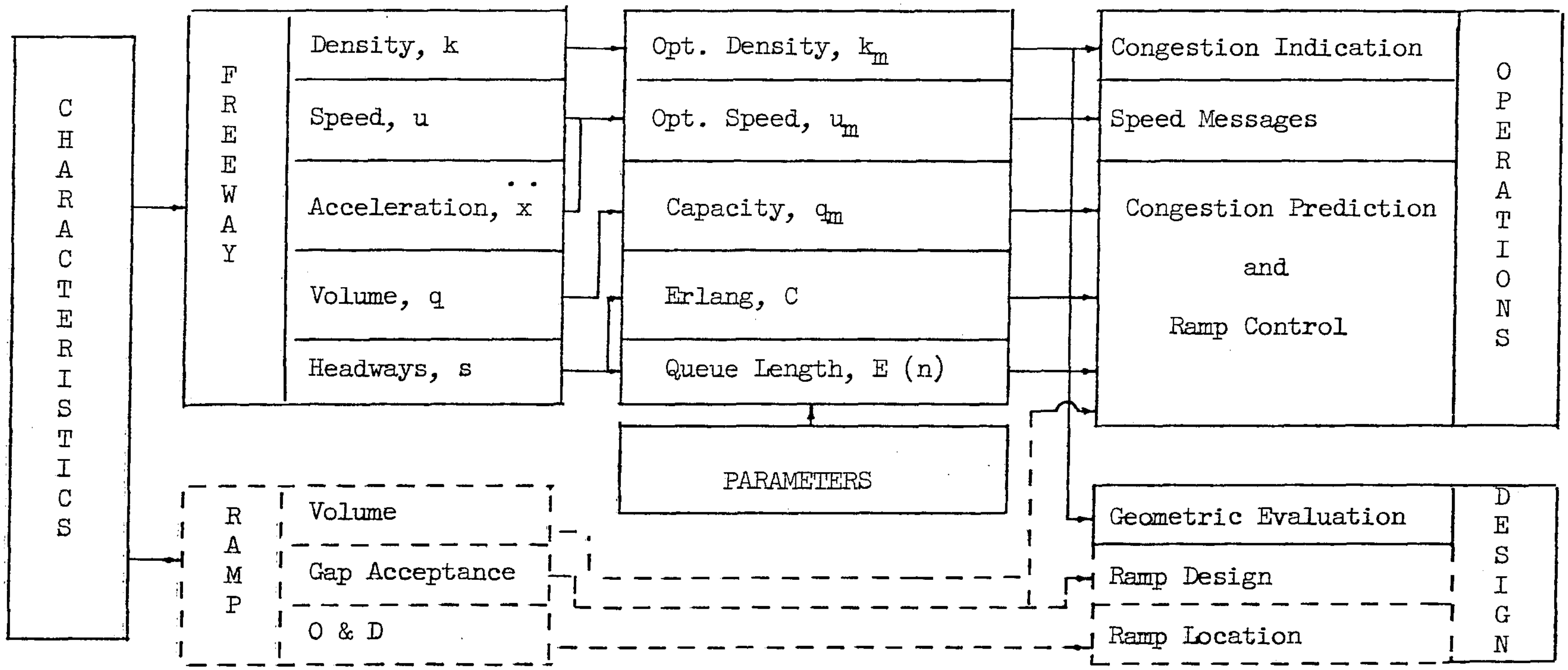
Freeway Surveillance Systems

Since the advent of the auto, forms of traffic control have been deemed necessary to maintain order and provide for safe, efficient operation. At intersections where the desire for safe movement is compromised by the available road space, the right of way is frequently alternated systematically between the conflicting flows. The most positive control device for achieving this assignment is the traffic signal, resulting in a stop-and-go driving pattern which contributes to highway congestion and driver frustration.

The advantages of the freeway are maintained only when the facility is operated under free flowing conditions. One key to improving urban freeway operation lies in increased surveillance. In its most basic form, urban freeway surveillance is limited to moving police patrols. Recently, heliocopters have been used for freeway surveillance in Los Angeles and other communities. Efficient operation of high density freeways is, however, more than knowing the locations of stranded vehicles; it may require closing or metering entrance ramps, or excluding classes of vehicles during short peak periods. Therefore, what is needed is a reliable, all weather source of surveillance information with no excessive time lag.

The broad concept of coordinated surveillance is usually referred to as traffic surveillance systems. In developing the Holland and Lincoln Tunnel Surveillance Systems, the Research Section of the Port of New York Authority[13] stated: "Traffic surveillance systems consist of all the equipment and men needed to keep traffic moving. This includes men and equipment to detect and measure continuously the main characteristics of traffic flow; to decide what action is needed to maintain good traffic movement; to control traffic routing, speed, flow and/or density; and to rectify conditions interfering with good traffic movement."

Experimentation with closed circuit television as a surveillance tool was initiated on the John C. Lodge Freeway in Detroit. This offers the possibility of seeing a long area of highway in a short or instantaneous period of time, made possible by spacing cameras along the freeway so that a complete picture can be obtained of the entire section of roadway. Evaluation of the freeway operation depends mostly on the visual interpretation of the observers. However, many traffic people believe that this is not enough. The Chicago Surveillance Research Project, for example, is predicated on the assumption that trained observers offered no uniform objectivity. In other words, if an expressway is operating well, this quality can be detected by observing operating characteristics. When the characteristics drop below a predetermined level, action may be taken. Although



ANALYSIS OF FREEWAY TRAFFIC CONGESTION

FIGURE 19

some attention was paid to the early investigation of the various traffic flow characteristics to determine which characteristics could be most useful to display the quality of operation, "the selection of parameters to be measured was tempered by the limitations of the manufactured detection equipment available." [12] Similarly, in describing a proposed surveillance system on the Seattle Freeway, Cottingham defines the basic equipment requirements as consisting of instantaneous density measuring computers. The point being made here is that so important a decision as the choice of a control parameter should not be made by decree.

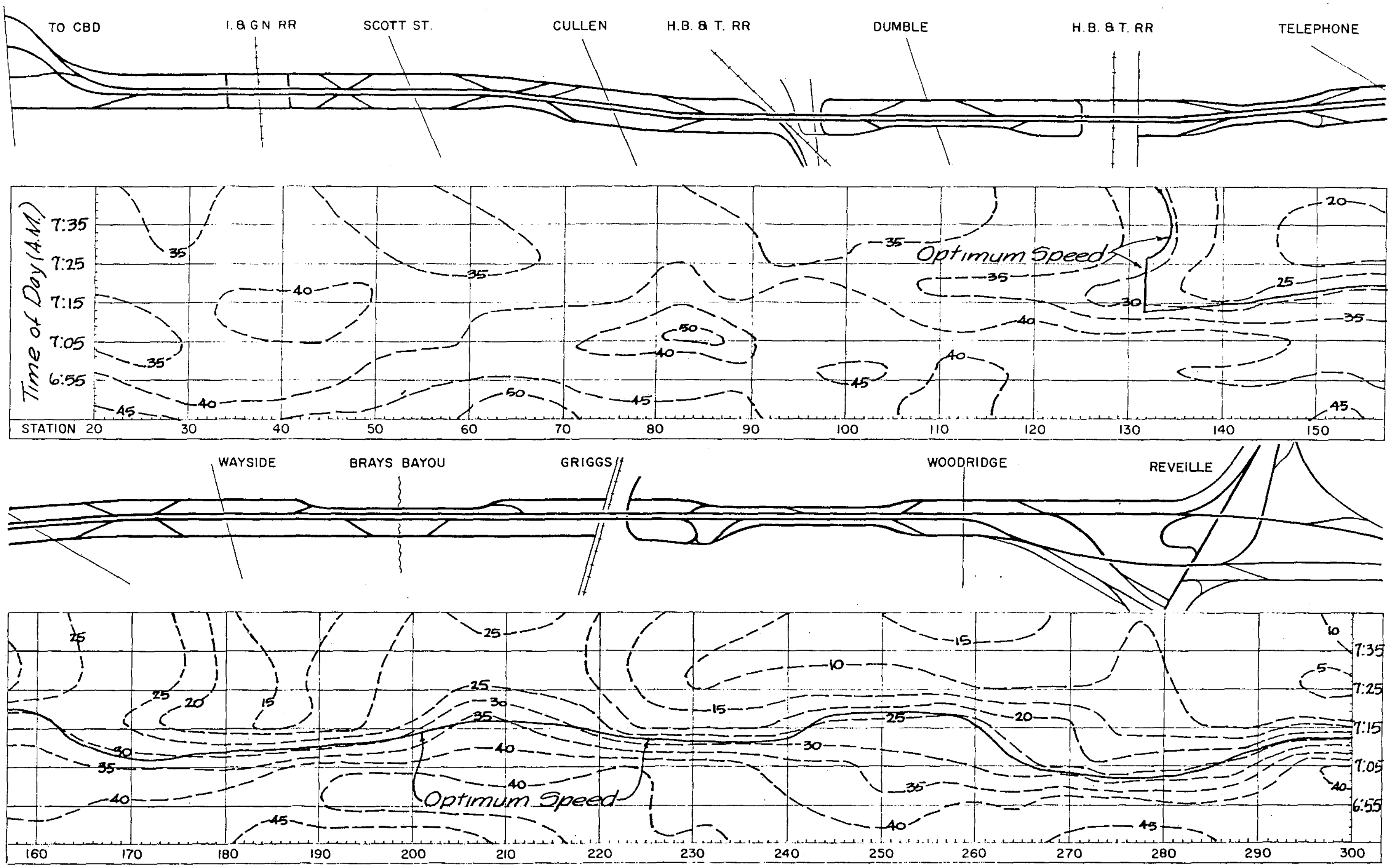
A traffic surveillance system should involve the continuous sampling of basic traffic characteristics for interpretation by established control parameters, in order to provide a quantitative knowledge of operating conditions necessary for immediate rational control and future design. This is illustrated in the form of a flow chart in Figure 19. The control logic of a surveillance system, or any system, for that matter, is that combination of techniques and devices employed to regulate the operation of that system. The analysis shows what information is needed and where it will be obtained. Then, and only then, can the conception and design of the processing and analyzing equipment necessary to convert data into operational decisions and design warrants be described. The solid lines in Figure 19 represent the portion of the total research covered in this study; the dashed lines indicate suggested future research. The three vertical blocks correspond to data collection and reduction, the contribution of theory, and the application of results in the broad areas of operations and design.

