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ACCUMULATIVE PROBABILITY MODEL FOR AUTOMATED NETWORK TRAFFIC ANALYSES

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16. Abstract

This report presents an illustration of the accumulative probability model which is applicable to ground transportation systems where high-speed and close headways are a performance requirement. The paper describes the model, illustrates it with a hypothetical problem, and then applies it to a network route that was actually configured in a Dual mode system study.

The paper also describes and gives a listing of a computer program called Dual which is used to illustrate the model and simulate various route structures.

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PREFACE

The work described herein was performed as a part of an overall program effort at the Transportation Systems Center, Department of Transportation. The purpose of this work phase was to assess the economic and technical feasibility of dual mode transportation systems in the urban environment. This program was sponsored by the Department of Transportation through the Office of System Engineering of the Assistant Secretary for Systems Development and Technology.

The report presents illustrations of the accumulative probability model, which was derived from a previous work concerning automated network traffic management (Report No. DOT-TSC-OST-72-7, "Automated Guideway Network Traffic Modeling").

Acknowledgment is given to Miss Sho Chu, a student at Northeastern University, for contributing her expertise in mathematical model development and for performing the necessary computer calculations which are contained herein.

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1. INTRODUCTION

This report presents illustrations of the AP (Accumulative Probability) model that was derived in reference 1 for the analyses of automated guideway-network traffic-management problems relating to ground-transportation systems such as dual mode and personal rapid transit. The AP model is especially applicable to systems where high-speed and close headways are performance requirements. The model as illustrated in this report is in conjunction with a deterministic reservation scheme such as that discussed in references 2 and 3. The specific illustrations pertain to that of determining system capacity and utilization for different user-service levels and system-service time intervals at various demand rates. The approach taken was to couple the AP model to a discrete event simulator, so that a first-order functional parametric analysis could be performed and the results verified. The effort led to the development of a digital computer program called DUAL that was used to perform the necessary calculations and simulations. DUAL can analyze many to one traffic routes, that is, many origins to one destination. It also provides a tool for analyzing a limited number of system configurations and for evaluating the effect of station spacing with respect to queue time. A listing of the program is contained in the appendix.

2. BACKGROUND

In a dual mode system, vehicles are capable of operating on conventional streets in a manual mode, and also, on specially constructed guideways in a completely automated mode. For an urban area, such a system could have many advantages over a rapid transit or conventional highway system since it has many features of a door-to-door high-speed transportation system. The high speed is maintained along the automated guideway portion by either a synchronous or asynchronous longitudinal control system.

The work presented in this paper is predicated on a synchronous system in which a vehicle-velocity profile has been determined for the automated guideway and is maintained by some means of control such as a fixed reference. Vehicles can be thought of as occupying hypothetical slots or cells along the automated guideway. The length of a slot is chosen in accordance with the system's safety, headway, and reliability requirements. The slots move along the guideway in groups called "cycles." The time a cycle travels from one point to another along the guideway can be determined from the guideway's velocity profile. The number of slots per cycle depends on the constraints of vehicle velocity, acceleration, deceleration, and ramp design. For a general discussion of dual mode concepts, see references 4 through 7.

The cycle size remains constant throughout the system for any given time interval. The merging of streams of vehicles occurs at what is termed "control" points along the guideway. At such points, vehicles either depart one cycle for another or cycles coalesce. Interchanges, junctions, and entrance-and-exit ramps are control point locations. At these points, traffic bottlenecks tend to occur. During a given time interval, the number of slots per cycle is fixed at some constant "n." This is a critical system design parameter. Consequently, a conflict could arise at control points if proper precautions are not taken.

Figure 2-1 shows an example of the merging of two cycles

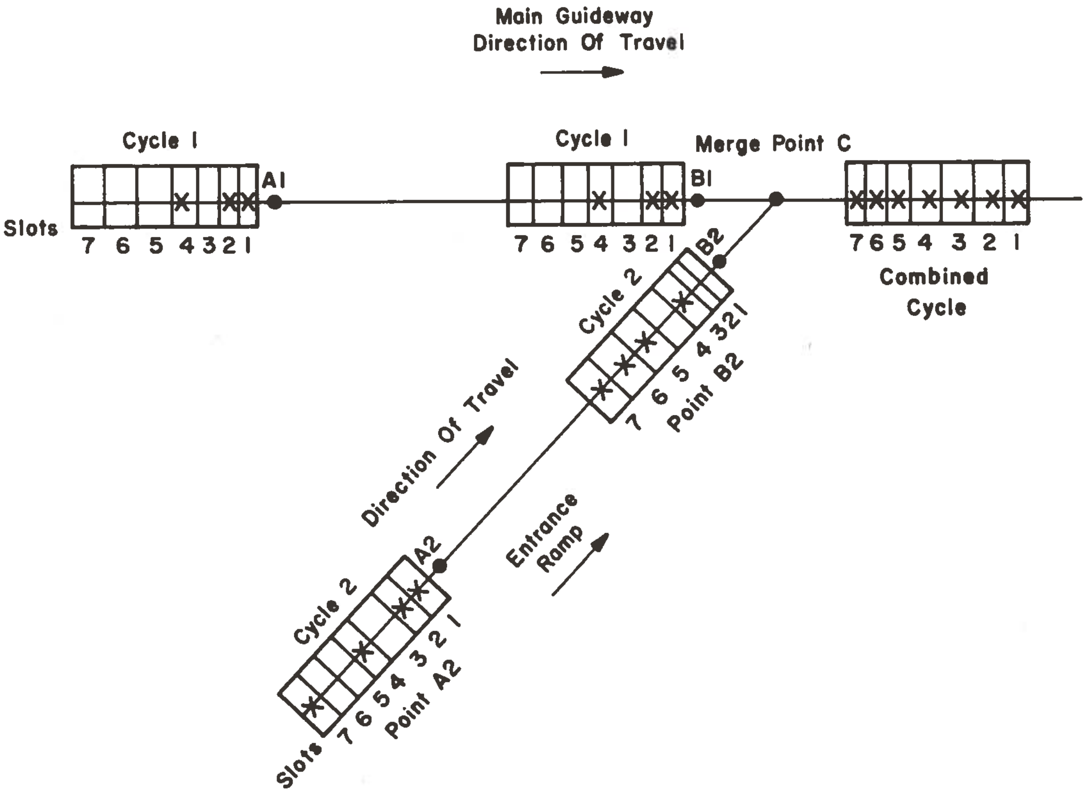

Figure 2-1 Vehicle Merging

between the main stream and an entrance. At points A1 and A2 which are equally distant from the merge point C, the system detects the position of vehicles within cycles by means of a wayside computer. In the example shown in figure 2-1, slots 1, 2, and 4 are occupied at point A1 on the main guideway, on the entrance ramp at position A2, slots 1, 2, 4 and 7 are occupied. The total number of vehicles in both cycles does not exceed the cycle limit. However, the vehicles must be rearranged within the cycles so that at point C a collision will not occur. This is accomplished at point B2 on the entrance ramp where the vehicle occupancy is shifted from slots 1, 2, 4, and 7 to slots 3, 5, 6, and 7. Therefore, at point C the merge can be successfully accomplished. The task of preventing more than a specified number of vehicles to occupy slots within cycles at control points, so that guaranteed passage will occur without queuing or "waiting" lines forming within the network is the function of a "deterministic" reservation system. In such a system, vehicles are not permitted on the automated guideway until passage can be reserved through all the control points contained along the desired route. Consequently, vehicles must wait at the entrance ramps until passage is obtained.

3. TRAFFIC MANAGEMENT

Traffic management in an automated transportation system is concerned with solving the problem of moving vehicles and people through stations and along guideway sections based on certain system constraints such as headway, space, safety, queuing, passenger reservation procedure, and user service level. These variables are usually formulated into an operating strategy that is employed to regulate traffic flow. Some of the various theories and procedures that can be devised are discussed in reference 8. Table 3-1 excerpted from that reference gives a concise comparison between quasi-synchronous and synchronous strategies which represent the most common state-of-the-art development. Regardless of which operating strategy is employed, the problem of determining system capacity still remains. Reference 9 presents some generalized mathematical models for various traffic management strategies. Based on this work, it appears that a guideway capacity model can be derived as follows:

Let the guideway be divided into p sections such that $\beta=1,\ldots,p$. Every section of the guideway can be generated by its capacity which depends on the vehicle and guideway design, control capabilities, and passenger comfort, etc. The capacity is defined as the maximum flow which can pass through this particular section.

Define $\phi_{j\beta k}(t)$ as the flow of vehicles passing through the $\beta^{\underline{th}}$ section from station j to station k in each route. If the travel times, t, remain constant with the assumption that there are no other routes between station j and station k, then, $\phi_{j\beta k}(t) = \phi_{jk}(t-\gamma_{j\beta})$. Thus the vehicle flow of the $\beta^{\underline{th}}$ section can be expressed by an inequality, such as

$$\phi_{\beta} \geq \sum_{j=1}^{p} \sum_{k=1}^{p} \phi_{jk}(t-\gamma_{j\beta}),$$

where ϕ_{β} which is defined as the capacity of the $\beta^{\underline{th}}$ section is the upper limit on the section flow.

To satisfy this constraint is very important, especially for the guideway sections directly downstream of a merge point, in order to assure safe merging and congestion-free operation. The AP model is a specific application of this general model. The AP model calculates the upper boundary limit of guideway sections based upon network traffic management constraints.

TABLE 3-1. CONTROL-STRATEGY COMPARISON SUMMARY

Variable	Quasi-synchronous Slot Non-Reservation Control (Historic Demand Modified)	Synchronous Slot/Cycle Deterministic Control
Network Capacity	Approaches deterministic strategy. Limited in terms of historic demand data and feedback-loop delays from critical intersections	Should have highest utilization measured in terms of vehicle throughput
Network Synchronization	Synchronization of slots not mandatory except during merging process. Vehicles allowed to slip without limit except at merge	An absolute must for entire system. Vehicles must occupy given cycles
Network Failure	Should be capable of link shutdown and start up without "serious problems" because of lack of synchronous requirements	Could be detrimental to system. No known convenient way to shut down and start up failed link because of synchronous requirements
Vehicle Performance	Vehicle can "slip slot" except during merge	Must maintain cycle always. Slowest vehicle in terms of maneuvering, input to cycle-size selection
Inter- and Ramp-maneuvering Design	Ramp length function of speed must allocate space for "some" queueing or provide abort lane	Ramp length minimum function of cycle size, speed, and vehicle maneuverability. No queuing space required
Entrance-Station Design	Function of input demand, throughput restrictions and processing time. First come first served	Function of input demand, output distinction of vehicle, and processing time. Design can accommodate serving vehicles on basis of destination rather than first come first served
Exit-Station Design	Station should allow "some" queueing area to accommodate unpredictable stochastic arrival of vehicles	Exit-station throughput can be accommodated with reservation scheme
Computer and Control Regulation	Central control system must apportion trip budgets to terminals to minimize queue problem at merges	Central control system must have ability to process reservation requests from terminals in real time, keep track of cycle occupancy, and maintain system synchronization
Passenger Convenience	Passenger-waiting time could be "split" among entrance station, guideway, and exit station. Prior knowledge of "exact" trip time not known	All passenger-waiting time done at entrance station. Once reservation requested, trip and waiting time are known.

4. ACCUMULATIVE PROBABILITY MODEL

For deterministic systems, reference 1 addressed the problem of "How much space must be allocated in a specific time interval for a given demand rate at a desired user service level along a particular route?"

4.1 TIME INTERVAL

In most urban ground transportation systems, traffic congestion usually varies with the time of day and peaks around what is commonly referred to as "rush" hours. Upon studying a particular system, it often becomes apparent that the heaviest traffic along a particular route occurs within some specified time interval (Δt). Estimates of such time intervals are essential to the design of any new system since they represent the heaviest system load or "worst" case.

