328125

PB 246 756

REPORT NO. DOT-TSC-FHWA-75-2

SIMULATION STUDIES FOR AN URBAN TRAFFIC CORRIDOR

Lawrence McCabe
Robert Ricci
Patricia Concannon

OCTOBER 1975
FINAL REPORT

DOCUMENT IS AVAILABLE TO THE PUBLIC THROUGH THE NATIONAL TECHNICAL INFORMATION SERVICE, SPRINGFIELD, VIRGINIA 22161

Prepared for

U.S DEPARTMENT OF TRANSPORTATION
FEDERAL HIGHWAY ADMINISTRATION
Office of Research
Washington DC 20590

Reproduced by
NATIONAL TECHNICAL INFORMATION SERVICE
U S Department of Commerce
Springfield VA 22151

NOTICE

This document is disseminated under the sponsorship of the Department of Transportation in the interest of information exchange. The United States Government assumes no liability for its contents or use thereof.

NOTICE

The United States Government does not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

PREFACE

This report concludes the development of the SCOT (Simulation of Corridor Traffic) model insofar as it demonstrates the ability of the model to replicate the movement of freeway traffic. A previous Urban Traffic Corridor Study performed by the Control and Simulation Branch of the Transportation Systems Center attempted to accomplish the same objective but was incomplete. The earlier effort was covered by Report No. DOT-TSC-FHWA-73-2 of January 1974 and is supplanted by this document.

This work was sponsored by the Traffic Systems Division of the Office of Research of the Federal Highway Administration.

The authors are indebted to Dr. Guido Radelat of the Federal Highway Administration for his advice and encouragement, to the Dallas Highway Department and Mr. James Carvell of the Texas Transportation Institute for their cooperation in the study, and to Messrs. Edward Lieberman and David Wicks of KLD Associates, Inc. for their efforts under contract number DOT-TSC-740.

TABLE OF CONTENTS

Preceding page blank

LIST OF ILLUSTRATIONS

LIST OF TABLES

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 methods and when a controlled experiment may be hazardous, expensive, and slow in producing meaningful results. Traffic flow in an urban grid-freeway integrated highway system represents a phenomenon of this type.

In 1970, General Applied Sciences Laboratory, Inc. developed a freeway simulation model called DAFT (Dynamic Analysis of Freeway Traffic) (1). 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 traffic control simulation model (UTCS-1) was developed by General Applied Science Laboratory, Inc. and Peat, Marwick, Mitchell and Co. under a contract with the Federal Highway Administration (FHWA) (2). This UTCS-1 model has been validated for urban traffic control systems, and its use is appropriate for the examination of surface street traffic control problems (3). 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, the FHWA in 1972 signed a project agreement with the Transportation Systems Center (TSC) to have such a model developed. The SCOT model developed and programmed by GASL under contract for TSC was the result of this effort (4).

During 1973, TSC performed studies of this model (5) for the purposes of calibration and validation with Dallas, Texas North Central Expressway as the test site. These calibration and validation studies showed that when freeway traffic flows were in the forced-flow region of the speed/density curve, i.e., $k>k_{opt}$ the tendency was for the affected link to jam. This jam then propagated backward and resulted in jamming the upstream links. An incremental increase in traffic volume caused the onset of forced-flow conditions but a large subsequent volume decrease was required to bring the state of traffic from the forced flow region back to the free-flow region.

Based on these studies, it was recommended that a data collection and reduction program for the Dallas Corridor test site be initiated, and a model calibration and validation be performed. During 1974 KLD Associates (6) under contract to TSC, implemented this data collection and reduction effort and completed the calibration and validation of the SCOT model. Substantial modifications were made to the freeway logic of the model as described in a later section in order to replicate freeway traffic.

The Dallas North Central Expressway is the site of the Dallas Corridor Control Project sponsored by 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. SCOT MODEL DESCRIPTION

SCOT is a computer model which may be applied to an urban traffic corridor and will simulate vehicular traffic on freeways, including on-and off-ramps and urban streets. It is essentially a combination of the macroscopic freeway simulation model (DAFT) and the operational urban street simulation model (UTCS-1). An urban traffic network containing up to 100 intersections of freeway and arterial links may be represented. Turning movements at each node or origin destination volumes for the entry and exit links may be used for describing the traffic flow. The urban traffic flow is modeled microscopically, that is, each vehicle speed is based upon the application of a car follower law, with modifications in speeds performed through simulated interactions with intersection regulatory devices such as traffic signals or stop signs. Queues formed by stopping at signals are discharged according to input discharge times and lead car speeds up to the limit are calculated based upon observed accelerations.

