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16. Abstract

The objective of this effort was to complete the development of the computer simulation model SCOT (Simulation of Corridor Traffic) designed to represent traffic flow on an urban grid-freeway integrated highway system by simulating an existing system. This report describes the status of the calibration, validation, evaluation, and application studies of this model to a Freeway Corridor, in Dallas, Texas. As of the present time, difficulties have been encountered in the validation process of the model when traffic density is higher than the density corresponding to maximum flow. It has been concluded that 1) the present available data needs to be supplemented by more data in order to calibrate properly the model (an absolute necessity for the model to replicate reality) and 2) the response of the model is not consistent with the behavior of turbulent freeway traffic flow although the model has performed well representing laminar flow. Therefore, it is recommended that a program of data acquisition and reduction followed by a model calibration and validation be undertaken.

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PREFACE

This Urban Traffic Corridor Study was performed by the Control and Simulation Branch at the Transportation Systems Center (TSC) for the Transportation Systems Division of the Office of Research of the Federal Highway Administration. The objective of this effort was to complete the development of the computer model SCOT (Simulation of Corridor Traffic) designed to simulate traffic flow on an urban grid-freeway integrated highway system by simulating the freeway system with the present Dallas Freeway ramp control system and by comparing these results with no ramp control.

Technical advice concerning calibration and validation requirements for the SCOT model was provided by Guido Radelat of FHWA and E. Lieberman of KLD Associates.

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1. INTRODUCTION

Simulation is an inexpensive method for evaluating the effect of traffic control strategies when the phenomena are too complex to be defined by analytical models and when a controlled experiment may be hazardous, expensive, and slow in producing meaningful results.

Ramp control strategies and frontage road control in freeways as well as network traffic control represent phenomena of this type. The FHWA during FY72 contracted with TSC to have an urban traffic corridor model SCOT (simulation of Corridor Traffic) developed and programmed. During FY73, TSC performed studies of this model in the area of calibration and validation with the Dallas, Texas North Central Expressway at the test site. At the start of this effort it was assumed that the calibration was complete and that substantial progress had been made towards validation of the model. However, this was not the case as the calibration parameters (speed/density) as noted in Table 3.1-1 of the Final Report[1] Vol. 1 were in error due to an inadequate data base. Secondly, as concerns the validation process, only several demonstration runs had been made.

In 1970 General Applied Science Laboratories, Inc. developed a freeway simulation model called DAFT (Dynamics Analysis of Freeway Traffic).[2] This model treated the freeway traffic as groups of cars rather than treating each car individually. Although never validated, DAFT appeared to be a suitable model for analyzing freeway traffic control strategies. On the other hand, an urban network simulation model was developed by General Applied Science Laboratories, Inc. and Peat, Marwick, Mitchell & Co. under a contract with the Federal Highway Administration. The UTCS-1 model was

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[1] General Applied Science Laboratories, Inc., Traffic Flow Simulation Study, the SCOT Model (Final Report), Contract DOT/TSC-161, February 1972.

[2] Lieberman, E. "Dynamic Analysis of Freeway Traffic," ASME Paper 70-TRAN-42, Joint Engineering Conf., Chicago, Illinois, 1970.

considered appropriate to examine surface street traffic control problems. However, neither model is adequate for analyzing an urban traffic network control strategy when the network includes surface streets and freeways connected by ramps. To meet this need FHWA in 1972 signed a project agreement HW-202 with TSC to have such a model developed. The SCOT model written by GASL under contract for TSC was the result of this effort. The model contains UTCS-1 to represent the surface streets and a DAFT type model to represent the freeway with both models interfaced so that a user can see the effect of freeway strategies on surface street behavior and surface street strategies on freeways. The test site chosen for the calibration, validation, and evaluation of the SCOT model was the northbound roadway of the Dallas North Central Expressway between McCommas Avenue and the Northwest Highway (Loop 12) with frontage road and several arterial streets. This is a 1.5 square mile network containing three miles of freeway.

The Dallas North Central Expressway is the site of the Dallas Corridor Control Project that is directed by Texas Transportation Institute (TTI) under a contract with the FHWA. This project is directly concerned with the installation, operation and evaluation of electronic traffic surveillance, communication and control systems to improve the flow of traffic on both an urban freeway and the adjacent surface street facilities.

2. CALIBRATION AND VALIDATION DATA

2.1 DATA REQUIREMENTS

As part of the effort to calibrate and to validate the SCOT program, the data requirements were determined, and the available data on the Dallas North Central Expressway was reviewed and gathered. These data requirements are summarized below:[3]

2.2 CALIBRATION DATA

1. One hundred pairs of speed/density data equally spaced between 10% and 90% of k_j for each freeway link and lane are needed. This data is used to determine the values of the parameters a, b, u_f, k_j and k_f in the equation that expresses the speed-density relationship for the section of freeway under consideration. This equation is

$$u = u_f \left[1 - \frac{k^a - k_f^a}{k_j^a - k_f^a} \right]^b , \; k > k_f$$

   where u = speed, u_f = free flow speed, k_j = jam density, k_f = density at transition from free flow to forced flow conditions, and a and b are exponent values. The accuracy by which the parameter values can be estimated is determined by using the parameter estimation curves appearing in the GASL DOT Contract #(DOT-TSC-161), Final Report, Vol. IV, Appendix III, Figure 1-4. Assuming values of 1.21 and 2.19 for a and b respectively and measurement errors of 10%, the curves show the following estimation error using 100 data points:

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[3] R. Ricci to G. Radelat, <u>Summary of Data Requirements for Calibration, and Validation of SCOT Model</u>, Technical Memorandum, October 1972.

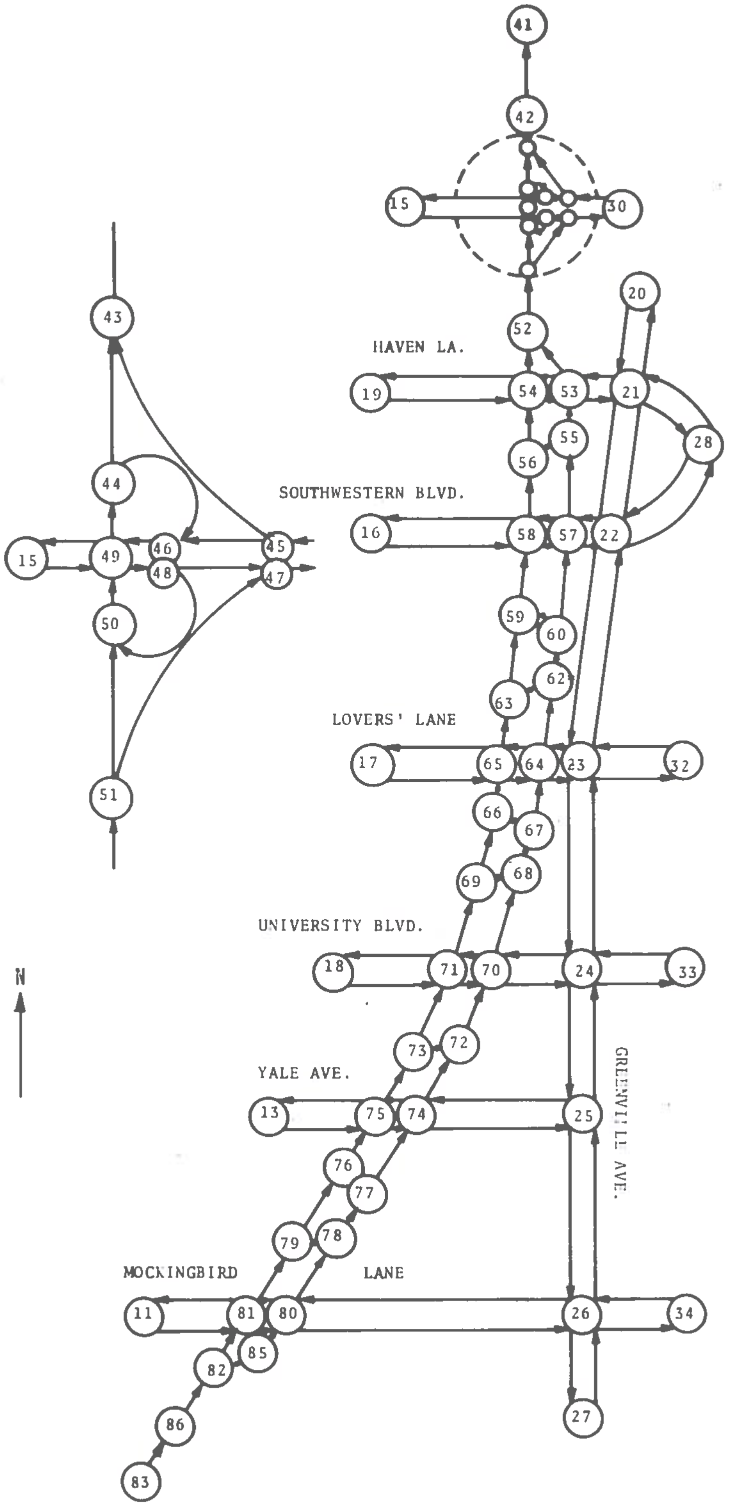

Figure 1. Dallas-Corridor 80-Node Test Network

Quantity	Error (per cent)
a	9
b	1
k_j	1.4
u_f	6

The values of a and b utilized here are the means of those used in a 80 node test network (Figure 1). It is considered that with these error magnitudes in a, b, k, and u_f the expected error of simulation results are within a 10% error tolerance value.

2. Statistical distributions of merge delay as a function of link volume on the freeway link immediately upstream of the merge point are required for all ramp entrances in the test network. Specifically these distributions may be defined as: a) probability (per cent) that a merging vehicle will be stopped at a merge point as a function of link volume, b) average delay experienced by a stopped vehicle at the merge point as a function of link volume and, c) cumulative distribution of merge delay as a percentage of the mean value vs. merge delay as a percent of mean value.
3. Geometric data and photographs of the test network area.

2.3 VALIDATION DATA

1. Average speeds for all lanes over a five minute interval or average speeds for each lane over a five minute interval (from 1600 to 1700 hours outbound section of freeway from McCommas Avenue to Northwest Highway Cloverleaf).
2. Traffic flow rates for all freeway lanes.
3. Flow rates for all entrance and exit ramps (times of observation for items 1, 2, and 3 should be concurrent).
4. Flow rates for each entry/exit link in 80-node test network.

5. Flow rates for each sink/source in 80-node test network.
6. Gap size and gap velocity versus acceptance of gap (gap length versus frequency of gap length).
7. Queue size measurements on entrance ramps.
8. Percent of trucks in traffic volumes.
9. Turning movements at the shortest interval available.