4.2 DEMAND RATE

Repeated observations of Δ t will reveal that the number of vehicles occurring within this interval is not constant, but forms what is referred to as a "distribution" of arrivals. This arrival pattern can be converted into a probability distribution function. The Poisson distribution is commonly used to describe arrival rates. Reference 10 contains a discussion on probability distributions. Reference 11 gives Molina's Poisson tables, and reference 12 discusses arrival rates. If the probability of exactly K arrivals in $T = \Delta t$ is denoted by $P_K(T)$, the Poisson distribution is expressed by the equation:

$$P_K(T) = \frac{(\lambda\ T)^K}{K!} \cdot e^{-\lambda T}, \qquad (4\text{-}1)$$

where the parameter λ is a constant that indicates the mean arrival rate and is often referred to simply as the demand rate. The average rate of arrivals in the time interval T is given by λT. A typical graph of the Poisson distribution with a mean value of

$\lambda T=4$ is shown in figure 4-1.

4.3 USER-SERVICE LEVEL

The user-service-level parameter is one of the most difficult to estimate. Reference 9 suggests that it should be expressed as a set of technical, economic, and political constraints. However, no objective function has yet been developed that will yield an easy answer. A discussion of what constitutes a satisfactory level of service is beyond the scope of this paper. It is sufficient for purposes herein to say that the level of service provided must satisfy users. In an urban dual mode system, it could be quite likely that the potential user of such a system will have an alternate route to follow other than the automated guideway. Consequently, the user service level must be high if the system is to be successfully operated. At the network entrances, it is the probability of entering the system within a specific time interval with a guaranteed reservation. Being a probability estimate denoted herein as P, it ranges in value from 0 to 1. The higher the value, the greater the probability and the less chance of queuing. Values of 0.7, 0.8, and 0.9 were used in the examples contained herein.

4.4 ROUTES

A route is composed of one destination point which could be an exit or another control point such as an intersection and one or more guideway entrances, which are referred to simply as control points in the remainder of this paper. For each such control point along a given route, an associated λ and P value can be established.

One of the most promising models that was developed in reference 1, is the AP model given as

$$P_j = F(X:\lambda) = \sum_{K=0}^{X_j} \frac{\left(\sum_{i=1}^{j} \lambda_i T\right)^K}{K!} \cdot \exp -\left(\sum_{i=1}^{j} \lambda_i T\right) \qquad (4\text{-}2)$$

where P_j = the user service level for the j^{th} entrance or control

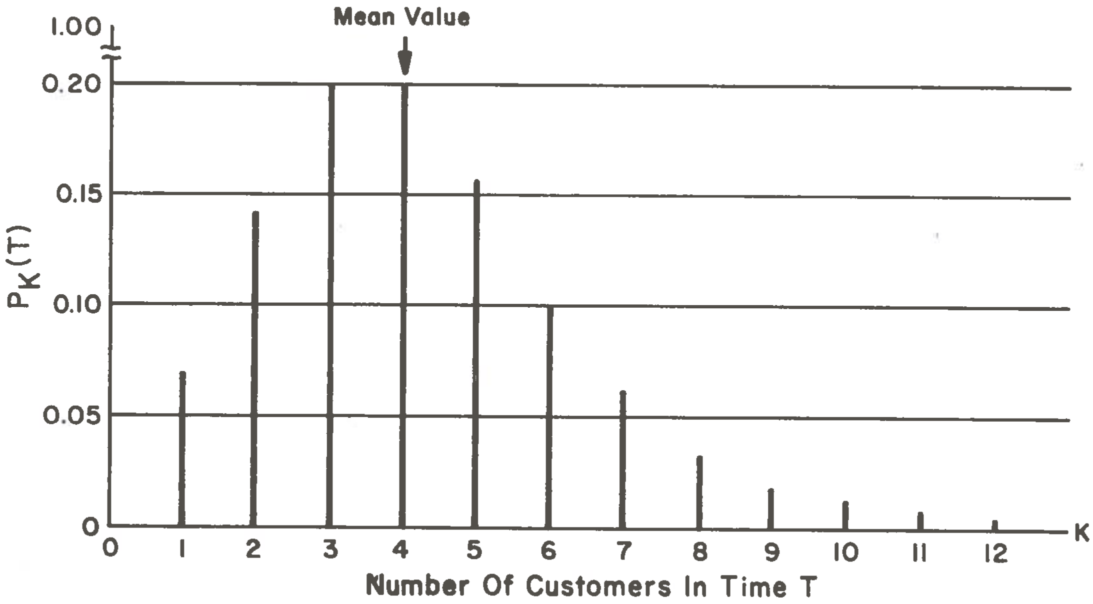

Figure 4-1 Poisson Arrival Distribution

point, λ_i = the demand rate at the j^{th} entrance or control point, where i=1,..., j, T=Δt = the specified time interval, and X_j= traffic control limit or metering limits that must be imposed at each j^{th} control point to assure that the desired user-service-level is met. The main advantage of the AP model is that it calculates control limits at each control point that can be used to regulate traffic flow and control queuing.

For example, if all the P_j values were set equal, then queuing at the control points could be normalized.

The related input variables names for program DUAL are as follows:

PROB(I) = P_j , and
DEMAND(I) = λ_i .

Appropriate X values (control limits) are calculated for each control point along the route.

Some of the input variables are listed below: (For a complete listing, see the appendix.)

VEL = Average vehicle velocity,
SLDIST = Slot distance in feet,
DIST(I) = Distance in miles between control points, and
SEC = System service time.

The system service time (SEC) is the time it takes to "load" vehicles onto the guideway. For example, a hypothetical system might be able to load 50 slots in 30 seconds. This represents a capacity of 6,000 slots per hour. To comply with a low cycle size number, the 50 slots could be divided into 10 cycles (5 slots each) and reservations could be made by groups. This group-cycle-slot concept is a means of keeping the cycle size small for merge control purposes. The desirability for small cycle size is given in reference 13. This paper elaborates on the effects of varying system service time which actually corresponds to the T parameter in formula (4-2).

5. DESCRIPTION OF DUAL

The computer program DUAL is written in FORTRAN to be translated by a FORTRAN G compiler. It requires approximately 200K of core to execute. A Monte Carlo technique is used in the simulation. Independent random numbers are generated for each control point. The first set of random numbers generated is used in conjunction with the arrival distribution to determine the number of arrivals that will occur in the time interval at each control point. From this set of numbers, a probability distribution of arrival sequences is derived, and a second set of random numbers is generated so that the arrival sequence can be determined. This procedure can be used to simulate vehicles arriving at the network entrances in a random sequence and requesting passage through control points along their route. A "warmup" period is allotted to the random number generator before any numbers are actually used. The simulated network is brought to a stable state by not recording any data until the network has been completely loaded at least once. This means that at least one group of users from the entrance farthest from the destination point has arrived at the destination point before any statistics are collected. Only interval units between control points are considered. As users request space, the reservation procedure checks to see if space is available at that particular entrance in the current time interval. If it is, then that interval's reservation total is increased. If it is not, then the next interval is checked and so on until space is found and a reservation can be made. Consequently, the simulation program can be considered as a discrete group or interval simulator as opposed to most automated guideway simulators which are discrete vehicle simulators. The groups move through the network. Tables are provided to keep tracks of the necessary statistics at each control point.

A theoretical system capacity is computed from the given average vehicle velocity (VEL) and slot-size distance (SLDIST). This value is compared to the capacity calculated using the AP model. If the theoretical capacity is exceeded it is noted on the printed output. However, the analysis continues and the regular output is provided.

Program features include:

a. IBM 360 system,
b. FORTRAN IV G compiler,
c. NAMELIST for input data,
d. 200K of core required,
e. Program operate under IBM time-share option (TSO).

6. CAPACITY CURVES

Program DUAL was used to calculate the curves contained in figures 6-1 through 6-4, which relate the system capacity to the user service level at various system service times for specific demand rates along a particular route. Slot size and vehicle speed are variables that depend on safety constraints and operating policies. They are used to calculate system capacity, as follows:

$$\text{Capacity} = \frac{\text{5280 (feet per mile) x speed (miles/hour)}}{\text{Slot size (feet)}} .$$

For example, if a hypothetical route had an accumulative peak demand of 5,500 and a system constraint of 6000 vehicles per hour, figure 6-3 shows a 0.7 user–service level could be established for a 30-second service time; a 0.8 value for a 60-second interval; and a 0.9 value for a 120-second interval. The user-service level gives the probability of entering the system within a specific service time interval. It can be considered as a confidence limit. One minus the user–service level equals the probability of being queued.

Tables 6-1 through 6-3 give the queue distribution for various service times by demand rate. The percentage given represents the percentage of users who had to wait a given number of service time intervals before being served. The tables also contain the total number of users served and the percentage of empties which was determined from a point between the destination and the nearest control point to it. The distance between control points was sufficiently long so that it did not influence the queuing. Five control points were used in the simulation and the demand rate was equally divided among them.

From inspection of these tables, it appears that station spacing should be equal in travel time to approximately twice the service time interval. Therefore as service time decreases, station-spacing requirements decrease but system-capacity requirements increase.

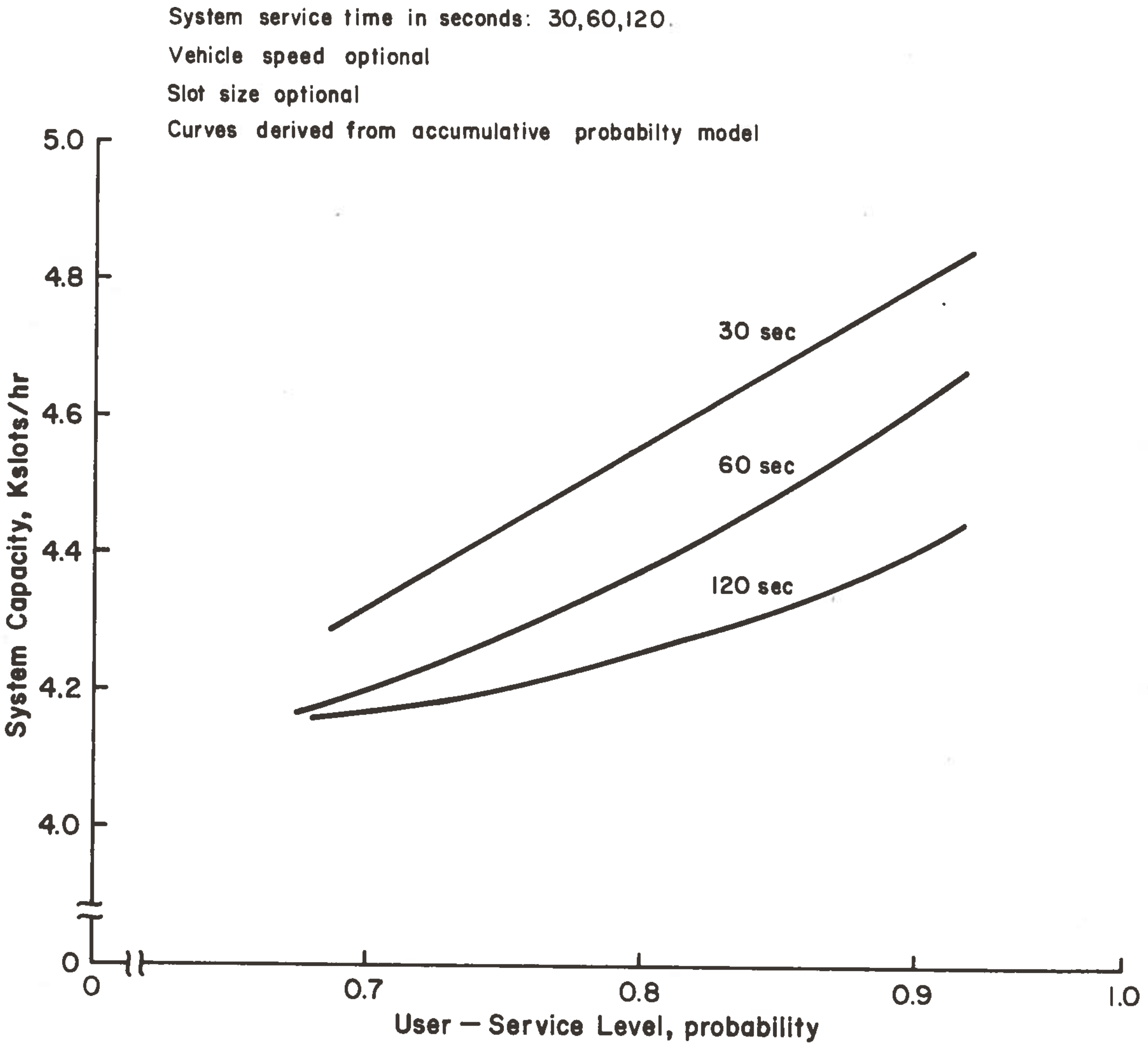

Figure 6-1 System Capacity Versus User Service Level (4000 Vehicles per Hour)