Congestion Prediction

In referring again to Figure 19, three of the five control parameters shown are excellent indicators of congestion. These are optimum density, optimum speed and the "critical" queue length. The critical queue length concept is discussed in another report entitled "Stochastic Aspects of Freeway Operations and Control."[14]

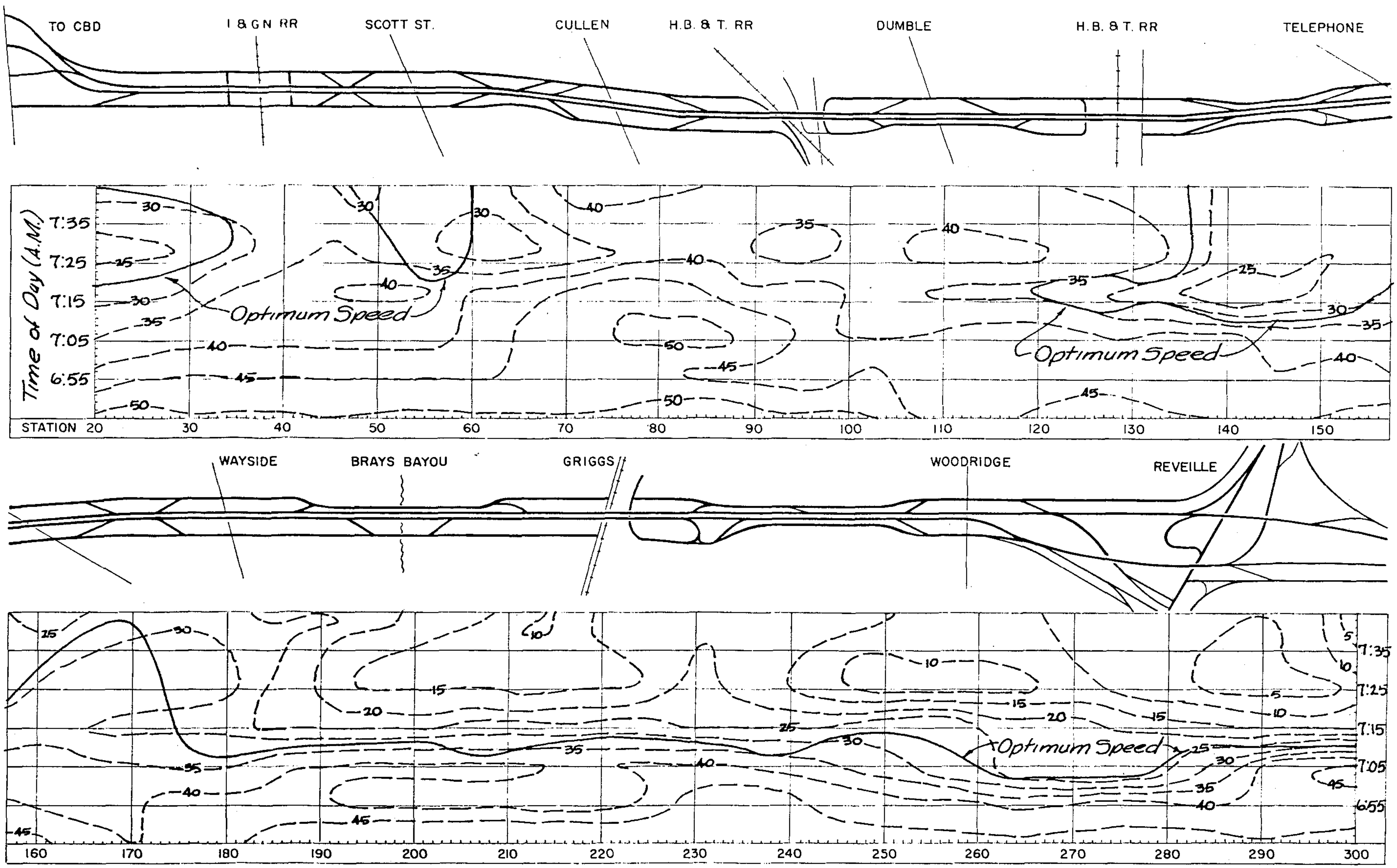
The advantages of the contour format in illustrating the variation of speed or density in both time and space were presented in the previous section. In Figures 20 and 25 speed and density contours are shown for each freeway lane. The appropriate control parameter is designated on each figure by a solid line. This line connects points of optimum speed or optimum density, whichever the case may be. The utilization of this type of control parameter provides a rational, objective definition of congestion. In the case of density, for example, k_m may vary from 50 to 80 vehicles per mile depending on the geometric and operation conditions.

The speed contours (Figures 20-22) afford the means for finding the travel times over portions of the freeway for any time during the study hour. This is accomplished by dividing the length of section by the average speed through the section. Similarly, the density contours (Figures 23-25) may be utilized to obtain



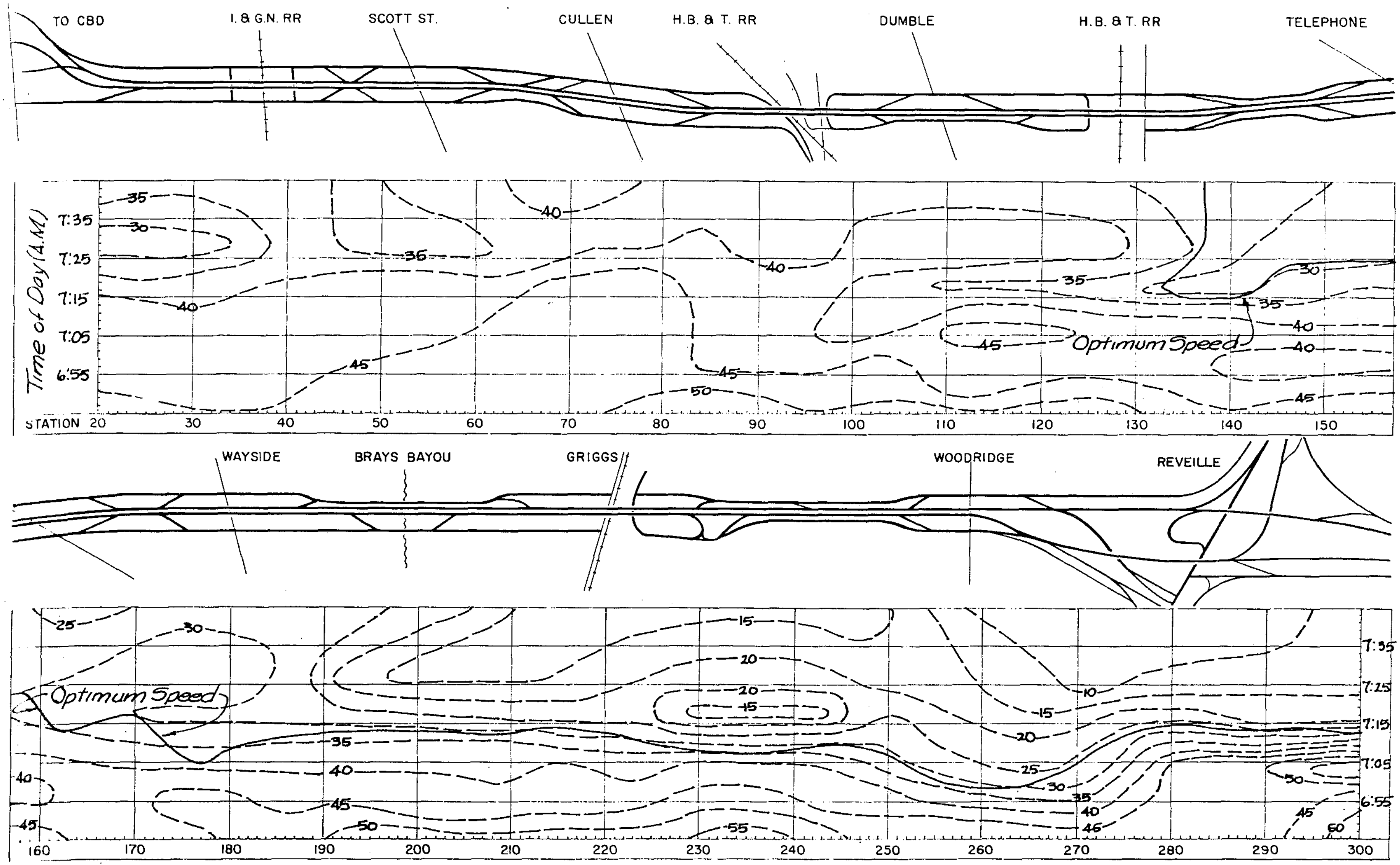
SPEED CONTOURS (SHOULDER LANE)

FIGURE 20



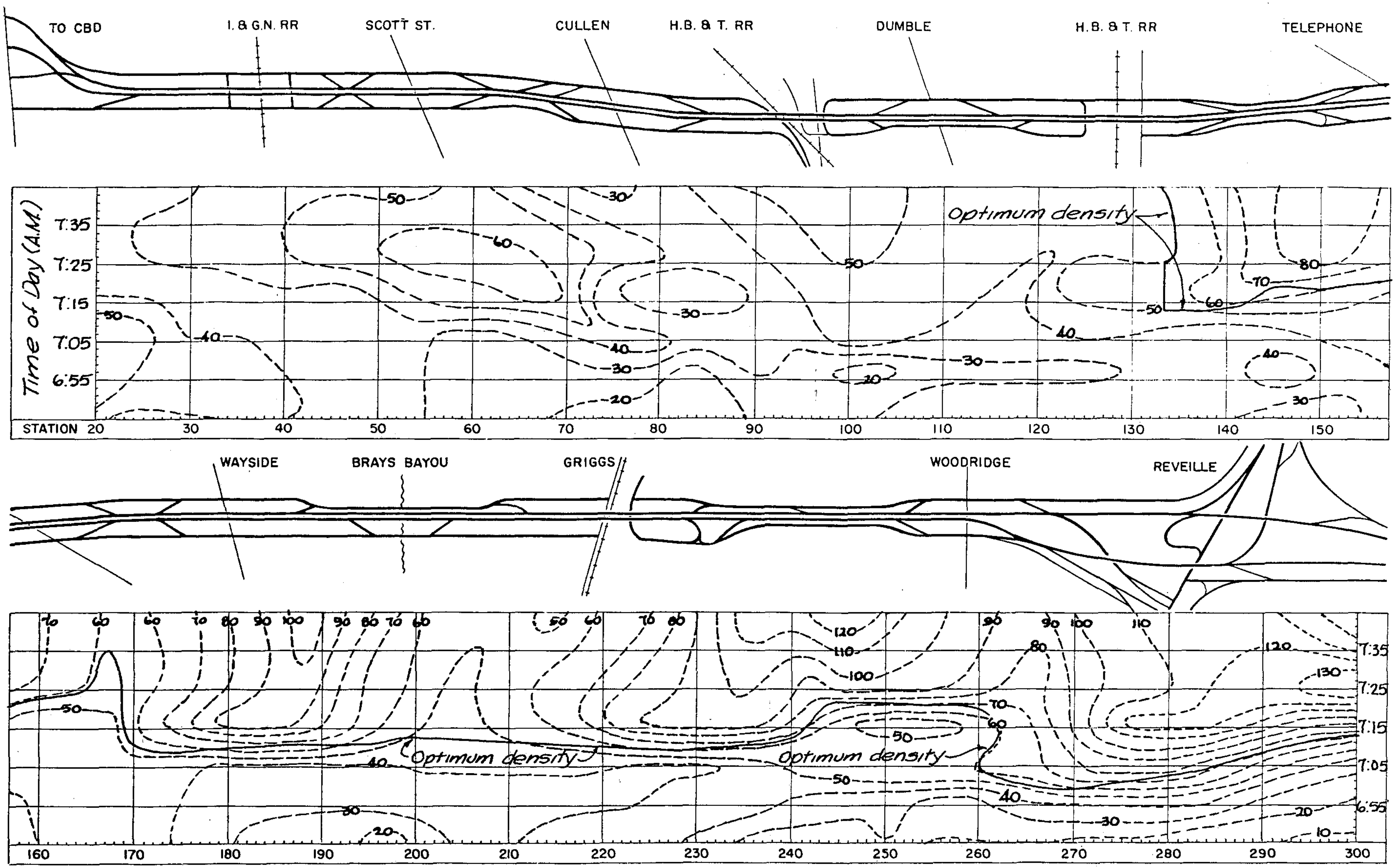
SPEED CONTOURS (CENTER LANE)