Discussions were held with the Texas Transportation Institute at Dallas, Texas and with the FHWA concerning the availability of freeway data. The result of these discussions was the furnishing by TTI of freeway data for ten different weekdays from Tuesday to Thursday that included the outputs of all detectors between A10 and A24 inclusive (Figure 2). The printed copy of the data (computer printouts) contain on and off ramp volumes at five minute intervals, freeway volumes at five-minute intervals, and speed density data for the outside lane at one minute intervals for the speed/volume sensors. (See Figures 3 and 4 for samples of data furnished.)

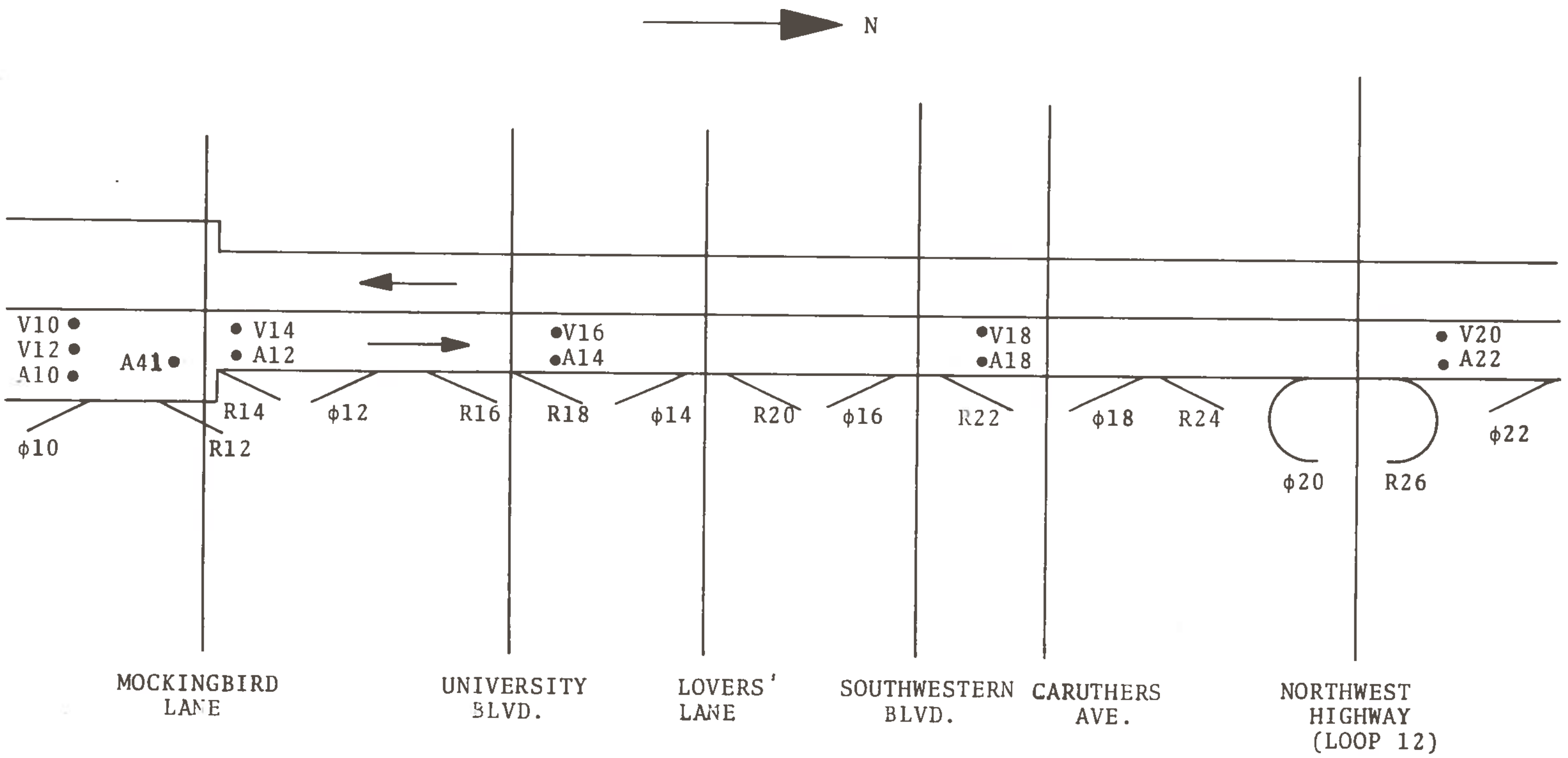

Figure 2. Detector Plan

```
DATE 11-30-72                             SUBSYSTEM NO.  9(B2)
                        TOTAL  TOTAL CALC                        MEAS        TEXAS A+M UNIVERSITY/TEXAS TRANSPORTATION INSTITUTE
TIME   MEAS   ADJ MEAS TRAVEL TRVLTM  SPD   DENS DELY KINETIC   SPD
        NIS   NIS -ADJ VEH-MI VEH-HR MI/HR V/MI V-HR ENERGY MI/HR     V14  A12  O12  V16  A14  R16  R18
 350PM   48   51   -2  2227.     47.  47    35.  0.0 105530.  45      132  136   24  141  108   16   23
 355PM   40   43   -3  2254.     47.  47    30.  0.0 108178.  45      132  133   28  146  110   19   26
 400PM   42   47   -5  2269.     45.  50    33.  0.0 114463.  45      132  148   15  146  106   17   24
 405PM   38   45   -7  2265.     46.  49    32.  0.0 111584.  47      131  126   37  151  111   16   25
 410PM   51   64  -13  2194.     55.  39    45.  5.2  87546.  44      132  136   23  131  111   14   22
 415PM   69   89  -20  2351.     77.  30    63. 24.7  71787.  38      153  157   10  144   99   26   33
 420PM   85   95  -10  2480.     92.  26    68. 36.8  66864.  36      151  154   10  159  122   11   27
 425PM   97  118  -21  2193.    107.  20    84. 58.2  44961.  31      141  132   19  128  110   21   21
 430PM  108  139  -31  2139.    129.  16    99. 81.4  35469.  29      138  133   11  130  103   10   28
 435PM  135  138   -3  2452.    139.  17    99. 84.5  43268.  34      149  151   15  155  122    8   34
 440PM  145  151   -6  2398.    145.  16   108. 91.7  39657.  37      151  142   16  149  122    4   24
 445PM  135  144   -9  2310.    148.  15   103. 96.6  36060.  28      135  139   16  154  115    4   27
 450PM  155  153    2  2316.    149.  15   109. 97.5  36024.  32      142  143   15  143  117    5   24
 455PM  148  145    3  2322.    149.  15   104. 97.3  36207.  29      138  141    8  151  120    7   16
 500PM  147  142    5  2332.    144.  16   101. 92.1  37766.  33      144  138   11  160  109    4   21
 505PM  141  129   12  2259.    136.  16    92. 85.7  37536.  29      136  131   16  151  113    3   17
 510PM  145  122   23  2217.    126.  17    87. 76.7  39026.  28      136  128   17  141  115    6   15
 515PM  145  110   35  2250.    116.  19    78. 65.9  43677.  28      131  134   18  145  118    2   18
 520PM  114  110    4  2442.    110.  22    78. 55.7  54254.  28      149  141   22  154  127    7   20
 525PM  116  109    7  2191.    110.  19    78. 61.3  43646.  30      138  127   18  136  112    7   26
 530PM  117  106   11  2220.    108.  20    76. 58.6  45655.  29      137  129   16  141  114    8   18
 535PM  105  111   -6  2239.    109.  20    79. 59.2  45995.  27      137  128   16  139  122    4   17
 540PM  113  125  -12  2155.    118.  18    89. 70.1  39369.  29      130  132   17  137  106    7   21
 545PM  116  134  -18  2118.    130.  16    96. 82.9  34513.  28      136  121   11  145   98    3   19
 550PM  131  122    9  2196.    128.  17    87. 79.1  37698.  28      133  127   16  142  114    3   20
 555PM  129  112   17  2215.    117.  18    80. 67.7  41962.  30      137  128   16  139  116    7   21
 600PM  138  112   26  2019.    112.  18    80. 67.1  36425.  30      131  118   16  123  101    8   24
 605PM  114  110    4  2205.    111.  19    78. 61.9  43805.  27      137  128   15  133  120    7   18
 610PM  115  107    8  2211.    109.  20    76. 59.8  44852.  27      133  130   15  144  113    3   17
 615PM  136  124   12  2329.    116.  20    88. 64.2  46784.  31      143  142   20  143  117    7   17
 620PM  109  109    0  2160.    117.  18    78. 63.9  39907.  27      128  120   24  142  112   10   23
 625PM  132  133   -1  2123.    121.  17    95. 73.8  37264.  26      139  135   12  119  107    8   29
 630PM  123  124   -1  2040.    129.  15    88. 83.6  32266.  24      127  116   23  127  103   15   30
 635PM   93   76   17  2114.    100.  21    54. 53.0  44770.  31      121  119   24  142  107   24   22
 640PM   81   47   34  2182.     62.  35    33. 13.5  76824.  44      131  127   22  139  111   12   30
 645PM   94   43   51  2142.     45.  47    30.  0.0 102019.  44      119  143   27  133  100   17   26
 650PM   43   48   -5  1973.     46.  42    34.  2.1  84628.  45      109  127   26  122   97   17   26
 655PM   45   55  -10  1962.     52.  37    39.  8.3  74034.  46      105  124   29  125   97   15   19
 700PM   15   30  -15  1765.     43.  41    21.  3.7  72499.  47       88  105   29  121   91   12   27
 705PM   44   40    4  1695.     35.  48    28.  0.0  82178.  46       91  116   25   97   86   12   23
 710PM   46   38    8  1711.     39.  43    27.  0.9  75088.  44       87  111   36   94   95   16   27
 715PM   44   32   12  1735.     35.  49    22.  0.0  86092.  44       96  119   18  110   78   15   32
 720PM   47   41    6  1733.     37.  46    29.  0.0  81225.  46       93  116   25   99   91   12   17
 725PM   61   50   11  1818.     46.  39    35.  5.5  71915.  45      100  116   36  106   91   14   27
 730PM   54   37   17  1660.     44.  37    26.  7.1  62540.  47       79  118   24   98   87   12   31
 735PM   29   31   -2  1675.     34.  49    22.  0.0  82585.  47       84  105   25  105   92    6   19
 740PM   37   42   -5  1525.     37.  41    30.  3.0  62929.  48       79  103   22   85   84   12   15
 745PM   24   31   -7  1511.     37.  43    22.  1.1  70179.  46       77   93   38  104   89    9   19
 750PM   39   37    2  1514.     34.  44    26.  0.3  67425.  46       79  108   20   85   77   14   23
 755PM   43   41    2  1427.     39.  36    26.  7.2  52250.  47       75   89   28   82   78   13   12
 800PM   24   20    4  1216.     25.  34    20.  7.0  42294.  45       56   85   19   71   67   10   21
```