The freeway portion operates macroscopically, with vehicles grouped in platoons as large as ten cars and is subject to the following speed density relationship within a given link:

$$u = u_f \text{ for } o \leq k \leq k_f$$

$$u = u_f \left[1 - \frac{k^a - k_f^a}{k_j^a - k_f^a} \right]^b \text{ for } k_f \leq k \leq k_c$$

$$u = 0.9 \text{ Qmax}/k \text{ for } k_c < k \leq k_j$$

$$Q = ku \quad o \leq k \leq k_j$$

In these equations u = speed, k = density, Q = flow, u_f = free flow speed, k_f = density at transition from free flow to forced conditions, k_j = jam density, and k_c is defined such that $u(k_c)k_c$ = 0.9 Qmax when k is greater than the density at Qmax. Qmax is the point at which the derivative of the Q(k) curve is zero excluding the condition $k = k_j$ and the model never lets speed become less than 7 mph for all densities. The values of these parameters are obtained from field data by a least squares curve-fitting technique as a result of calibration effort that must precede the application of the model. A typical plot of the calibration speed density relationship is shown in Figure 1. Also plotted is the volume Q, which is the product of speed and density.

A primary attribute of the model is its universality of application. The model may be applied to any geometric configuration and traffic demand conditions due to its network representation of the roadway system and its non-restrictive manner in which the signal control, traffic routing, and incoming demand may be specified.

Input data (Figure 2) required for operation of the model consists of the descriptions of the links, traffic signal data and entry-link traffic flows. The links are described in terms of the node numbers of their extremities, the numbers of lanes, the span, the percentages of turning traffic at the intersections, the destination nodes of traffic discharged through the link, and, for freeways, the values of a, b, k_f and k_j. The free-flow speed for each link is also included, which for urban streets is the speed limit. Generally, links are described as extending from intersection to intersection on urban streets. On the freeway, they may extend from ramp to ramp or until a change in roadway slope is encountered.

Traffic signal data for each node includes cycle durations, phasing information and the node numbers of the approaching links. Information concerning sign control or specialized codes such as green arrow indications is also input. The time lost upon signal changes and the mean queue discharge times are included as input for urban streets. In addition, if freeway ramps are signalized, metering rates and freeway gap acceptance criteria are specified. The link data and input statistics may be updated throughout the simulation by the use of subintervals, at which time statistics are gathered for outputs. A typical and convenient subinterval length is five minutes.

The available output statistics and measures of effectiveness (Figure 3) describe traffic processed through each link in terms