FIGURE 21



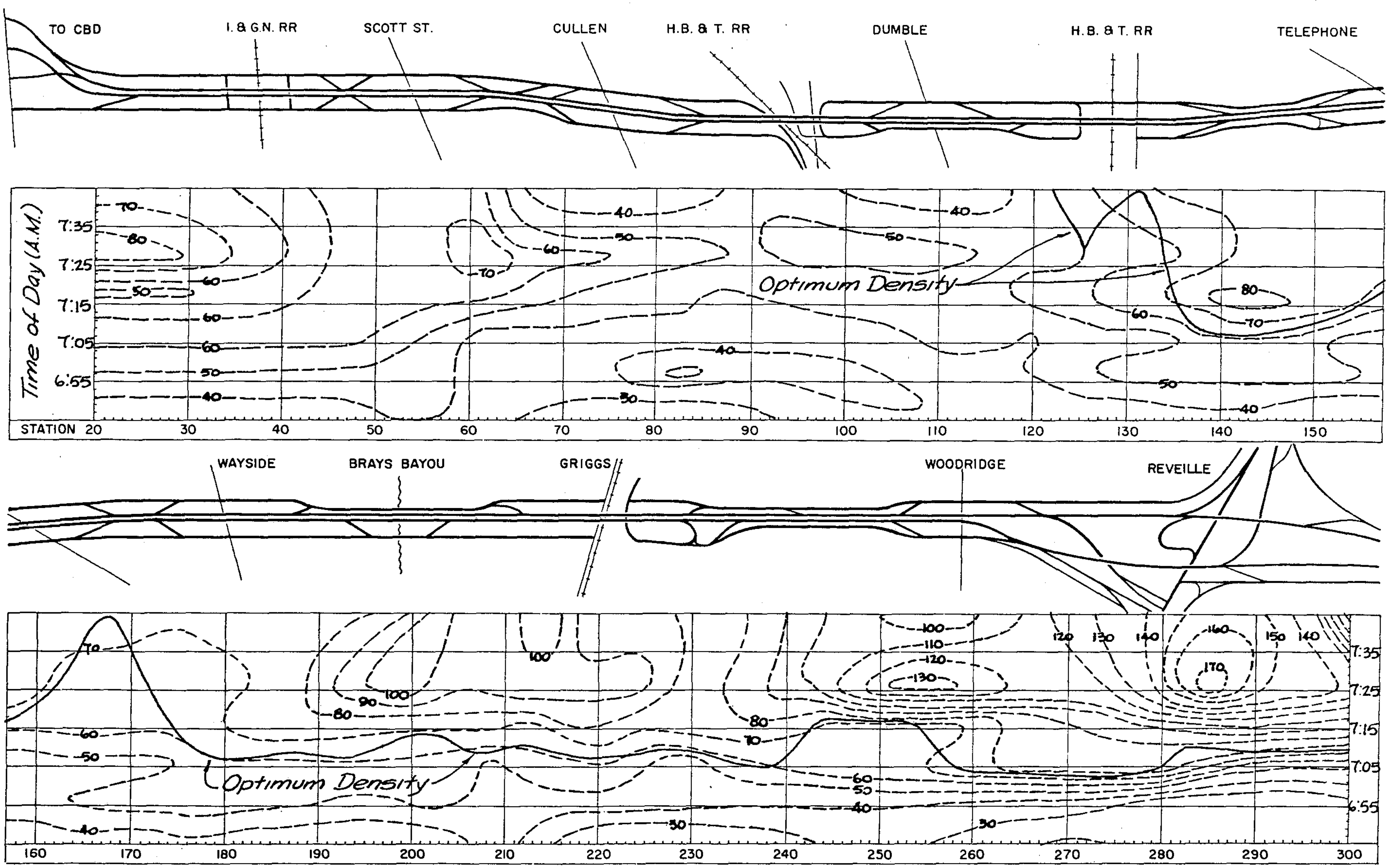
SPEED CONTOURS (MEDIAN LANE)

FIGURE 22



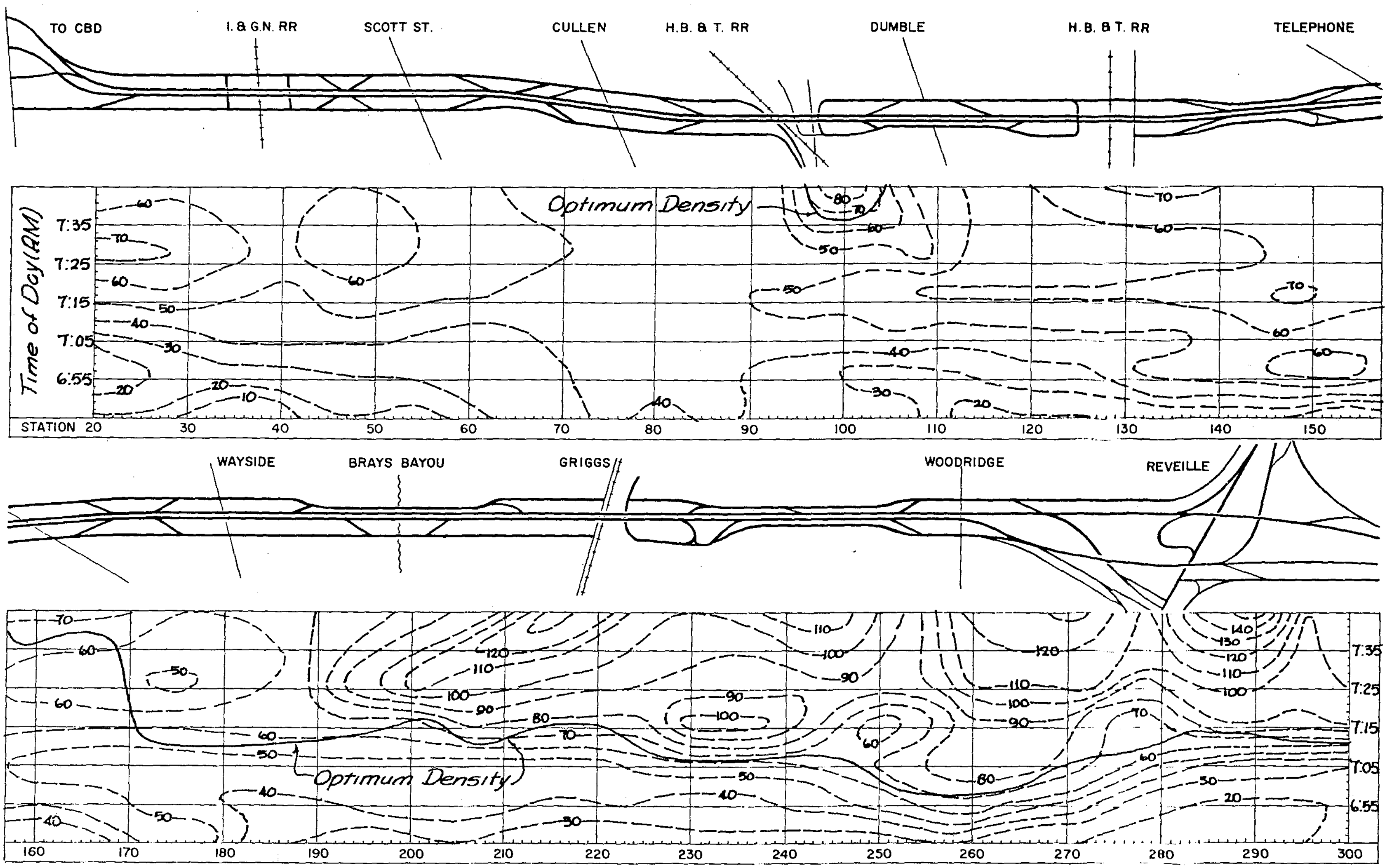
DENSITY CONTOURS (SHOULDER LANE)

FIGURE 23

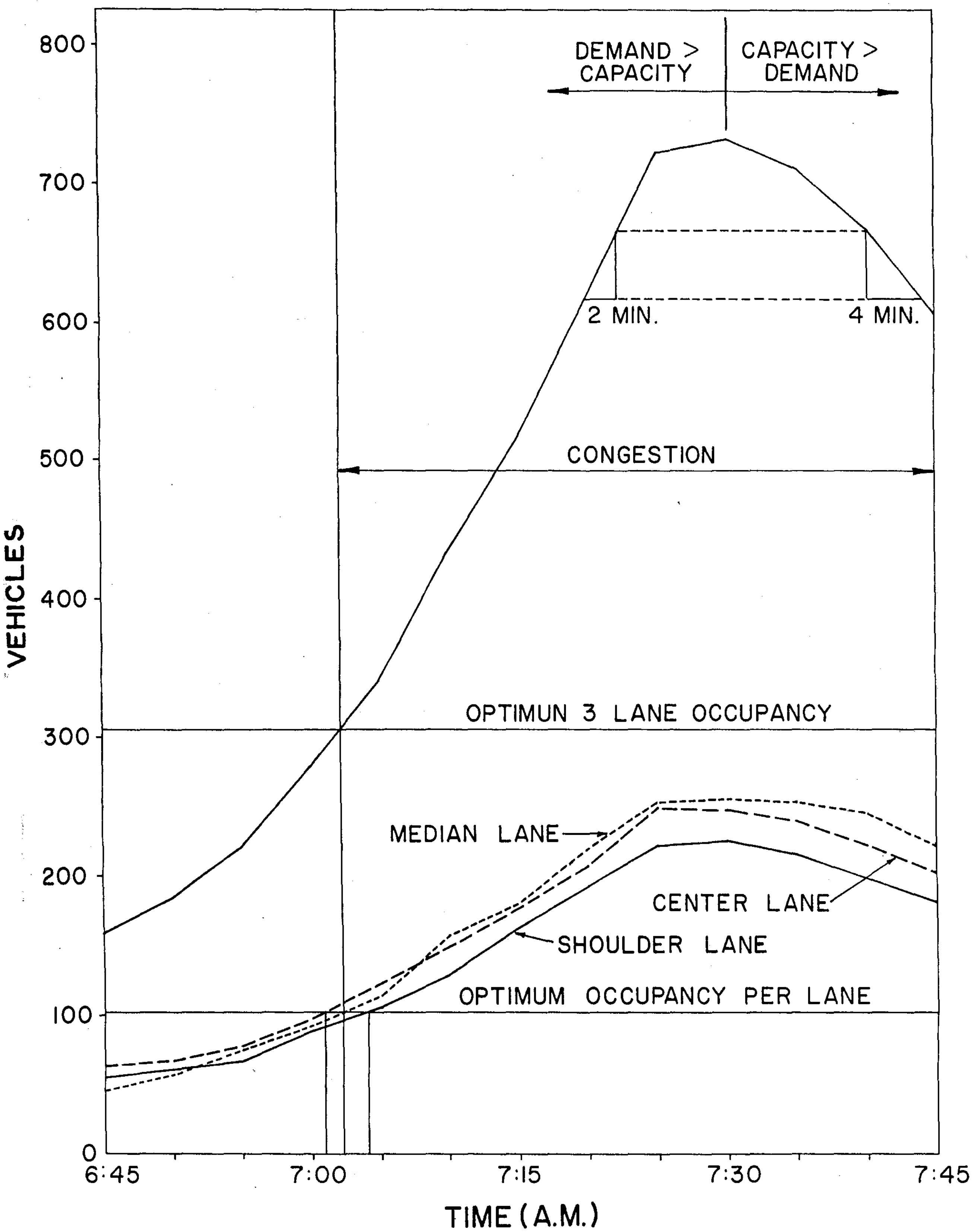


DENSITY CONTOURS (CENTER LANE)

FIGURE 24



DENSITY CONTOURS (MEDIAN LANE)



OCCUPANCY STUDY OF THE REVEILLE-GRIGGS SYSTEM OBTAINED FROM DENSITY CONTOURS

FIGURE 26

Table 5

A COMPARISON OF CONGESTION PREDICTING PARAMETERS ON THE INBOUND SHOULDER LANE

Station	Time of Incipient Congestion	
	Optimum Speed →	Optimum Density
300	7:11 a.m. →	7:12 a.m.
290	7:09	7:08
280	7:02	7:02
270	7:03	6:59
260	7:15	7:05
250	7:19	7:21
240	7:11	7:11
230	7:11	7:08
220	7:13	7:10
210	7:17	7:11
200	7:13	7:13
190	7:10	7:11
180	7:09	7:09
170	7:08	7:12
160	7:19	7:22
150	7:18	7:19
140	7:15	7:12
130	7:12	7:12

the inventory of vehicles in a specific section of freeway. Integration under a horizontal line cutting the density contours yields, dimensionally, "vehicles" (the product of vehicles per distance times distance). This is illustrated in Figure 26 for the section of freeway between Stations 315 and 215 (inbound). The occupancy curves obtained for each lane and for the total inbound traffic portray the buildup and dissipation of congestion. If the limits of the system are defined so that entry is always under conditions of free flow and the exit point in the system (Station 215) is located at, or downstream from, the system bottleneck, then the rate of change of occupancy gives the excess of demand over capacity (positive slope), or of capacity over demand (negative slope). For example at 7:20 AM demand exceeds capacity by a rate of 25 vehicles per minute and at 7:40 capacity exceeds demand by 12.5 vehicles per minute. The indication is that congestion builds up at twice the rate that it dissipates, which is rather typical of the theoretical "busy period" queueing phenomena.

