A SYSTEMS APPROACH TO THE CAPACITY ANALYSIS OF NORTH BROADWAY AVENUE AND BRIDGE, KANSAS CITY, MISSOURI

by 1264

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The nomographs that appear in the text were developed by William L. Smith as a simplifying procedure to utilize a stochastic approach to capacity problems.

INTRODUCTION

Capacity analysis of a roadway system continues to be a major concern for transportation planners and traffic engineers. While great strides have been made to determine the existing and future demands and desire for travel on a given roadway or highway network, the complete analysis of the same roadway to determine its ability to handle these demands has been piecemeal due to limited knowledge of particular situations and how they relate to the complete system.

With the introduction of the 1965 Highway Capacity Manual (1) and the subsequent work by Jack E. Leisch (2) on intersection capacity, the ability to analyze certain traffic conditions has been greatly advanced. However, continuing research is still necessary to bring capacity analysis to a point where entire systems can be readily evaluated without extensive work and cost.

An attempt was made in this report to apply a different approach to evaluate the capacity on a part of an existing transportation network while considering the impacts on the rest of the network and the surrounding environment and the limitations they impose.

PURPOSE

The purpose of this paper is two-fold. The first was to apply a systems approach utilizing stochastic analysis as well as current methods to evaluate present facilities and proposed alternatives, and the second was to apply and evaluate a technique for analyzing existing traffic conditions through time-lapse photography.

SCOPE

The work was limited to the analysis of three basic traffic conditions as they occurred on one roadway and related to each other. The three conditions were:

1) A free flow highway
2) A tollbooth facility located on a bridge, and
3) Two major intersections providing the interface of the study network with a freeway facility.

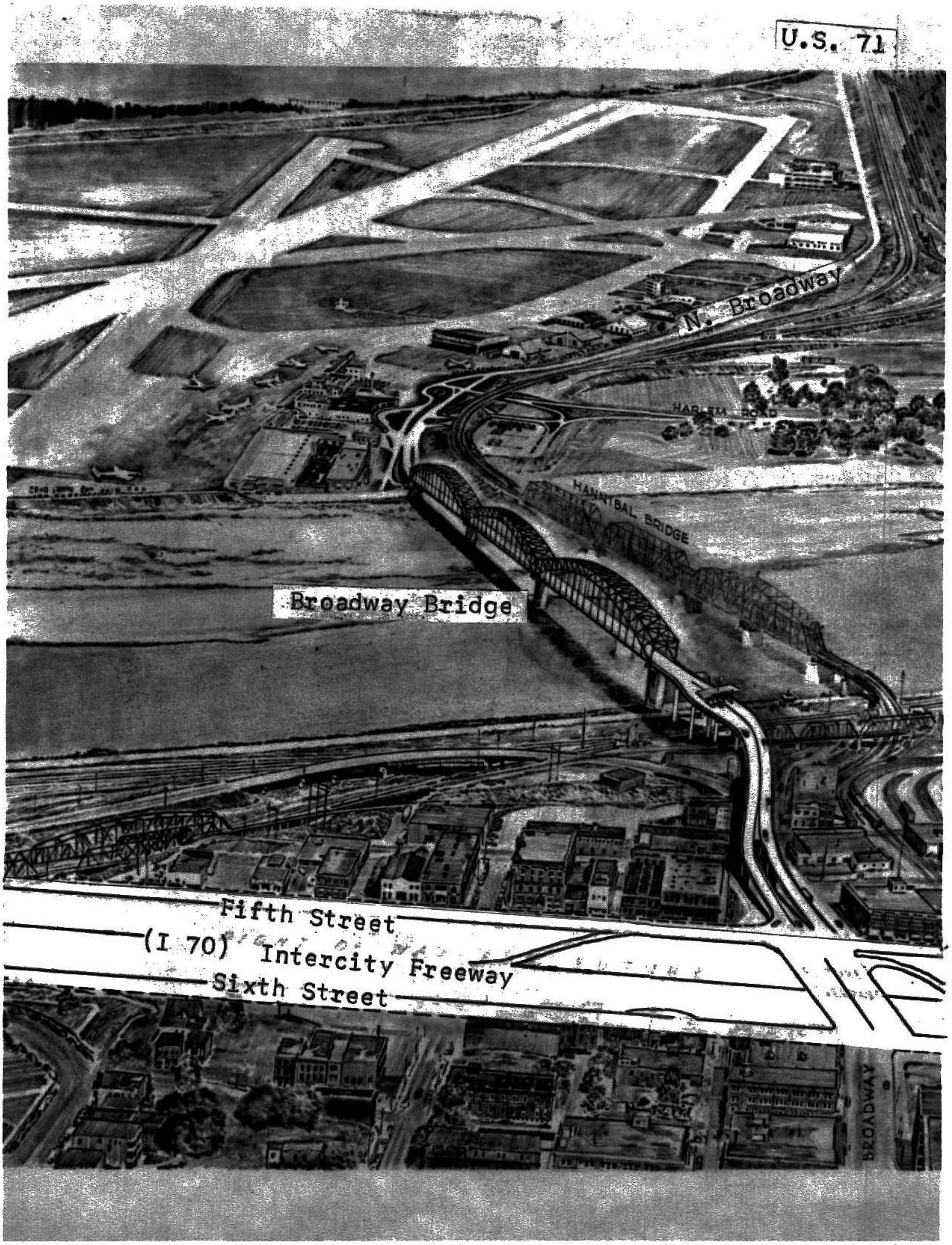
STUDY LOCATION

The location selected for study was Broadway Avenue in Kansas City, Missouri, from the intersection at Sixth Street and Broadway, through the intersection with Fifth Street, and north across the Broadway Bridge to the intersection of Broadway with U.S. Highway 71 (see Plate 1). This particular section of the transportation network is of particular interest to the city as it provides the major link to the existing Kansas City Municipal Airport with the Central Business District and the Intercity Freeway which is a part of Interstate 70. This section has also been designated as an expressway in the future network. The completion of the new Kansas City International Airport located approximately 20 miles north of the Central Business District will have a profound effect on the demand for this facility.

Broadway is a six-lane facility between Sixth and Fifth Streets. The approaches to and from the bridge are two separated two-lane ramps with a right-hand turn lane to the west, a southbound lane between the two ramps, and a north-bound lane to the east (see Plate 1). The bridge is basically four lanes except for a 100-foot section that is widened to accommodate six lanes for tollbooth operations. The remainder of North Broadway is four lanes until it passes the existing airport where it narrows to two lanes for the remainder of the section analyzed.

EXPLANATION OF PLATE I

Overall View of Study Area


U.S. 71
N. Broadway
HARLEM ROAD
HANNIBAL BRIDGE
Broadway Bridge
Fifth Street
(I 70) Intercity Freeway
Sixth Street
BROADWAY

SYSTEMS APPROACH TO CAPACITY ANALYSIS

Too often in the past, once the problem statement has been structured, the engineer utilizes a process or procedure to analyze the situation and develop a solution based only on the problem statement, without regard to the creation of other problems that might be imposed by the solution. The systems approach is a problem-solving process which formalizes an approach to direct the user to select an optimum solution through the consideration of all interactions between any possible solution and the environment that surrounds the proposal. Environment implies the physical, economic, social and political conditions that may affect or be affected by the solution. As an example, the massive freeway has been shown to be the most safe, rapid and efficient type of roadway but some of the social and economic conflicts it imposes have prevented its widespread use as a "cure-all" to the transportation problem.

The ttansportation system is considered as an "open system" as it has effects on the environment and in turn, the environment affects it. In a "closed system", only the environment affects the system.

The systems approach is by no means a new process but its application to traffic engineering and transportation planning has not been widespread. The process is only intended to "ensure that all relevant variables, conditions and aspects are considered and consistent designs obtained" (3).

As with any process, definite steps may be outlined to guide the approach and indicate the flow of information. The outline of the problem-solving process used in this report is shown in Fig. 1, with the information flows indicated. The important feature of this process is the repetition or iteration of the various steps to ensure that the results are in consonance with each of the foregoing concepts.

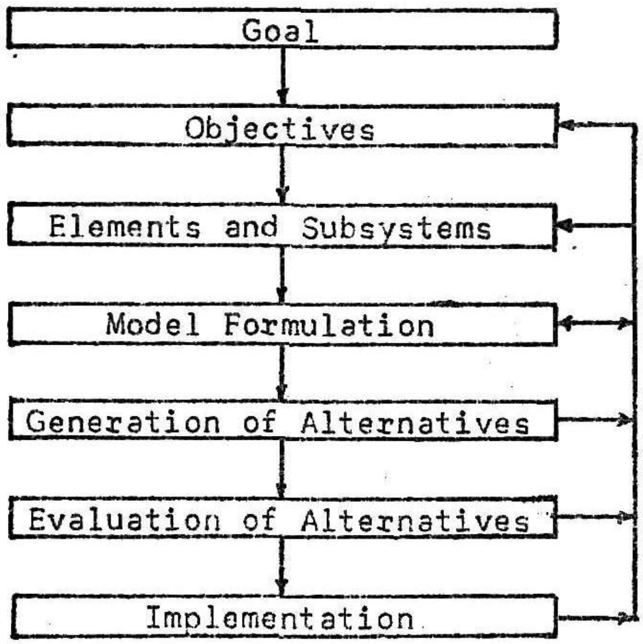


Figure 1. Steps in the Systems Process.