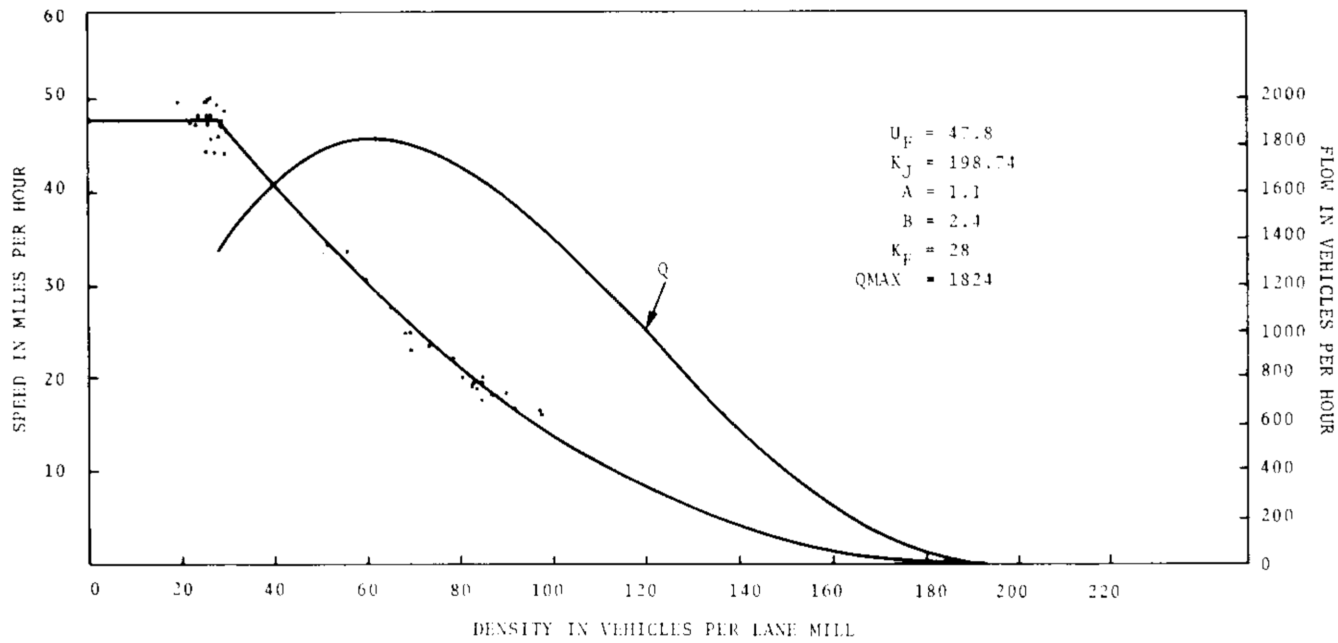

Figure 1. Typical Speed/Density Relationship

NOT REPRODUCIBLE

SIMULATION OF TRAFFIC

THE SCOT MODEL

SCOT VALIDATION

N C EXPRESSWAY , DALLAS , TEXAS 714 03/12/74

SEED FOR RANDOM NUMBER GENERATOR IS 7581

LINK	LANE	SPAN	POCK L	POCK R	MEAN U-F	H	TURNING MOVEMENTS LEFT	THRU	RT	DIAG	DESTINATION NODES LEFT	THRU	RT	DIAG	FREEWAY KF / NON-FREEWAY LOST	KJ / PED	A / TYPE	B / G	LANE CHAN 1	2	3	4	5	L	IDENTIFICATION
(701, 1)	3	500	FRWY		61		0	85	15	0	0	2	11	0	20	183	72	20						1	FREEWAY ENTRY
(1, 2)	3	670	FRWY		69		0	100	0	0	0	3	0	0	15	239	2	17						2	FREEWAY LINK 1
(2, 3)	3	500	FRWY		65		0	92	8	0	0	4	13	0	15	205	15	17						3	FREEWAY LINK 2
(3, 4)	2	1180	FRWY		52		0	100	0	0	0	5	0	0	20	181	161	36						4	FREEWAY LINK 3
(4, 5)	2	550	FRWY		57		0	100	0	0	0	6	0	0	20	238	139	51						5	FREEWAY LINK 4
(5, 6)	2	470	FRWY		61		0	94	6	0	0	7	16	0	20	183	72	20						6	FREEWAY LINK 5
(6, 7)	2	940	FRWY		54		0	100	0	0	0	8	0	0	20	191	137	33						7	FREEWAY LINK 6
(7, 8)	2	640	FRWY		52		0	90	10	0	0	9	18	0	20	183	110	22						8	FREEWAY LINK 7
(8, 9)	2	900	FRWY		54		0	100	0	0	0	10	0	0	20	181	118	26						9	FREEWAY LINK 8
(9, 10)	2	1000	FRWY		54		0	100	0	0	0	706	0	0	20	191	137	33						10	AUXILIARY LINK
(1, 11)	1	250	0	0	35	25	0	100	0	0	0	12	0	0	31	3	1	2	0	0	0	0	0	11	OFF RAMP 1
(3, 13)	1	375	0	0	35	25	0	100	0	0	0	14	0	0	31	3	1	2	0	0	0	0	0	12	OFF RAMP 2
(14, 21)	1	310	0	0	35	25	0	100	0	0	0	4	0	0	31	3	1	2	0	0	0	0	0	13	ON RAMP 3-UPPER
(21, 4)	1	220	0	0	35	25	0	100	0	0	0	5	0	0	31	3	4	2	0	0	0	0	0	14	ON RAMP 3-LOWER
(6, 16)	1	150	0	0	35	25	0	100	0	0	0	17	0	0	31	3	1	2	0	0	0	0	0	15	OFF RAMP 4
(8, 18)	1	155	0	0	35	25	0	100	0	0	0	19	0	0	31	3	1	2	0	0	0	0	0	16	OFF RAMP 5
(19, 22)	1	300	0	0	35	25	0	100	0	0	0	9	0	0	31	3	1	2	0	0	0	0	0	17	ON RAMP 6-UPPER
(22, 9)	1	150	0	0	35	25	0	100	0	0	0	10	0	0	31	3	4	2	0	0	0	0	0	18	ON RAMP-LOWER
(11, 12)	2	350	0	6	35	25	0	28	72	0	0	13	802	0	31	3	1	2	0	0	0	0	0	19	FRONTAGE 1
(802, 12)	1	400	0	0	ENTRY	25	0	0	100	0	0	0	13	0	31		1	2	0	0	0	0	0	20	MOCKINGBIRD ENTRY
(12, 13)	2	825	0	0	35	25	0	100	0	0	0	14	0	0	31	3	1	2	0	0	0	0	0	21	FRONTAGE 2
(13, 14)	2	400	0	0	35	25	0	61	0	39	0	15	0	-21	31	3	1	2	0	0	0	0	0	22	FRONTAGE 3
(14, 15)	2	990	0	6	35	25	0	81	19	0	0	16	803	0	31	3	1	2	0	0	0	0	0	23	FRONTAGE 4
(803, 15)	1	400	0	0	ENTRY	25	0	0	100	0	0	0	16	0	31		1	2	0	0	0	0	0	24	YALE ENTRY
(15, 16)	2	700	0	0	35	25	0	100	0	0	0	17	0	0	31	3	1	2	0	0	0	0	0	25	FRONTAGE 5
(16, 17)	2	730	0	6	35	25	0	81	19	0	0	18	804	0	31	3	1	2	0	0	0	0	0	26	FRONTAGE 6
(804, 17)	1	400	0	0	ENTRY	25	0	0	100	0	0	0	18	0	31		1	2	0	0	0	0	0	27	UNIVERSITY ENTRY
(17, 18)	2	870	0	0	35	25	0	100	0	0	0	19	0	0	31	3	1	2	0	0	0	0	0	28	FRONTAGE 7
(18, 19)	2	310	0	0	35	25	0	61	0	39	0	20	0	-22	31	3	1	2	0	0	0	0	0	29	FRONTAGE 8
(19, 20)	2	920	0	0	35	25	0	100	0	0	0	805	0	0	31	3	1	2	0	0	0	0	0	30	FRONTAGE 9