A comparison of congestion predicting parameters on the inbound shoulder lane is shown in Table 5. The times of incipient congestion obtained from the control parameters (optimum speed and optimum density) for the 18 locations compared show rather close agreement. It seems appropriate, at this time to distinguish between indicators and predictors of congestion. It is apparent that this dual quality exists in the three parameters discussed. However, the significance of some means of predicting congestion on a freeway system in the utilization of this warning time to minimize its undesirable effects. This principle will be considered in the next section.

Freeway Control

Freeway design does not always eliminate the need for sound traffic regulation. A reasonably homogeneous traffic stream, particularly with respect to speed, is essential for efficient freeway operations. Pedestrians, bicycles, animals and animal-drawn vehicles are excluded from freeways. Motor scooters, non-highway (farm and construction) vehicles and processions, such as funerals, are also generally prohibited from the freeway. Towed vehicles, wide loads which impede the normal movement of traffic may be barred during the peak traffic hours or during inclement weather.

Minimum speed limits are being increasingly used and have been found of great benefit, particularly on high-volume sections. The effect of this type of control is to reduce the number of major accident potential lane change maneuvers. The effects of slow-moving vehicles on both capacity and accident experience are so pronounced that a greater use of minimum limits appear probable. There is a need to eliminate all vehicles incapable of compatible freeway operation.

Among the many techniques for controlling freeway traffic, ramp metering at entrance ramps and changeable-advisory speed limit signs located on the freeway itself offer the most promise. The speed limit signs display normal speed limit signs or multivalue reduced speeds. They may be controlled by command signals from a traffic regulating center. Optimum speed, u_m, offers an ideal parameter as a basis for this type of control. Two neon matrices would be utilized with the left hand or tens matrix capable of displaying digits 2, 3, 4, or 5. The right hand or units matrix would display digits 0 and 5. The signs would be mounted over each lane. The advisory speeds would be determined for each lane from the speed contours for that lane (see Figure 20-22). Abrupt changes of speed in the traffic stream would be avoided by gradually reducing advisory speeds before bottlenecks. The optimum speeds would be flashed minutes before incipient congestion to combat breakdowns.

Congestion occurs on a freeway section when the demand exceeds the capacity of that section for some period of time. Because congestion can lower the rate of flow, a short period in which demand exceeds capacity can cause a longer period of congestion. A location in which the capacity is lower than the capacity of adjacent sections is called a bottleneck. Bottlenecks can be caused by changes in the freeway alignment (horizontal or vertical) or reduction in the freeway section (reduction of number of lanes, reduction in lane widths, the presence of an entrance ramp, etc.). Accidents, disabled vehicles and maintenance or law enforcement operations can also cause temporary bottlenecks by reducing the effective capacity or level of service provided.

Because the control of vehicles entering the freeway, as against the control of vehicles already on the freeway, offers a more positive means of preventing congestion, considerable emphasis is being placed on the technique or ramp metering. Entrance ramp metering may be oriented to either the total freeway capacity or to the capacity of the outside freeway lane. A capacity-oriented ramp control system restricts the volume rate on the entrance ramps in order to prevent the flow rates at up-stream bottlenecks from exceeding the capacities of the bottlenecks. The capacity profiles (Figures 11 - 13) illustrate the utility of the optimum flow, q_m (possible capacity) control parameter in the capacity-oriented type analysis.

APPENDICES

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The following conclusions are drawn regarding the announced objectives of this investigation.

1. Utilizing the analogy of a one-dimensional compressible fluid, a generalized macroscopic model of traffic flow was formulated and tested against the measured characteristics. The model is statistically significant and conceptually realistic when applied to freeway flow.

2. A generalized microscopic model was formulated based on the car-following theories. Solution of the macroscopic and microscopic equations yields equivalent equations of state.

3. A comparison of the congestion predicting attributes of the two control parameters--optimum speed and optimum density--yielded close agreement in defining the time of incipient congestion throughout the length of the Gulf Freeway.

The following additional conclusions are drawn regarding the data presented in this report.

1. The employment of time-lapse aerial photographic methods to measure such over-all operational characteristics as speed and density, and such local properties as acceleration, relative speed, and headways, is feasible.

2. "Contour maps" provide an excellent means of illustrating variations in traffic characteristics in both time and space.

3. By plotting the control parameters on the contour maps, it is apparent that approximately sixty percent of the Gulf Freeway operates above optimum density and below optimum speed at some time during the morning peak hour.

4. Based on 516 regression analyses, it can be stated that statistically significant relationships exist between the three principal operational characteristics - speed, density, and volume.

5. Because of this relationship, three important congestion control parameters can be determined. They are optimum speed, optimum density, and optimum flow (possible capacity).

6. The procedures outlined in this study for determining these three control parameters are especially significant since they could be applied on newly constructed congestion-free facilities. Based on free-flowing, uncongested operation, the control parameters could be computed for future use. The effects of new generators could be anticipated and possibly avoided. Determination of the control parameters would enable one to predict at what time in the future, freeway controls would be needed.

Recommendations

The control parameters established in this research provide a basis for the formulation of a rational "Level of Service" Index. Level of Service, as applied to traffic operation on a particular roadway, refers to the quality of the driving conditions afforded a motorist. In addition to the variables designated as control parameters, factors involved are: (1) travel time, (2) traffic interruption, (3) freedom to maneuver, (4) safety, (5) driving comfort and convenience, and (6) vehicular operational costs. Additional research is needed to establish a quantitative measure of these qualitative level of service factors, as a means of adjusting the control parameters in much the same manner that safety factors are utilized in structural design.

Regarding the results of this investigation, it is recommended that congestion should be defined in terms of all of the following: optimum density, optimum speed, and optimum flow (possible capacity). Each of these control parameters has important applications. Density provides a single valued indication of congestion. The optimum density defines that density for which flow is a maximum. Similarly, the optimum speed reveals that speed which maximizes vehicular flow, and should be utilized as a basis for changeable speed messages in a freeway control system. Because a surplus of traffic demand over freeway capacity leads inevitably to an operational breakdown, the optimum flow (possible capacity) control parameter is important.

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APPENDIX A

SPEED-CONCENTRATION MEASUREMENTS FROM PHOTOS
STRIP 4 6:45:37-6:48:20

STATION	LANE 1		LANE 2		LANE 3		ALL LANES	
	MPH	VPM	MPH	VPM	MPH	VPM	MPH	VPM
311-294	44.5	14.4	46.7	37.4	49.8	7.6	46.6	59.4
305-287	41.6	9.4	45.8	39.3	43.8	20.1	44.6	50.1
299-281	42.4	10.8	45.3	30.5	46.3	16.5	44.8	51.7
292-275	46.3	16.7	47.6	30.5	48.8	11.9	47.5	58.0
286-269	46.1	20.3	48.2	25.8	48.1	14.5	47.7	54.8
280-263	45.6	20.1	46.3	18.2	46.0	22.2	46.0	48.7
274-256	41.6	22.6	45.2	26.4	47.9	24.3	45.2	69.5
267-250	41.2	19.7	46.4	28.7	48.8	32.1	46.1	79.6
260-243	41.2	30.1	47.5	31.6	48.2	28.7	46.1	84.5
254-237	42.2	29.0	47.2	33.1	49.7	26.8	46.2	84.2
248-230	46.2	26.0	50.6	27.1	54.7	27.5	50.7	79.8
241-223	39.5	35.6	52.4	22.0	56.0	29.3	48.2	78.0
235-217	40.1	47.4	52.2	20.5	52.4	21.8	46.2	90.3
227-209	39.4	49.0	51.2	25.1	51.9	23.0	46.5	86.2
220-202	43.8	39.0	50.3	41.6	50.1	27.9	47.8	97.2
213-196	45.9	30.6	50.4	38.6	51.3	34.6	48.9	98.3
207-189	47.6	18.3	50.1	32.3	49.5	20.9	49.7	72.5
200-182	46.0	23.1	48.8	30.8	47.4	28.9	48.3	85.2
194-176	47.3	24.3	45.8	30.6	45.1	34.0	46.8	190.2
187-169	41.2	35.5	42.4	40.0	42.9	54.1	43.0	114.2
180-163	39.1	43.8	40.2	36.3	43.2	55.4	40.7	120.8
175-157	41.5	48.4	41.4	37.9	46.0	38.2	41.2	120.4
169-151	45.7	39.5	44.7	31.9	48.0	30.1	43.9	97.3
162-145	42.4	27.4	46.1	31.4	46.4	16.9	46.4	72.7
155-138	42.2	28.7	43.3	35.6	44.1	29.3	43.9	89.1
149-131	42.2	30.6	42.6	38.9	47.2	29.2	42.9	91.5
142-124	44.1	33.2	45.1	32.3	51.2	29.6	45.3	187.4
135-118	44.2	44.7	47.8	36.3	49.8	24.1	47.1	105.9
129-111	41.9	33.1	45.1	35.7	45.7	24.3	45.2	97.4
122-105	37.6	40.7	41.4	39.1	49.9	17.7	40.6	98.7
117-106	38.5	38.3	44.4	39.9	50.3	31.2	43.3	101.0
110- 93	42.8	22.8	47.7	38.7	49.5	32.7	47.4	92.9
104- 86	41.3	27.0	47.8	33.8	52.8	36.6	46.6	92.4
97- 79	46.6	19.4	50.7	28.3	52.0	42.2	51.0	83.3
90- 72	46.0	18.1	52.1	26.6	49.1	38.9	50.6	86.2
83- 66	45.6	17.3	49.0	26.0	48.5	41.9	48.3	78.6
77- 60	51.7	21.7	47.4	30.0	49.3	32.0	48.8	77.6
71- 54	50.7	22.5	48.3	37.6	43.1	33.1	49.3	88.8
63- 46	46.2	31.2	47.6	43.9	47.1	19.4	47.3	89.0
55- 38	43.1	37.5	45.9	36.8	44.0	24.5	45.1	90.7
47- 30	40.9	43.0	46.9	32.0	41.7	6.3	43.4	81.4
40- 23	40.3	40.5	45.9	36.6	44.5	9.5	42.4	81.1
34- 17	43.4	39.5	49.7	38.2	46.4	23.1	45.8	81.9