Goals and Objectives

There is often confusion between the meanings of a goal and an objective. As used in this process, a goal refers to a desired result which is not necessarily attainable, such as the elimination of poverty. An objective, on the other hand, refers to an attainable end result of specific programs that are directed toward the achievement of a goal.

The goal of this or any other urban area transportation system is to develop a network of facilities that provides a desirable means of circulation.

From certain fragments of data and information, it appeared as though the Broadway network might not provide a very desirable link in the circulation system. Hence, the objective selected was to conduct an inquiry into the Broadway Avenue subsystem's role in the transportation framework for the Kansas City area.

Systems Elements

Identification of the subsystems in the system and environment is perhaps the most important step in the problem-solving process. If certain factors that affect or can be affected by proposed alternatives are not identified, certainly the optimum solution might well not be considered.

The elements or subsystems of any system are many and varied and must include more than physical properties alone. Once this approach is selected, the two basic subsystems become the study area system and the environment system. With the goal and objective established, the following elements were identified and considered:

1) Existing network under study

2) Current traffic volumes on the entire network

3) Existing river crossings

4) Existing and predicted land use and population characteristics

5) Predicted traffic volumes for 1990

6) Modes of travel

7) Topography

8) Economic development and financial resources

9) Level of service.

From these elements, four subsystems were developed:

1) Land use, or those factors which control the demand for facilities and influence the location for access, such as the airport, residential areas, and business district;

2) Topography, or the physical factors which influence location and construction costs, such as elevations and rivers;

3) Modes, or the type of vehicles, that utilize the facilities including alternate means, such as rail and air service;

4) Design of the facility, or the ability of the network to carry traffic under the constraints imposed.

Each of these subsystems have a direct bearing on the capacity of the network and impose constraints on the generation of alternative solutions for improvements. The first three are components of the environment system and the last is a component of the network system.

The various maps and publications by the Kansas City Metropolitan Planning Commission provide an accurate description and prediction of the physical and economic development of the land use subsystem. The topography subsystem is well defined through various city and contour maps. The modal subsystem is dynamic and can have a very beneficial or detrimental effect on the demand and capacity of a given facility. For this study, the modes were assumed to remain the same as were observed during the data collection period, namely 95 per cent automobiles.

The design subsystem is the main consideration in the analysis of capacity. For a given facility, the capacity is more dependent upon the design than any other element. This subsystem includes the concept of "level of service" which is a qualitative measure of the operating conditions on a network. Capacity has been defined as "the maximum number of vehicles which has a reasonable expectation of passing over a given section of a lane or roadway in one direction (or both) during a given time period under prevailing roadway and traffic conditions", normally expressed in vehicles per hour (1). Although the maximum capacity is important to know, the "service volume" or capacity under acceptable conditions is the objective utilized in a design procedure. Six levels of service (A, B, C, D, E and F) have been defined for identifying operating conditions and although the maximum capacity lies between levels "E" and "F", the capacity at level of service

"C" is determined as suitable or acceptable for urban transportation design (1).

Model Formulation

One of the best methods available for describing a system or subsystem is the use of models. While physical scale models and analog or functional comparison models are very useful to describe some systems, the symbolic or theoretical models offer the most realistic approach to many traffic situations.

To describe the network under study, four models were thought to have the best possibilities of representing the study network;

1) Free flow model utilizing the Highway Capacity Manual for determination of capacity on the two- and four-lane sections of the network;
2) Queueing theory to determine capacity at the tollbooth operations;
3) Intersection model utilizing a stochastic approach to capacity; and
4) Ramp merging model utilizing critical gap theory.

Method of Data Collection

An investigation of the tollbooth and intersection operations was necessary for the calibration of the models to be used. Since there were six different tollbooths on the bridge and seven separate movements to observe at each intersection, it was decided to use time-lapse photography and the actual counts were obtained by one person through the viewing of each frame.

Location Photography

Time-lapse pictures were obtained of the tollbooth operation and the two intersections by the use of a Paillard-Bolex H-16 Rex 16 mm movie camera, tripod mounted, utilizing a Pan-Cinor 85 zoom lens adjustable from 17 to 85 mm with a reflex view-finder. Single frames were taken at two-second intervals by the use of the Samenco MC-6 Movie Control. A Gossen Lunasix lightmeter was used for accurate light readings. Color film was utilized to aid in the analyzing procedure. Since a power source was available, batteries were not utilized. At a two-second interval, a single winding provided twenty minutes of operation time and the automatic winding motor was not utilized. Thus a two-foot reel of film will take 4000 frames or operate for approximately two hours and ten minutes at two-second intervals.

The tollbooths were photographed on Thursday, June 19, 1969, from 2:50 PM to 3:10 PM, 4:50 PM to 5:10 PM, and from 5:12 PM to 5:22 PM. The two intersections were photographed on Friday, June 20, 1969, from 4:30PM to 4:50PM and from 4:52 PM to 5:12 PM. This provided one offpeak and two evening peak period observations.

The photographs of the tollbooths were taken from the top of the elevator shaft on the Folgers Coffee Warehouse at the northwest corner of Seventh Street and Broadway Avenue. The photographs of the two intersections were taken from the sixth floor of the same building (see Fig. 2 and 3).

Film Analysis

Once the film had been developed, viewing was accomplished with a Keystone Belmont K161 16 mm projector with a Lafayette adaptor and remote control box for frame-by-frame viewing. There was a frame counter mounted on the projector. A Lafayette reflecting screen was available so that the viewer could control the projector and study the picture at close range; however, the 10-by-14 inch screen was not large enough for the detailed counts. A normal movie screen was utilized and although the viewer had to move back and forth from the screen to the projector, more accurate results were obtained.

The type of data sheet used in the analysis of the tollbooth operation is shown in Fig. 4.

Figure 2. Sample Frame of Tollbooth Observations.

Figure 3. Sample Frame of Intersection Observations.

Frame	Gate 1			Gate 2			Gate 3				
	In	Out	Q	In	Out	Q	In	Out	Q	S.B. Arr.	N.B. Arr.
15150		/	1		/	6			7		
51	/		1	/		2	/		7		
52		/	2			2			6	//	/
53	/		1			6		/	5		/
54		/	1		/	6	/		5	/	/
55	/		1	/		4			6		
56			2		/	2			6	/	/
57	/	/	1	/		2		/	5		/
58			1		/	2	/		5		/
59	/	/		/		1			5		
60			1			1		/	4		//

Figure 4. Sample Data Sheet, Tollbooths.

The first column was used for the frame number. Three large columns were provided for each tollbooth with separate columns under each for the time of entrance into the tollbooth, time of exit from the tollbooth, and the number of vehicles in the queue. The two columns at the right were used for marking the arrival of vehicles from the south and north. It was rather easy to determine when a vehicle entered or left the tollbooth area as the ends of the structure provided fairly sharp lines. The number in a queue was counted in each frame; however, these counts did not include the vehicle being serviced. To determine the time of vehicle arrivals, a strip of tape was placed on the screen a sufficient distance away from the tollbooths so that the queues would not back through the point of arrival observation. Arrivals were determined when a vehicle crossed these lines. Observations to the nearest second could be determined by positioning the marks on the data sheet in the spaces or through the lines separating the frames.

For example, as shown in Fig 4, in frame #15152, there were two vehicles in a queue behind tollbooth #1, two in a queue behind tollbooth #2, and six in a queue behind tollbooth #3. There were two arrivals from the north and one arrival from the south. Between frames #15152 and #15153, the vehicle in tollbooth #1 completed its service time. In frame #15153, the next vehicle began its service time in tollbooth #1 and there was one vehicle in the queue. Six vehicles were in a queue behind tollbooth #2. A vehicle completed its service time in tollbooth #3 and there were five vehicles in that queue. There was also an arrival from the south during this frame. Before the next frame, there was an arrival from the north.

Because of the location of the camera, only the three northbound tollbooths were analyzed.

The type of data sheet used in the analysis of the intersection operation is shown in Fig. 5.