Figure 3. Sample Data at Five-Minute Intervals - Dallas North Central Expressway Input/Output Study

```
                                                                                                   DATE 11/30/1972
TIME       WASH/HASK      MCCOMM/MONT    MOCKB/YALE     UNIVERSITY     CARUTH         LOOP 12        PARK           WALNUT HILL

1637 SPEED IN=76OUT=40    IN=44OUT=34    IN=40OUT=34    IN=51OUT=39    IN=41OUT=46    IN=34OUT=42    IN=40OUT=35    IN=40OUT=50
     FLOW     55     78      66     83      66     69      49     57      54     65      62     60      55     62      48     56
     DENS     14     39      30     48      49     60      28     43      39     42      54     42      41     53      36     33

1638 SPEED IN=70OUT=35    IN=51OUT=34    IN=32OUT=40    IN=52OUT=44    IN=44OUT=55    IN=36OUT=51    IN=42OUT=45    IN=30OUT=49
     FLOW     49     83      68     83      65     61      51     62      62     67      64     56      56     65      55     66
     DENS     14     47      26     48      60     45      29     42      42     36      53     32      40     43      55     40

1639 SPEED IN=74OUT=43    IN=49OUT=31    IN=41OUT=34    IN=50OUT=37    IN=32OUT=51    IN=36OUT=44    IN=36OUT=46    IN=27OUT=49
     FLOW     59     73      54     86      57     60      47     69      60     66      63     57      57     59      54     52
     DENS     15     33      22     55      41     52      28     55      56     38      52     38      47     38      60     31

1640 SPEED IN=75OUT=45    IN=45OUT=24    IN=47OUT=25    IN=46OUT=39    IN=40OUT=45    IN=35OUT=44    IN=34OUT=46    IN=22OUT=53
     FLOW     52     93      94     77      56     54      59     61      61     68      56     52      57     62      57     63
     DENS     13     41      41     64      35     64      38     46      45     45      48     35      50     40      77     35

1641 SPEED IN=81OUT=38    IN=47OUT=27    IN=45OUT=21    IN=45OUT=39    IN=39OUT=46    IN=28OUT=45    IN=37OUT=51    IN=34OUT=49
     FLOW     52     86      67     77      56     55      56     63      55     69      59     56      59     63      56     55
     DENS     12     45      28     57      37     78      37     48      42     45      63     37      47     37      49     33

1642 SPEED IN=77OUT=27    IN=51OUT=23    IN=38OUT=21    IN=42OUT=34    IN=44OUT=49    IN=30OUT=47    IN=30OUT=45    IN=32OUT=55
     FLOW     59     88      57     86      59     65      55     63      46     67      58     62      52     57      53     67
     DENS     15     65      22     74      46     92      39     55      31     41      58     39      52     38      49     36

1643 SPEED IN=71OUT=37    IN=48OUT=24    IN=42OUT=25    IN=45OUT=34    IN=42OUT=42    IN=33OUT=32    IN=23OUT=45    IN=41OUT=47
     FLOW     43     85      57     87      60     59      51     59      50     70      58     62      57     61      55     57
     DENS     13     45      23     72      42     70      34     52      35     50      52     58      74     40      40     36

1644 SPEED IN=79OUT=41    IN=53OUT=22    IN=42OUT=13    IN=45OUT=36    IN=40OUT=43    IN=36OUT=44    IN=34OUT=39    IN=39OUT=49
     FLOW     43     91      65     86      50     53      45     66      58     63      57     53      42     62      57     64
     DENS     10     44      24     78      35    122      30     55      43     43      47     36      37     47      43     39

1645 SPEED IN=77OUT=19    IN=51OUT=16    IN=40OUT=12    IN=46OUT=38    IN=38OUT=41    IN=29OUT=30    IN=30OUT=45    IN=34OUT=51
     FLOW     45     80      58     86      62     58      52     66      57     72      60     56      51     66      57     65
     DENS     11     84      22    107      46    145      33     52      45     52      62     56      51     44      50     38

1646 SPEED IN=59OUT=32    IN=49OUT=17    IN=40OUT=15    IN=45OUT=33    IN=34OUT=45    IN=29OUT=40    IN=30OUT=42    IN=35OUT=43
     FLOW     49     89      60     80      47     53      60     59      52     69      54     56      54     64      58     61
     DENS     14     55      24     94      35    106      40     45      45     46      55     42      54     45      49     42

1647 SPEED IN=70OUT=39    IN=49OUT=22    IN=45OUT=21    IN=31OUT=38    IN=42OUT=50    IN=31OUT=45    IN=31OUT=44    IN=32OUT=46
     FLOW     43     86      57     56      65     61      52     64      53     64      63     55      60     61      49     64
     DENS     12     44      23     50      43     87      50     50      37     38      60     36      58     41      45     41

1648 SPEED IN=70OUT=39    IN=42OUT=12    IN=40OUT=24    IN=41OUT=41    IN=44OUT=47    IN=27OUT=47    IN=36OUT=45    IN=31OUT=53
     FLOW     47     81      60     72      63     58      52     53      55     64      65     60      55     62      52     56
     DENS     13     41      28    120      47     72      38     38      37     40      72     38      45     41      50     31

1649 SPEED IN=73OUT=24    IN=51OUT=20    IN=32OUT=28    IN=48OUT=40    IN=39OUT=49    IN=29OUT=51    IN=33OUT=42    IN=23OUT=50
     FLOW     44     91      72 [illegible]  67     66      39     76      57     65      52     51      54     62      51     65
     DENS     11     62 [illegible] [illegible] 62  70      24     55      43     39      54     30      49     44      66     39
```

Figure 4. Sample Data at One-Minute Intervals - Dallas North Central Expressway Real-Time Central-Location, Speed and Flow

3. CALIBRATION STUDY

3.1 FREEWAY LINKS

For the freeway part of the SCOT program, the speed/density relationship

$$u = u_f \left[1 - \frac{k^a - k_f^a}{k_j^a - K_f^a} \right]^b , \quad k > k_f$$

characterizes traffic behavior on the freeway. For each freeway link or section, the five parameters, a, b, u_f, k_j and k_f, of this speed/density relationship must be determined for input to the SCOT program. Using experimental speed/density data for each link, a computer program called SRCH calculates the parameters for that link.

For the Dallas North Central Expressway calibrations, experimental data was obtained from TTI. For this calibration effort, only one day's data, that of 11/30/72, was used. Two types of data in the form of computer data sheets were obtained from TTI: (Figures 3 and 4.)

1. Five-minute volume and speed data for the detectors shown on the map in Figure 2.
2. Minute speed, flow and density data at specified locations along the Dallas Corridor. An accompanying data sheet listed the detectors used in obtaining the flow and speed at each location.

The locations chosen for the calibrations were at the five speed detectors located on the section of the Dallas Corridor used in the test network (Table 1).

TABLE 1 CALIBRATION LOCATION

Location No.	Speed Detector	Identifying Link
1	41	82, 81
2	12	79, 76
3	14	69, 66
4	18	56, 54
5	22	44, 43

To obtain the necessary speed density data at each location, both types of TTI data were used, the density being calculated from the flows and speeds as follows: $k = \frac{Q}{U} = \frac{\text{hourly flow/lane}}{\text{speed}}$ veh/lane mile. To find the hourly flow per lane, Q, at each five minute interval, the five-minute data was used in the following manner:

$$Q = \frac{(\quad \text{detector flows})\ 12}{\text{No. of lanes}} = \text{hourly flow per lane.}$$

Therefore, for each location, the hourly flow per lane for each five-minute time interval is:

$$Q_1 = \frac{(V10 + V12 + A10 + O10 - R12 - R14)\ \ 12}{2},$$

$$Q_2 = \frac{(V14 + A12)\ \ 12}{2},$$

$$Q_3 = \frac{(V16 + A14)\ \ 12}{2},$$

$$Q_4 = \frac{(V18 + A18)\ \ 12}{2}, \text{ and}$$

$$Q_5 = \frac{(V20 + A22)\ \ 12}{2}.$$

In determining the speed, the five-minute speed data was not used because it was a subsection speed rather than a link speed. Instead, an average five-minute speed was calculated from five minutes of minute speed data. Since the minute data covered only a two-hour period in both morning and afternoon, only 50 speed/density density points were available.

Using these five-minute interval speed/density points, the SRCH program generated a series of admissible parameters for each location. From each series, a "best" set was chosen on the basis of "best" k_f, lowest rms and lowest ΔQ values (ΔQ being the difference between the calculated and observed values of maximum flow.) Figures 5a to 9a show the speed/density experimental data and the speed density curve calculated from the parameter found by the SRCH program for each location. Also, plotted is the computed Q curve where:

$$Q = ku$$

As can be seen from the experimental data, when this five-minute interval method is used, the range of density does not extend out to 150 veh/mile. It was felt that for an accurate calibration, data must extend out at least that far. Therefore, wherever possible, the minute flow data was used to give additional points in this high density region. Since the minute flow data did not correspond to the speed detector but to a point downstream after the next on ramp, it was necessary to subtract out this on ramp flow and recalculate the flow just at the speed detector. Then, using the corresponding minute speed, minute density points were calculated as above:

$$k = \frac{\text{flow}}{\text{speed}} .$$

Again, using both the five-minute and the minute interval speed density data points, the SRCH program generated another series of admissible parameters for each location. Choosing the "best" set from each series, another speed-density curve was calculated for each location. Figures 5b - 9b show the experimental data with the additional points, the new calculated speed/density curve and the Q curve for each location.

Table 2 shows the five parameters at each location for the two calibrations.