SPEED CONCENTRATION MEASUREMENTS FROM PHOTOS

STRIP 6 6:55:32-6:58:06

STATION	LANE 1		LANE 2		LANE 3		ALL LANES	
	MPH	VPM	MPH	VPM	MPH	VPM	MPH	VPM
309-290	41.6	18.8	40.2	24.7	42.8	21.4	41.4	58.0
302-284	45.2	24.4	40.8	21.7	46.8	18.3	44.0	62.3
293-275	39.7	41.4	39.3	27.2	46.8	19.7	41.3	86.4
287-270	41.3	45.5	41.1	24.5	44.5	20.6	42.0	93.4
280-262	42.9	42.2	39.9	36.7	33.5	49.1	38.7	123.9
273-255	38.8	39.7	38.5	34.2	34.9	60.3	37.0	131.1
267-248	40.1	26.4	41.1	39.8	37.0	69.4	38.8	126.0
259-242	36.2	31.3	41.1	43.1	41.4	54.1	39.8	126.1
251-235	38.5	35.8	43.2	40.6	43.3	46.1	41.8	121.6
246-228	42.6	46.1	49.7	41.3	48.4	38.6	46.9	117.4
238-221	41.9	45.1	45.8	45.5	46.5	38.8	44.8	121.5
232-215	36.9	38.3	39.1	46.6	40.7	41.7	39.1	120.8
224-207	38.5	33.3	36.3	45.9	38.4	39.0	37.7	117.1
218-201	38.4	34.2	37.7	45.9	38.3	49.4	38.1	129.6
211-194	36.2	38.0	36.4	53.0	36.2	45.2	36.3	132.4
205-188	36.4	35.7	37.0	46.8	37.5	47.0	37.0	132.9
198-181	41.1	32.5	41.3	51.3	42.0	40.7	41.5	125.5
191-175	41.7	38.8	42.4	55.5	45.3	39.3	43.1	137.1
184-167	40.4	38.7	41.3	55.7	47.4	45.7	43.0	137.4
176-160	39.6	48.6	38.4	51.0	43.8	54.4	40.7	133.9
170-153	37.1	41.8	38.6	48.8	39.3	53.0	38.4	144.7
163-146	39.5	34.0	41.2	50.7	39.4	60.5	40.1	145.9
155-139	38.8	43.0	40.1	51.6	38.5	62.1	39.1	151.7
149-132	39.2	33.8	40.7	53.3	39.1	53.2	39.7	141.3
141-124	41.5	33.2	43.0	57.5	42.3	52.3	42.4	138.7
134-117	42.3	25.8	42.6	45.1	42.3	37.6	42.4	87.9
126-110	40.1	27.5	43.2	37.4	43.2	37.0	42.2	91.7
120-105	39.3	24.4	42.6	29.9	42.5	27.3	41.5	78.8
112- 98	45.9	15.2	45.2	40.2	46.6	27.6	45.8	76.3
106- 90	45.2	22.9	42.9	44.4	43.8	34.1	43.7	95.3
100- 83	43.6	31.4	43.5	47.2	43.7	38.5	43.6	102.0
92- 76	35.9	16.4	45.2	50.8	45.2	48.4	43.1	85.1

SPEED CONCENTRATION MEASUREMENTS FROM PHOTOS
STRIP 7 7:03:44-7:06:39

STATION	LANE 1		LANE 2		LANE 3		ALL LANES	
	MPH	VPM	MPH	VPM	MPH	VPM	MPH	VPM
309-291	48.8	30.6	50.4	46.4	56.6	29.2	51.3	104.7
302-285	39.7	40.9	47.0	47.5	53.6	34.6	46.3	116.0
296-278	27.1	59.6	35.4	52.0	48.5	36.5	36.0	135.1
289-272	24.0	82.4	24.7	82.0	45.1	45.2	28.7	206.1
282-264	21.4	83.9	20.0	84.0	29.1	68.7	23.0	232.2
275-258	24.5	68.2	18.2	82.8	22.2	83.4	21.5	236.7
269-251	29.9	59.5	26.1	76.4	22.9	90.0	25.8	276.3
263-245	31.4	61.1	28.4	67.3	27.6	76.7	29.0	203.5
256-238	35.2	56.7	34.0	66.5	34.7	65.9	34.6	189.1
250-232	37.8	52.1	38.2	59.9	38.8	58.1	38.3	171.2
244-226	40.7	40.1	40.3	35.9	40.6	56.7	40.5	155.9
237-219	41.8	37.8	40.5	42.0	39.9	55.7	40.6	137.7
230-212	40.3	40.4	39.6	59.3	38.3	48.8	39.4	145.6
224-205	41.2	43.3	40.1	57.4	39.7	46.6	40.3	146.0
217-199	42.6	41.8	42.4	49.0	43.8	46.1	42.9	130.1
210-192	40.7	41.5	42.0	56.4	42.8	48.2	42.0	140.4
203-185	40.8	35.7	41.3	57.7	41.1	48.1	41.1	139.4
196-179	39.8	36.2	39.8	56.4	39.2	45.5	39.6	137.6
184-172	34.4	38.9	35.4	58.8	36.9	47.0	35.6	143.1
182-165	35.1	46.2	34.9	46.7	38.2	43.5	36.1	132.0
176-158	35.2	46.0	35.9	48.0	39.3	42.1	36.7	137.0
169-151	38.3	51.2	38.5	42.1	41.4	47.6	39.5	139.9
162-144	39.5	42.3	39.3	47.0	40.7	52.4	39.9	130.4
156-138	40.1	38.4	38.8	57.5	41.1	59.4	40.0	154.7
149-131	44.9	28.1	41.3	58.1	45.0	52.3	43.6	125.8
143-125	44.2	23.1	40.7	46.8	44.6	48.8	43.1	127.7
136-118	42.2	39.5	40.0	44.9	42.5	49.8	41.5	131.9
129-111	44.5	35.2	43.2	38.8	45.7	45.0	44.5	119.5
121-103	40.6	44.9	42.9	46.3	46.3	43.9	43.1	125.7
144- 96	37.5	40.1	40.4	37.4	40.1	49.9	39.4	128.5
108- 90	37.3	40.5	39.6	34.2	38.4	45.2	38.4	121.2
101- 83	44.4	32.5	46.7	35.3	43.2	48.6	44.6	112.3
94- 76	51.5	36.2	51.8	38.3	47.5	43.9	50.0	117.0
87- 69	48.8	43.9	51.2	35.5	48.1	45.9	49.4	112.6
81 -63	43.7	39.6	47.9	31.7	46.2	43.9	45.8	103.7
73- 56	43.2	28.6	45.2	33.4	45.9	39.9	44.9	100.3
66- 49	37.8	27.3	39.4	44.7	44.0	37.9	40.5	107.7
59- 42	38.1	36.2	38.1	59.0	41.9	44.7	39.2	121.5
52- 35	40.6	34.9	38.9	67.7	43.1	43.7	40.6	143.3
45- 28	39.7	39.5	38.6	64.1	41.6	43.2	39.7	144.7
38- 22	34.5	40.0	37.9	65.7	41.8	35.4	37.9	140.7
32- 16	31.3	59.1	35.9	67.1	44.5	30.4	36.0	150.4

SPEED CONCENTRATION MEASUREMENTS FROM PHOTOS

STRIP 9 7:15:55-7:18:34

STATION	LANE 1		LANE 2		LANE 3		ALL LANES	
	MPH	VPM	MPH	VPM	MPH	VPM	MPH	VPM
311-294	10.0	106.9	13.3	106.1	17.1	93.9	13.5	248.7
304-287	12.4	95.7	12.6	106.6	18.0	89.5	14.2	291.0
298-281	9.5	114.9	13.5	111.5	19.8	88.2	13.7	311.5
292-274	10.2	129.4	15.7	106.1	23.1	74.6	15.2	303.6
285-268	11.5	125.5	18.3	92.5	23.5	62.4	16.5	281.2
278-262	21.0	86.8	22.2	88.1	16.8	87.1	19.9	255.8
271-256	24.3	63.4	23.9	77.1	17.9	88.2	21.7	219.7
266-249	29.6	44.9	29.8	64.3	20.8	75.8	26.1	179.7
259-242	26.4	46.1	26.4	62.4	27.4	54.6	26.7	165.4
252-235	23.8	67.0	22.8	71.9	14.5	87.0	19.8	218.7
246-228	17.7	91.1	21.5	79.6	14.7	105.7	17.7	272.8
239-222	18.1	95.4	22.9	77.5	14.5	103.1	18.1	277.9
233-215	18.9	89.8	26.3	72.2	24.7	75.3	23.0	238.3
227-209	28.1	70.2	25.4	82.0	22.8	79.4	25.3	229.7
222-204	33.7	57.2	26.2	70.0	24.0	79.5	27.4	202.5
215-197	37.3	46.8	26.7	74.6	24.6	81.9	28.3	206.1
209-191	25.3	50.5	72.7	71.5	25.0	67.4	24.2	192.5
202-184	16.8	74.5	22.6	75.0	26.9	68.6	22.0	219.3
195-177	13.8	97.6	23.4	79.0	28.5	69.2	21.1	242.6
188-170	17.2	91.1	27.1	68.8	29.5	66.3	23.9	224.7
182-164	19.6	70.2	28.5	62.9	29.1	61.2	25.4	195.7
176-158	26.9	46.7	29.9	67.7	31.1	63.0	29.6	177.4
169-152	31.3	41.8	32.4	63.8	34.5	65.7	32.9	171.1
163-145	30.7	54.3	28.5	72.6	36.1	69.9	31.9	190.0
156-138	27.9	60.4	24.0	78.7	32.0	70.6	27.8	207.0
150-132	22.6	68.0	20.9	81.7	28.0	68.8	23.6	218.0
143-126	26.4	59.0	26.7	69.6	29.7	65.8	27.6	194.8
136-118	28.9	57.4	30.8	60.5	32.9	64.7	30.9	183.5
130-113	32.5	46.8	33.0	53.5	33.8	62.7	33.2	163.0
122-106	35.4	39.4	33.7	47.4	35.0	62.0	34.7	145.3
117-101	34.8	35.5	35.1	44.6	35.3	60.2	35.1	137.8
111- 94	39.8	36.6	39.2	41.5	39.7	54.8	39.6	135.3
104- 88	43.0	40.4	44.3	41.2	45.1	51.1	44.3	130.0
96- 80	38.6	24.2	43.6	39.4	42.8	45.2	42.2	109.8
91- 74	42.5	24.2	47.6	42.0	45.7	47.3	45.7	106.4
84- 67	38.2	29.5	49.6	44.2	50.0	42.4	46.6	113.6
77- 61	37.8	65.1	44.5	53.7	46.6	41.7	42.7	148.7
70- 56	38.3	58.7	40.0	62.9	42.2	53.6	40.1	173.4
64- 48	37.0	55.6	40.7	65.1	43.3	56.0	40.4	168.0
57- 42	40.6	39.1	41.1	69.7	43.0	58.3	41.6	170.1
50- 36	39.9	39.6	37.9	54.6	41.9	49.1	39.9	147.2
43- 29	39.8	38.0	35.5	57.1	39.9	52.6	38.4	127.9
36- 24	37.0	36.6	28.3	47.3	37.6	60.3	34.3	143.8
30- 17	37.4	37.4	28.8	41.5	38.4	54.3	35.2	120.9