SIXTH AND BROADWAY									
Frame	N	N-E	S	S-E	E	E-S	E-N	Phase	Cycle
15997	26	6	18-1	4*				1	1
16024					19-1*	2	11-1*	2	
16042	33-3	4	13-1	3*				1	2
16069					22-1*	5	13*	2	
16087	39	8	23-3	2*				1	3
16114					25-1*	5	6-1*	2	
16132	40-2	5	22-1	3*				1	4
16159					17-2*	5	12*	2	
16177	26-1	3-1	21	4*				1	5
16204					22-2*	2	11-2*	2	

Figure 5. Sample Data Sheet, Intersections

The first column was used for the frame number at the start of a signal phase. The remaining columns indicate each traffic movement. The first number indicates passenger vehicles, the second denotes commercial vehicles. A star at the side indicates there was still a queue of vehicles desiring to move through the intersection at the end of the phase, or an indication that the phase was loaded. The cycle length, phase length, and time lag between intersections could be determined by using the frame numbers.

The total time expended for the repeated viewing of approximately 2100 separate frames and tabulation of data was less than three eight-hour man-days.

Results

The following information was obtained from the film analysis:

1) Tollbooths--one ten minute offpeak and two ten minute peak traffic periods (300 frames per period):

   a) To obtain arrival frequency distributions, the number of arrivals in every three frames, or the arrivals per each six seconds, was tabulated for both directions in each of the three observation periods; thus, six frequency distributions were obtained. (Headway frequency distributions may be tabulated by counting the number of frames between arrivals and multiplying by two.)

   b) The service time frequency distributions were obtained by doubling the number of frames between the start and end of each vehicle's service time. Distributions were obtained for each of the tollbooths during each of the three observation periods. Distributions were also made of the three tollbooths operating collectively by combining the three tollbooth frequency distributions for each period; thus twelve frequency distributions were obtained.

c) Queue length frequency distributions were obtained by tabulating the numbers in the "Q" column. For multiple channel calculations, the three queue lengths per frame for each of the tollbooths were added together and tabulated. For single channel calculations, the queue lengths at each gate were tabulated. Twelve frequency distributions were obtained; however, only the average length was determined.

d) Hourly arrival rates were obtained by multiplying the number of arrivals in the ten-minute periods by six.

e) Hourly service rates were obtained by dividing 3600 by the average service rate found from the frequency distribution.

2) Intersections--two twenty minute peak periods (600 frames per period):

a) Volumes for each movement and arrival direction

b) Percentage of commercial vehicles

c) Percentage of turns

d) Percentage of loaded cycles for each movement.

Specific results of the analysis are shown in Tables 1 - 4.

The frequency distributions obtained for arrivals and service times were tested against various theoretical distributions, most notably the Poisson distribution for arrivals and the Negative Exponential distribution for service times. Utilizing the Chi-Square test (for goodness of fit), the observed frequency distributions for arrivals were found to conform closely enough to Poisson distributions so that the hypothesis was accepted. It was noted by inspection that the service time frequency distributions did not reasonably approximate Negative Exponential distributions but looked more like Normal distributions. The Chi-Square test was performed to compare the observed and Normal distributions with favorable results. Other research with service times has shown this to be a better approximation (3,4). Regardless of the service time distributions, it was decided that queueing theory was the best model to evaluate capacity at the tollbooths.

Arrivals	Observed Frequency	Poisson Frequency	Comments
0	28	24.4	Northbound Offpeak
1	27	34.4	Mean = 1.41
2	26	24.4	Observed Chi-Square = 2.50
3	16	16.9	2 degrees of freedom
4	1	--	Allowable Chi-Square = 5.99
5	2	--	95% confidence level
			Good fit
			Hourly arrival rate = 846
0	13	6.0	Northbound peak
1	13	16.9	Mean = 2.81
2	22	23.8	Observed Chi-Square = 12.83
3	19	22.3	4 degrees of freedom
4	12	15.6	Allowable Chi-Square = 9.49
5	11	8.8	95% confidence level
6	6	6.6	Fair fit
7	4	--	Hourly arrival rate = 1704
0	33	39.1	Southbound offpeak
1	49	36.7	Mean = 0.94
2	13	17.2	Observed Chi-Square = 7.40
3	2	7.0	2 degrees of freedom
4	2	--	Allowable Chi-Square = 5.99
5	1	--	95% confidence level
			Fair fit
			Hourly arrival rate = 564
0	28	27.3	Southbound peak
1	31	35.4	Mean = 1.30
2	25	23.0	Observed Chi-Square = 0.80
3	15	14.3	2 degrees of freedom
4	1	--	Allowable Chi-Square = 5.99
5	0	--	95% confidence level
			Good fit
			Hourly arrival rate = 780

Table 1. Distribution Analysis of Arrivals

Service Times	Observed Frequency	Normal Frequency	Comments
1	0	--	Gate 1
2	7	9.8	Mean service time = 4.28
3	20	15.6	Observed Chi-Square = 3.82
4	26	22.2	3 degrees of freedom
5	17	19.9	Allowable Chi-Square = 7.82
6	9	11.8	95% confidence level
7	3	5.8	Good fit
8	1	--	Mean queue length = 1.63
9	2	--	
1	0	--	Gate 2
2	4	--	Mean service time = 4.58
3	13	20.0	Observed Chi-Square = 5.64
4	34	23.8	2 degrees of freedom
5	20	22.9	Allowable Chi-Square = 5.99
6	13	15.6	95% confidence level
7	6	7.6	Good fit
8	0	--	Mean queue length = 3.13
9	2	--	
1	0	--	Gate 3
2	2	--	Mean service time = 4.46
3	17	19.4	Observed Chi-Square = 1.39
4	30	28.2	2 degrees of freedom
5	31	28.3	Allowable Chi-Square = 5.99
6	10	13.5	95% confidence level
7	1	3.6	Good fit
8	1	--	Mean queue length = 4.78
9	1	--	
1	0	--	Combined Gates
2	13	20.2	Mean service time = 4.44
3	50	45.2	Observed Chi-Square = 14.39
4	90	73.9	4 degrees of freedom
5	68	72.6	Allowable Chi-Square = 9.49
6	32	40.6	95% confidence level
7	10	14.1	Fair fit
8	2	3.2	Mean queue length = 6.89
9	5		

Table 2. Distribution Analysis of Service Times.

SIXTH AND BROADWAY						
Movement	Phase	Green Time(sec)	No. Lanes	Veh./Hr.	% Comm'l Veh.	% Loaded Cycles
N			2	1450	2.87	0
N-E		54	1	213	4.68	0
S			2	847	2.36	33
S-E			1	170	1.24	100
E			1	802	6.24	42
E-S		36	1	165	12.10	4
[illegible]-E-N			1	437	4.20	33

Table 3. Intersection Data, Sixth and Broadway

FIFTH AND BROADWAY						
Movement	Phase	Green Time(sec)	No. Lanes	Veh./Hr.	% Comm'l Veh.	% Loaded Cycles
N			3	1439	3.45	0
N-E		48	1	462	3.75	0
S			2	795	1.27	4
S-W			1	295	7.35	0
W			1	357	17.75	0
W-N		42	1	562	5.63	4
W-S			1	148	10.10	0

Table 4. Intersection Data, Fifth and Broadway.

Model Calibration

The free flow model needed no calibration as capacity was determined from physical conditions. In order to use the queueing theory model, several assumptions had to be made (4,5). Drew's formulas (4) were utilized for single and multiple channel queueing processes. The two basic formulas considered were:

1. $E(m) = \dfrac{q^2}{Q(Q - q)}$ single channel

2. $E(m) = \dfrac{P_o\left(\frac{q}{Q}\right)^4}{18\left(1 - \frac{q}{3Q}\right)^2}$ multiple channel (three)

where:

$E(m)$ = expected number in the queue
q = arrival rate (vehicles/hour)
Q = service rate (vehicles/hour)

$$P_o = \frac{1}{1 + \frac{q}{Q} + \frac{1}{2}\left(\frac{q}{Q}\right)^2 + \frac{q^3}{3Q^2(2Q - q)}}$$

In order for these equations to accurately reflect the actual conditions, the distribution of vehicle arrivals should be Poisson and the distribution of service times should be Negative Exponential. As was noted in the results of the data analysis, the observed service times did not conform to a Negative Exponential distribution with any degree of accuracy. Ignoring that fact, the formulas were tested to compare the expected queue lengths with those observed.

The multiple channel equation was not found to be very accurate for either the offpeak volumes or the peak hour volumes. Records from the tollbooth operations showed that the precentage of vehicles to use each tollbooth remained constant from day to day, namely 25%, 36%, and 39% for tollbooths #1, #2, and #3 respectively. These percentages were applied to the arrival volumes and the single channel equation seemed to give more desirable comparisons. Table 5 shows the comparison of results. Some inaccuracies were probably caused by the short length of the third tollbooth lane. Despite the inaccuracies, the queueing theory equations were utilized to determine the capacity at the tollbooths.