Figure 2. Input Data

CUMULATIVE STATISTICS SINCE BEGINNING OF SIMULATION

PRESENT TIME IS 16 5 11. ELAPSED SIMULATED TIME IS 5 MINUTES, 11 SECONDS

LINK STATISTICS

LINK	VEH-MILES	VEH TRP	MOV. TIME V-MIN	DELAY TIME V-MIN	M/T	TOTAL TIME V-MIN	T-TIME / VEH. SEC	T-TIME/ VEH-MILE SEC/MILE	D-TIME / VEH SEC	D-TIME/ VEH-MILE SEC/MILE	PCT STOP DELAY	AVG. SPEED MPH	AVG. OCC.	STOPS /VEH	AVG SAT PCT	CYCL FAIL
(701, 1)	32.9	347	32.3	7.1	.82	39.4	6.8	72.0	1.2	13.0	0	50.0	6.7	0.00	9	0
(1, 2)	38.2	301	32.1	27.2	.54	59.3	11.8	93.1	5.4	42.7	0	38.7	11.3	0.00	11	0
(2, 3)	28.4	300	26.0	14.7	.64	40.7	8.1	85.9	2.9	31.1	0	41.9	7.7	0.00	10	0
(3, 4)	62.6	280	71.6	16.2	.82	87.8	18.8	84.2	3.5	15.6	0	42.8	16.8	0.00	14	0
(4, 5)	31.9	306	33.0	11.5	.74	44.5	8.7	83.8	2.2	21.6	0	43.0	8.7	0.00	16	0
(5, 6)	25.9	302	26.4	12.7	.68	39.1	7.8	87.2	2.5	28.3	0	41.3	7.1	0.00	15	0
(6, 7)	50.2	282	55.4	14.4	.79	69.8	14.8	83.4	3.1	17.2	0	43.2	13.8	0.00	15	0
(7, 8)	34.1	281	39.1	9.9	.80	49.1	10.5	86.4	2.1	17.5	0	41.7	9.4	0.00	15	0
(8, 9)	43.5	255	47.4	8.6	.85	56.0	13.2	77.2	2.0	11.9	0	46.6	10.7	0.00	12	0
(9, 10)	55.3	292	61.9	15.3	.80	77.1	15.8	83.7	3.1	16.6	0	43.0	14.7	0.00	15	0
(1, 11)	2.5	52	4.0	.0	1.00	4.0	4.6	97.8	.0	.0	0	36.8	.8	0.00	6	0
(3, 13)	1.6	22	2.7	1.7	.61	4.4	12.0	168.4	4.7	65.9	64	21.4	.9	.23	5	0
(14, 21)	1.8	31	3.3	1.7	.66	4.9	9.5	162.1	3.2	54.6	58	22.2	1.0	.13	6	0
(21, 4)	1.3	31	2.2	2.4	.48	4.7	9.0	216.9	4.7	113.6	57	16.6	.9	.90	8	0
(6, 16)	.5	18	.8	.4	.67	1.2	4.1	143.1	1.3	47.1	98	25.1	.3	.11	3	0
(8, 18)	.8	28	1.3	.4	.78	1.6	3.5	118.9	.8	26.3	97	30.3	.3	.04	4	0
(19, 22)	2.3	41	3.6	7.9	.31	11.5	16.9	297.1	11.6	203.5	86	12.1	2.2	.37	15	0
(22, 9)	1.2	43	2.1	2.7	.44	4.7	6.6	232.2	3.7	131.1	54	15.5	.9	.91	12	0
(11, 12)	3.5	53	6.1	12.1	.33	18.2	20.6	310.9	13.7	206.8	98	11.6	3.5	.66	8	0
(12, 13)	9.6	63	17.5	8.9	.66	26.4	25.2	164.7	8.5	55.5	3	21.9	5.0	.17	6	0
(13, 14)	6.4	84	11.4	6.8	.63	18.1	12.9	170.9	4.8	63.7	0	21.1	3.5	0.00	9	0
(14, 15)	10.5	56	18.1	9.8	.65	27.9	29.9	159.6	10.5	55.9	55	22.6	5.4	.91	5	0
(15, 16)	6.2	47	11.2	7.6	.60	18.8	24.0	181.8	9.7	73.2	2	19.8	3.6	.13	5	0
(16, 17)	9.5	69	16.7	18.7	.47	35.4	30.7	222.3	16.2	117.4	49	16.2	6.8	.91	9	0
(17, 18)	9.5	58	17.1	9.4	.64	26.5	27.4	166.5	9.7	59.2	2	21.6	5.1	.17	6	0
(18, 19)	5.1	87	9.2	5.9	.61	15.2	10.5	178.3	4.1	69.8	0	20.2	2.9	0.00	9	0
(19, 20)	9.2	53	16.9	11.9	.59	28.8	32.6	187.1	13.5	77.5	77	19.2	5.5	.58	6	0