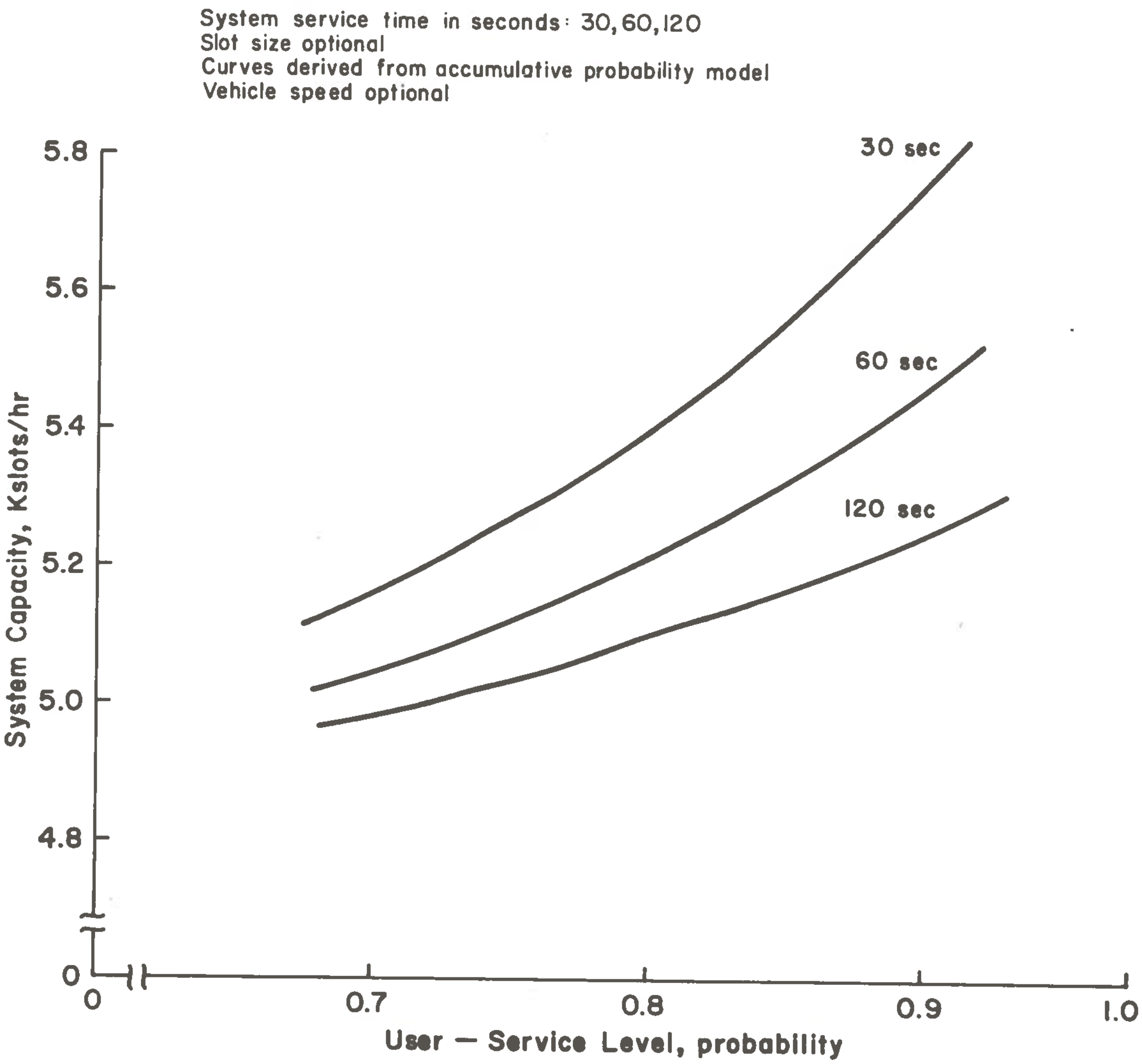

Figure 6-2 System Capacity Versus User-Service Level (4800 Vehicles per Hour)

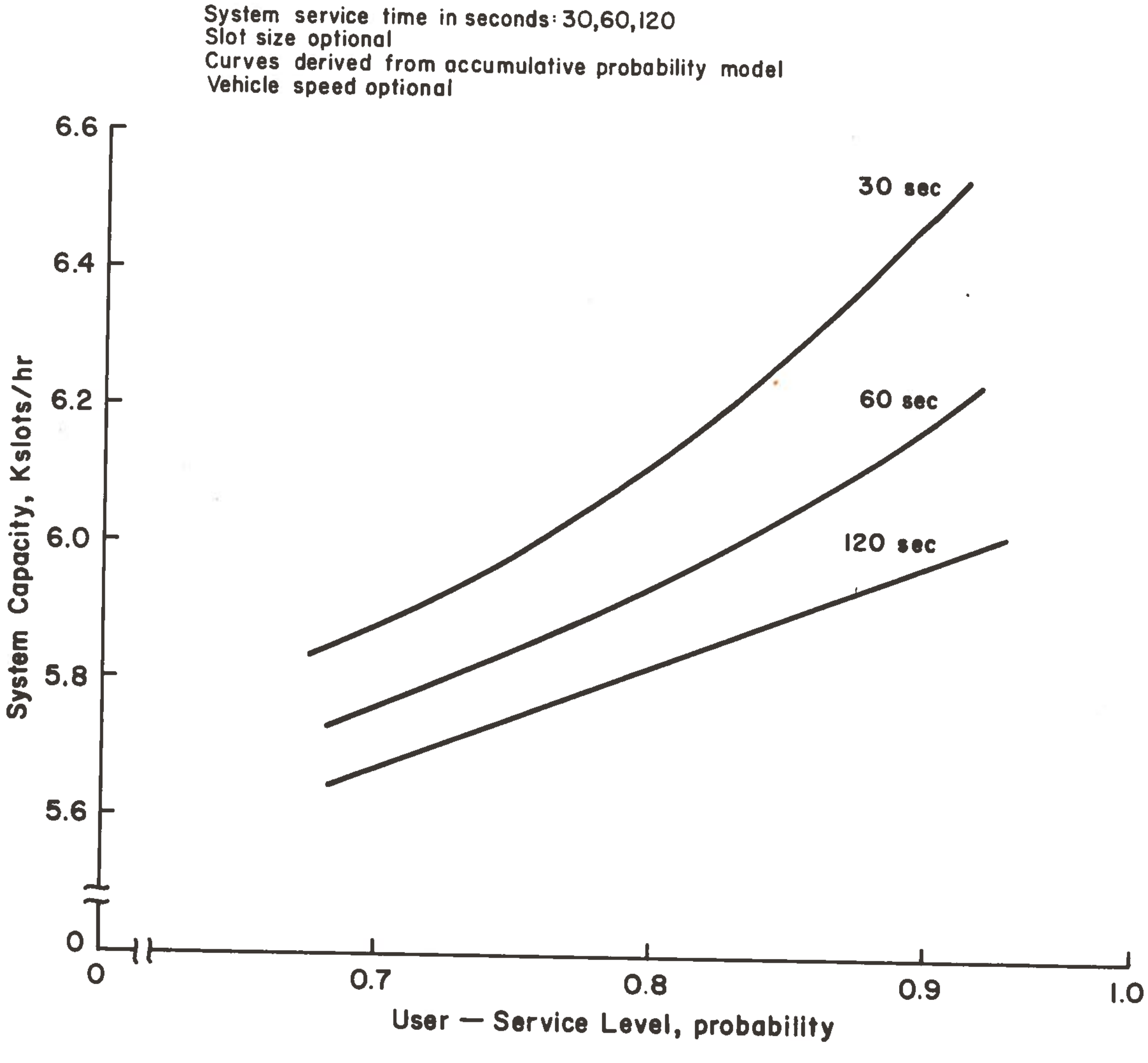

Figure 6-3 System Capacity Versus User-Service Level (5500 Vehicles per Hour)

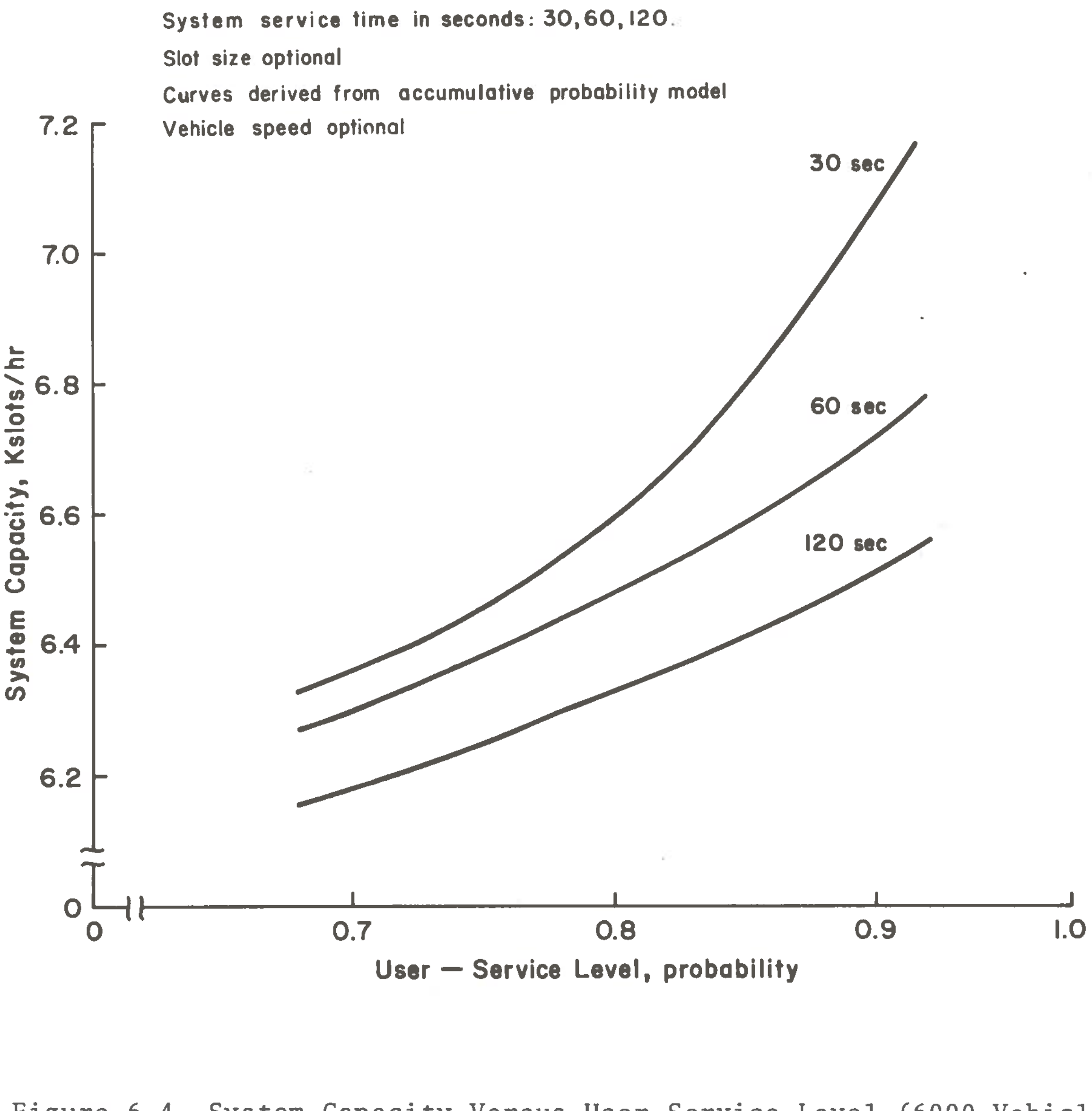

Figure 6-4 System Capacity Versus User-Service Level (6000 Vehicles per Hour)