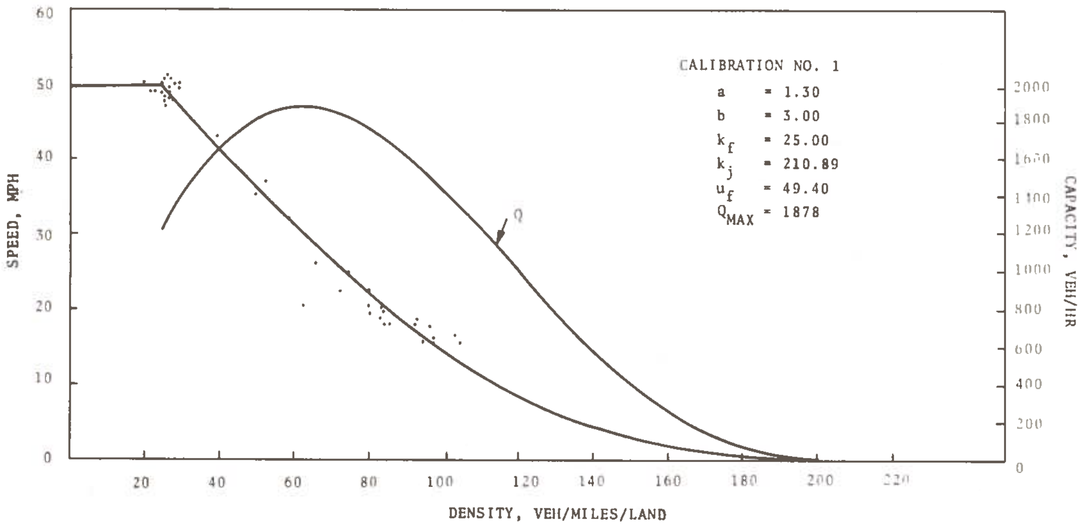

Figure 5a. Speed/Density Relationship at Location No. 1

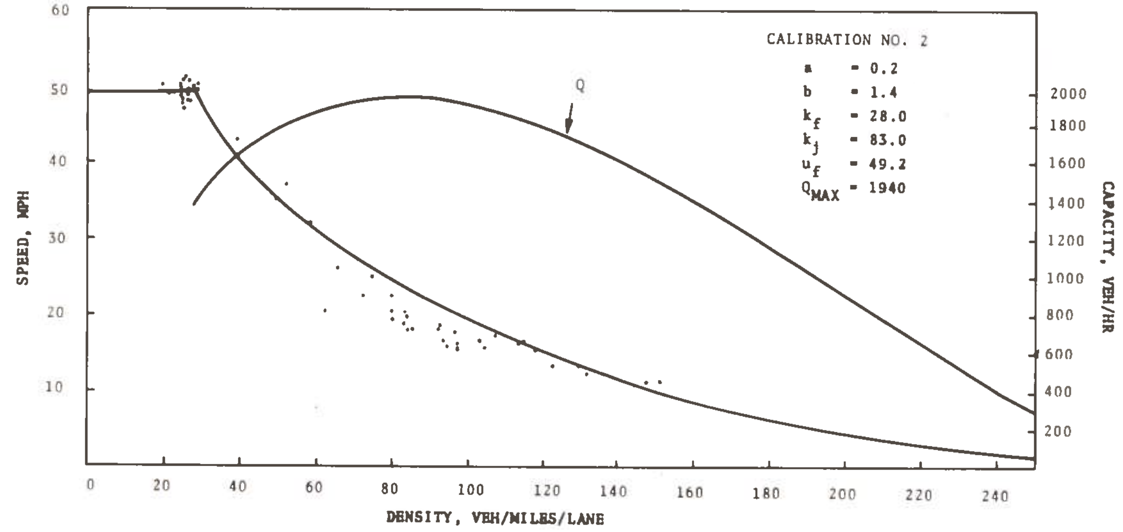

Figure 5b. Speed/Density Relationship at Location No. 1

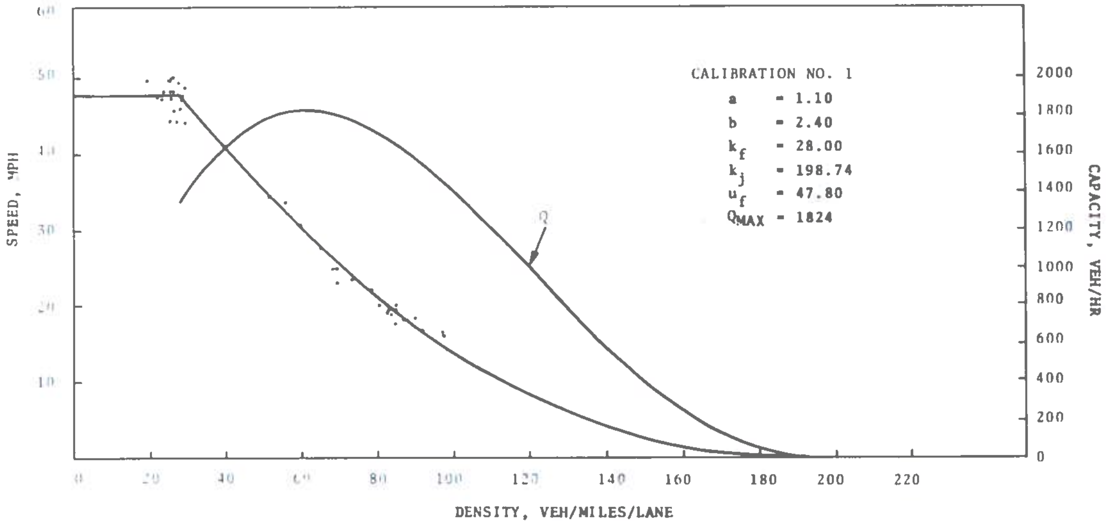

Figure 6a. Speed/Density Relationship at Location No. 2

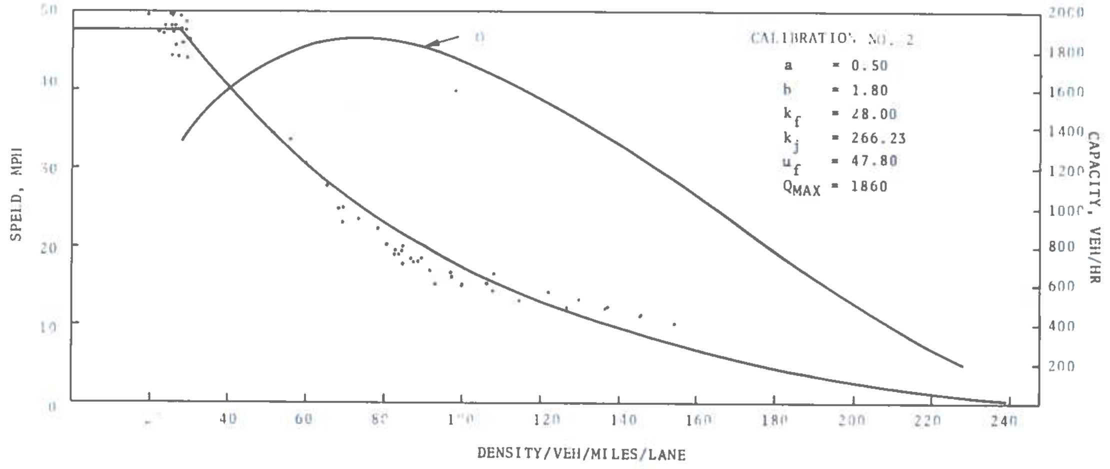

Figure 6b. Speed/Density Relationship at Location No. 2

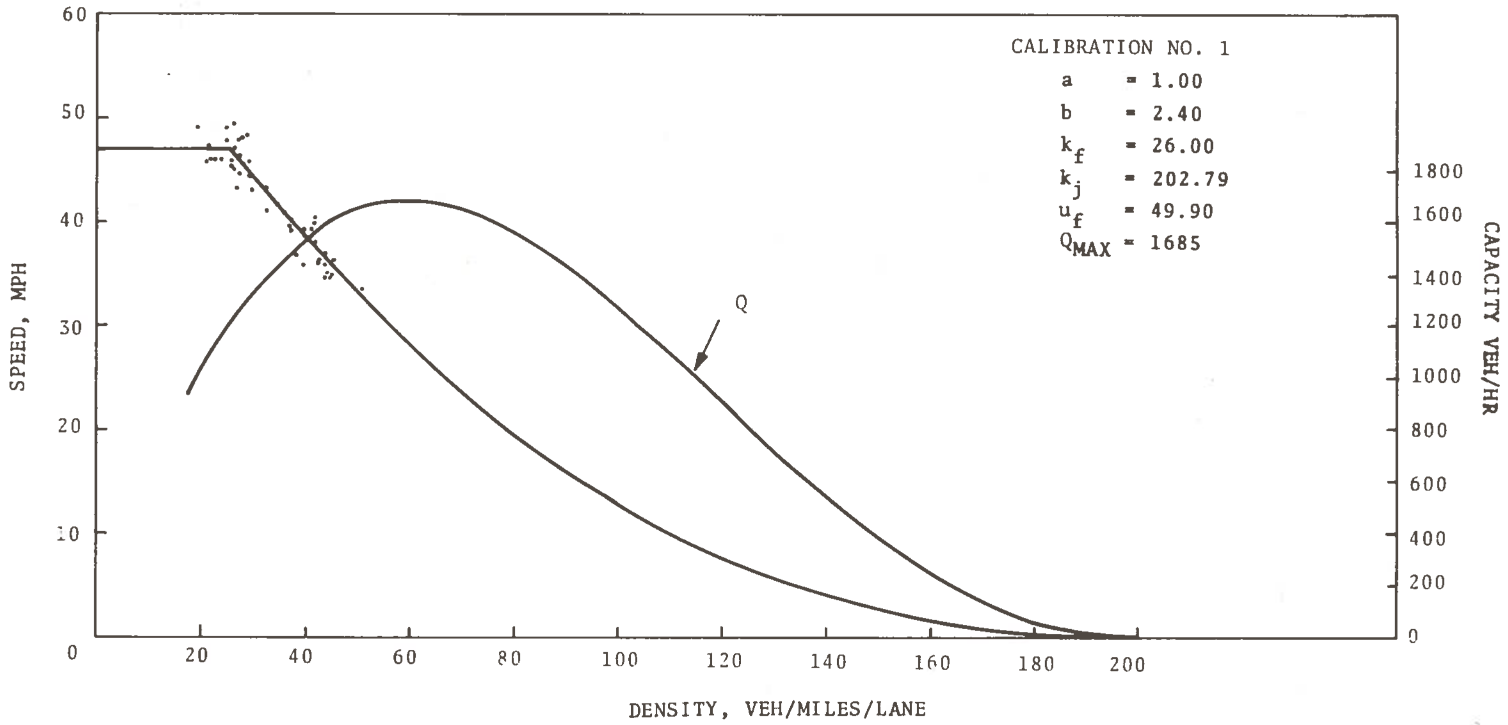

Figure 7. Speed/Density Relationship at Location No. 3

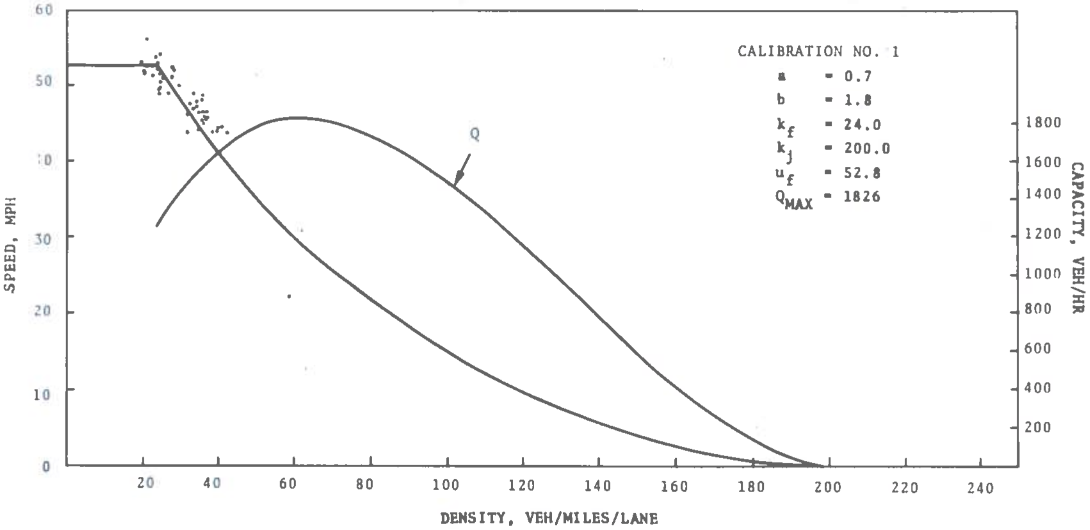

Figure 8a. Speed/Density Relationship at Location No. 4

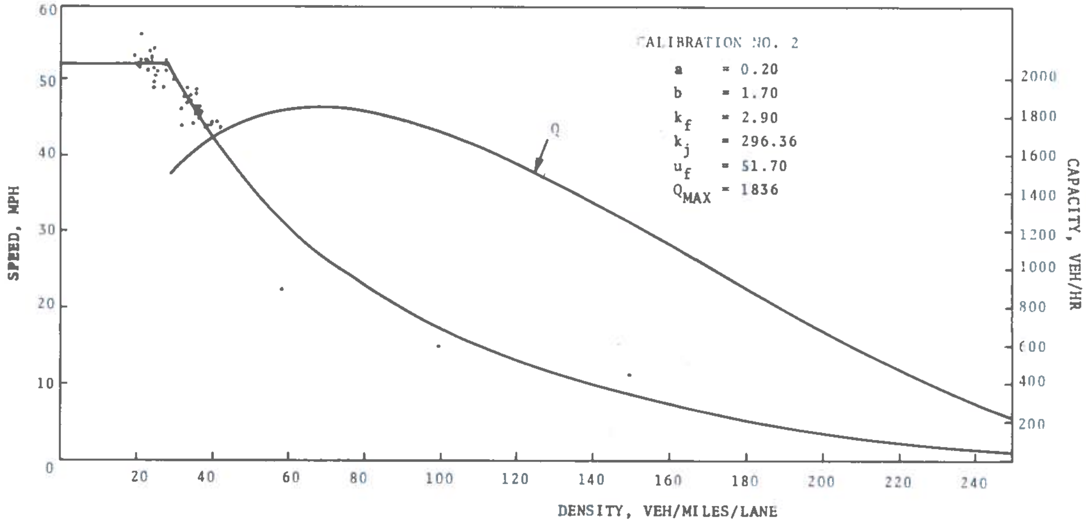

Figure 8b. Speed/Density Relationship at Location No. 4

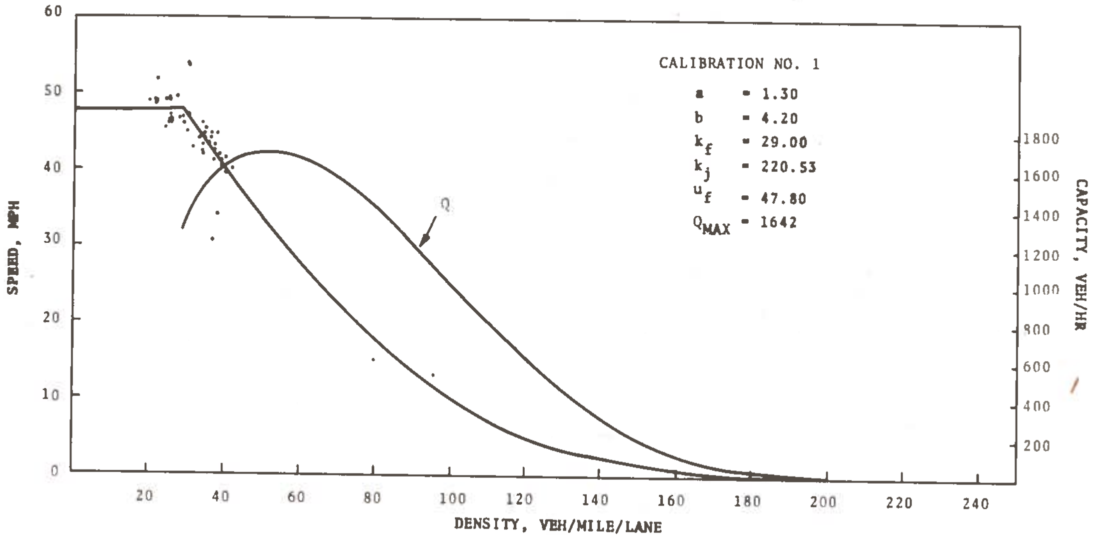

Figure 9a. Speed/Density Relationship at Location No. 5

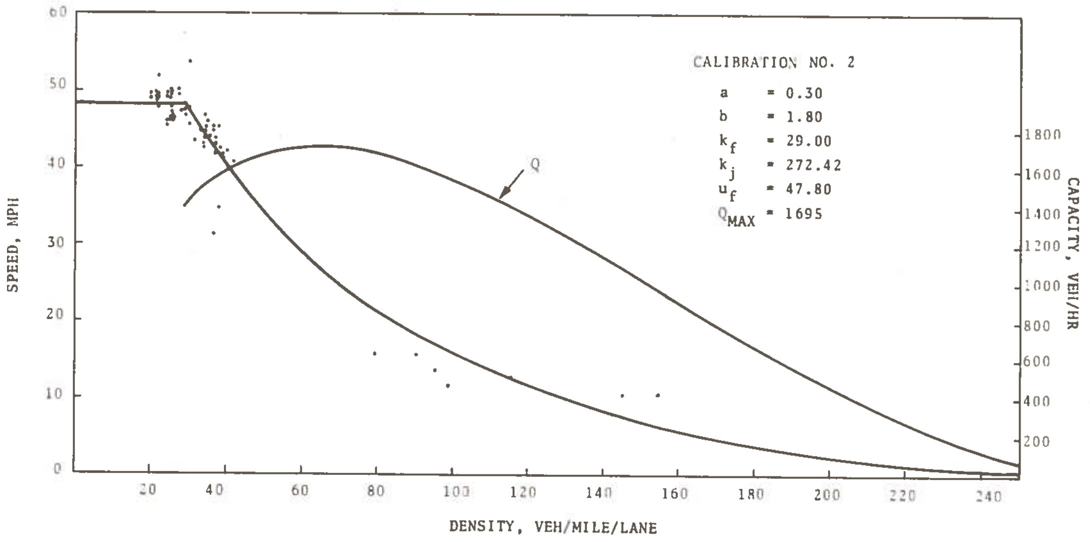

Figure 9b. Speed/Density Relationship at Location No. 5

TABLE 2 CALIBRATION SUMMARY

Location	Link	Calibration No. 1						Calibration No. 2						Field Data
		a	b	k_f	k_j	u_f	Q_{max}	a	b	k_f	k_j	u_f	Q_{max}	Q_{max}
1	82,81	1.3	3.0	25	211	49.4	1878	0.2	1.4	28	283	49.2	1940	1926
2	79,76	1.1	2.4	28	199	47.8	1824	0.5	1.8	28	266	47.8	1860	1860
3	69,66 56,54	1.0	2.4	26	203	46.9	1685	--	--	--	--	--	--	1686
4	56,54	0.7	1.8	24	201	52.7	1826	0.2	1.7	29	296	51.7	1852	1836
5	44,43	1.3	4.2	29	221	47.8	1692	0.3	1.8	29	272	47.8	1695	1698

Calibration No. 1 - TTI DATA 11/30/72

Flows from five minute data
Speed from average of five minutes of minute data

Calibration No. 2 - TTI DATA 11/30/72

Additional minute data added to above in high density region

3.2 MERGE DELAY DATA