Channel	Equation Used	Arrival Rate	Service Rate	Observed Queue Length	Theoretical Queue Length
Gate 1					
Offpeak	Single Channel	211	567	0.03	0.22
Peak		421	841	0.79	0.50
Gate 2					
Offpeak	Single Channel	305	650	0.33	0.42
Peak		607	786	1.97	2.62
Gate 3					
Offpeak	Single Channel	330	745	0.53	0.35
Peak		657	807	4.11	3.57
Combined					
Offpeak	Multiple Channel	846	668	0.73	0.12
Peak		1686	810	6.89	0.67

Table 5. Comparison of Results, Queueing Model.

Instead of using the nomographs developed from the Highway Capacity Manual for determining intersection capacity, two new nomographs were developed by using the formulas:

1. $$M = \frac{(C)(V)}{3600}$$

where:

M = mean arrivals (veh.)
C = cycle length (sec)
V = hourly volume (veh/hr).

2. $$P(X > k) = 1 - \sum_{x=0}^{k} \frac{m^x e^{-m}}{x!}$$

where:

P(X>k) = probability of arrivals being greater than average cleared vehicles
k = number of vehicles cleared through intersection
m = average arrival rate.

3. $$t = \frac{L}{S}$$

where:

t = delay time (sec)
S = approach speed (ft/sec)
L = length from stopline to far edge of conflicting approach + length of one car (ft).

In addition, vehicle headways observed by Capelle and Pinnell (6) were utilized to determine effective green times.

The ramp-merging portion of the intersection model needed no calibration since the nomographs provided in the Highway Capacity Manual (1) and Traffic Flow Theory and Control (4) were utilized.

Generation and Evaluation of Alternatives

Once the system was described and modeled, the next step was to evaluate the capacity of the existing network and begin to analyze various improvements. Instead of trying to evaluate the specific capacities of each section with alternate improvements, a design capacity was selected in order to direct the analysis toward a certain objective. This objective was to develop a capacity on the network through improvements that would adequately handle predicted volume.

Several studies have been made to determine the anticipated demand on the Broadway Avenue network for the year 1990. The latest figure, developed by Howard, Needles, Tammen and Bergendoff, Consulting Engineers, is a desired line assignment of 100,000 vehicles per day. Since directional splits and peak hour percentages vary so widely, an upper and lower limit were determined using a 60-40 directional split with a 12% peak hour factor and a 50-50 split with an 8% peak hour factor. This gave a range of between 4,000 and 7,200 vehicles per hour with which to generate improvements to enable the accommodation by the network.

The approach to the generation of alternatives was to start with the least expensive improvements and progress until the desired capacity was obtained. Table 6 lists the possible improvements that were considered for each section of the network.

Section	Alternative Improvements
Free flow	1. Null or no change 2. Develop to four lanes 3. Addition of lanes
Tollbooths	1. Null or no change 2. Reduction of service time 3. Removal of tollbooths 4. Additional tollbooths and lanes
Intersections	1. Null or no change 2. Cycle and phase changes 3. Addition of lanes 4. Full scale pattern change

Table 6. Possible Alternative Improvements.

To evaluate the specific proposals, an iterative process (shown in Fig. 6) was used to progressively bring the network to anticipated capacity.

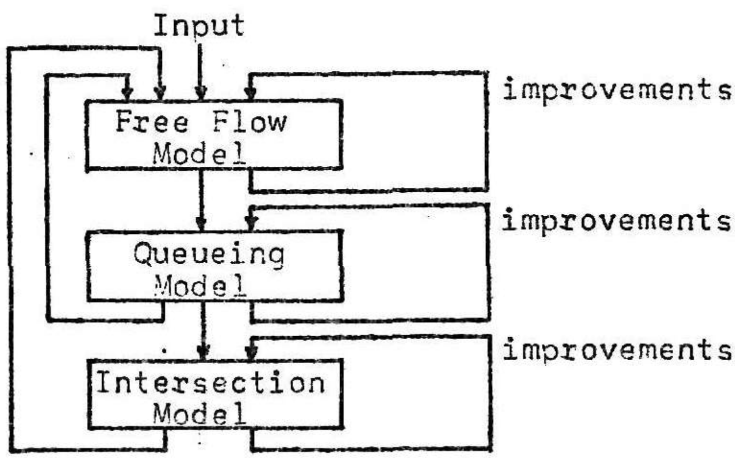


Figure 6. Iterative Evaluation Process.

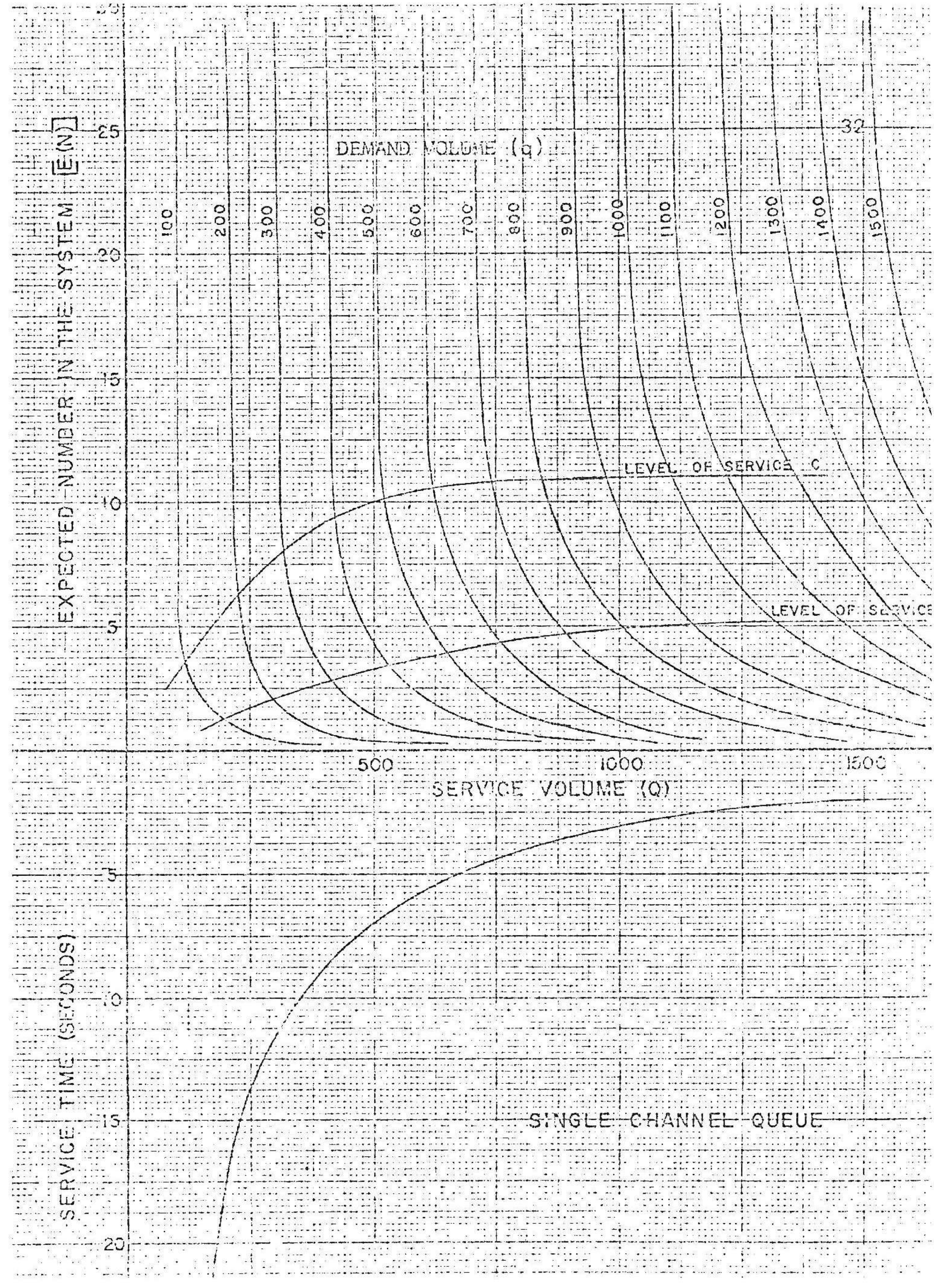
The process was begun at the north end of the network with the free flow highway that was access controlled. To evaluate the null alternative, the limiting factor was determined to be the two-lane portion north of the airport. Utilizing the Capacity Manual, the capacity in one direction at a level of service "C" was determined to be 840 vehicles per hour (vph). At maximum capacity this figure increased to 1200 vph. Since the capacity of this facility would not handle the predicted volume, an iteration of this model was necessary.

The first improvement considered was to improve the two-lane portion to a separated four-lane facility comparable with the remainder of the free flow section. This would increase the capacity in one direction to 3000 vph at a level of service "C" and a maximum capacity of 4000 vph. Another iteration was made considering the improvement of the section to a six-lane freeway. This provided a desirable capacity of 4500 vph and a maximum capacity of 6000 vph. This fell within the expected limits so this portion was determined to be adequate with the improvements considered and the next section was evaluated.