TABLE 6-1. PERCENTAGE OF QUEUE FOR A SYSTEM SERVICE TIME OF 30 SECONDS

FOR: 5 ENTRANCES
DISTANCE: 6 MILES BETWEEN ENTRANCES
DEMAND: 4000 VEH/HR

Sec ob.	Interval 1 30	2 60	3 90	4 120	5 150	6 180	7 210	Empties	Total Served
	%	%	%	%	%	%	%	%	
0.7	24.46	5.87	1.76	1.73	0.54	0.20	0.33	4.32	9570
0.8	18.26	3.79	1.8	0.33				7.74	9866
0.9	9.64	0.22						10.82	10147

DEMAND: 4800 VEH/HR

Sec Prob.	Interval 1 30	2 60	3 90	4 120	5 150	Empties	Total Served
	%	%	%	%	%	%	
0.7	27.66	9.43	3.00	0.78	0.007	4.05	12587
0.8	17.18	1.87				7.08	12828
0.9	8.10	0.30	0.02			11.35	13138

DEMAND: 5500 VEH/HR

Sec Prob.	Interval 1 30	2 60	3 90	4 120	5 150	Empties	Total Served
	%	%	%	%	%	%	
0.7	26.00	7.10	0.86	0.04		4.08	15232
0.8	16.04	0.90	0.01			6.92	15440
0.9	5.77	0.09				10.80	15732

DEMAND: 6000 VEH/HR

Sec Prob.	Interval 1 30	2 60	3 90	4 120	5 150	Empties	Total Served
	%	%	%	%	%	%	
0.7	24.52	4.97	0.91	0.33	0.02	3.67	17063
0.8	15.57	1.11				6.35	17260
0.9	6.23	0.09				11.36	17677

TABLE 6-2. PERCENTAGE OF QUEUE FOR A SYSTEM SERVICE TIME OF 60 SECONDS

FOR: 5 ENTRANCES
DISTANCE: 6 MILES BETWEEN ENTRANCES
DEMAND: 4000 VEH/HR

Sec Prob.	Interval 1 60	2 120	3 180	4 240	Empties	Total Served
	%	%	%	%	%	
0.7	18.98	1.51	0.22		3.40	24508
0.8	10.60	0.13			6.73	24794
0.9	4.70				10.75	25063

DEMAND: 4800 VEH/HR

Sec Prob.	Interval 1 60	2 120	3 180	4 240	Empties	Total Served
	%	%	%	%	%	
0.7	17.77	2.70	0.77	0.006	3.74	30595
0.8	9.86	0.21	0.003		6.51	30757
0.9	4.39	0.10			9.99	31050

DEMAND: 5500 VEH/HR

Sec Prob.	Interval 1 60	2 120	3 180	4 240	Empties	Total Served
	%	%	%	%	%	
0.7	17.14	0.81			3.54	35698
0.8	8.44	0.05			6.08	35862
0.9	3.56				9.28	36027

DEMAND: 6000 VEH/HR

Sec Prob.	Interval 1 60	2 120	3 180	4 240	Empties	Total Served
	%	%	%	%	%	
0.7	15.82	1.05			3.72	39503
0.8	7.82	0.12			6.08	39712
0.9	3.51	0.03			9.05	39920

TABLE 6-3. PERCENTAGE OF QUEUE FOR A SYSTEM SERVICE TIME OF 120 SECONDS

FOR: 5 ENTRANCES
DISTANCE: 6 MILES BETWEEN ENTRANCES
DEMAND: 4000 VEH/HR

Sec Prob.	Interval 1 120	2 240	3 360	Empties	Total Served
	%	%	%	%	
0.7	12.01	0.75	0.03	3.24	54624
0.8	7.24	0.20		5.08	54624
0.9	3.34	0.01		8.00	54917

DEMAND: 4800 VEH/HR

Sec Prob.	Interval 1 120	2 240	3 360	Empties	Total Served
	%	%	%	%	
0.7	8.12	0.46		4.10	65768
0.8	4.06	0.01		6.15	66085
0.9	1.81			8.63	66085

DEMAND: 5500 VEH/HR

Sec Prob.	Interval 1 120	2 240	3 360	Empties	Total Served
	%	%	%	%	
0.7	2.69	0.01		6.53	73824
0.8	1.20			8.74	73824
0.9	0.45			10.84	73824

DEMAND: 6000 VEH/HR

Sec Prob.	Interval 1 120	2 240	3 360	Empties	Total Served
	%	%	%	%	
0.7	1.05			9.90	77709
0.8	0.56			11.89	77709
0.9	0.19			14.22	78088

Figures 6-5 through 6-7 show the percentage of empty slots as a function of the user-service level for various demands at a constant system service time. The differences in the percentage of empties among the 30-and 60-second-system service time-interval demand curves are not as pronounced as they are among the demand curves for the 120-second-system time interval. The percentage of empties subtracted from 100 yields the percent utilization along the route measured from a point between the destination and the closest control point to it.

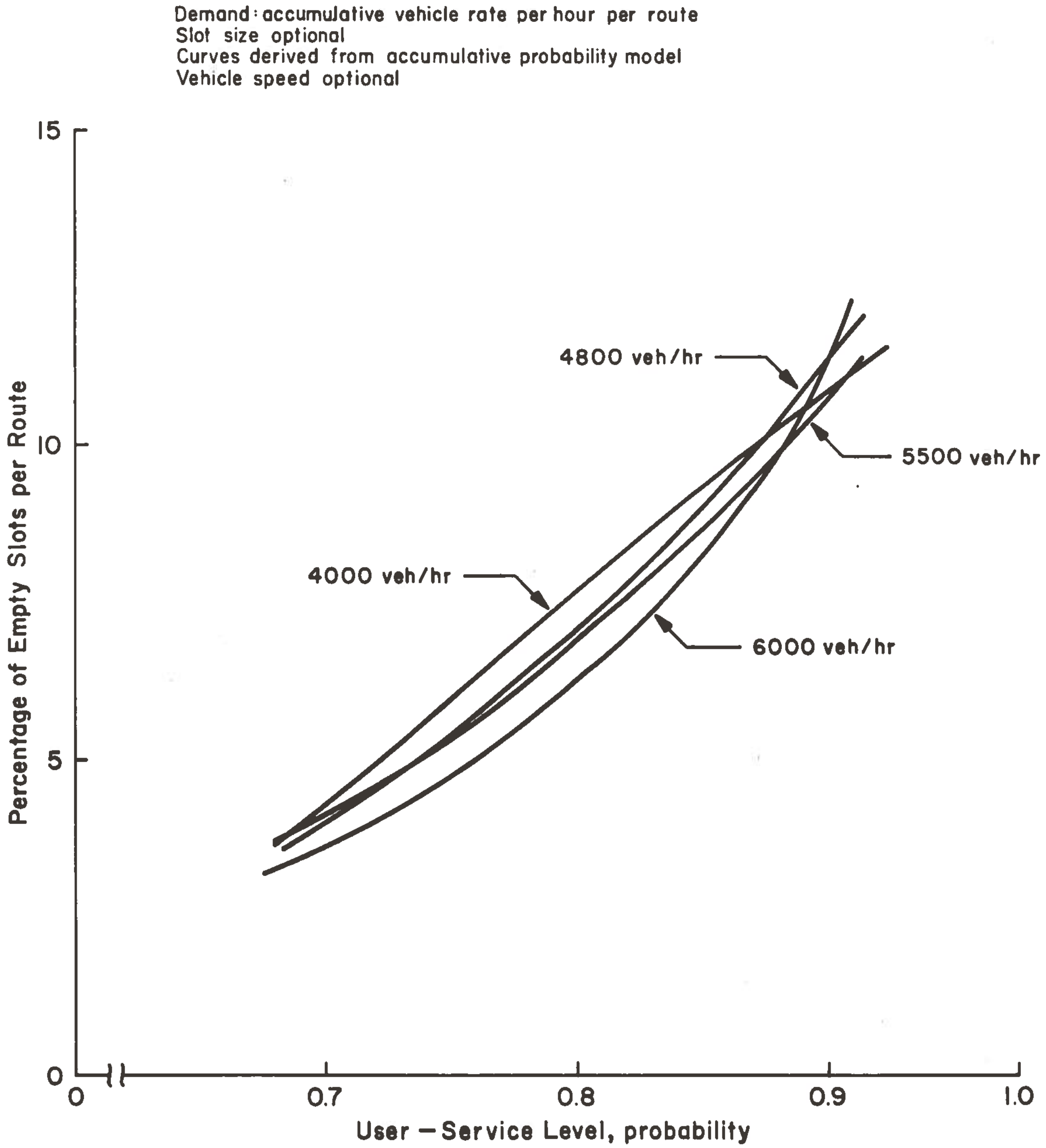

Figure 6-5 Percentage of Empty Slots per Route Versus User-Service Level (30 seconds)

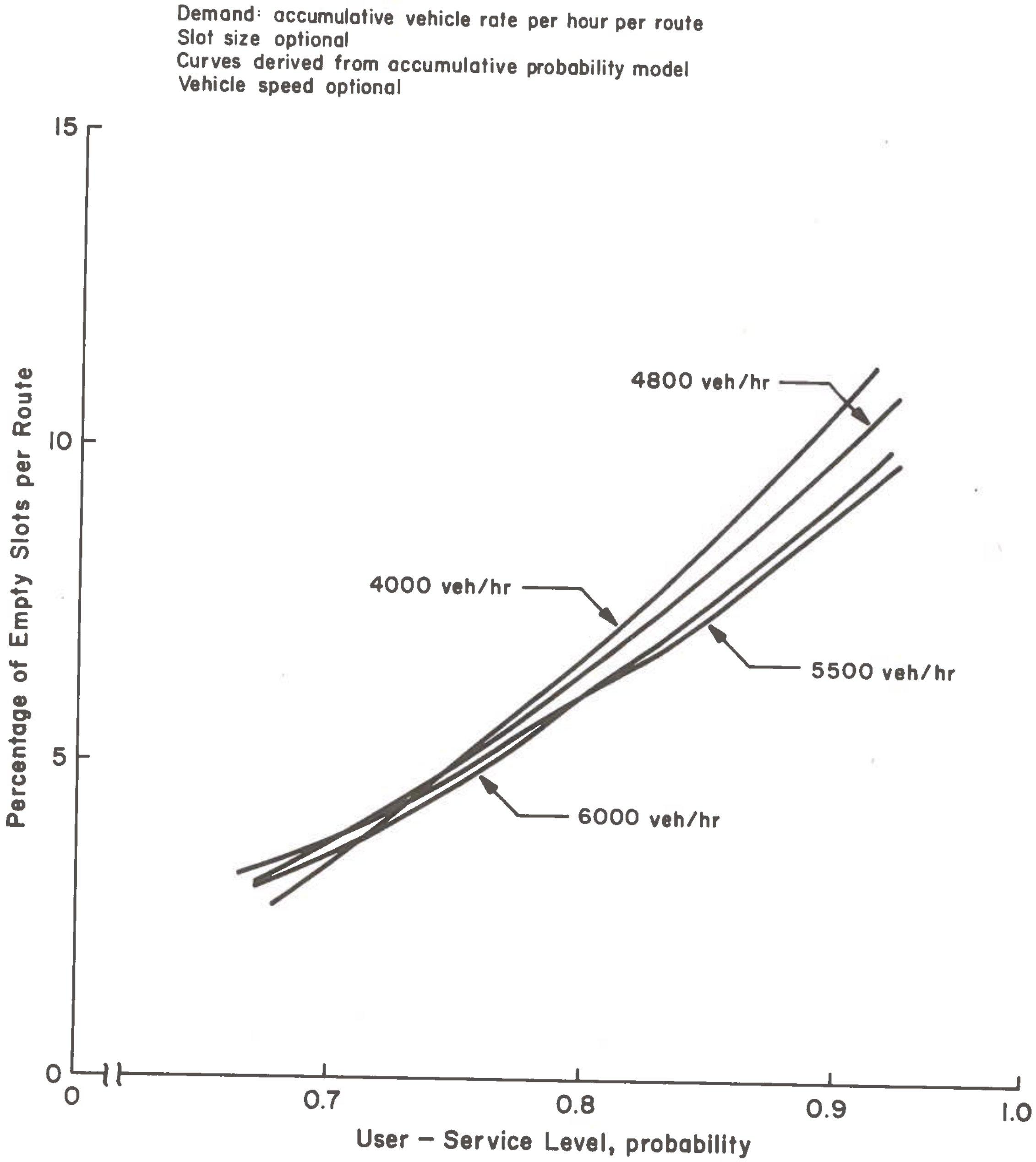

Figure 6-6 Percentage of Empty Slots per Route Versus User-Service Level (60 seconds)