From two hours of video tapes, deliverables of the GASL contract, showing the operation of Ramps 12 (Yale Avenue), and 14 (Lovers' Lane) in the North Central Expressway, measurements were made to determine the mean delay time experienced by vehicles entering the freeway. The Yale video tape was made on November 16, 1971 (cloudy and warm weather) in two sections: a 46-minute period running from 1640 to 1720 hours during the evening peak traffic when the ramp was metered and filmed and a 20-minute off-peak period in the morning running from 1000 to 1020 hours. Also, in the case of Lovers' Lane, two sections of film were made: (a) A 40-minute video in the evening rush (fair and cool weather) in November 29, 1971, and (b) a 20-minute off peak period in the morning.

In order to record the data from the tape, two methods were used. For Yale Avenue, a stop watch and timer, and for Lovers' Lane a brush pen recorder[4] were used to record the point in time that the middle of a car would pass a pre-set location in the ramp or freeway. (See Figure 10 for a diagram of the intersection and location of the two points at which data was recorded: (a) the ramp point of decision, and (b) the merge point.) At the same time, the volume of cars in the outside lane of the freeway was recorded on a minute by minute basis.

The point of decision is the point on the on-ramp at which the driver must decide whether to accept or reject the oncoming gap on the freeway. The merge point is the place at which the car from the ramp enters the mainstream of traffic on the freeway. Recorded was the time it took a vehicle to travel from the point of decision to the merge point including the amount of time the vehicle spent stopped, if any, prior to merging with the freeway traffic. The results of this effort are summarized in Tables 3a and 3b where the entrance ramp merge-delay (sec/vehicle) is given

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[4] Drottar, E. P., A Study of Gap Acceptance and Critical Gap Determination, DOT/TSC Internal Report, August 1972.