NETWORK STATISTICS

VEHICLE-MILES= 327.69 VEHICLE-MINUTES= 483.2 VEHICLE-TRIPS (EST.)= 376 STOPS/VEHICLE= .25

MOVING/TOTAL TRIP TIME= .726 AVG. SPEED (MPH)=40.69 MEAN OCCUPANCY= 92.7 VEH. AVG DELAY/VEHICLE= 21.11 SEC

TOTAL DELAY= 132.3 MIN. DELAY/VEH-MILE= .40 MIN/V-MILE TRAVEL TIME/VEH-MILE= 1.47 MIN/V-MILE

STOPPED DELAY AS A PERCENTAGE OF TOTAL DELAY= 9.4

SEED FOR RANDOM NUMBER GENERATOR IS 64838103

NOT REPRODUCIBLE

Figure 3. Typical Output Data

of the numbers of vehicles discharged, the total time of travel, the average link speed during the subinterval and the average occupancy. In addition, travel time per vehicles, delay times, stops per vehicle, the percent of the delay due to stops and the locations and number of cycle failures are included as outputs. A record of the elapsed simulated time appears for each subinterval. An intermediate output for urban links is also available. This includes the numbers of vehicles which have performed turns during the subinterval and the queue length at the current time on a per lane basis.

To utilize the model, data must be taken for calibration purposes. This includes determination of the network topology, determinations of turning movement percentages and the traffic light and entry link statistics. For the freeway, an extensive set of measurements of speed versus density is required for each link. These measurements need not be obtained simultaneously for each link, although, an attempt should be made to obtain data that includes as high a vehicle density as possible. Data at high densities permits better speed-density curve fit via the SRCH program.

The computer running efficiency for the model is about 1 minute of computer time for every 6 minutes of real time for a network of 27 nodes and an average of 247 vehicles when simulated on the CDC6600 computer with a sample rate of one second for arterial streets and four seconds for the freeway. The model is programmed in Fortran IV for the CDC6600 or IBM 360/75 computers.

3. DALLAS NORTH CENTRAL EXPRESSWAY

The Dallas North Central Expressway (7), a portion of which is represented in Figure 4, is a fully access-controlled freeway that extends from downtown Dallas generally northward to Richardson, Texas a distance of approximately 12 miles. It may be described as a depressed freeway with diamond-type interchanges at all but two interchange locations. The freeway has three lanes in each direction from the downtown area to the Mockingbird crossover and two lanes in each direction from that point north. Running parallel to the expressway are frontage roads that are continuous except at the railroad crossing just south of Mockingbird, the Loop 12 cloverleaf interchange, and the IH635 interchange.