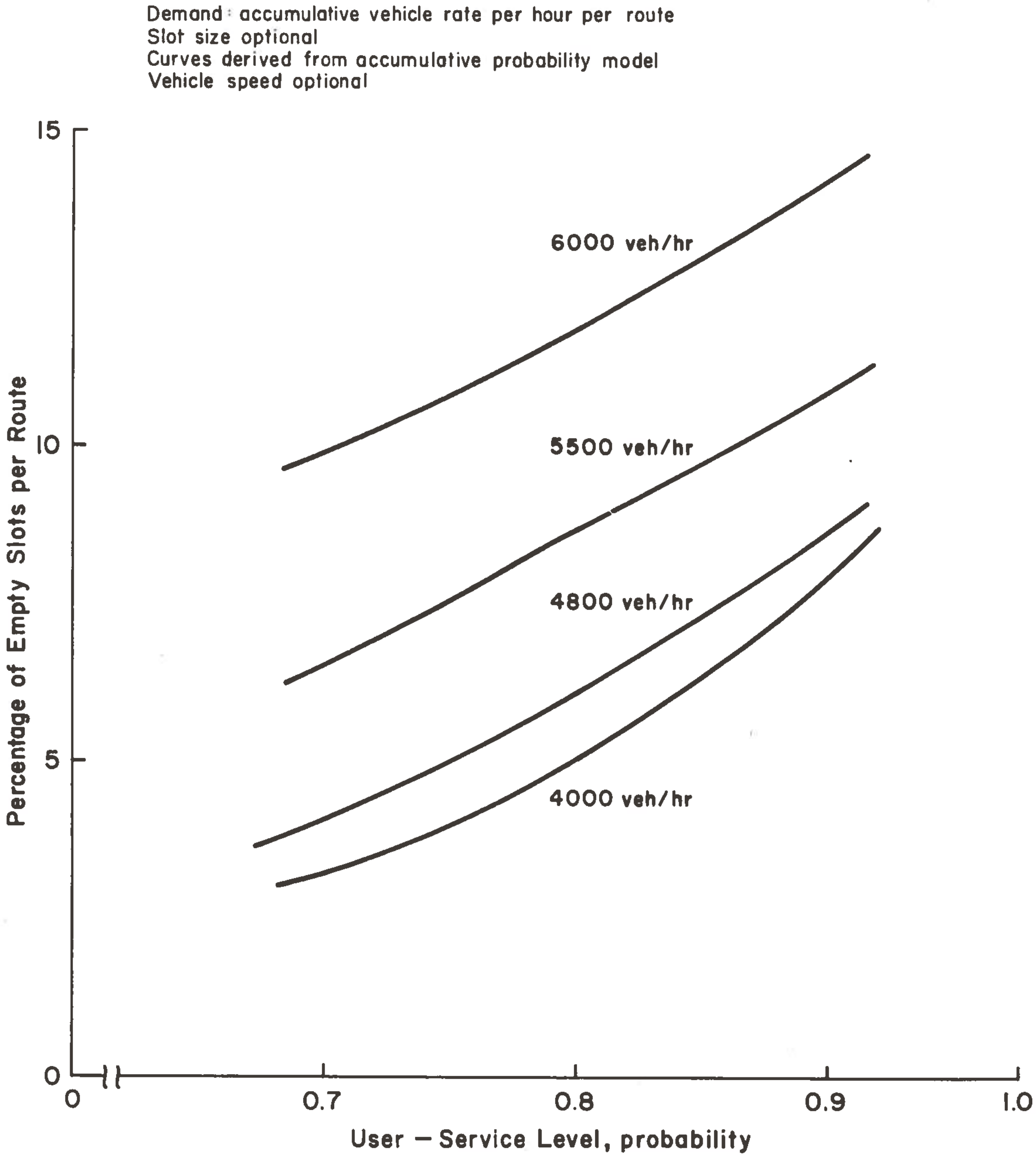

Figure 6-7 Percentage of Empty Slots per Route Versus User-Service Level (120 seconds)

7. DUAL OUTPUT

The following hypothetical problem illustrates the use and output of the computer program DUAL.

Problem: Find the required control limits and calculate the queue distribution at each of five DUAL mode entrances spaced 6 miles apart with a demand of 1100 vehicles per hour, per entrance, a user level of service equal to 0.7 per entrance, a system service time of 60 seconds, an average velocity of 60 mph, and a slot distance of 53 feet.

The output of DUAL for this problem is given in figures 7-1 and 7-2. Block 1 in figure 7-1 shows the program introduction which is printed out at the beginning of each computer run. Block 2 shows the computer input data. Block 3 is a data check printout of the input variable values. Figure 7-2 gives the statistical output for this problem. INTERVAL SIZE gives the number of slots required in the service time interval. LIMITS gives the control limits required at each entrance starting at the farthest one away from the destination point to regulate the traffic flow in accordance with the user level of service. TOTAL SERVED equals the total of users serviced on the route. The PERCENTAGE OF EMPTIES equals the percentage of empty slots. The statistics for each entrance or control point is then given as follows: SERVED equals the number of users served at that particular control point. QUEUE equals the number of users who had to wait the corresponding extra service time interval.

For comparison to an unregulated or stochastic system, figure 7-3 shows what would happen if no control limits were imposed. In this case, almost all the queuing occurs at entrance 5, which is the entrance closest to the destination point. What has happened is that the "up stream" entrances have taken all the slots away from those down-

```
          THIS IS THE DUAL MODE FUNCTIONAL PERFORMANCE ANALYSES
          PLEASE FOLLOW MY INSTRUCTIONS
          WRITE &DATA IN COLUMN 2
          LEAVE A SPACE AND INPUT THE FOLLOWING
          VARIABLES IN EQUATION FORMAT
OCK 1     DEMAND(I)=DEMAND IN VEHICLES/HOUR
          DIST(I)=DISTANCE BETWEEN CONTROL POINTS IN MILES
          STARTING FROM DESTENATION POINT
          VEL=VEHICLE AVERAGE SPEED IN MILES/HOUR
          SLDIST=SLOT DISTANCE IN FEET
          PROB(I)=USER LEVEL OF SERVICE EXPRESSED AS
          A DECIMAL FROM 0 T0 1
          NE=NUMBER OF CONTROL POINTS MAX. IS 5
          END INPUT BY SPACE&END
          EXAMPLE OF SAMPLE INPUT DATA
          &DATA DEMAND(1)=1500,DIST(3)=3,SLDIST=53, &END
          ENTER NEW DATA
OCK 2      &DATA NE=5,DIST=5*6.,DEMAND=5*1100,PROB=5*.7,SEC=60., &END
          &DATA
          NE=          5,DIST=  6.0000000     ,  6.0000000     ,  6.0000000     ,  6.
          0000000     ,  6.0000000     ,SLDIST=  53.000000     ,PROB=
           0.69999999     , 0.69999999     , 0.69999999     , 0.69999999     , 0.69999
LOCK 3    999     ,DEMAND=  1100.0000     ,  1120.0000     ,
            1100.0000     ,  1100.0000     ,  1100.0000     ,VEL=  60.000000     ,LIM=
                     0,              0,              0,              0,              0,
          SEC=  60.000000     ,NWRITE=             0,CYC=              0,SAMP= 0.0
             ,FINISH= 0.0
          &END
```

Figure 7-1 DUAL Output

```
         INTERVAL SIZE=  96LIMITS=        20        39        58        77
     96

         TOTAL SERVED =     35698


         PERCENTAGE OF EMPTIES       3.54

         SERVED =     6883

              INTERVAL      QUEUE      ENTRANCE      1
                  1            1343
                  2             100

         SERVED =     6948

              INTERVAL      QUEUE      ENTRANCE      2
                  1             975
                  2               6

         SERVED =     6728

              INTERVAL      QUEUE      ENTRANCE      3
                  1             914
                  2              34

         SERVED =     6795

              INTERVAL      QUEUE      ENTRANCE      4
                  1             740

         SERVED =     8344

              INTERVAL      QUEUE      ENTRANCE      5
                  1            2147
                  2             151
END OF PROBLEM
ENTER NEW DATA
```

Figure 7-2 Statistical Output -- Control Limit

```
 &DATA NE=5,DIST=5*6.,DEMAND=5*1100,PROB=5*.7,SEC=60.,LIM=5*96,
 CYC=96, &END
&DATA
NE=           5,DIST=  6.0000000      ,  6.0000000      ,  6.0000000      ,  6.
0000000     ,  6.0000000      ,SLDIST=  53.000000     ,PROB=
 0.69999999     , 0.69999999     , 0.69999999     , 0.69999999     , 0.69999
999     ,DEMAND=  1100.0000     ,  1100.0000     ,
  1100.0000     ,  1100.0000     ,  1100.0000     ,VEL=  60.000000     ,LIM=
          96,          96,          96,          96,          96,
SEC=  60.000000     ,NWRITE=            0,CYC=           96,SAMP= 0.0
   ,FINISH= 0.0
&END
   31    24    18    12     6



       INTERVAL SIZE=  96LIMITS=       96       96       96       96
   96

       TOTAL SERVED =    35698

       PERCENTAGE OF EMPTIES       3.60

       SERVED =     6883

           INTERVAL      QUEUE      ENTRANCE      1

       SERVED =     6948

           INTERVAL      QUEUE      ENTRANCE      2

       SERVED =     6728

           INTERVAL      QUEUE      ENTRANCE      3

       SERVED =     6795

           INTERVAL      QUEUE      ENTRANCE      4
                1             2

       SERVED =     8344

           INTERVAL      QUEUE      ENTRANCE      5
                1             2420
END OF PROBLEM  2              746
ENTER NEW DATA  3               98
                4               19
```

Figure 7-3 Statistical Output -- No Control Limit stream. This could lead to customer dissatisfaction, especially if it were known in the early planning stages when the urban area users have an opportunity to review the proposed new system.

Figure 7-4 shows how a slight adjustment of the control limits in this particular example more evenly distributes the queues among the entrances. The total percentage of users who were queued at each entrance is as follows:

Entrance No.	Queued Percent
1	20.96
2	24.66
3	18.51
4	22.01
5	23.03

```
 &DATA NE=5,DIST=5*6.,DEMAND=5*1100.,PROB=5*.7,SEC=60.,LIM(1)=20,
 LIM(2)=38,LIM(3)=57,LIM(4)=75,LIM(5)=96,CYC=96, &END
&DATA
NE=            5,DIST=  6.0000000     ,  6.0000000     ,  6.0000000     ,  6.
0000000     ,  6.0000000     ,SLDIST=  53.000000     ,PROB=
 0.69999999     , 0.69999999     , 0.69999999     , 0.69999999     , 0.69999
999    ,DEMAND=  1100.0000     ,  1100.0000     ,
  1100.0000     ,  1100.0000     ,  1100.0000     ,VEL=  60.000000     ,LIM=
         20,          38,          57,          75,          96,
SEC=  60.000000     ,NWRITE=              0,CYC=              96,SAMP= 0.0
   ,FINISH= 0.0          ,MERG=              0,            0,
         0,           0,           0
&END
   31    24    18    12     6




         INTERVAL SIZE=  96LIMITS=      20       38       57       75
96

         TOTAL SERVED =     35698

         PERCENTAGE OF EMPTIES       3.52

         SERVED =      6883

              INTERVAL       QUEUE     ENTRANCE       1
                  1             1343
                  2              100

         SERVED =      6948

              INTERVAL       QUEUE     ENTRANCE       2
                  1             1664
                  2               50

         SERVED =      6728

              INTERVAL       QUEUE     ENTRANCE       3
                  1             1120
                  2              126

         SERVED =      6795

              INTERVAL       QUEUE     ENTRANCE       4
                  1             1389
                  2              107

         SERVED =      8344

              INTERVAL       QUEUE     ENTRANCE       5
                  1             1894
                  2               28
END OF PROBLEM
```

Figure 7-4 Statistical Output -- Adjusted Control Limit

8. QUEUING

Before discussing how the AP model relates to queuing theory, it is appropriate to define some of the more common queuing terms. As indicated in formula (4-1), the mean arrival rate λ in time interval T is denoted by λ T. The mean interarrival time in T equals $1/\lambda$; that is, the reciprocal of the mean arrival rate, as would be expected. The accumulative probability distribution function for interarrival times, F(t), indicates that the interarrival time is less than a particular time t, and is given by

$$\text{Prob (interarrival time} < t) = F(t) = 1-e^{-\lambda t} = 1-e^{\frac{-t}{T_a}} \qquad (8\text{-}1)$$

where T_a = mean interarrival time.