Instead of laboring over the queueing theory equations to determine capacity, a nomograph was utilized to facilitate the arrival at approximate capacities. Plates II and III are the nomographs representing the single channel and multiple (three) channel equations, respectively, with the

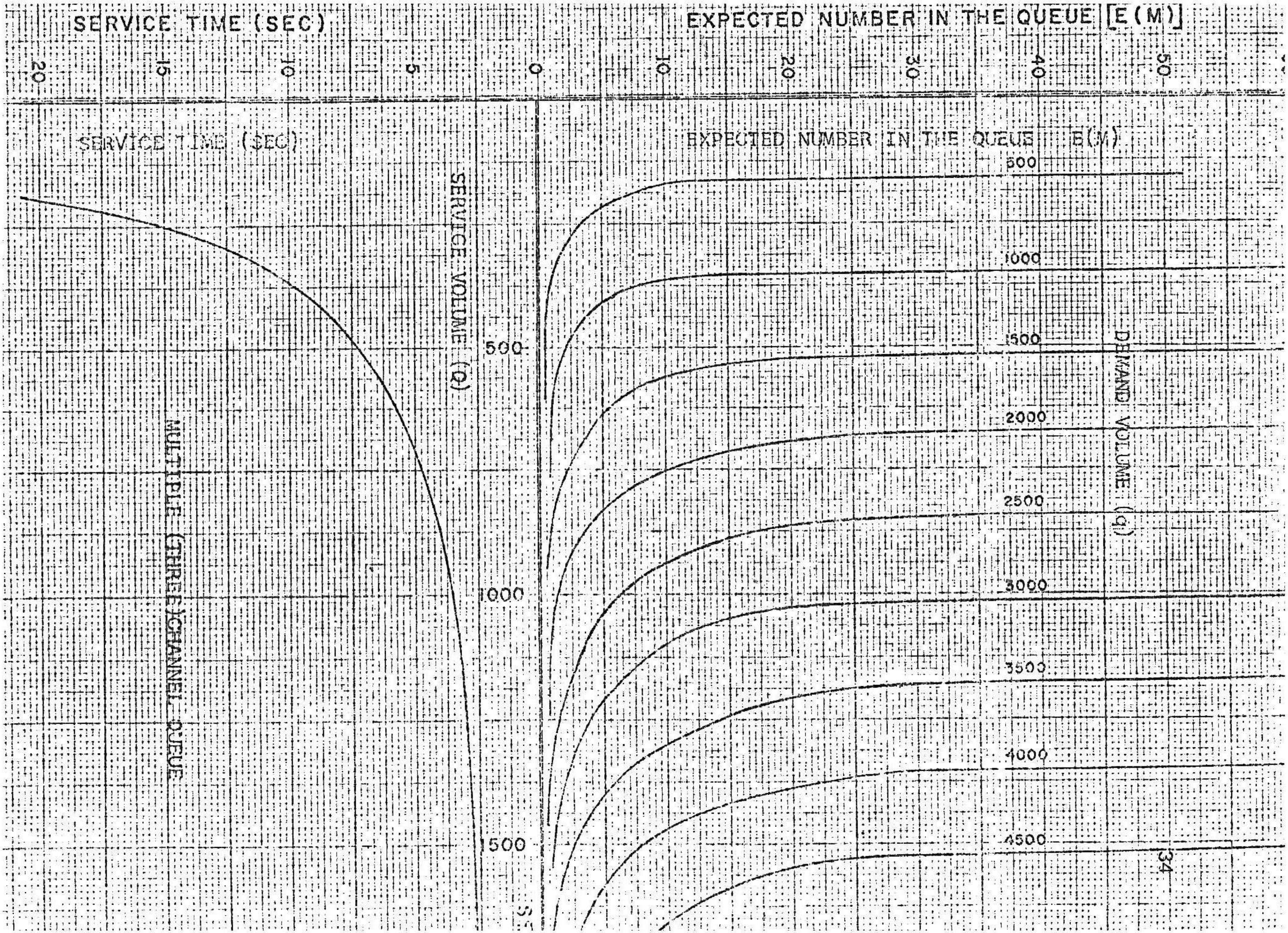
EXPLANATION OF PLATE II

Nomograph for Single Channel Queueing System


32
DEMAND VOLUME (q)
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
EXPECTED NUMBER IN THE SYSTEM [E(N)]
25
20
15
10
5
LEVEL OF SERVICE C
LEVEL OF SERVICE
500
1000
1500
SERVICE VOLUME (Q)
SERVICE TIME (SECONDS)
5
10
15
20
SINGLE CHANNEL QUEUE

EXPLANATION OF PLATE III

Nomograph for Multiple (Three) Channel Queueing System


SERVICE TIME (SEC)
EXPECTED NUMBER IN THE QUEUE [E(M)]
20
15
10
5
0
10
20
30
40
50
SERVICE TIME (SEC)
EXPECTED NUMBER IN THE QUEUE E(M)
SERVICE VOLUME (Q)
500
1000
1500
MULTIPLE (THREE)CHANNEL QUEUE
DEMAND VOLUME (q)
500
1000
1500
2000
2500
3000
3500
4000
4500
34

parameters of arrival rate, service rate, average service time and expected number in the system. The lines denoting level of service were plotted by solving the following equations for various demand volumes:

Level of service "C" $$0.3 = 1 - \sum_{x=0}^{k} \frac{m^x e^{-m}}{x!}$$

Level of service "B" $$0.1 = 1 - \sum_{x=0}^{k} \frac{m^x e^{-m}}{x!}$$

where:

m = demand volume
K = service volume.

Entering the nomographs with an average service time, the capacity at a given level of service was readily determined.

For the null alternative, the single channel nomograph was utilized and the capacities of the three tollbooths were added together. At a level of service "C" the capacity was determined to be 1900 vph and the maximum capacity 2200 vph. These figures were below the capacity developed from the previous model so an iteration of the queueing model was necessary considering improvements.

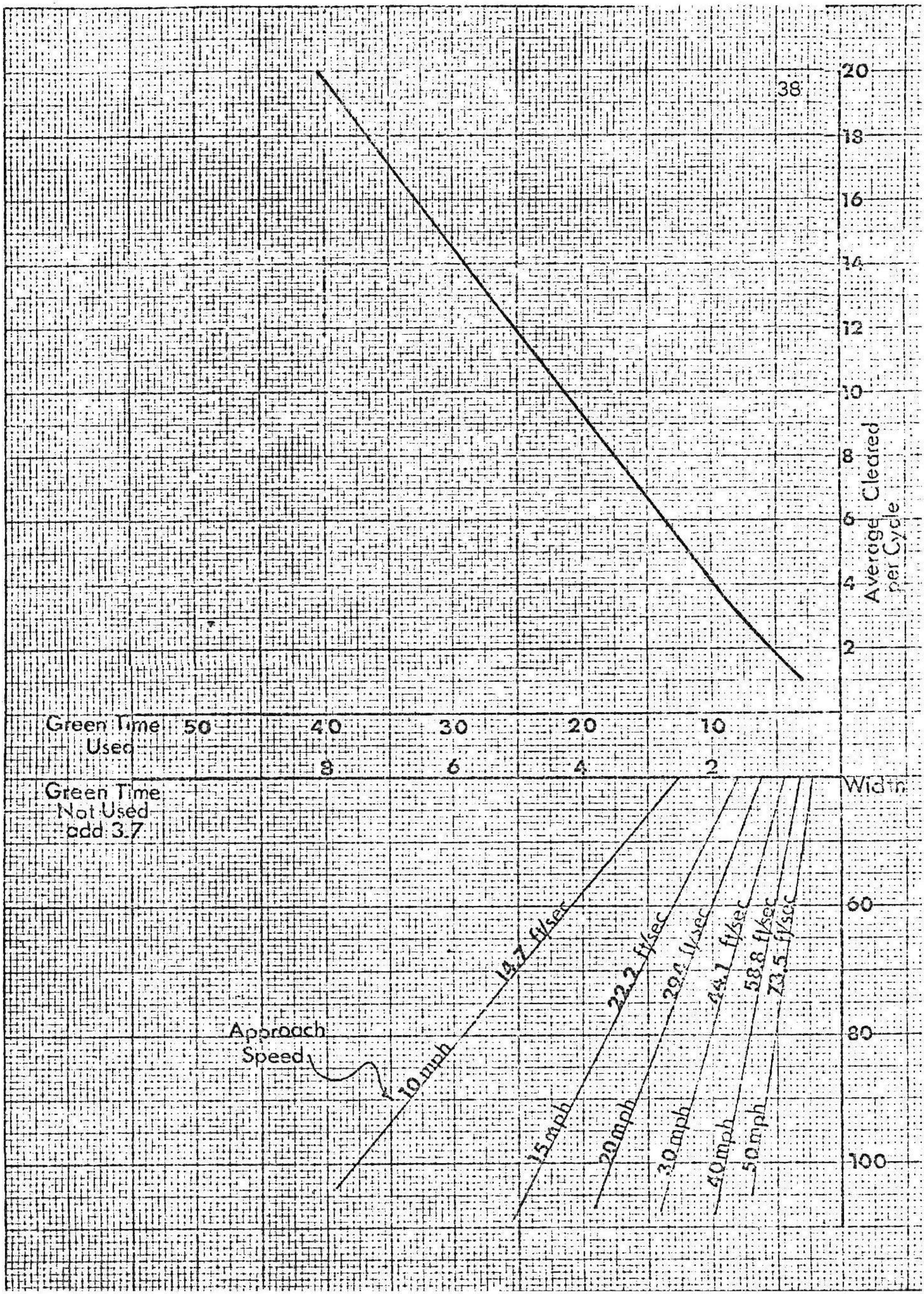
Developing reduced service times through the use of automatic coin collectors and lengthening the third tollbooth lane to accommodate longer queues was the first improvement considered. Assuming that each tollbooth would handle one-third of the volume and the average service time was lowered to 3.5 seconds during the peak hour, which is about the minimum average time that could be realized, a capacity of 2550 vph at level of service "C" and maximum capacity of 2800 vph was determined from the multiple channel nomograph. However, this again did not provide the desired capacity so another iteration was necessary.