SPEED CONCENTRATION MEASUREMENTS FROM PHOTOS
STRIP 1 7:25:15-7:28:02

STATION	LANE 1		LANE 2		LANE 3		ALL LANES	
	MPH	VPM	MPH	VPM	MPH	VPM	MPH	VPM
307-291	4.2	138.5	5.1	141.1	13.6	97.7	7.0	375.3
301-276	6.6	127.0	4.5	146.2	13.4	97.6	7.5	369.6
294-276	8.2	120.0	4.4	174.2	12.4	100.6	7.6	392.1
288-269	12.4	106.6	8.6	137.7	11.3	88.6	10.5	331.6
281-262	10.9	95.5	11.6	113.6	9.2	113.3	10.6	321.5
275-257	10.0	76.3	10.0	117.7	11.7	109.8	10.7	298.0
269-252	10.2	88.1	9.6	127.4	14.5	111.3	11.4	318.4
264-246	12.2	94.8	8.1	141.7	19.4	90.4	12.4	327.3
258-240	12.3	96.8	8.4	127.0	19.8	89.2	12.8	308.6
251-233	13.1	87.4	13.4	99.1	23.8	86.9	16.6	276.1
245-227	11.4	102.0	19.4	84.5	22.9	81.1	17.5	251.8
239-221	10.5	92.4	21.8	72.5	23.4	81.6	18.0	246.5
233-215	15.5	81.3	15.0	95.9	20.8	91.9	17.1	270.2
226-209	21.0	66.6	14.5	95.4	17.9	92.8	17.4	257.8
220-202	23.6	56.7	11.6	98.2	13.7	101.2	15.0	255.3
214-198	25.9	46.5	13.0	90.9	13.3	107.9	15.6	246.3
209-195	22.9	58.6	14.4	108.7	14.2	114.7	16.1	271.9
203-187	18.2	69.9	15.7	97.9	16.3	91.6	16.6	261.9
197-180	15.1	98.2	22.6	78.6	26.2	64.8	20.7	239.5
190-174	18.6	82.0	30.5	68.4	34.5	52.5	26.8	201.6
184-167	25.8	65.1	35.2	67.3	36.5	49.6	32.1	177.0
178-161	30.1	50.7	34.2	66.0	33.6	52.0	32.8	169.5
172-155	23.3	66.9	31.6	69.1	30.9	53.5	28.5	188.2
165-148	19.8	74.7	27.6	78.4	28.1	60.6	25.0	211.5
160-143	16.8	84.7	25.2	74.2	27.1	67.4	23.4	195.0
154-137	21.3	79.1	26.3	73.2	29.5	60.2	25.8	187.3
148-131	24.9	59.0	28.9	67.1	32.4	53.4	28.6	180.2
142-125	33.2	47.4	37.4	53.8	37.4	53.6	36.0	147.0
136-119	36.8	49.5	41.0	50.5	42.1	49.5	39.7	126.4
130-112	38.6	38.1	40.7	45.6	43.7	47.7	41.0	109.3
123-107	36.2	49.7	41.1	49.9	44.6	49.4	40.8	145.2
117-100	36.2	49.3	41.7	55.2	44.7	52.6	41.0	155.1
111- 94	36.6	52.7	38.5	53.7	42.8	45.3	39.3	137.3
104- 88	32.6	47.5	33.9	54.4	35.5	41.1	34.0	140.1
99- 81	36.3	40.2	35.3	48.7	39.8	40.0	37.0	129.3
93- 76	39.2	37.8	37.8	54.0	41.2	42.5	39.3	130.9
88- 71	38.6	41.7	36.0	57.5	40.6	50.2	38.1	145.2
82- 65	36.5	50.2	34.4	63.4	40.6	49.3	36.9	163.0
76- 59	35.0	59.0	30.8	63.7	38.1	54.7	34.4	175.7
71- 53	33.0	63.4	28.4	73.3	35.9	57.2	32.0	190.6
65- 48	32.1	66.5	30.9	64.4	33.1	59.5	32.0	190.2
60- 43	35.7	60.8	32.2	62.5	34.2	64.0	34.0	190.4
54- 37	37.3	53.5	36.0	59.9	35.6	64.2	36.2	172.6
49- 31	38.1	50.1	33.2	60.0	36.6	56.5	35.8	165.5
43- 25	36.8	44.0	27.7	71.5	30.6	64.1	31.1	167.5
37- 19	35.9	41.6	25.6	80.6	28.1	70.5	29.1	172.7

SPEED CONCENTRATION MEASUREMENTS FROM PHOTOS

SPEED 3 7:44:43-7:47:35

STATION	LANE 1 MPH	LANE 1 VPM	LANE 2 MPH	LANE 2 VPM	LANE 3 MPH	LANE 3 VPM	ALL LANES MPH	ALL LANES VPM
311-294	17.4	62.9	19.4	64.1	25.2	99.1	20.3	178.2
305-288	8.9	101.0	8.9	133.0	10.9	94.2	9.5	302.5
299-281	6.8	115.4	5.0	151.5	5.7	152.1	5.8	407.9
293-276	9.0	119.4	5.6	156.5	6.0	145.0	6.7	423.8
287-269	10.3	110.7	7.5	135.7	7.8	108.1	8.5	358.0
280-263	11.7	102.2	7.5	128.6	7.3	132.9	8.6	345.8
275-257	17.5	84.3	10.8	111.9	8.0	126.0	11.5	319.3
267-250	18.5	93.7	13.3	97.0	8.7	126.5	13.1	307.7
262-250	16.7	105.2	15.9	97.4	17.0	87.8	16.5	283.9
262-244	9.6	131.7	13.3	107.6	11.0	111.8	11.2	345.7
255-237	9.9	116.6	15.2	89.8	11.5	118.4	12.0	320.2
249-230	12.9	109.0	18.7	72.3	12.4	101.7	14.2	280.6
243-225	14.6	73.9	16.6	81.2	12.9	100.2	14.6	251.7
236-218	19.1	61.6	16.1	79.1	11.2	126.3	14.8	216.5
230-212	26.4	49.2	10.3	108.4	10.3	133.1	12.9	286.4
224-206	26.0	53.4	14.7	94.4	17.3	96.1	18.3	243.4
218-200	24.5	55.3	16.2	101.5	21.6	88.7	20.1	240.5
212-194	15.7	75.3	22.7	80.3	25.5	76.1	21.3	229.8
206-187	13.5	108.5	24.9	77.3	26.2	69.5	20.6	253.8
193-180	13.5	87.2	24.9	73.8	25.7	62.7	20.8	222.0
191-173	23.2	67.0	27.6	70.6	26.8	60.9	25.9	198.9
185-167	28.6	55.1	26.7	76.2	25.4	72.5	26.8	205.2
179-161	24.8	66.0	24.5	70.9	24.4	74.8	24.6	210.8
172-154	20.7	79.7	25.0	70.8	25.7	73.5	23.7	226.6
165-147	20.8	85.9	27.5	72.5	30.3	66.6	25.9	227.5
160-141	21.2	76.9	29.5	71.4	32.4	67.8	27.4	216.4
153-135	25.6	63.0	29.8	72.3	31.6	73.1	29.2	201.6
147-129	31.8	49.3	32.0	69.7	33.6	73.5	32.5	192.0
141-123	35.9	43.5	34.3	58.5	35.1	70.4	35.1	168.8
135-116	37.4	49.1	35.9	41.6	37.2	58.7	36.9	143.3
128-110	32.1	40.7	38.4	33.1	38.0	49.9	36.1	120.9
122-104	31.1	48.8	39.4	33.2	37.7	47.4	35.6	128.2
116- 98	30.5	54.5	37.8	38.5	37.7	46.8	35.0	137.5
109- 91	30.3	54.5	38.8	45.2	38.2	44.9	35.3	142.2
102- 84	33.3	49.2	39.7	38.5	37.9	46.2	36.7	135.3
95- 78	36.6	30.5	40.5	29.3	39.1	44.2	38.7	103.9
89- 72	40.0	28.4	42.9	28.8	41.8	44.3	41.6	101.6
82- 64	40.1	38.7	58.0	38.0	42.2	44.8	40.2	112.8
75- 57	36.3	52.7	31.4	63.3	38.2	58.0	35.3	155.8
70- 51	34.9	44.1	31.1	64.6	37.1	57.4	34.2	163.7
63- 45	32.5	49.3	23.6	64.7	34.3	60.6	31.7	172.4
56- 38	35.1	46.8	32.9	60.0	35.5	56.9	34.4	157.8
51- 32	35.2	44.5	34.0	59.8	37.4	54.5	35.4	156.5
44- 27	34.5	33.8	33.9	59.3	37.9	58.2	35.4	132.7
39- 21	35.5	37.1	34.2	62.8	42.2	51.5	37.0	118.0
31- 15								

APPENDIX B

REGRESSION ANALYSES OF MACROSCOPIC EQUATIONS OF STATE
SHOULDER LANE LINEAR MODEL: u=a-bk

STATION	b	a	t	SIGNIFICANT
312-294	.3483	49.17	5.33	**
306-288	.3381	47.52	8.56	**
299-281	.3486	49.20	12.67	**
292-274	.3552	53.05	16.67	**
286-268	.3807	55.08	10.32	**
280-262	.4538	57.49	9.11	**
273-255	.4929	55.43	4.96	**
267-249	.3684	49.00	5.39	**
261-243	.3219	47.13	4.71	**
254-236	.3418	50.69	6.79	**
248-230	.4603	60.05	7.88	**
241-223	.4233	57.56	11.36	**
235-217	.5203	60.05	5.44	**
229-211	.5202	59.26	3.55	*
223-205	.6020	63.13	2.83	*
216-198	.8460	71.90	2.75	
210-192	.6519	61.35	5.79	**
204-186	.5769	59.15	19.86	**
197-179	.4053	55.27	19.00	**
190-172	.4603	56.42	8.47	**
183-165	.6450	66.22	14.36	**
176-158	.5702	61.35	0.73	
169-151	.5078	58.72	3.17	*
162-144	.4924	58.29	12.01	**
155-137	.4395	56.12	11.41	**
148-130	.5433	58.81	15.18	**
141-123	.6697	65.35	14.19	*
134-118	.3910	55.35	2.11	
128-110	.3403	52.20	1.88	
121-103	.0774	39.96	0.45	
115- 97	.3068	49.22	2.96	*
108- 90	.4358	54.36	9.67	**
101- 83	.4847	57.98	2.94	*
95- 77	.0908	43.62	0.34	
89- 71	.0054	42.67	0.02	
82- 64	.1896	47.06	1.38	
76- 58	.2961	54.18	3.06	*
69- 51	.2724	51.46	2.01	
63- 45	.2532	49.92	1.70	
56- 38	.3859	55.36	2.08	
50- 32	.3494	53.96	1.98	
44- 26	.5246	60.41	1.43	
37- 19	.1023	32.40	0.14	
31- 13	.3035	49.79	1.52	