The Expressway operates at or near possible capacity in the peak traffic hours of 7-9 am and 4-6 pm with typical peak-hour volumes in the Mockingbird area at 4700 to 5500 vehicles per hour. Metered ramp control is presently in operation for both peak directions. The objective of ramp control is to keep the freeway operating at near optimum flow. This is accomplished by limiting entering traffic in order to keep the freeway volume below its breakdown capacity. The rate of flows allowed for each entrance ramp is set according to measured traffic parameters on the freeway as shown in the Figure 4. The A-type detectors indicate volume and speed and the V-type are used for volume alone. In addition, on-and off-ramp volumes are monitored by the O and R detectors. The Dallas North Central Expressway ramp control system uses the traffic data collected each minute to set the ramp metering rates for the following minute. The ramp vehicles are then essentially released at a uniform rate such that if a rate of six vehicles per minute is selected for a ramp, a vehicle is released on the ramp every ten seconds to enter the mainstream of the freeway. In addition to determining a metering rate for each ramp, the system also tries to match entering ramp vehicles to available gaps in the outside traffic lane. If a gap is found, the vehicle is released. If no gap is available by the end of the release cycle, the vehicle is released to find its own way onto the freeway.

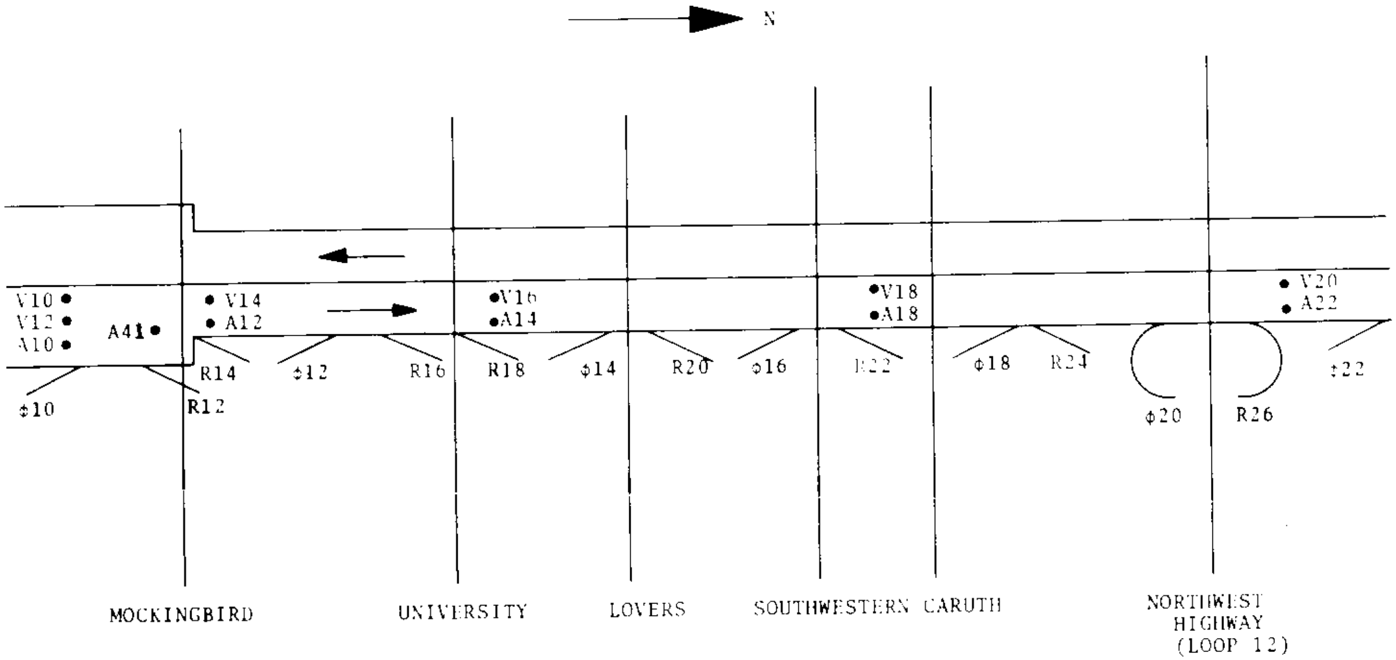

Figure 4. Dallas Corridor and Detector Plan

The test network (Figure 5) chosen for the calibration and validation of the SCOT model is a 1.2 mile north-bound section of the Dallas North Central Expressway that stretches from just south of Mockingbird Lane to Lover's Lane, including the parallel sections of the frontage road and six ramps, and four are off-ramps. Although there is sufficient capacity to handle the existing northbound traffic demands in the three lane section from downtown Dallas to Mockingbird, the dropping of a lane at Mockingbird and weaving maneuvers in that area restrict traffic flow movement and cause a significant drop in vehicle speed.