Similar to λ, the mean system service rate is often denoted by μ and the mean service time by $\frac{1}{\mu} = T_s$. The "server utilization" is denoted by ρ. It measures the fraction of time that a control point is busy. It is expressed by server utilization, $\rho = \frac{\lambda}{\mu}$ (in a no-loss single-server system).

In most queuing problems, λ and μ are given, and interest centers around determining appropriate queue parameters such as queue length and/or queue waiting times. On the other hand, the AP model tries to relate μ to λ through the user level of service, P, in formula (4-2). In other words, given a user level of service and a demand rate, it calculates a control limit which can be considered as a system service rate for a particular control point. This type of problem is quite different from the normal queuing problem. However, once the AP model yields the necessary information then queuing parameters can be estimated.

For example, consider the control limit of 20 calculated for the first entrance given in figure 7-4 as μ for a service time interval T of 60 seconds. A λ value for the first entrance is computed from the demand of 1100 per hour as $\lambda = 18.3$ per minute. Consequently, $\rho = \frac{\lambda}{\mu} = \frac{18.3}{20} = 0.92$.

Considering μ as a constant service rate not exponentially distributed, then the mean waiting line length, L_w, is given by

$$L_w = \frac{2\rho - P^2}{2\ (1-\rho)} = \frac{2 \times 0.92 - (0.92)^2}{2\ (0.08)} = 6.21 \text{ vehicles.}$$

The mean waiting line time, T_w, is given by

$$T_w = \frac{\rho}{2\mu(1-\rho)} = \frac{0.92}{2 \text{x} 20(0.08)} = 0.29 \text{ min.} = 17.25 \text{ sec.}$$

Caution must be used in trying to relate these queuing statistics derived from continuous functions to those calculated by DUAL such as given in figure 7-4. This is because DUAL does not calculate what is commonly referred to in simulation as an "event" table using interarrival times for determining the arrival of user at entrances. It does not use formula (8-1). Instead, a double Monte Carlo is employed.

The first one uses λ values calculated from the Poisson distribution with λT equal to the mean arrival <u>rate</u> in the T interval specified for the SEC. It assigns λ values to each control point. The random number generator uses a different seed for each control point. The probability distribution used in the second Monte Carlo is obtained from the λ values. For example, the probability of a user arriving at entrance E_i in the next T interval is given by $P_i = \frac{\lambda_i}{\lambda'}$, where $\lambda' = \sum_{i=1}^{N} \lambda_i$, and N = total number of entrances. λ' is determined for each T interval, and the order in which they arrive is determined by the second Monte Carlo being performed λ' times. The advantage of this double Monte Carlo procedure is that it saves computer storage and execution time. The disadvantage is that the resulting statistics are given in discrete time intervals and average values, if of interest, are difficult to determine. Nevertheless, the statistics presented give a good approximation of the queues.

9. APPLICATION

To illustrate DUAL, a hypothetical route was randomly selected from a dual-mode network that was previously configured during a cost-benefit analysis that used the Boston metropolitan area in one of the scenarios. The route structure is given in figure 9-1. R1, the route of interest, begins in Woburn, a suburb of Boston, and ends in the North End of Boston. E1 through E5 represent control points. E1, E2, and E4 are at entrance points, whereas E3 and E5 are at the interchanges of routes R2 and R3. The demands given at these control points represent the added traffic flow on R1 going to Boston. Users who would travel into Boston on R1 from R2 and R3 would not be queued at E3 or E5 since they represent interchanges, but, if queuing were required, it would take place at their respective points of origin. The demand rates shown are for daily peak-hour, personal-vehicle traffic.

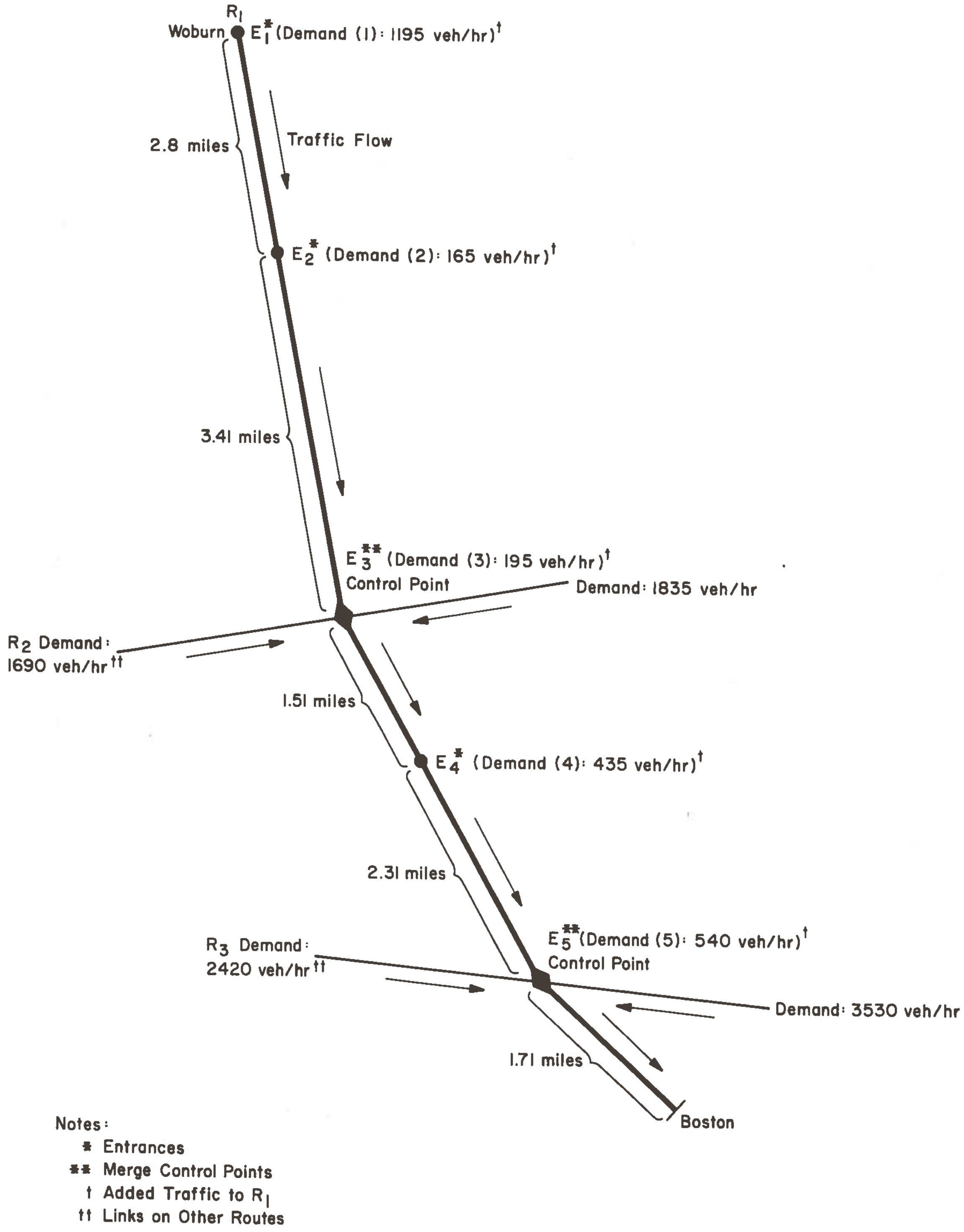

Figure 9-1 A Hypothetical Route Structure -- From Woburn to Boston

10. PROBLEMS

The problems are (a) to calculate the minimum system capacity required in terms of slots per hour in accordance with the demand rates, and (b) to establish control-point limits along R1 so that traffic can be regulated.

11. STRATEGY

The characteristics of PRT systems, such as closed-loop, captive, and grid-type network, make them more applicable to non-deterministic reservation schemes than dual-mode systems which are mostly open-loop and non-captive. The use of a non-deterministic reservation system in an open-loop network, such as the one R1 is a segment of, depends on either the existence of alternative routes which have to be advantageous with respect to travel characteristic, or extended guideways which have to be cost-effective. The alternate automated guideway routes for R1 offer no travel advantages over the existing manual roadway network, and a forced use of them might result in user dissatisfaction. Extended guideways have some potential; however, much more development has to be performed because this concept is less efficient since it increases travel time. Therefore, at this point in time of dual-mode development, a deterministic reservation scheme appears to be more adaptable to cases similar to R1. For these reasons, the selection of the AP model seems to be a reasonable choice.

Since E3 and E5 represent interchange control points and a small portion of the traffic from R2 and R3 is to be diverted to R1, a high user-service level value of 1.0 was choosen for these control points. A user-service level of 0.9 was assigned to E1, E2, and E4, respectively. It is assumed that the DUAL-mode guideway is constructed for a small personal vehicle, which could be publicly owned, approximately 10 feet in length. A slot length of 72 feet was selected, so that emergency braking in the order of 0.7g for the lead car and 0.6g for the car following would result in a low impact velocity, assuming a small reaction time and a vehicle speed of 60 miles per hour. The average guideway speed is taken for this problem to be 55 miles per hour. The result is a system guideway constraint of not more than 4000 vehicles or slots per hour. These system parameters are conservative values which are within the generally considered technological objective of 6000 vehicles per hour for a dual-mode guideway.

```
THIS IS THE DUAL MODE FUNCTIONAL PERFORMANCE ANALYSES
PLEASE FOLLOW MY INSTRUCTIONS
WRITE &DATA IN COLUMN 2
LEAVE A SPACE AND INPUT THE FOLLOWING
VARIABLES IN EQUATION FORMAT
DEMAND(I)=DEMAND IN VEHICLES/HOUR
DIST(I)=DISTANCE BETWEEN CONTROL POINTS IN MILES
STARTING FROM DESTENATION POINT
VEL=VEHICLE AVERAGE SPEED IN MILES/HOUR
SLDIST=SLOT DISTANCE IN FEET
PROB(I)=USER LEVEL OF SERVICE EXPRESSED AS
A DECIMAL FROM 0 T0 1
NE=NUMBER OF CONTROL POINTS MAX. IS 5
END INPUT BY SPACE&END
EXAMPLE OF SAMPLE INPUT DATA
&DATA DEMAND(1)=1500,DIST(3)=3,SLDIST=53, &END
ENTER NEW DATA
 &DATA NE=5,SEC=60.,SLDIST=72.,VEL=55.,DIST(1)=1.71,DIST(2)=2.31,
 DIST(3)=1.51,DIST(4)=3.41,DIST(5)=2.8,DEMAND(1)=1195,DEMAND(2)=165,
 DEMAND(3)=195,DEMAND(4)=435,DEMAND(5)=540,PROB(1)=.9,PROB(2)=.9,
 PROB(3)=1.,PROB(4)=.9,PROB(5)=1., &END
&DATA
NE=          5,DIST=  1.7099991     ,  2.3099995     ,  1.5099993     ,  3.
4099998     ,  2.7999992     ,SLDIST=  72.000000     ,PROB=
 0.89999998     , 0.89999998     ,  1.0000000     , 0.89999998     ,  1.0000
000     ,DEMAND=  1195.0000     ,  165.00000     ,
  195.00000     ,  435.00000     ,  540.00000     ,VEL=  55.000000     ,LIM=
          0,          0,          0,          0,          0,
SEC=  60.000000     ,NWRITE=          0,CYC=          0,SAMP= 0.0
   ,FINISH= 0.0
&END
```

Figure 11-1 Computer Output -- Analysis of Route R_1

```
          INTERVAL SIZE=  66LIMITS=      25       28       46       40
      66

          TOTAL SERVED =    18098

          PERCENTAGE OF EMPTIES      33.28

          SERVED =      8407

              INTERVAL      QUEUE     ENTRANCE     1
                   1            355

          SERVED =      1224

              INTERVAL      QUEUE     ENTRANCE     2
                   1            126
                   2             14

          SERVED =      1346

              INTERVAL      QUEUE     ENTRANCE     3

          SERVED =      3052

              INTERVAL      QUEUE     ENTRANCE     4
                   1            285
                   2             17

          SERVED =      4069

              INTERVAL      QUEUE     ENTRANCE     5
END OF PROBLEM
ENTER NEW DATA
```

Figure 11-2 Computer Output -- Program of Dual

Results

Table 11-1 gives the input data used for this problem. Figures 11-1 and 11-2 show the appropriate computer output. The data for the E3 and E5 interchange are given as entrances 3 and 5.