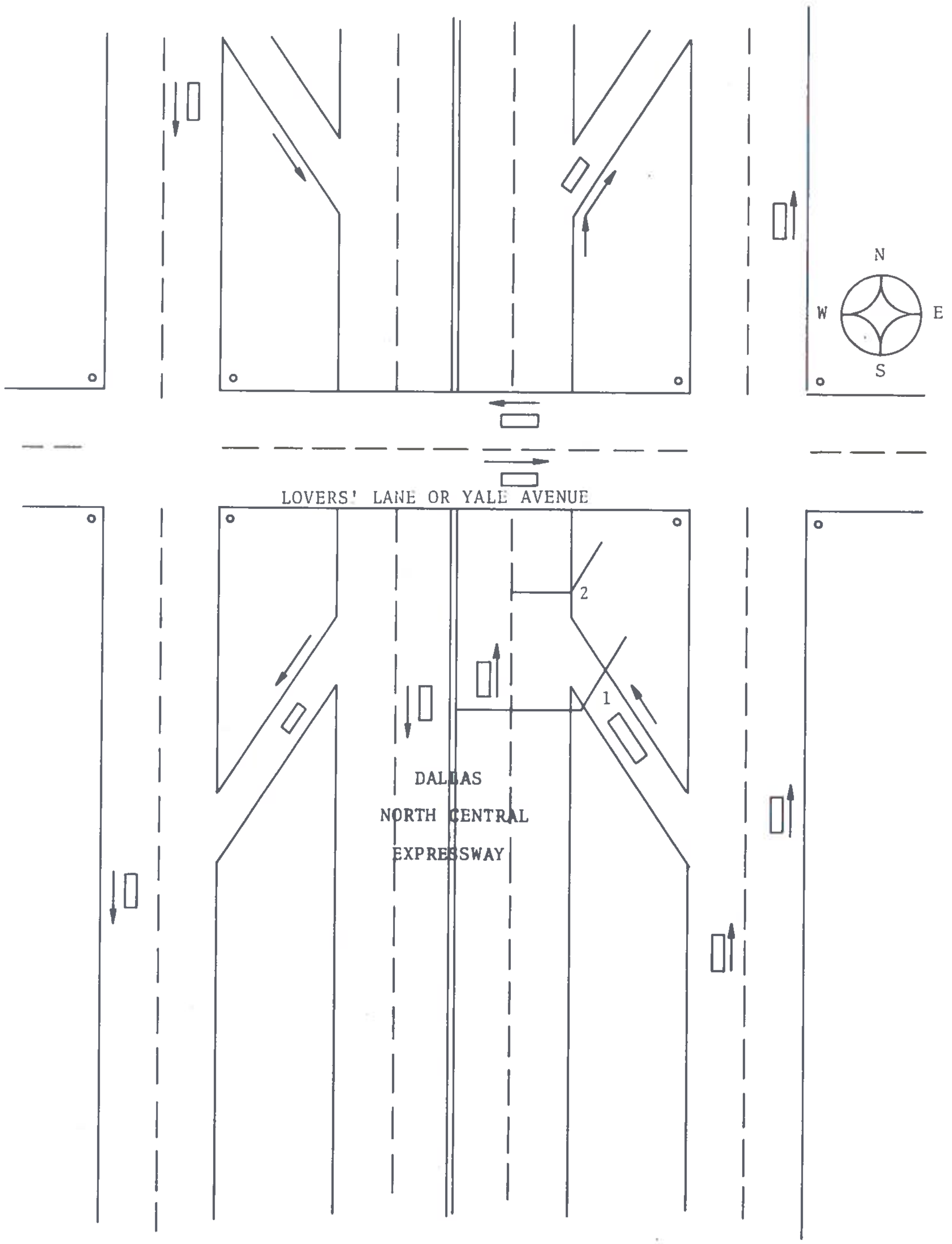

Figure 10. Diagram of Study Intersection and of the Two Points of Measurement

as a function of outside lane volume (vehicles per hour). Unfortunately, it was not possible to obtain merge-delay data for outside lane volumes greater than 1200 vph from the video tapes because these traffic volumes were not present.

TABLE 3a ENTRANCE RAMP DELAY FOR YALE AVENUE (RAMP 12)

Outside Lane Volume (vph)	Entrance Ramp Merge Delays (sec/veh)
900 to 1,000	6.7
1,000 to 1,100	7.4
1,100 to 1,200	10.0
1,200 to 1,225	10.0
> 1,225	Not available from video data

TABLE 3b ENTRANCE RAMP DELAY FOR LOVERS' LANE (RAMP 14)

Outside Lane Volume (vph)	Entrance Ramp Merge Delays (sec/veh)
800 to 900	10.8
900 to 1,000	14.8
1,000 to 1,030	12.0
> 1,030	Not available from video data

On the basis of this data, the Yale Avenue entrance ramp has been classified as category 3 (high and ramp metered-short merge area) and Lovers' Lane as category 2 (intermediate) as specified in Table 3, entrance ramp merge delays of the GASL final report, Contract DOT-TSC-161 (Table 4).

It has also been noted that a higher percentage of vehicles travelled in the outer lane than predicted by Table 1 of the above report. In fact, approximately 50% of the traffic volume is in the outer lane.

TABLE 4 ENTRANCE RAMP MERGE DELAYS

Outside Lane Volume (vph)	Entrance Ramp Merge Delays (sec/veh)						
	Low	Intermediate		High and **Ramp Metered-Short Merge Area		*Ramp Metered - Long Merge Area	
		$k \leq k_{opt}$	$k \geq k_{opt}$	$k \leq k_{opt}$	$k \geq k_{opt}$	$k \leq k_{opt}$	$k \geq k_{opt}$
≤ - 600	9	4.0	6	2.8	6	1	3.5
601 - 800	14	4.8	6	3.3	6	1	3.5
801 - 1000	18	0.8		4.0	6	1	3.5
1001 - 1200	18	12.0		5.1	6	1	3.5
1201 - 1400	18	18.0		7.2		3.5	
1401 - 1600	18	18.0		12.0		7.0	
> - 1600	18	18.0		18.0		12.0	

* The data for the "Ramp Metered-Long Merge Area" category was derived by viewing the video tapes of the Dallas North Central Expressway.

** The "Ramp Metered-Short Merge Area" category was observed to be similar to the tabular values for the "High" category and so they were combined.

To properly simulate the role played by ramp merging, some additional calibration data is required. Specifically, statistical distributions of merge delay as a function of link volume are needed. These distributions could take the forms shown in Figures 11a, 11b, and 11c.[5]

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[5] E. Lieberman, Private Communication to R. Ricci, March 25, 1973.

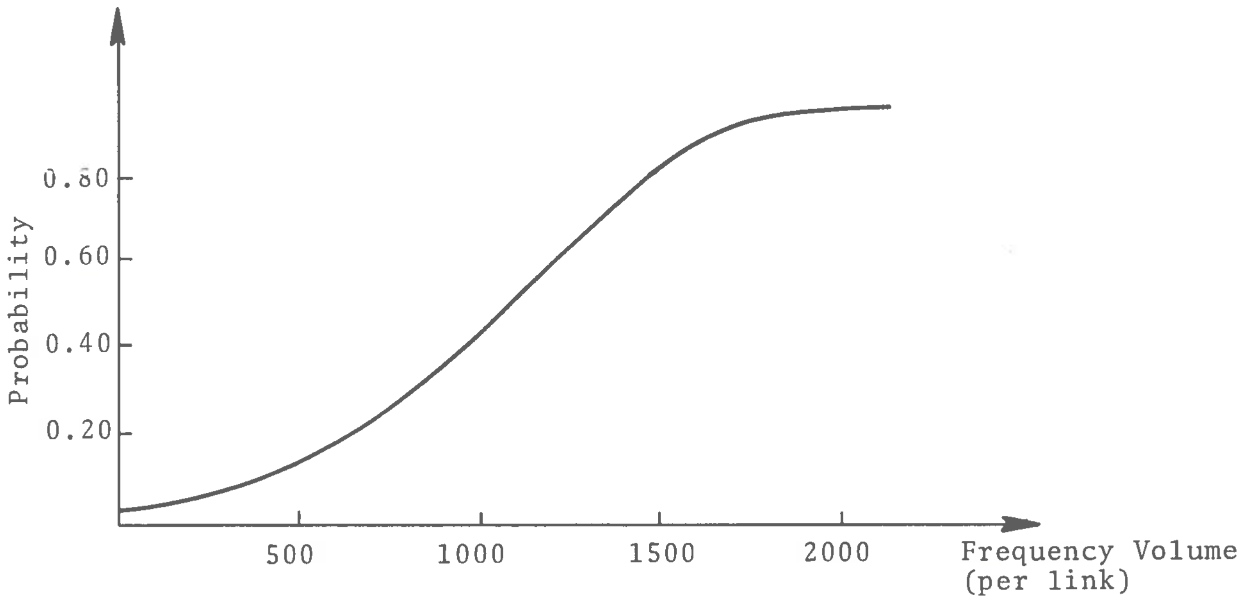

Figure 11a. Probability that a Merging Vehicle will be Stopped at the Merge Point