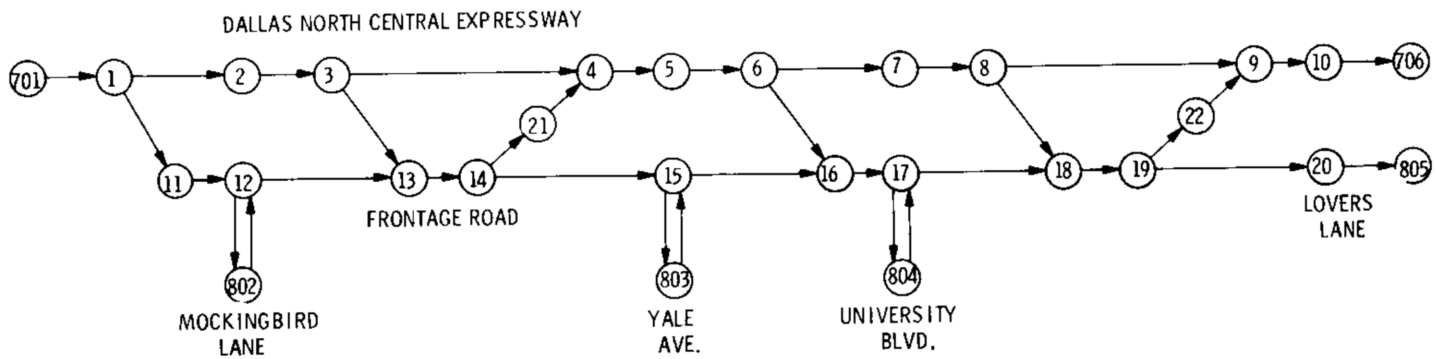

Figure 5. Test Network (6)

4. DATA COLLECTION

Data for the calibration and validation of the SCOT model was collected during the period 25 February 1974 through 12 March 1974 on the 1.2 mile north-bound section of the Dallas North Central Expressway test network. Several different techniques were used to collect the data: aerial photography, super 8 mm movies, 35 mm still photographs, mechanical counters, and floating car methodology. For calibration, the data collected included: 1) vehicle volume and density for each freeway link (8 links) 2) frontage road free-flow speeds, 3) queue discharge rates, 4) ramp-merge delays and 5) geometric characteristics of the test network. Other required calibration data such as vehicle turning movements, signal phasing, offset and timing, and percentage of trucks in traffic volumes were taken from previous studies (5). For validation, the following data was collected: 1) freeway-link vehicle content and 2) freeway and ramp volume counts. Because the urban street portion of the model (UTCS-1) had previously been validated, only the freeway required measurement and testing.

For calibration, the largest bulk of data was collected in order to resolve the speed density relationships for the eight freeway links. The basic data collection technique was the use of density traps. Density traps were defined so as to correspond to visible landmarks, e.g., light poles and signs on or beside the roadway. Typical trap lengths used were 260 feet. For six of the eight freeway links it was possible to film an entire density trap with one super 8 mm camera from an elevated position. For the other two links where the entire density trap could not be viewed via an elevated camera it was necessary to use two super 8 mm cameras, one at each end of the density trap, and one 35 mm still camera with a wide angle lens to record the vehicle density at each minute. Filming frequency for all freeway link speed-density data was nominally three frames per second.

Frontage road free-flow speeds were determined from floating car data. The floating car method is defined as the travel time measurement of a vehicle which attempts to pass as many vehicles as pass it. In this way, an average traffic speed is approximated. For free-flow speed calibration, the floating car runs were made during light flow conditions.

Queue discharge data for the two study area intersections was collected using a ground based super 8 mm movie camera with the filming frequency set at approximately five frames per second. The camera recorded the passage of vehicles across the stop line as well as the signal face.

Ramp merge delay data was also determined via super 8 mm film at a nominal film frequency of 5 frames per second. The camera was positioned to record the entire region from the ramp metering signal and parallel freeway section to the next downstream underpass.

The validation data base for the SCOT model was collected during the period 4:00 to 5:30 p.m., 12th March, 1974. Two basic types of data were collected for the SCOT validation: 1) aerial photographs, and 2) ground based 8 mm motion pictures. All data collection activities were coordinated by synchronizing watches located at each data station prior to the actual run.