The system guideway service time for the demand rate along R1 is 66 slots per 60 seconds, which yields a required guideway capacity of 3960 per hour, and is within the system constraint of 4000. The control limits which will regulate the traffic flow through each control point are given as follows:

Control Point No.	Control Limit 60 Veh/Sec No.
E1	25
E2	28
E3	46
E4	40
E5	66

The limit E4 shows a decrease from E3 because the user service level decreased. Queuing would occur at E4 in the station entrance and not on the guideway.

TABLE 11-1. DUAL-INPUT DATA--VARIABLE NAMES AND VALUES

NAME	VALUE	COMMENTS
NE	5	1. Entrances
SEC	60 sec	2. System service time
SLDIST	72 ft.	3. Slot distance
VEL	55 mph	4. Vehicle average speed
DIST(1)	1.71 miles	5. Distance between destination point in Boston and entrance E5
DIST(2)	2.31 miles	6. Distance between entrances E4 and E5
DIST(3)	1.51 miles	7. Distance between entrances E3 and E4
DIST(4)	3.41 miles	8. Distance between entrances E2 and E3
DIST(5)	2.8 miles	9. Distance between entrances E1 and E2
DEMAND(1)	1195 veh/hr.	10. Demand at E1
DEMAND(2)	165 veh/hr.	11. Demand at E2
DEMAND(3)	195 veh/hr.	12. Demand at E3
DEMAND(4)	435 veh/hr.	13. Demand at E4
DEMAND(5)	540 veh/hr.	14. Demand at E5
PROB(1)	0.9	15. User-service level at E1
PROB(2)	0.9	16. User-service level at E2
PROB(3)	1.0	17. User-service level at E3
PROB(4)	0.9	18. User-service level at E4
PROB(5)	1.0	19. User-service level at E5

12. CONCLUSIONS

a. An analysis of guideway capacity using the AP model indicates that network management strategies could be developed for certain configurations which would obtain high system utilization within reasonable user-waiting times.

b. Program DUAL, which simulates the AP model and analyzes many-to-one type routes, calculates control limit values that can be used in network management strategies to regulate traffic flow and avoid "downstream" type traffic congestion.

c. The mean arrival rate per time interval is sufficient to use for analysis in the AP model. However, it appears that the mean time between arrivals would be a more useful parameter to use when constructing a network simulator.

d. The simulation portion of DUAL is only intended to verify the results of the AP model in a limited number of applications. A many-to-many type network simulator would be a more practical type to employ for a complete network analysis.

13. REFERENCES

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APPENDIX

DUAL-PROGRAM STATISTICS

Computer	IBM 360
Language	FORTRAN IV (IBM Version)
Compiler	G
Core Required	Approximately 200K (Bytes)
Input Data Format	NAMELIST
Operating Mode	TSO or Batch

I. DUAL-LOGICAL FLOW DESCRIPTION OUTLINE

A-1. The main program calls subroutine Input which reads in the input data in a NAMELIST format and calls subroutine DEM to calculate a table of expected probabilities for each control point. The tables are based on the Poisson distribution with λ equal to the demand rate expressed in the system service time interval SEC.

A-2. If FINISH is greater than zero, execution is terminated.

A-3. If the AP model is to be used to calculate control limits, then CYCLE and LIM must not be assigned input values.

A-4. Subroutine ACCUM uses the AP model to calculate the required control point limits per time interval.

A-5. A double Monte Carlo is employed. The first one uses λ values calculated from the Poisson distribution with λT equal to the mean arrival rate in the T interval specified for the system service time (SEC). It assigns λ values to each control point. The random number generator uses a different seed for each control point. The probability distribution used in the second Monte Carlo is obtained from the λ values. For example, the probability of a user arriving at entrance E_i in the next T interval is given by $P_i = \frac{\lambda_i}{\lambda'}$

where $\lambda' = \sum_{i=1}^{N} \lambda_i$, and N = total number of entrances,

P_i is determined for each T interval, and the order in which they arrive is determined by the second Monte Carlo being performed λ' times. As each user arrives, a check is made to determine if space is available within the service time limit. If no space is available, then each subsequent time interval is examined until a reservation can be made.

A-6. A count of the number of empty slots in each time interval is taken after the last E(NE) control point.

A-7. The first Monte Carlo procedure is replicated 450 times, and for each replication, the second Monte Carlo is repeated λ' times.

A-8. The appropriate statistics as shown in figure 7-3 are printed out.

A-9. If FINISH equals zero, then the program asks for another set of input data, otherwise it terminates execution.

II. DUAL-INPUT VARIABLES

CYC	The maximum number of slots that must be available per system service time interval to be used in conjunction with LIM.
DEMAND (I)	Maximum user-demand rate per hour.
DIST (I)	Distance between control points in miles starting from destination point.
FINISH	Used to terminate the program execution by setting it to a value greater than 0.
LIM (I)	Used to establish limit at each control point when it is desirable not to use the AP model. CYC must also be specified.
NE	Number of control points.
NWRITE	Used to print out a list of the total number of users who will arrive in the given time interval at each control point by assigning a value of 1. It is only used to diagnose the operation of the program. It should not be used during normal program application.
PROB(I)	The user-service level expressed as a decimal from 0 to 1.
SAMP	The maximum number of time-interval replications that will be used in the simulation. The program is preset to a maximum of 450.
SEC.	System service-time interval expressed in seconds.
SLDIST.	The slot distance expressed in feet.
VEL.	The average vehicle velocity for the guideway.

III. LISTING PROGRAM OF DUAL

```
L
00400           DIMENSION NPAE(5),EMPTY(2000),NA(5)
00410           DIMENSION DI(5),PR(5)
00500           DIMENSION IXX(5),RAND(5),E(200,5),IQE(5),NRAND(5)
00600           DIMENSION MERGE(5),Q(500,5),CYTOT(2000)
00700           DIMENSION ISUMQ(5)
00701           DIMENSION LIMIT(5),IRES(400,5)
00702           DIMENSION IENT(5)
00703            DIMENSION LCOUNT(5)
00704            DIMENSION NDIST(17,5)
00706           DIMENSION DIST(5)
00710           DIMENSION PROB(5),LAMBDA(5)
00711           FIN=0.
00712           I0=0
00800           REAL LAMBDA
00802           INTEGER SEMPTY,SNA,CYCLE,SAMPLE,DIFF,EMPTY,CYTOT,Q,E
00804   152     CONTINUE
00806           DO 160 I=1,5
00808           NPAE(I)=0
00810           ISUMQ(I)=0
00812           IENT(I)=0
00814           LCOUNT(I)=0
00816   160     CONTINUE
00818           SEMPTY=0
00820           SNA=0
00822           CYCLE=0
00824           SAMPLE=0
00826           DIFF=0
00830           ND=45
00832           DO 161 I=1,2000
00834           EMPTY(I)=0
00836           CYTOT(I)=0
00840   161     CONTINUE
00842           DO 162 I=1,5
00844           DO 162 J=1,17
00846           NDIST(J,I)=0
00850   162     CONTINUE
00852           DO 163 I=1,5
00854           DO 163 J=1,400
00856           IRES(J,I)=0
00858   163     CONTINUE
00860           DO 164 I=1,5
00862           DO 164 J=1,500
00864           Q(J,I)=0
00866   164     CONTINUE
00868           DO 165 I=1,5
00870           DO 165 J=1,45
00872           E(J,I)=0
00874   165     CONTINUE
01110 C   NWRITE=1  FOR FULL PRINTOUT
01120 C   NWRITE=0  FOR PARTIAL PRINTOUT
01150           TOTDIS=0.
01160           CALL INPUT(LAMBDA,DI,PR,VE,SLD,NEE,E,LIMIT,TDEL,IWRITE,CYC
LE,
01162         1 SAMPLE,FIN,I0)
01180           IF(FIN.GT.0.) GO TO 151
01552           NE=NEE
01553           SLDIST=SLD
```

```
      VEL=VE
      DO 150 I=1,NE
      PROB(I)=PR(I)
  150 DIST(I)=DI(I)
      IF(CYCLE.GT.0) GO TO 144
      CALL ACCUM(NE,PROB,LAMBDA,LIMIT)
  144 DO 140 I=1,NE
      IF(LIMIT(I)) 142,142,140
  142   LIMIT(I)=1
  140 CONTINUE
      CYCLE=LIMIT(NE)
      CALL MATCH(CYCLE,SLDIST,VEL,TDEL)
      CYDIST=SLDIST*FLOAT(CYCLE)
      DO 20 J=1,NE
      I=NE+1-J
      TOTDIS=DIST(I)+TOTDIS
      MERGE(I)=TOTDIS/CYDIST
   20 CONTINUE
      WRITE(6,1001)(MERGE(I),I=1,NE)
 1001 FORMAT(1X,5I5/)
      SAMPLE=450
      RAND(1)=65729
      RAND(2)=65759
      RAND(3)=65771
      RAND(4)=65789
       RAND(5)=65797
       IXXX=67797
      MM=0
      ITSUMQ=0
      LSNA=0
       ISNA=0
      IE=0
       IXP=40
      IP=2*MERGE(1)
       IPP=IP
      IQL=1
      DO 29 I=1,NE
      IXX(I)=RAND(I)
   29 CONTINUE
      DO 55 I=1,10
      IX=IXX(I)
      CALL RANDU (IX,IY,YFL)
      IXX(I)=IY
   55 CONTINUE
      DO 56 I=1,10
      IX=IXXX
      CALL RANDU(IX,IY,YFL)
      IXXX=IY
   56 CONTINUE
      DO 11 L=1,SAMPLE
   58 CONTINUE
      DO 4 J=1,NE
      IX=IXX(J)
      CALL RANDU(IX,IY,YFL)
      XYFL=YFL * 1000.0
      IXX(J)=IY
      NRAND(J)=XYFL
      IF(NRAND(J)-1000) 57,57,58
   57 CONTINUE
      DO 1 I=1,ND
```

```
08100          N=I
08200          IF(E(I,J)-NRAND(J)) 1,2,2
08300  2        NA(J)=N-1
08400          GO TO 13
08500  1       CONTINUE
08600  13      SNA=SNA+NA(J)
08700  4       CONTINUE
08800          ISNA=ISNA+SNA
08810          IF(SNA.EQ.0)  GO TO 12
08900         NPA=1000/SNA
09000          NPAE(1)=NA(1)*NPA
09100          DO 15 I=2,NE
09200  15       NPAE(I)=(NA(I) * NPA) +NPAE(I-1)
09300  60      CONTINUE
09400          DO 19 I=1,SNA
09500          IX=IXXX
09600          CALL RANDU (IX,IY,YFL)
09700          AFYL=YFL * 1000.0
09800           IRAND=AFYL
09900          IXXX=IY
10000         IF(IRAND-1000) 59,59,60
10100  59       CONTINUE
10200          DO 17 J=1,NE
10300          K=J
10400          IF(NPAE(J)-IRAND) 17,18,18
10500  17       CONTINUE
10600  18       M=MERGE(K)
10601           IL=1
10700  22       IF(CYTOT(M)-LIMIT(K)) 80,21,21
10900  21       M=M+1
11000           IL=IL+1
11010           GO TO 22
11020  80       CONTINUE
11100          IF(M-MM) 42,42,43
11200  43       MM=M
11300  42       CONTINUE
11400          CYTOT(M)=CYTOT(M)+1
11500          MK=MERGE(K)
11600 C        M=CYCLE N0., K=ENTRANCE N0.
11610           Q(M,K)=Q(M,K)+1
11620           IF(L-IPP) 72,72,89
11630 89         CONTINUE
11640           LCOUNT(K)=LCOUNT(K)+1
11701          IRES(IL,K)=IRES(IL,K)+1
11702          IF(IQL-IL) 73,72,72
11703  73       IQL=IL
11704  72       CONTINUE
11705          IF(L-IPP) 79,79,78
11706 78       IENT(K)=IENT(K)+1
11707  79      CONTINUE
11800  19      CONTINUE
12000          IF(L-IPP) 62,62,63
12100  63      CONTINUE
12105          LSNA=LSNA+SNA
12110          IF(IWRITE.EQ.0) GO TO 12
12111           WRITE(6,83)(LCOUNT(I),I=1,NE),SNA
12114  83       FORMAT(/10X,6I12)
12200     12   DIFF=CYCLE-CYTOT(MERGE(NE)-1)
12300          IF (DIFF) 26,26,23
12400  23      EMPTY(L)=DIFF
```

```
            SEMPTY=SEMPTY+EMPTY(L)
      62     CONTINUE
      26    CONTINUE
            DO 27 I=1,NE
            MERGE(I)=MERGE(I)+1
      27    CONTINUE
             IF(IP-L) 32,32,31
      32    CONTINUE
            DO 35 K=1,NE
             II=MERGE(K)
            DO 36 I =II,MM
      36     ISUMQ(K)=ISUMQ(K) +Q(I,K)
            ITSUMQ=ITSUMQ + ISUMQ(K)
      35    CONTINUE
            IF(IWRITE.EQ.0) GO TO 14
             WRITE(6,65)
      65     FORMAT(1H ,T7,'EVENT',T24,'QUEUE',T40,'SERVED')
            WRITE (6,34) IP,ITSUMQ,ISNA
      34       FORMAT(1H ,/5X,I9, 10X,I9,5X,I9)
            WRITE(6,66)
      66    FORMAT(1H ,T10,'ENTRANCE N0.',T30,'QUEUE')
            DO 40 I=1,NE
            WRITE (6,41) I,ISUMQ(I)
      41     FORMAT(/10X,I9,10X,I9)
      40     CONTINUE
      14    ITSUMQ=0
            DO 61 I=1,NE
      61    ISUMQ(I)=0
            IP=IP+5
             ISNA=0
      31    CONTINUE
             SNA=0
             DO 85 I=1,NE
             LCOUNT(I)=0
      85     CONTINUE
      11    CONTINUE
            XCYCLE=CYCLE
            XS=SEMPTY
              XAMPLE=SAMPLE
              XIPP=IPP
              PEREMP=XS/(XAMPLE*XCYCLE-XIPP)*100.0
             WRITE(6,91)
      91     FORMAT(1H1,///)
             WRITE(6,92) CYCLE,(LIMIT(I),I=1,NE)
      92     FORMAT(10X,'INTERVAL SIZE=',I4,'LIMITS=',5I8)
            WRITE(6,76) LSNA
      76    FORMAT(//10X,'TOTAL SERVED =',I9)
            WRITE(6,30)PEREMP
      30     FORMAT(//10X,'PERCENTAGE OF EMPTIES',F10.2)
            DO 71 M=1,NE
            WRITE(6,77) IENT(M)
      77     FORMAT(/10X,'SERVED =',I9)
             WRITE(6,75) M
      75     FORMAT(//14X'INTERVAL',5X,'QUEUE',5X,'ENTRANCE',I6)
            DO 71 I=2,IQL
            N=I-1
            IF(IRES(I,M).EQ.0) GO TO 71
            WRITE(6,74) N,IRES(I,M)
      74    FORMAT(1H ,10X,I9,5X,I9)
      71    CONTINUE
```