REGRESSION ANALYSES OF MACROSCOPIC EQUATIONS OF STATE
SHOULDER LANE PARABOLIC MODEL: $u=a-bk^{1/2}$

STATION	b	a	t	SIGNIFICANT
312-294	5.292	65.77	5.43	**
306-288	4.948	62.18	6.81	**
299-281	5.162	64.82	8.99	**
292-274	5.578	72.03	11.32	**
286-268	5.992	76.23	9.16	**
280-262	6.598	79.37	7.01	**
273-255	6.767	77.37	4.44	*
267-249	5.229	66.12	5.08	**
261-243	5.094	66.14	4.89	**
254-236	5.823	73.90	7.90	**
248-230	7.346	87.63	7.49	**
241-223	6.932	84.40	10.14	**
235-217	8.205	91.28	5.56	**
229-211	7.626	86.55	3.42	*
223-205	8.371	91.86	2.75	*
216-198	10.783	105.97	2.71	
210-192	7.632	82.58	4.98	**
204-186	7.996	85.46	18.34	**
197-179	6.317	77.76	29.74	**
190-172	7.137	82.91	8.74	**
183-165	9.496	100.72	13.55	**
176-158	7.981	89.25	.72	
169-151	7.326	84.82	3.09	*
162-144	7.058	82.65	11.79	**
155-137	6.557	79.60	10.43	**
148-130	7.370	82.99	18.98	**
141-123	8.861	94.26	15.27	**
134-118	4.685	69.04	1.92	
128-118	4.121	64.55	1.81	
121-103	1.006	43.19	0.49	
115- 97	3.479	58.67	3.24	*
108- 90	5.163	69.22	8.20	**
101- 83	5.924	75.85	2.72	
95- 77	0.731	44.81	0.25	
89- 71	0.280	44.06	0.10	
82- 64	2.195	53.22	1.44	
76- 58	3.932	66.70	3.53	*
69- 51	3.513	62.30	2.09	
63- 45	3.526	62.00	1.83	
56- 38	5.141	72.36	2.06	
50- 32	4.559	68.76	1.99	
44- 26	6.685	81.68	1.41	
37- 19	1.242	28.64	0.14	
31- 13	4.145	63.79	1.49	

REGRESSION ANALYSES OF MACROSCOPIC EQUATIONS OF STATE
SHOULDER LANE EXPONENTIAL MODEL: ln k=a-bu

STATION	b	a	t	SIGNIFICANT
312-294	.0480	5.068	4.50	*
306-288	.0543	5.174	4.49	*
299-281	.0531	5.218	5.51	**
292-274	.0466	5.298	6.81	**
286-268	.0422	5.251	6.58	**
280-262	.0390	5.121	5.21	**
273-255	.0356	4.929	3.84	*
267-249	.0478	5.228	4.50	*
261-243	.0443	5.210	4.90	**
254-236	.0401	5.188	7.47	**
248-230	.0327	5.042	6.00	**
241-223	.0343	5.099	8.82	**
235-217	.0279	4.834	5.54	**
229-211	.0265	4.776	3.24	*
223-205	.0222	4.608	2.66	
216-198	.0188	4.411	2.66	
210-192	.0381	4.966	4.25	*
204-186	.0364	4.915	13.20	**
197-179	.0421	5.217	33.30	**
190-172	.0450	5.017	8.93	**
183-165	.0281	4.845	12.61	**
176-158	.0039	4.026	0.70	
169-151	.0264	4.775	3.00	*
162-144	.0391	5.155	9.95	**
155-137	.0400	5.204	8.47	**
148-130	.0403	5.126	24.18	**
141-123	.0339	4.971	15.30	**
134-118	.0314	4.945	1.74	
128-110	.0346	4.981	1.72	
121-103	.0211	4.443	0.54	
115- 97	.0794	6.552	3.43	*
108- 90	.0616	5.913	6.90	**
101- 83	.0343	4.965	2.51	
95- 77	.0049	3.543	0.16	
89- 71	.0074	3.716	0.17	
82- 64	.0691	6.255	1.49	
76- 58	.0673	6.463	4.17	*
69- 51	.0555	5.896	2.20	
63- 45	.0465	5.572	1.97	
56- 38	.0347	5.092	2.08	
50- 32	.0385	5.238	2.00	
44- 26	.0184	4.440	1.39	
37- 19	.0016	3.618	0.13	
31- 13	.0294	4.812	1.45	

REGRESSION ANALYSES OF MACROSCOPIC EQUATIONS OF STATE
CENTER LANE LINEAR MODEL: u=a-bk

STATION	b	a	t	SIGNIFICANT
312-294	.4337	59.30	4.19	*
306-288	.3709	57.03	6.83	**
299-281	.3151	51.05	13.67	**
292-274	.2795	49.74	8.43	**
286-268	.3309	51.54	9.49	**
280-262	.3587	52.26	14.00	**
273-255	.3734	53.37	19.80	**
267-249	.3924	55.86	10.15	**
261-243	.3530	53.99	6.60	**
254-236	.4170	59.05	9.15	**
248-230	.5880	70.32	10.68	**
241-223	.6004	69.05	6.24	**
235-217	.5714	64.65	15.41	**
229-211	.5121	63.69	5.51	**
223-205	.5565	68.68	7.49	**
216-198	.6437	73.57	14.47	**
210-192	.4743	63.77	6.66	**
204-186	.5074	64.20	6.75	**
197-179	.5121	64.82	7.24	**
190-172	.5587	67.80	4.36	*
183-165	.2935	51.22	1.83	
176-158	.3542	54.89	5.70	**
169-151	.4181	57.81	5.77	**
162-144	.4545	61.19	6.72	**
155-137	.4952	63.69	6.91	**
148-130	.5353	67.17	4.70	**
141-123	.4209	60.65	3.21	*
134-118	.6337	70.69	7.03	**
128-110	.6171	66.16	3.30	*
121-103	.1009	44.15	0.49	
115- 97	.1769	47.84	0.70	
108- 90	.3398	54.44	1.17	
101- 83	.6557	70.21	3.27	*
95- 77	.3773	60.48	1.60	
89- 71	.3665	59.47	1.47	
82- 64	.3022	56.49	1.86	
76- 58	.3424	56.16	1.83	
69- 51	.4677	63.86	3.15	*
63- 45	.6069	73.76	2.26	
56- 38	.2665	54.03	1.15	
50- 32	.3353	56.48	1.88	
44- 76	.4251	60.73	3.68	*
37- 19	.3089	52.21	1.48	
31- 13	.3199	53.43	1.54	

REGRESSION ANALYSES OF MACROSCOPIC EQUATIONS OF STATE

CENTER LANE PARABOLIC MODEL: $u=a-bk^{1/2}$

STATION	b	a	t	SIGNIFICANT
312-294	7.251	87.63	4.24	*
306-288	6.284	80.93	5.74	**
299-281	5.418	71.36	10.97	**
292-274	5.139	70.68	10.36	**
286-268	5.510	71.89	12.65	**
280-262	5.613	71.81	14.29	**
273-255	5.964	75.38	15.90	**
267-249	6.619	82.18	14.68	**
261-243	6.398	81.29	10.15	**
254-236	7.162	88.16	10.83	**
248-230	8.868	101.97	8.10	**
241-223	8.209	95.38	5.18	**
235-217	7.764	89.50	10.43	**
229-211	7.564	90.14	5.27	**
223-205	9.434	107.44	7.98	**
216-198	10.405	114.50	15.99	**
210-192	7.866	95.10	7.34	**
204-186	7.817	93.24	6.45	**
197-179	7.368	90.38	5.71	**
190-172	8.179	97.30	3.96	*
183-165	4.189	65.93	1.78	
176-158	5.254	74.09	5.40	**
169-151	5.929	78.37	5.54	**
162-144	6.607	84.58	6.37	**
155-137	7.273	89.80	5.76	**
148-130	8.006	96.60	4.15	*
141-123	5.862	80.64	2.99	*
134-118	8.794	100.96	6.76	**
128-110	8.234	93.48	3.39	*
121-103	1.279	48.17	0.50	
115- 97	2.255	54.99	0.70	
108- 90	4.369	68.40	1.12	
101- 83	8.346	96.63	3.23	*
95- 77	4.849	75.89	1.62	
89- 71	4.534	73.22	1.39	
82- 64	3.802	68.11	1.71	
76- 58	4.578	71.15	1.80	
69- 51	6.845	88.52	3.16	*
63- 45	8.926	106.35	2.28	
56- 38	3.935	68.34	1.21	
50- 32	4.883	74.07	2.01	
44- 26	5.873	80.48	3.56	*
37- 19	4.702	69.78	1.51	
31- 13	4.909	71.81	1.52	

REGRESSION ANALYSES OF MACROSCOPIC EQUATIONS OF STATE
CENTER LANE EXPONENTIAL MODEL: ln k=a-bu

STATION	b	a	t	SIGNIFICANT
312-294	.0279	4.914	4.04	*
306-288	.0337	5.105	4.53	*
299-281	.0435	5.241	7.31	**
292-274	.0441	5.344	9.05	**
286-268	.0458	5.304	12.14	**
280-262	.0475	5.318	8.86	**
273-255	.0428	5.263	10.42	**
267-249	.0372	5.184	12.31	**
261-243	.0363	5.193	16.60	**
254-236	.0329	5.119	10.08	**
248-230	.0282	4.984	6.08	**
241-223	.0307	5.021	4.21	*
235-217	.0371	5.141	7.10	**
229-211	.0319	5.056	4.74	**
223-205	.0241	4.902	8.01	**
216-198	.0238	4.876	14.99	**
210-192	.0297	5.076	7.13	**
204-186	.0307	5.066	5.72	**
197-179	.0328	5.158	4.64	**
190-172	.0259	4.963	3.61	*
183-165	.0291	5.017	1.74	
176-158	.0449	5.576	5.06	**
169-151	.0422	5.437	5.24	**
162-144	.0381	5.339	5.76	**
155-137	.0327	5.170	4.88	**
148-130	.0262	4.990	3.67	*
141-123	.0328	5.207	2.77	*
134-118	.0301	5.071	6.42	**
120-110	.0270	4.817	3.37	*
121-103	.0147	4.281	0.50	
115- 97	.0133	4.252	0.65	
108- 90	.0159	4.363	1.06	
101- 83	.0271	4.883	3.18	*
95- 77	.0258	4.860	1.62	
89- 71	.0264	4.805	1.31	
82- 64	.0385	5.325	1.57	
76- 58	.0338	5.127	1.77	
69- 51	.0310	5.164	3.16	*
63- 45	.0196	4.810	2.31	
56- 38	.0241	4.984	1.26	
50- 32	.0344	5.302	2.14	
44- 26	.0399	5.464	3.42	*
37- 19	.0252	4.888	1.55	
31- 13	.0231	4.833	1.50	

REGRESSION ANALYSES OF MACROSCOPIC EQUATIONS OF STATE

MEDIAN LANE LINEAR MODEL: u=a-bk

STATION	b	a	t	SIGNIFICANT
312-294	.4279	55.29	4.15	*
306-288	.4548	57.55	5.43	**
299-281	.3454	53.64	7.18	**
292-274	.3591	54.13	7.54	**
286-268	.4409	54.05	9.94	**
280-262	.3618	51.93	11.43	**
273-255	.4099	57.95	13.12	**
267-249	.4248	61.05	6.35	**
261-243	.4739	61.10	4.84	**
254-236	.5017	64.52	8.79	**
248-230	.4867	67.29	30.78	**
241-223	.5669	70.96	17.49	**
235-217	.5002	63.70	13.20	**
229-211	.3799	56.43	9.36	**
223-205	.3852	57.61	9.24	**
216-198	.4729	63.34	9.21	**
210-192	.4006	57.56	7.02	**
204-186	.5246	64.30	15.40	**
197-179	.5716	65.75	11.00	**
190-172	.6261	69.76	2.47	
183-165	.7487	76.28	2.09	
176-158	.4708	61.35	2.93	*
169-151	.4568	60.85	3.94	*
162-144	.3292	54.64	2.74	
155-137	.4014	59.68	3.01	*
148-130	.3536	56.15	2.45	
141-123	.3923	60.29	3.70	*
134-118	.3579	58.67	5.65	**
128-110	.3802	59.68	4.81	**
121-103	.1820	49.60	1.71	
115- 97	.4172	60.26	4.85	**
108- 90	.4172	58.61	1.70	
101- 83	.1560	50.00	0.47	
95- 77	.8620	83.13	0.85	
89- 71	.8025	81.45	1.42	
82- 64	1.2164	99.50	2.75	*
76- 58	.4805	64.74	5.79	**
69- 51	.4111	61.64	3.93	*
63- 45	.2692	53.92	3.08	*
56- 38	.2792	54.65	2.66	
50- 32	.3388	56.47	4.73	**
44- 26	.1832	46.79	2.32	
37- 19	.1764	45.67	2.11	
31- 13	.3168	54.28	4.01	**