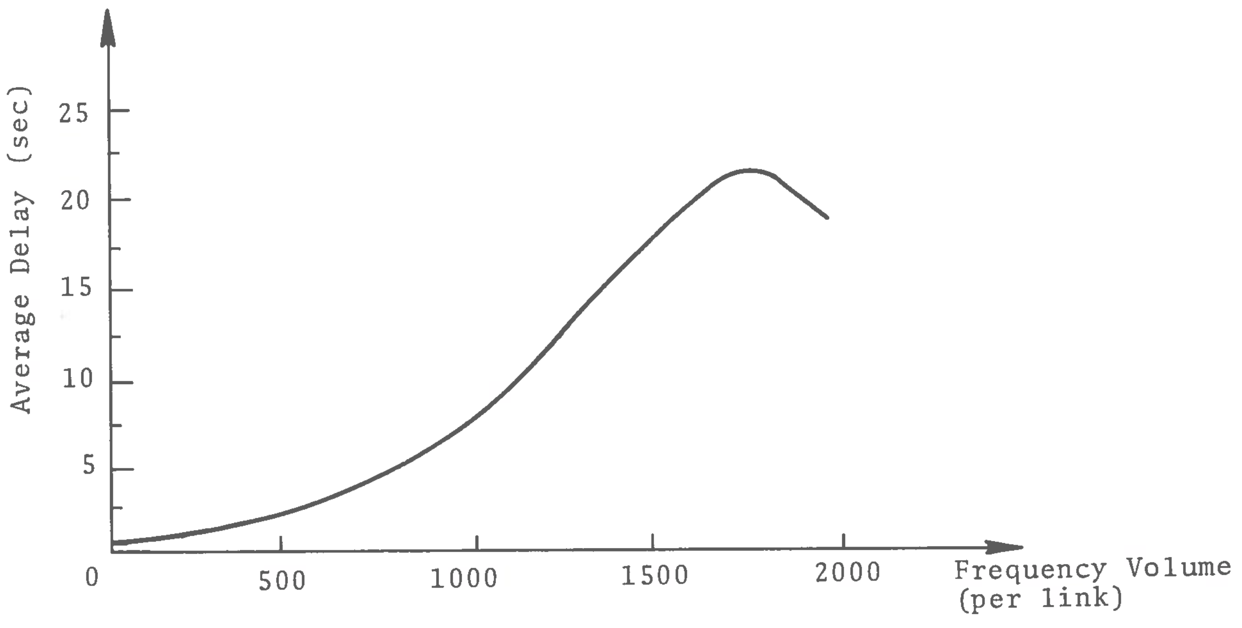

Figure 11b. Average Delay Experiment by a Stopped Vehicle at the Merge Point

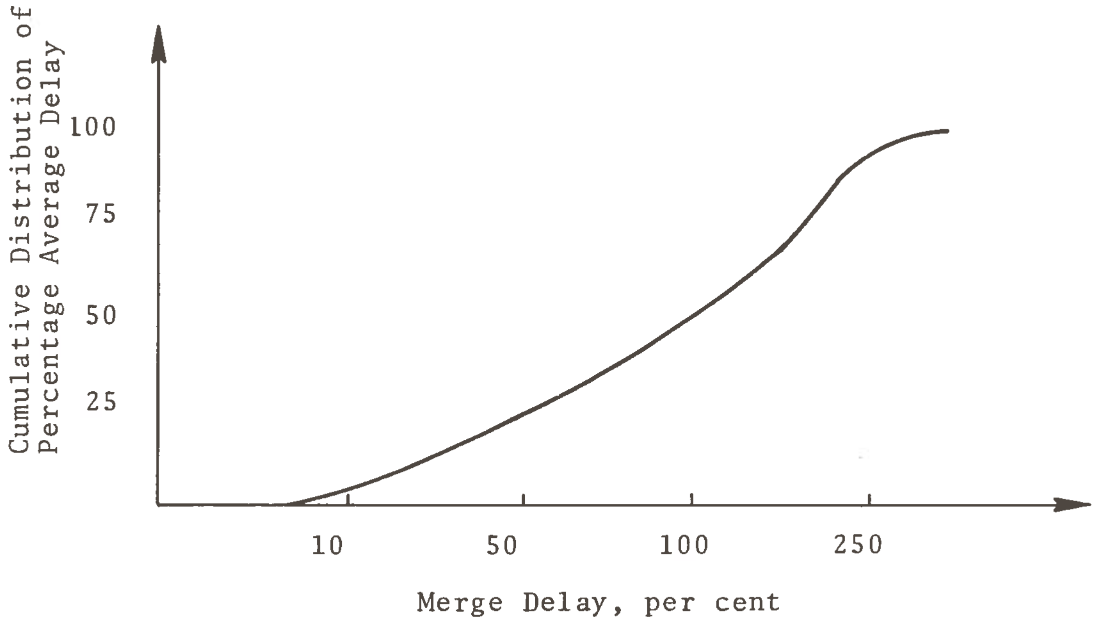

Figure 11c. Cumulative Distribution of Merge Delay as a Percentage of the Mean Value

4. EVALUATION OF SCOT MODEL

For the evaluation and validation process, two networks have been used, 1) a 80-node, 1.5 square-mile network containing three miles of the Dallas North Central Freeway extending from Mockingbird Lane to the Loop 12 interchange (Figure 1) and 2) a 36-node, 0.6-square-mile mini-network containing 1.3 miles of the freeway extending from Mockingbird Land to Lovers' Lane (Figure 12).

The following types of evaluation runs were made:

a. Categorization of freeway links,

b. Real-time freeway input volumes versus artificial artificial impulse responses, and

c. Evaluation runs.

4.1 CATEGORIZATION OF FREEWAY LINKS

The applicable values of the five calibration parameters (a, b, k, k_f, u_f) vary from link to link. This reflects variations in geometry, pavement, grade, and other considerations. Before the model can be exercised, it is necessary to determine the values of these five parameters for each category of freeway link. A category of links is comprised of members which exhibit similar pavements, geometries, etc., which yield basically the same operating conditions. In its final report, GASL determined that five categories based principally on the percent of grade of the freeway links were appropriate for the 80-node test network. However, the results to date indicate that this is not the case. As noted in the Highway Capacity Manual (1965)[6], the effect of upgrades of up to seven percent on passenger-car capacity is generally negligible. Therefore, the approach taken here is "category" calibration by freeway sections where a section of freeway is defined as being continguous to a sensor (both northbound and southbound of the volume/speed sensors). In the case of the

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[6] Highway Research Board, Highway Capacity Manual 1965, Special Report 87, National Academy of Science, 1966.

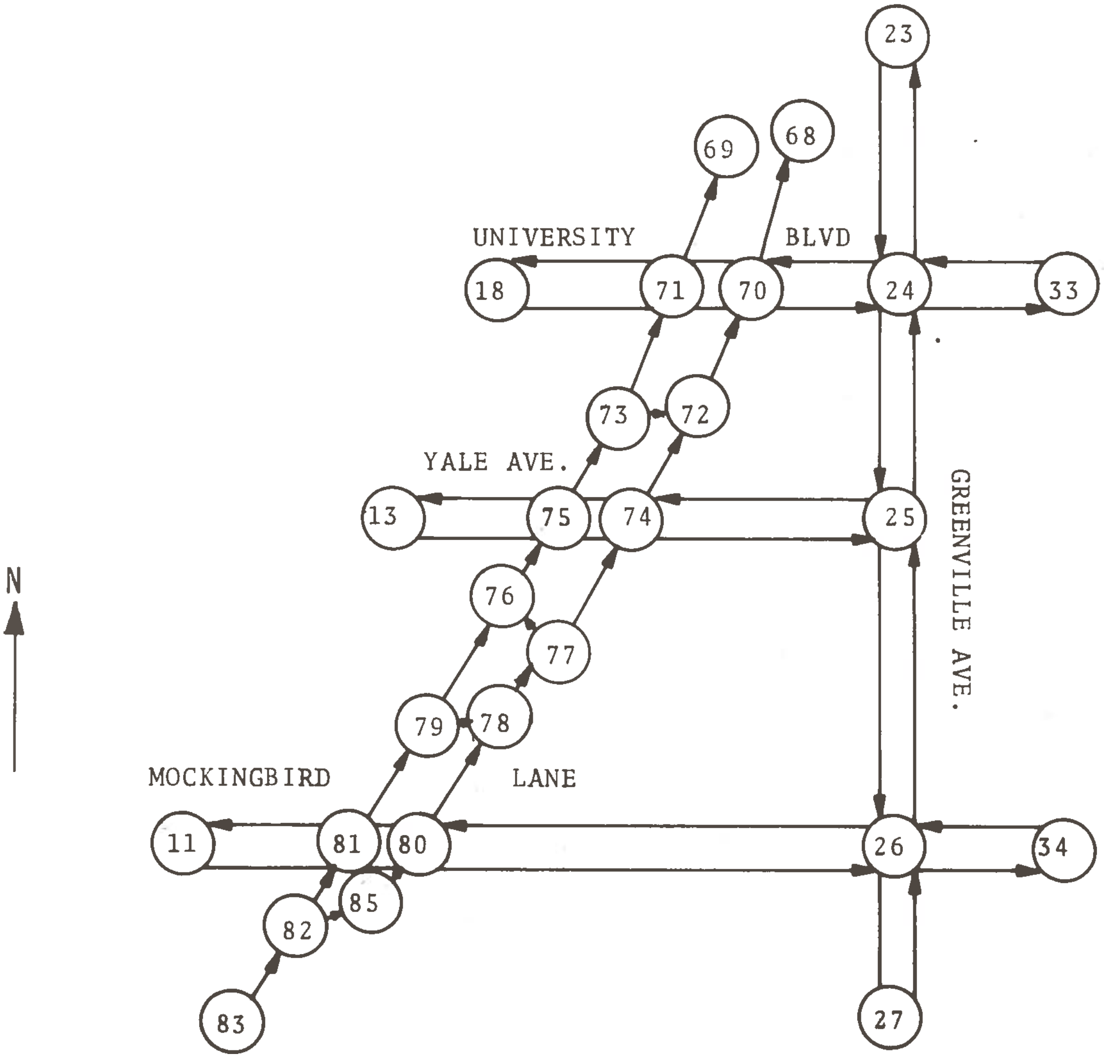

Figure 12. Medium Network -- Dallas Corridor

80-node network, this means five categories and in the mini-network, three categories.

4.2 ARTIFICIAL PULSING

As a result of a mid-November 1972 meeting held in Dallas with representatives of FHWA, TTI, and TSC concerning data requirements for calibration and validation of the SCOT model, ten days of freeway data (in the form of computer printouts) were received from TTI. (See Figure 2 for detector outputs A10 through A24.) Printed copies of the data contain on-and-off ramp volumes, freeway speeds for the outside lanes, and densities.

Investigation of the vehicle-flow information for November 10, 1972, one of the days for which data was received, showed a significant rise (149 cars/min) between 1510 and 1515 hours at the freeway entry link. Following this period, the traffic flow remained near 4400-4500 veh/hr. Because no real-time speed/density data were available for this date, confirmation of densities was not possible. It was estimated that densities remained on the constricted flow portion of the capacity curve from the 1515 hours pulse.

The period of interest for this simulation was 1700-1715 hours. A computer simulation over the total duration 1515-1715 hours appeared prohibitively expensive. For this reason, a pulse representing a large (7800 veh/hr) flow was introduced. This peak was chosen to represent the same number of cars introduced in one minute as would have been introduced in five at the 3:10 to 3:15 period. Results are shown in Tables 5 through 10 for simulation runs 11, 12, and 13 for input-data flows, overall speed-statistics/speed-comparisons for field and simulated data, vehicle flows and densities. In runs 12 and 13 the time base of the pulse has been lengthened with a correspondling greater volume introduced. Speeds, especially in run 13, approach those of the TTI data and vehicle flows are accurate to within 12%. The density calculations however, do not compare well especially in link 79, 76 (see Figure 1). In summary, for these runs, differences in simulation and field data for Q

TABLE 5 DURATION AND FLOW RATE FOR LINK (83.86)
(VEH/HR)

Interval	Run 11	Run 12	Run 13*
1	60sec 3800	60sec 3800	60sec 3800
2	60sec 4300	60sec 4300	60sec 3800
3	60sec 7800	180sec 7800	120sec 7800
4	300sec 4560	300sec 4560	300sec 4560
5	300sec 4440	300sec 4440	300sec 4440
6	300sec 4236	300sec 4236	300sec 4236

*Border line link parameters changed from CAT. C to CAT A for 3 links.

TABLE 6 OVERALL SPEED STATISTICS
(Subsystem B Node 79 to 44)

	mph
TTI Data (DOT-FH-11-7835)	34.1
Floating Driver Data (9/14/71)*	37
TTI Field Data - Subsection B2	32
Subsection B4	47
Subsection B6	46
Sim. Run 11	39.2
Sim. Run 12	32.3
Sim. Run 13	33.2

*Nodes 81-49, All others Nodes 79-44.