The next economical improvement would be the removal of the tollbooths. This would have required a change in the model utilized since it would become a free flow system. Assuming that tollbooths were a requirement, the next improvement was the addition of tollbooths and lanes. The addition of two lanes and tollbooths on the bridge, providing four tollbooths per direction, would be the practical limit without construction of a new bridge. Assuming each tollbooth would take one-fourth of the volume and an average service time of 3.5 seconds, the capacity at level of service "C" was found to be 3400 vph and the maximum capacity 3700 vph. This figure was below the expected range of volumes and the removal of the tollbooths would become a necessity for the next iteration. Removing the tollbooths changed the model to free flow and the capacity for the improved six-lane bridge would be somewhat lower than the six-lane freeway but above the minimum 4000 vph at level of service "C".

Continuing to the intersection model, the nomographs shown in Plates IV and V were utilized to determine capacities for specific movements. Entering the bottom graph of the first nomograph with the distance to clear the

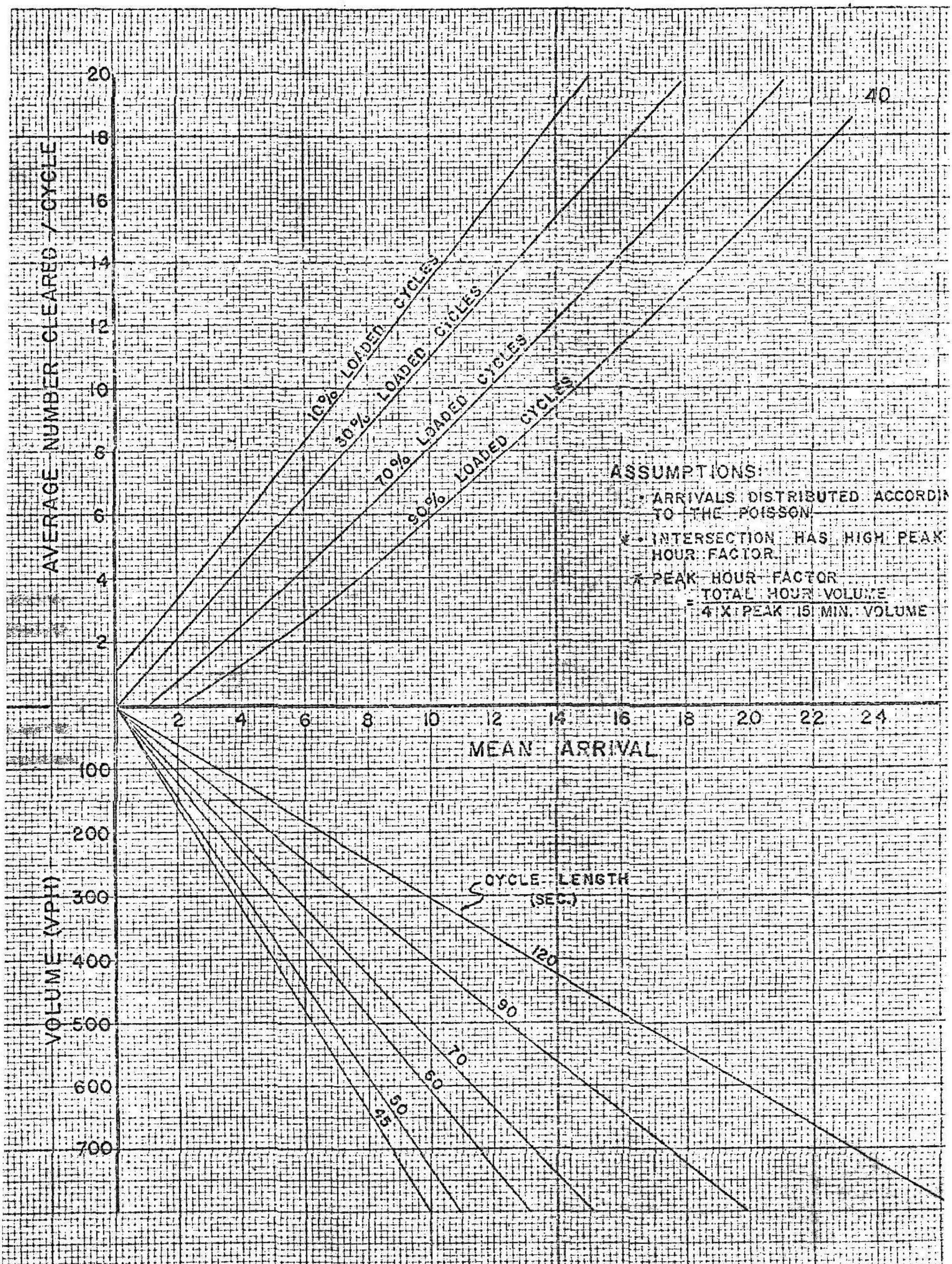
EXPLANATION OF PLATE IV

Nomograph for Intersection Analysis


38
20
18
16
14
12
10
8
6
4
2
Average Cleared per Cycle
Green Time Used
50
40
30
20
10
8
6
4
2
Green Time Not Used add 3.7
Width
60
80
100
14.7 ft/sec
22.2 ft/sec
29.4 ft/sec
44.1 ft/sec
58.8 ft/sec
73.5 ft/sec
Approach Speed
10 mph
15 mph
20 mph
30 mph
40 mph
50 mph

EXPLANATION OF PLATE V

Nomograph for Intersection Analysis


AVERAGE NUMBER CLEARED / CYCLE
VOLUME (VPH)
MEAN ARRIVAL
10% LOADED CYCLES
30% LOADED CYCLES
70% LOADED CYCLES
90% LOADED CYCLES
40
ASSUMPTIONS:
ARRIVALS DISTRIBUTED ACCORDIN
TO THE POISSON
INTERSECTION HAS HIGH PEAK
HOUR FACTOR.
PEAK HOUR FACTOR
= TOTAL HOUR VOLUME / 4 X PEAK 15 MIN. VOLUME
CYCLE LENGTH
(SEC.)
120
90
70
60
50
45
20
18
16
14
12
10
8
6
4
2
2
4
6
8
10
12
14
16
18
20
22
24
100
200
300
400
500
600
700

intersection and the average approach speed, the green time not utilized can be deducted from the actual green time at the intersection. Entering the top graph of the same nomograph with the reduced green time, the average number of vehicles clearing the intersection may be determined. Entering the second nomograph with the average number of vehicles cleared and selecting the correct level of service (or per cent of loaded cycles) and cycle length will determine the capacity of the movement. For turning movements, a reduction factor of 1.3 for right turns and 1.6 for left turns (3) was utilized to correct the volume. This procedure may be reversed to determine the proper green time for a specified demand volume.

The first step was to evaluate the existing intersections with present volumes to determine the level of service for each movement. The theoretical capacities were obtained by using an approach speed of 25 mph. The evaluations are shown in Table 7.

Movement	Pres. Serv. Level	Distance to Clear (ft)	Green Time Used (sec)	Avg. Cleared (veh)	Acceptable Capacity (vph)	Max. Capacity (vph)
SIXTH STREET						
N	C	65	48.4	24	1740	2200
N-E	F	40	49.2	25	720	850
S	B	65	48.4	24	1740	2200
S-E	C	55	48.7	3	75	160
E	B	100	29.2	14	520	750
E-S	C	40	31.2	15	420	610
E-N	B	75	30.1	15	340	490
FIFTH STREET						
N	C	65	42.4	20	2160	2850
N-E	B	--	No Sig.	--	1200	1500
S	C	65	42.4	20	1450	1900
S-W	B	45	43.1	21	580	800
W	B	115	34.7	17	620	870
W-N	C	50	36.9	18	510	710
W-S	C	65	36.4	18	410	570

Table 7. Capacity Analysis of Existing Intersections.