REGRESSION ANALYSES OF MACROSCOPIC EQUATIONS OF STATE
MEDIAN LANE PARABOLIC MODEL: $u=a-bk^{1/2}$

STATION	b	a	t	SIGNIFICANT
312-294	5.591	70.69	3.81	*
306-288	6.456	77.84	4.67	**
299-281	5.522	72.41	7.32	**
292-274	5.501	71.91	6.84	**
286-268	6.111	72.55	8.70	**
280-262	5.940	74.33	16.93	**
273-255	6.562	82.15	11.00	**
267-249	7.277	90.82	6.63	**
261-243	7.147	86.98	4.81	**
254-236	7.850	93.50	7.88	**
248-230	7.906	97.29	32.01	**
241-223	8.971	104.54	16.99	**
235-217	7.281	88.53	9.30	**
229-211	6.214	80.03	15.48	**
223-205	6.637	84.50	17.09	**
216-198	7.753	93.73	10.06	**
210-192	6.265	80.48	8.14	**
204-186	7.870	92.80	13.89	**
197-179	8.245	94.92	12.36	**
190-172	9.008	101.91	2.43	
183-165	10.710	114.41	2.04	
176-158	6.813	85.70	2.82	*
169-151	6.420	82.94	3.76	*
162-144	4.019	65.70	2.59	
155-137	5.374	76.90	2.84	*
148-130	4.833	72.21	2.32	
141-123	5.425	78.61	3.51	*
134-118	4.780	74.27	5.77	**
128-110	4.822	74.55	4.30	*
121-103	2.066	55.11	1.56	
115- 97	5.345	77.06	4.70	**
108- 90	5.657	77.61	1.82	
101- 83	2.230	57.90	0.51	
95- 77	11.715	122.90	0.86	
89- 71	10.728	117.24	1.43	
82- 64	16.522	155.54	2.79	*
76- 58	6.236	84.82	5.28	**
69- 51	5.523	79.93	3.95	*
63- 45	3.236	63.02	2.87	*
56- 38	3.560	65.53	2.53	
50- 32	4.140	68.68	4.07	*
44- 26	1.719	49.61	1.90	
37- 19	1.841	49.51	1.74	
31- 13	4.119	67.01	3.24	*

REGRESSION ANALYSES OF MACROSCOPIC EQUATIONS OF STATE
MEDIAN LANE EXPONENTIAL MODEL: $\ln k = a - bu$

STATION	b	a	t	SIGNIFICANT
312-294	.0453	5.122	3.00	*
306-288	.0368	4.922	3.96	*
299-281	.0455	5.269	5.62	**
292-274	.0471	5.293	4.73	**
286-268	.0473	5.170	6.62	**
280-262	.0434	5.227	11.09	**
273-255	.0383	5.216	7.35	**
267-249	.0307	5.127	5.93	**
261-243	.0324	5.086	4.56	**
254-236	.0312	5.064	6.19	**
248-230	.0321	5.182	13.79	**
241-223	.0285	5.038	12.18	**
235-217	.0367	5.214	6.41	**
229-211	.0417	5.345	15.56	**
223-205	.0370	5.258	19.48	**
216-198	.0311	5.101	10.28	**
210-192	.0412	5.339	6.97	**
204-186	.0338	5.136	9.90	**
197-179	.0333	5.112	13.35	**
190-172	.0183	4.630	2.39	
183-165	.0130	4.436	1.99	
176-158	.0265	4.914	2.70	
169-151	.0343	5.195	3.51	*
162-144	.0510	5.776	2.42	
155-137	.0363	5.346	2.68	
148-130	.0339	5.211	2.18	
141-123	.0398	5.508	3.25	*
134-118	.0569	6.175	5.56	**
128-110	.0527	6.008	3.82	*
121-103	.0596	6.153	1.43	
115- 97	.0495	5.821	4.47	*
108- 90	.0256	4.781	1.95	
101- 83	.0089	4.145	0.55	
95- 77	.0040	3.979	0.87	
89- 71	.0115	4.328	1.45	
82- 64	.0130	4.383	2.84	*
76- 58	.0441	5.690	4.76	**
69- 51	.0456	5.754	3.97	*
63- 45	.0748	6.862	2.67	
56- 38	.0594	6.273	2.40	
50- 32	.0653	6.454	3.57	*
44- 26	.1280	8.497	1.61	
37- 19	.0940	7.165	1.44	
31- 13	.0550	5.927	2.69	

REGRESSION ANALYSES OF MACROSCOPIC EQUATIONS OF STATE
TOTAL INBOUND (3 LANES) LINEAR MODEL: u=a-bk

STATION	b	a	t	SIGNIFICANT
312-294	.1346	54.10	4.71	*
306-288	.1287	52.76	7.52	**
299-281	.1149	50.93	32.16	**
292-274	.1124	52.04	18.37	**
286-268	.1315	54.32	40.60	**
280-262	.1309	53.28	30.60	**
273-255	.1421	55.25	13.49	**
267-249	.1413	56.03	11.87	**
261-243	.1016	46.66	4.98	**
254-236	.1434	58.03	7.79	**
248-230	.1733	66.11	20.77	**
241-223	.1754	64.64	11.53	**
235-217	.1807	62.93	10.93	**
229-211	.1666	59.72	4.85	**
223-205	.1816	64.53	15.84	**
216-198	.2050	67.81	10.00	**
210-192	.1758	62.30	8.82	**
204-186	.1904	65.48	19.03	**
197-179	.1761	64.28	14.32	**
190-172	.1969	66.42	7.99	**
183-166	.1996	65.86	4.97	**
176-158	.1805	63.17	7.12	**
169-151	.1785	62.96	11.14	**
162-144	.1541	59.60	8.78	**
155-137	.1566	60.10	4.18	*
148-130	.1670	61.27	6.06	**
141-123	.1583	61.23	5.03	**
134-118	.1404	58.27	4.00	*
128-110	.1450	58.05	3.60	*
121-103	.0513	45.58	0.90	
115- 97	.1528	57.81	3.93	*
108- 90	.2216	66.36	4.85	**
101- 83	.1939	64.78	2.67	
95- 77	.1646	61.86	1.65	
89- 71	.1757	63.98	1.47	
82- 64	.1261	57.98	2.87	*
76- 58	.1207	57.05	3.16	*
69- 51	.1272	57.67	2.73	*
63- 45	.1140	55.72	2.80	*
56- 38	.1099	55.50	1.95	
50- 32	.1311	57.63	3.79	*
44- 26	.1224	54.19	3.37	*
37- 19	.1371	54.22	4.60	**
31- 13	.1690	58.21	4.53	*

REGRESSION ANALYSES OF MACROSCOPIC EQUATIONS OF STATE
TOTAL INBOUND (3 LANES) PARABOLIC MODEL: $u=a-bk^{1/2}$

STATION	b	a	t	SIGNIFICANT
312-294	3.525	74.51	4.67	**
306-288	3.316	70.99	6.25	**
299-281	3.140	69.15	20.29	**
292-274	3.197	71.96	24.09	**
286-268	3.471	74.58	32.94	**
280-262	3.344	72.16	12.44	**
273-255	3.736	78.11	10.95	**
267-249	3.886	81.31	13.15	**
261-243	2.086	54.42	3.42	*
254-236	4.033	84.80	8.20	**
248-230	4.656	95.46	13.53	**
241-223	4.559	92.58	8.71	**
235-217	4.666	91.87	9.59	**
229-211	4.317	86.60	4.98	**
223-205	4.907	96.52	14.75	**
216-198	5.334	101.48	9.77	**
210-192	4.448	89.17	8.71	**
204-186	4.864	95.35	14.33	**
197-179	4.548	92.55	11.15	**
190-172	5.111	99.02	7.81	**
183-165	5.008	96.97	4.79	**
176-158	4.568	91.84	7.15	**
169-151	4.305	88.48	8.34	**
162-144	3.592	79.65	6.53	**
155-137	3.783	82.29	3.87	*
143-130	4.034	85.06	5.33	**
141-123	3.683	82.24	4.51	*
134-118	3.179	75.98	3.66	*
128-110	3.193	75.44	3.39	*
121-103	1.076	51.15	0.89	
115- 97	3.136	73.67	3.89	*
108- 90	4.753	91.65	4.88	**
101- 83	4.140	86.75	2.62	
95- 77	3.346	78.69	1.61	
89- 71	3.789	84.24	1.48	
82- 64	2.745	72.69	2.80	*
76- 58	2.685	71.67	3.19	*
69- 51	2.981	74.77	2.83	*
63- 45	2.673	71.10	2.93	*
56- 38	2.475	69.14	1.91	
50- 32	2.876	73.13	3.57	*
44- 26	2.622	67.92	3.12	*
37- 19	2.955	69.81	4.14	*
31- 13	3.800	79.24	4.74	**

REGRESSION ANALYSES OF MACROSCOPIC EQUATIONS OF STATE
TOTAL INBOUND (3 LANES) EXPONENTIAL MODEL: ln k=a-bu

STATION	b	a	t	SIGNIFICANT
312-294	.0385	6.094	4.16	*
306-288	.0438	6.196	4.86	**
299-281	.0491	6.351	10.00	**
292-274	.0468	6.411	11.89	**
286-268	.0460	6.354	12.49	**
280-262	.0476	6.375	6.81	**
273-255	.0406	6.259	10.05	**
267-249	.0380	6.245	2.22	
261-243	.0692	6.773	7.19	**
254-236	.0346	6.199	8.75	**
248-230	.0318	6.181	6.51	**
241-223	.0322	6.150	8.14	**
235-217	.0321	6.091	4.90	**
229-211	.0317	6.056	11.31	**
223-205	.0301	6.080	9.06	**
216-198	.0280	6.000	7.11	**
210-192	.0347	6.171	9.90	**
204-186	.0319	6.117	8.47	**
197-179	.0331	6.202	7.46	**
190-172	.0284	6.040	4.60	**
183-165	.0269	5.969	7.03	**
176-158	.0323	6.164	6.55	**
169-151	.0359	6.281	5.06	**
162-144	.0430	6.510	3.52	*
155-137	.0340	6.233	4.62	**
148-130	.0354	6.254	3.99	*
141-123	.0382	6.406	3.33	*
134-118	.0415	6.503	3.19	*
128-110	.0412	6.442	0.88	
121-103	.0292	5.911	3.82	*
115- 97	.0493	6.709	4.89	**
108- 90	.0338	6.116	2.56	
101- 83	.0282	5.941	1.57	
95- 77	.0226	5.671	1.48	
89- 71	.0208	5.621	2.69	*
82- 64	.0482	6.805	3.19	*
76- 58	.0527	6.993	2.93	*
69- 51	.0430	6.620	3.05	*
63- 45	.0490	6.862	1.88	
56- 38	.0392	6.512	3.38	*
50- 32	.0507	6.911	2.90	*
44- 26	.0532	6.878	3.74	*
37- 19	.0526	6.754	4.86	**
31- 13	.0422	6.368		

PUBLICATIONS

Project 2-8-61-24
Freeway Surveillance and Control

1. Research Report 24-1, "Theoretical Approaches to the Study of Control of Freeway Congestion" by Donald R. Drew.

2. Research Report 24-2, "Optimum Distribution of Traffic Over a Capacitated Street Network" by Charles Pinnell.

3. Research Report 24-3, "Freeway Level of Service as Influenced by Volume Capacity Characteristics" by Donald R. Drew and Charles J. Keese.