TABLE 7 COMPARISON OF SPEED-SIMULATION RESULTS (RUNS 11, 12, and 13) WITH FIELD DATA FROM TTI 11/10/72

Speed Comparisons	Simulated Data (15 min)			Field Data (mph)	
Subsection A6 (Nodes 86 to 79)	11	12	13	Measure	Calculated
86,82	48.9	10.3	44.8		
82,81	45.4	40.4	42.3		
81,79	49.9	22.9	16.3		
Av. =	48.1	24.5	34.3	28	24
Subsection B2 (Nodes 79 to 69)					
79,76	35.2	9.0	9.4		
76,75	23.5	31.0	29.3		
75,73	45.0	45.8	45.6		
73,71	37.2	39.6	39.0		
71,69	48.7	48.6	48.2		
Av. =	37.9	34.8	34.3	32	26
Subsection B4 (Nodes 69 to 56)					
69,66	42.2	42.1	42.6		
66,65	25.6	34.0	40.6		
65,63	49.4	48.3	49.6		
63,59	41.8	43.2	42.4		
59,58	30.1	33.9	40.6		
58,56	49.5	49.4	49.5		
Av. =	39.8	41.8	44.2	47	43
Subsection B6 (Nodes 56 to 44)					
56,54	33.8	36.6	34.8		
54,52	49.9	50.	50.3		
52,51	52.9	53.0	52.4		
51,50	53.0	53.2	53.0		
50,49	51.3	51.6	50.9		
49,44	44.1	44.1	43.9		
Av. =	47.5	48.1	47.6	46	43

TABLE 8 COMPARISON OF VEHICLE-FLOW-SIMULATION RESULTS

Link	Simulation			Field	$\%\left(\frac{Sim-Field}{Sim}\right)$
	Run 11	12	13		13
(86,82)	1116	1076	1125	1103	1.9
(79,76)	862	725	743	816	- 9.8
(69,66)	785	722	736	799	- 8.5
(56,54)	792	779	793	854	- 7.6
(44,43)	731	709	731	815	-11.5

TABLE 9 COMPARISON OF DENSITIES FOR LINKS

Links	Field Data		Simulation								
			Run 11			Run 12			Run 13		
	Speed (5 Min)	K(Veh/M)	Occ.	Speed	K	Occ.	Speed	K	Occ.	Speed	K
81,79	17	90	13.1	49.9	27	27.9	22.9	57	37.9	16.3	78
79,76	18.5	78	14.8	35.2	46	55.0	9.0	171	52.9	9.4	164
69,66	35	50	10.3	42.2	36	10.0	42.1	35	9.3	42.6	33
56,54	41	44	11.3	33.8	46	10.3	36.6	41.8	10.6	34.8	43
44,43	41	36	4.9	44.1	21	4.8	43.4	20	4.8	44.2	20

TABLE 10 COMPARISON OF ENTRANCE AND EXIT FLOWS
(15 Minutes)

RAMP	SIMULATION RUN 13	FIELD
OFF 82,85	151	123
OFF 79,78	136	129
ON 87,76	68	53
OFF 73,72	30	15
OFF 69,68	69	63
ON 88,66	55	78
OFF 63,62	44	61
ON 89,59	53	77
OFF 56,55	23	21
ON 90,52	49	74
OFF 51,47	79	80
ON 48,50	36	17
OFF 44,46	66	62
ON 45,43	62	64

(flow rates) vary from 11% to 2% and for speeds from 15 to 2% for various links of the freeway.

Because an analytical justification could not be made for the use of large pulses to compress the time base of afternoon freeway traffic, this approach was discontinued. Rather than model the input flow rates that take place over a two hour period in the afternoon rush (1510 to 1715 hours) the period of time (1610 to 1640 hours) of December 5, 1972 was selected where there occurs a transition from vehicle free flow to constricted flow. During this period, measured speeds at Mockingbird/Yale drop from 49 to 20 mph in approximately ten minutes and thereafter remain low. During the same period, McCommas/MONT speeds drop from 49 to 27 mph and continue slowing thereafter.

The 36-node test network, utilizing freeway links running from Node 83 to Node 71 and all of the urban streets south of and including University Boulevard, was modeled. Freeway input and turning rates were adjusted to reproduce the volumes appearing on the one-minute and five-minute data printouts. Because ramp data is not available from the one-minute data, turning rates were estimated by taking the ratio of volumes at Node 76 to those at Node 83 and assigning equal turn-off percentages at Nodes 72 to 79 to achieve this ratio. Vehicles entering through ramp 77,76 are imbedded in the one-minute data, and must be estimated per minute by averaging the five-minute ramp data. These values are subtracted from the Node 76 volume counts.

Subintervals of one-, two-, and five-minute durations were run because it was thought that a pulse of short duration might be necessary and sufficient to produce a change from free to constricted flow. Because of the filtering nature of the program, output turning percentages did not match the input for a one-minute simulation and this length subinterval was discarded.

The two-minute subinterval matched the flow of vehicles reasonably closely as shown in the following comparison (Table 11). The data described include that taken at Node 79 using detectors V14 and A12 plus that of the on ramp using Detector 012. The values are from the one minute TTI printout.

TABLE 11 VEHICLE FLOW

Time	TTI Data	SCOT Node 76
1611-1612	111	114
1613-1614	134	129
1615,1616	110	119
1615,1616	125	125
1619-1620	116	121
Totals	596	608

TABLE 12 SUMMARY OF TEN MINUTES SIMULATION TIME

TTI Field Data	Run 21	Run 23
V14 & A12	79,76	79,76
568	577	579
012	77,76	77,76
28	27	33
R12	82,85	82,85
89	94	84
R14	79,78	79,78
74	83	81

A summary of results using the five-minute subinterval (run 21) and the two-minute (run 23) is shown (Table 12). The TTI field data to which it is compared is taken from the five-minute printouts.

Freeway volumes for both cases are adequately simulated; however, neither example forces the traffic to operate on the constricted flow portion of the Q,k curve. This is seen from the wave-speed data (Table 13).

TABLE 13 dQ/dk FOR FREEWAY LINKS

Run No.	Link	Time (min.)									
		2	4	6	8	10	12	14	16	18	20
21	79,76	16	8	8	6	6	13	16	19	19	16
23	79,76	16	13	16	13	8	8	6	6	10	13
21	76,65	6	2	0	-3	-3	0	0	9	9	6
23	76,65	9	6	9	6	6	2	0	-3	0	0

(Note that run No. 23 begins five minutes later than run No. 21.)

The value of dQ/dk of link 79,76 remains positive throughout, indicating that free flow is maintained. In addition, the average speed through link 79.76 remains high (35 mph or more).

As a result of this series of simulation runs, it was concluded that (a) no significant difference in the behavior of the simulated traffic occurs whether a two or a five-minue subinterval is chosen, and (b) that the calibration of the freeway links was in error since the traffic only flows in the force flow region. Therefore, in all future simulations, five-minute subintervals were used, and it was also concluded that the calibration parameters identified in the GASL Final Report (Table 3.1.1) were in error. A recalibration of the sensor data was then undertaken as described previously in the calibration section.

4.3 COMPUTER RUNS

After recalibration on five-minute aggregations of data numerous computer runs were made under varying conditions of traffic input flow, turning rates, number of filter samples used in the calculation of k, density of veh/mile, and etc. All these computer runs indicated a tendency for the freeway links that have traffic flows in the forced-flow region of the speed density curve to jam. This congestion then propagates to other upstream links.

Initially, this was thought to be due to an improper calibration curve in the region of density above 90 veh/mile. In this region, there is an absence of data points when five-minute aggregations of data are plotted. Because of this absence of data, an error, while small in absolute terms of speed but possibly large when expressed as a percentage, is introduced. In the range of 130 to 150 veh/mile these calibrations yield flows of 800 to 1000 veh/mile/lane, while in actual fact, flows are insensitive over a wide range of density (below jam conditions) and remain close to capacity. In practice, a precipitous drop in speed is accompanied by a sharp increase in density but an imperceptible change in flow rate.

In the absence of reliable data in the high-density region, the model was modified so as to enforce a discharge flow rate of 90 percent of capacity in this high-density regime. This was achieved by over-riding the speed obtained from the calibration with a value calculated to provide the 90 percent of capacity discharge flow rate.

The justification for this approach lies not only in observed behavior but also from considerations of microscopic behavior. If a lane density of 155 veh/mile and an average vehicle length of 17 feet are considered, then the physical spacing between vehicles will be also 17 feet. Application of the rule of thumb of one car spacing per 10 mph, indicates a safe vehicle speed of 10 mph. This would amount to a flow of 1550 vehicles per hour per lane, which is reasonably consistent with the enforcement of 90 percent of capacity. Although there is justification for this approach as seen above, it was determined after a number of computer simulation runs that this was not the cause of the tendency for the freeway links that have traffic flows in the forced flow region of the speed/density curve to jam.

The platoon concept used in the SCOT model results in "slugs" of vehicles traversing each link. In order to smooth the effects of these slugs, the calculation of k(veh/mile) is filtered over time. Initially, this calculation was performed over 15 (4-second) time intervals giving a filtered k value based on one minute of past history. It was found that the response time of the model was not fast enough to react to changes in input volume flows. For example, real field data shows a flow rate of 4100 veh/hr into the freeway entry mode just south of Mockingbird Lane for one five-minute interval and then 4900 veh/hr for the next interval. This rapid change in input flows required a fast response time. As a result, the number of sample intervals over which k is now calculated has been reduced to five samples with an appropriate improvement in response time.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

a. The existing TTI data must be supplemented in order to allow proper calibration of the model, a necessary requirement for the model to replicate reality.

b. The response of the model is not consistent with the behavior of turbulent freeway traffic flow although the model has performed well in representing laminar flow.

Specifically, lane specific speed/density data for each freeway link and lane are needed. The number of sensors-per-test network should be increased from the presently available two for the mini-test network to seven since there are seven freeway links and from five for the 80 node test network to 22. In addition, statistical distributions of merge delay as a function of link volume on the freeway link immediately upstream of the merge point are required for all ramp entrances in the test network. Specifically, these distributions may be defined as: (i) probability (percent) that a merging vehicle will be stopped at a merge point as a function of link volume, (ii) average delay experience by a stopped vehicle at the merge point as a function of link volume, and (iii) cumulative distribution of merge delay as a percentage of the mean value vs. merge delay as a percent of mean value.

When traffic flows are in the forced-flow retion of the speed/density, i.e., k>kopt the tendency is for the affected link to jam. This jam then results in other upstream links to jam. It appears that the speed/density relationship is characterized by a hysteresis effect, i.e., an incremental change in traffic volume may cause k>kopt but a large incremental change is required to bring the state of traffic from the forced-flow region to the free-flow region.

5.2 RECOMMENDATIONS

It is recommended that a program of data acquisition and reduction to supplement the presently available TTI data be undertaken using the Dallas North Central Expressway as the test bed. This should be followed by model calibration and validation.