From the analysis it was determined that the volume that could be taken off the bridge was only 1450 vph at an acceptable level of service and 1800 vph maximum. The existing conditions allowed 2590 vph to enter the bridge under desirable conditions and 3520 maximum. However, because the signalized intersections on South Broadway only released two blocks of traffic at one time, this entering capacity is reduced to about 2300 vph desirable and 2770 vph maximum. This brought the system to its first breakdown with the environment. This existing volume of 1450 vph from the south became a controlling factor.

Using the 1990 predicted volumes, the Kansas City Transportation Department utilized a computer program to develop predicted directional volume assignments. Updating their information led to the hourly volumes shown in Fig. 7.

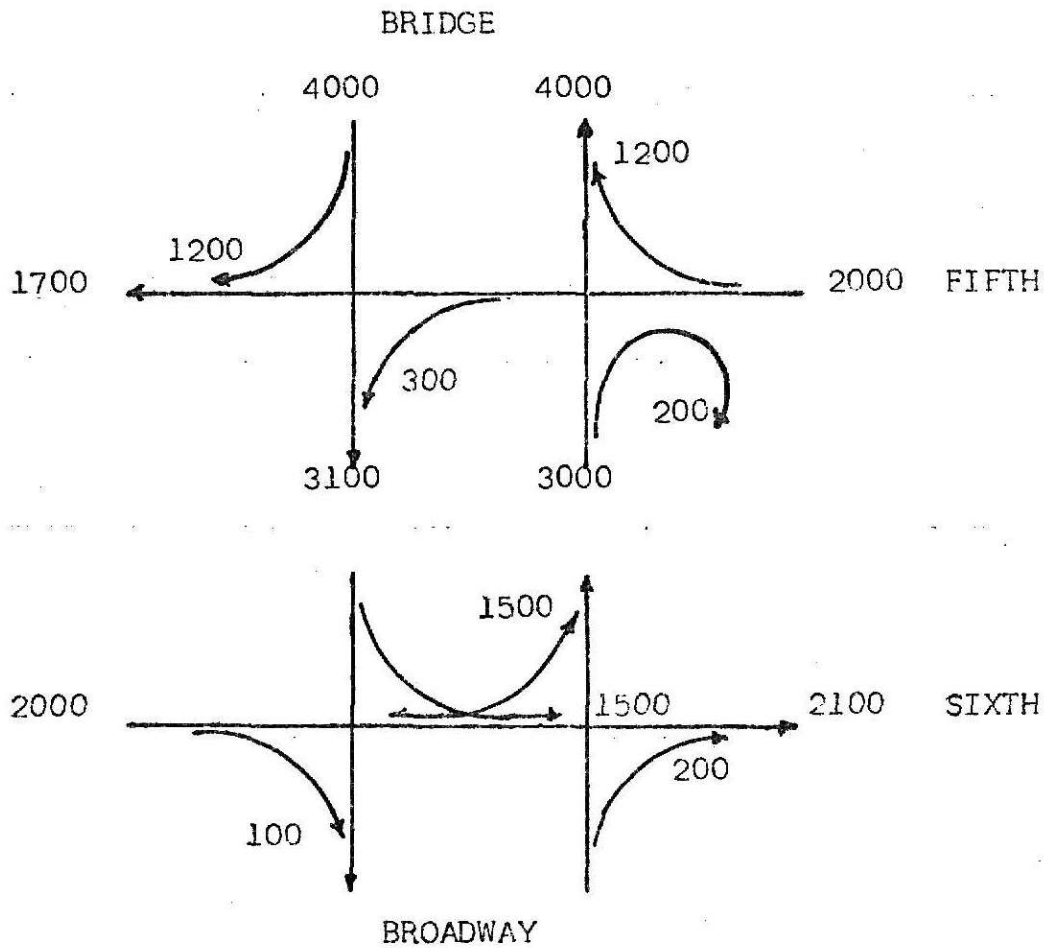


Figure 7. Future Volume Assignments.

As was seen from the existing demand volumes, the conflicting left turn movement at Sixth was the most pressing demand that could not be handled. A cycle or phase change would not improve the capacity to the extent necessary, so the first improvement considered was the addition of a separate right hand reverse lane which would make the two intersections operate as a parclo-A interchange. Additionally, the bridge ramps would be widened to three lanes and two extra lanes added to the overpass between Fifth and Sixth. With these improvements, the intersections could handle an input of 3700 vph onto the bridge. The other movements could be handled but at a lower level of service than desired.

The next improvement considered was a complete reconstruction of the intersections with four lanes leading to and from the bridge, eliminating other northern access, four lanes in each direction on the freeway overpass, and a two-lane direct-access ramp for southbound traffic turning east on the freeway. This would handle less than 2900 vph at an acceptable level of service from the bridge or 3700 vph at maximum capacity. The inputs onto the bridge would be adequate to handle the anticipated volume and all other movements would be adequately served.

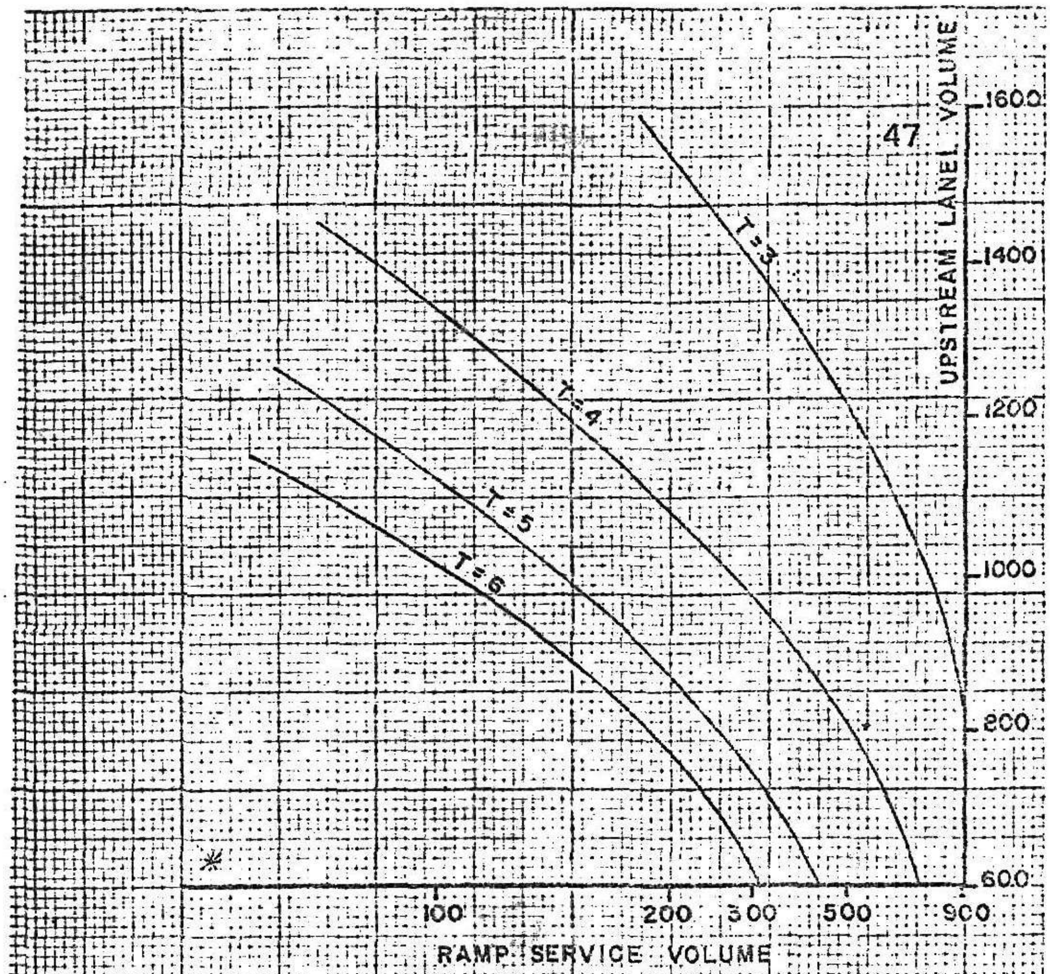
As was noted before, the existing signalization south of this network limits the volume of traffic that can be put into or taken from the Sixth Street intersection to 1450 vph in each direction. Until this part of the environment system can be improved, the capacity of the improved intersections will be lowered.