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16170          WRITE(6,153)
16180   153    FORMAT(' END OF PROBLEM')
16190          IF(FIN.EQ.0.) GO TO 152
16195   151    CONTINUE
16200          STOP
16300          END
16420          SUBROUTINE DEM(YLAM,I,IP)
16430         DIMENSION IP(200,5)
16440           PROB=0.
16450           AFAC=ALOG(1.)
16460           ALAM=ALOG(YLAM)
16470           DO 10 KK=1,44
16480           K=KK-1
16490           PROB=EXP(FLOAT(K)*ALAM-AFAC-YLAM)+PROB
16500           AFAC=ALOG(FLOAT(KK))+AFAC
16510          IF(PROB.GT.1.) GO TO 20
16520          IP(KK,I)=PROB*1000.+.5
16530          IF(PROB.GT..9995) GO TO 20
16540   10      CONTINUE
16550   20     RETURN
16560          END
16580           SUBROUTINE ACCUM(NUM,P,YLAM,KX)
16590           DIMENSION YLAM(5),P(5),KX(5)
16600          MAX=500
16610           Y=0.
16620           DO 10 J=1,NUM
16630           Y=Y+YLAM(J)
16640           OLDDIF=0.
16650           COMPAR=0.
16660           ALAM=ALOG(Y)
16670           AFAC=ALOG(1.)
16680           DO 20 KK=1,MAX
16690           K=KK-1
16700           COMPAR=EXP(FLOAT(K)*ALAM-AFAC-Y)+COMPAR
16710           AFAC=ALOG(FLOAT(KK))+AFAC
16720           DIFF=COMPAR-P(J)
16730           IF(DIFF-0.)30,40,50
16740   50      IF(OLDDIF.EQ.0.) GO TO 40
16750    60     IF(ABS(DIFF).GT.ABS(OLDDIF)) K=K-1
16760           GO TO 40
16770   30       OLDDIF=DIFF
16780   20      CONTINUE
16790           WRITE(6,104)
16800   104    FORMAT(5X,25HNO X VALUE HAS BEEN FOUND)
16810   40      KX(J)=K
16820   10      CONTINUE
16830           RETURN
16840           END
16900           SUBROUTINE MATCH(ISIZE,DSLOT,VEL,TDEL)
16910           TSLOT=DSLOT/(VEL*5280./3600.)
16920           SIG=3600./TSLOT
16930           S=ISIZE*3600./TDEL
16940           IF(S-SIG) 10,10,30
16950   30     WRITE(6,102)DSLOT,VEL,SIG
16951   102    FORMAT(1X,13HHEADWAY (FT.),2X,1H=,2X,F8.3,5X,
16952     X    17HVELOCITY (FT/SEC),2X,1H=,2X,F7.3/8X,
16953     X    48HACCORDING TO SYSTEM CONSTRAINTS, MAX. SLOTS/HOUR,
16954     X    2X,1H=,2X,F9.3)
16960          WRITE(6,103) S
16961   103    FORMAT(//11X,
```

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16962       X  43HDEMAND RATE CALCULATION REQUIRES SLOTS/HOUR,2X,
16963       X  1H=,2X,F11.3)
16970          WRITE(6,130)
16971    130   FORMAT(/1X,48HDEMAND RATE IS NOT COMPATIBLE WITH SYSTEM LI
MITS)
16980     10   RETURN
16990          END
17000          SUBROUTINE INPUT (LAMBDA,DI,PR,VE,SLD,NEE,E,
17010       1  LIMIT,TDEL,IWRITE,CYCLE,SAMPLE,FIN,I0)
17100          DIMENSION DEMAND(5),DIST(5),PROB(5),LAMBDA(5)
17110          DIMENSION DI(5),PR(5)
17115          DIMENSION E(200,5)
17116          DIMENSION LIM(5),LIMIT(5)
17117          DATA NWRITE/0/
17118          INTEGER CYCLE,CYC
17119          INTEGER SAMPLE
17120          REAL LAMBDA
17122 C        NWRITE=IWRITE
17124 C        LIM=LIMIT
17126 C        SEC=TDEL
17128 C        CYC=CYCLE
17200          NAMELIST /DATA/NE,DIST,SLDIST,PROB,DEMAND,VEL,
17220       1  LIM,SEC,NWRITE,CYC,SAMP,FINISH
17300          IF(I0.GE.1) GO TO 18
17310          I0=I0+1
17500          WRITE(6,1)
17600  1       FORMAT(' THIS IS THE DUAL MODE FUNCTIONAL PERFORMANCE ANAL
YSES')
17700          WRITE(6,2)
17800 2        FORMAT(' PLEASE FOLLOW MY INSTRUCTIONS')
17900          WRITE(6,3)
18000  3       FORMAT( ' WRITE &DATA IN COLUMN 2')
18100          WRITE(6,4)
178200   4      FORMAT(' LEAVE A SPACE AND INPUT THE FOLLOWING')
178300          WRITE(6,5)
178400   5      FORMAT(' VARIABLES IN EQUATION FORMAT')
178500          WRITE(6,6)
178600   6      FORMAT(' DEMAND(I)=DEMAND IN VEHICLES/HOUR')
178700          WRITE(6,7)
178800   7      FORMAT(' DIST(I)=DISTANCE BETWEEN CONTROL POINTS IN MILES
')
178900          WRITE(6,8)
179000   8      FORMAT(' STARTING FROM DESTENATION POINT')
179100          WRITE(6,9)
179200    9     FORMAT(' VEL=VEHICLE AVERAGE SPEED IN MILES/HOUR')
179300          WRITE(6,10)
179400   10     FORMAT(' SLDIST=SLOT DISTANCE IN FEET')
179500          WRITE(6,11)
179600   11     FORMAT(' PROB(I)=USER LEVEL OF SERVICE EXPRESSED AS')
179700          WRITE(6,12)
179800   12     FORMAT(' A DECIMAL FROM 0 T0 1')
179810          WRITE(6,17)
179900          WRITE(6,13)
179911   17     FORMAT(' NE=NUMBER OF CONTROL POINTS MAX. IS 5')
180000   13     FORMAT(' END INPUT BY SPACE&END')
180100          WRITE(6,14)
180200   14     FORMAT(' EXAMPLE OF SAMPLE INPUT DATA')
180300          WRITE(6,15)
180400   15     FORMAT(' &DATA DEMAND(1)=1500,DIST(3)=3,SLDIST=53, &END')
180405   18     CONTINUE
```

```
180410           SEC=1.
180412           NWRITE=0
180414           CYC=0
180430           FINISH=0.
180445           LIM(1)=0
180446           LIM(2)=0
180447           LIM(3)=0
180448           LIM(4)=0
180449           LIM(5)=0
180450           DEMAND(1)=1800.
180451           DEMAND(2)=1800.
180452           DEMAND(3)=1800.
180453           DEMAND(4)=1800.
180454           DEMAND(5)=1800.
180455           PROB(1)=.987
180456           PROB(2)=.987
180457           PROB(3)=.987
180458           PROB(4)=.987
180459           PROB(5)=.987
180460           DIST(1)=.5
180461           DIST(2)=.5
180462           DIST(3)=.5
180463           DIST(4)=.5
180464           DIST(5)=.5
180465           VEL=60.
180466           SLDIST=53
180467           NE=5
180480           WRITE(6,19)
180485   19      FORMAT(' ENTER NEW DATA')
180500           READ(5,DATA)
180510           WRITE(6,DATA)
180600           DO 16 I=1,NE
180700           LAMBDA(I)=DEMAND(I)
180710           DI(I)=DIST(I)*5280.
180720           PR(I)=PROB(I)
180730           LIMIT(I)=LIM(I)
180800   16       CONTINUE
180810           NEE=NE
180820           SLD=SLDIST
180825           FIN=FINISH
180830           VE=VEL
180832           TDEL=SEC
180834           IWRITE=NWRITE
180836           CYCLE=CYC
180841           DO 20 I=1,NE
180842           LAMBDA(I)=LAMBDA(I)/3600.*TDEL
180843           YLAM=LAMBDA(I)
180844           CALL DEM(YLAM,I,E)
180845   20      CONTINUE
180900           RETURN
181000           END
END OF DATA
```