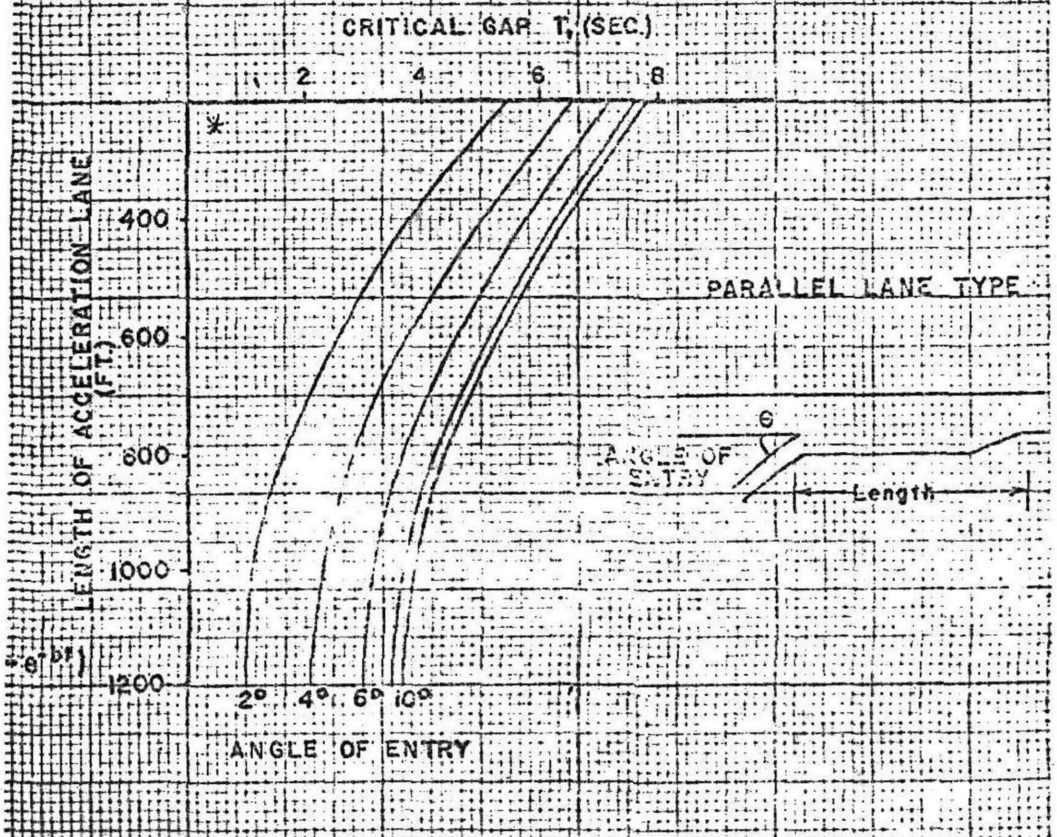
To investigate the other interfaces with the environment, i.e. ramp access to the freeway, the nomograph in the Highway Capacity Manual (Fig. 8.2) and the nomograph shown in Plate VI were utilized (4,6). The existing freeway consists of six lanes; however, there are so many access ramps that the two outside lanes are only used for merging. The predicted volume on this freeway is 3700 vph in each direction, which is little more than the present volume.

Assuming a small angle of entry and a fairly long acceleration lane, it was apparent that the freeway would operate at almost maximum capacity and could not accept more than 500 vph from the ramps. This would make the queues on the ramps build up until they backed into the intersections, creating a breakdown at that point in the system. Again, the environment limited the capacity at which the intersection portion of the Broadway network could operate. The freeway would have to be improved to an eight-lane facility, with reduced volumes, to permit the intersection to operate at an acceptable level of service. Although it might be possible to improve the study network to accept the predicted volume, the environment will not allow this output at the interface with the freeway. Accepting the present conditions of the environment, an iteration of each step in the evaluation process was made to determine the capacity and needed

EXPLANATION OF PLATE VI

Nomograph for Ramp Merging


UPSTREAM LANEL VOLUME
1600
1400
1200
1000
800
600
T=3
T=4
T=5
T=6
100
200
300
500
900
RAMP SERVICE VOLUME


CRITICAL GAP T, (SEC.)
2
4
6
8
LENGTH OF ACCELERATION LANE (FT.)
400
600
800
1000
1200
PARALLEL LANE TYPE
θ
ANGLE OF ENTRY
Length
2°
4°
6°
10°
ANGLE OF ENTRY

improvements that the environment would allow. The intersection was the controlling section and the capacity at level of service "C" was determined to be 1500 vph on the north-south network with a maximum capacity of 1900 vph. This is only a small increase over the present volume utilizing the network; however the improvements would not be unreasonably expensive and should provide adequate service for several years. An investigation of the Intercity Freeway and other possible corridors should dictate any further improvements to the Broadway network.

CONCLUSIONS

Through the work done on this report, the methods employed seem to offer a very sound approach to a variety of capacity problems.

The systems approach utilized in this report is a process that is being used more and more in the engineering field. The science and knowledge of physical and material problems is not enough to cope with the goals of the public. Formalizing the process of problem-solving through a systems approach has enabled the incorporation of social values, political considerations, and other non-physical impacts into the "nuts and bolts" proposals.

Had the problem of providing capacity alone on the Broadway network been considered without regard to the rest of the environment, an expensive facility that could not be fully utilized might have been the end recommendation.

While only three conditions were analyzed in this study, the systems approach lends itself well to much larger networks with any type of traffic situations. Applying probability considerations to model the conditions seemed to provide a more realistic method of analysis.

Data collection and analysis is the backbone of almost any capacity determination. The technique of time-lapse photography offers some real advantages over other methods of data collection. Since the actual traffic operations are recorded at any given time, each item of information can be analyzed in relation to the existing conditions that affect the other data to be gathered. Other methods require that the information be gathered at different time periods due to lack of equipment or manpower. The ease of operation and the limited manpower required for this technique make it well worthwhile.

Although not considered here, there are many possibilities for different observations from film analysis. To name a few:

1) Waiting time
2) Speeds
3) Space and time gaps
4) Densities
5) Parking
6) Lane changes.

If numerous surveys are to be performed, the initial investment for photographic equipment will be more than offset by the reductions of time and manpower. One drawback that must be considered is the inability to locate the camera at the optimum position for observation. However, the increasing use of aerial photography and the possibilities of the helicopter may well eliminate this drawback. Another limitation would be inclement weather.

From the data observed and utilizing the approach outlined in this report, the following was concluded:

1) When the new airport is opened, the two-lane portion of North Broadway should be improved to a

separated four-lane facility to provide comparable service to that which exists on the southern portion at the present time.

2) Provision of separate green time (approximately 6 seconds) for southbound left turns at the intersection of Sixth and Broadway would eliminate the poor level of service for that movement and still retain acceptable levels for the other directional volumes.

3) The Broadway network is operating at or near the design capacity due to the interface of the south portion with the Intercity Freeway and the Central Business District. Other improvements to the network would not improve the overall operation of the system until this interface can be simplified and improved.

4) Consideration should be given to the elimination of divertable traffic that presently utilizes the Intercity Freeway and capacity improvements should be investigated for the Central Business District Loop.

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A SYSTEMS APPROACH TO THE CAPACITY ANALYSIS OF NORTH BROADWAY AVENUE AND BRIDGE, KANSAS CITY, MISSOURI

by

JAY EUGENE FAULCONER

B.S., Kansas State University, 1963

AN ABSTRACT OF A MASTER'S REPORT

submitted in partial fulfillment

of the requirements for the degree

MASTER OF SCIENCE

Department of Civil Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1969

ABSTRACT

It was the purpose of this work to examine the existing traffic conditions and evaluate various improvements to increase the capacity on Broadway Avenue from the two intersections connecting with Interstate 70, across the bridge, and north to the intersection with U.S. Highway 71.

Two basic methods were utilized in this study:

1) A systems approach to capacity evaluation utilizing stochastic methods where possible, and
2) Data collection and analysis through the use of time-lapse photography.

The systems approach was utilized as a method to provide a more realistic approach to the evaluation of capacity on a specific roadway network when considering the overall impact of the environment as well as the impacts on the environment.

The initial objective of the inquiry was to determine what improvements to the network could be made to increase the capacity to predicted 1990 volumes. The network was considered as one large subsystem of the larger system of major trafficways. The network was then broken down into three smaller subsystems and analytical models were described for each system. The three models utilized were:

1) Free flow--Highway Capacity Manual determination
2) Tollbooths--Queueing theory determination
3) Intersections--Stochastic determination.

While there were many improvements that would increase the capacity of the network, nothing less than major reconstruction on the bridge and intersections would enable this network to handle the predicted volumes. More important than this, however, is that the results showed that major improvements would be of little value until the Intercity Freeway, Interstate 70, was improved, as the interface at the end of the network is operating nearly at maximum capacity at the present time.

The data collected served as the initial input to determine the capacity of the existing network and as an indication of the validity of the use of the queueing model. Although the data obtained through photography did not verify all the theoretical distributions, the method proved most beneficial as an inexpensive and rapid means of gathering extensive data for various situations.