Aerial photographs were taken at approximately one-minute intervals throughout the ninety-minute data collection period. The photographs were taken from a fixed-wing aircraft flying at 6,000 feet above the study area. The entire study area was clearly visible in each fine grain 9-inch black and white photograph taken. Each photograph contained a reference clock time that was synchronized with the ground master watch.

At each of seven freeway data stations, 8 mm motion pictures were taken at a rate of three frames per second. These data stations were set up to coincide with each ramp junction and the downstream side of each underpass. The filming was also augmented by hand counting to provide data during film changing and in the event of camera failure.

5. DATA REDUCTION AND CALIBRATION

Films of the freeway-link density traps were reduced by counting vehicles passing one end of the trap and periodically recording trap content. Trap content was evaluated at a six-second time interval in order to resolve vehicle densities to approximately one vehicle per lane-mile. A specifically designed program then processed the raw vehicle count and content data to produce one, two, and four minute data aggregates of volume and density. Speed was then obtained for each aggregation via the relationship speed=volume/density.

This speed-density data was then punched in a format required for a speed-density curve fit program called SRCH. This SRCH program (6) applies a least squares procedure to fit the data with the previously described speed/density relationship. Inputs to the program consist of the speed density values and the allowable ranges of k_f, k_j and a. In addition, the values of density at free flow and speed and density at Qmax are input. The combination of these parameters which produce minimum or near minimum least squares error and satisfies the observed value of capacity, are output by the SRCH program.

Once candidate families of curves were established, a further review was required to choose the single "best" equation for each link. Because of the results of chi-square statistical tests only SRCH candidates based on one minute data aggregates were considered. From the chi-square tests, it was found that speed-density data populations are sensitive to aggregation period duration. As the aggregation period gets shorter, the range of density points tends to widen. Since it was desired that the speed-density calibration curves be generated for the widest density range possible, the shortest practical aggregation period, one minute, was selected. The calibration speed density relationship for each link was then chosen by reviewing maximum flow rate, Qmax, and the optimum density, k_{opt}.

For most links, the peak flow was approximately 1800 vehicles per hour per lane. For the first two links, with a lane drop at the down stream end of link number two, the maximum flows averaged approximately 1300 vehicles per hour per lane. To preserve generality in the model, lane specific flow and speeds were not obtained, thus, the same speed-density relationship applies to all lanes for a given link during the entire simulation.

The films of the metered on-ramps were reduced to provide both travel times for ramp vehicles and evaluations of freeway lane 1 flow rate as a percentage of total flow. For this ramp metered freeway system, it was determined that 47 percent of the total volume flows in lane 1 at all flow regimes. In addition, travel times of all delayed ramp vehicles at each ramp were classified by freeway lane 1 rate. The ramp merge delay at peak flow averaged approximately 5.3 seconds and approximately 84 percent of all vehicles trying to merge at peak flow conditions experienced a delay. Under the measured forced flow conditions, the delays averaged 6.1 seconds, and all vehicles were delayed. Queue discharge parameters for the two signalized intersections in the study network were found from the queue discharge data. The differences in frame counts were converted to vehicle headways and lost times.

For the validation process, the aerial photographs taken throughout the validation period were examined to determine content on a per link basis. A validation simulation subinterval of five minutes was chosen so that the content corresponding to the time period between each fifth aerial photograph was determined. As concerns freeway volumes, each validation film was then reduced so as to provide freeway and ramp counts for the period between consecutive aerial photos. The aerial photographs were coordinated by recognizing the corresponding vehicle patterns in some frames of the movie films. The vehicles crossing each link boundary were counted and recorded for each period.

Initial computer simulation runs of the model indicated a sensitivity of the model to small parametric changes. Consequently, significant modifications of the speed-density formulation and freeway logic of the SCOT model were made. First, the resolution of the "a" parameter of the speed-density relation was increased from an accuracy of .1 to a resolution of .01. This allowed use of parametric curves that exhibit a smaller error with respect to the calibration data. Secondly, an inter-link speed "look ahead" feature to represent the interaction of contiguous freeway links was added whereby a vehicle platoon on the last 30 percent of a link experiences a density equal to the average of the densities of the link it is travelling on and the link it is about to enter. In other words, the vehicle platoon is able to foresee the density on the next link to a certain extent. In addition, a 50 percent density smoothing factor has been implemented for the re-evaluation of density after each filtering period. This smoothing alleviates the effect of sudden changes in density. Essentially, the density of traffic on any link now includes part of the density from the preceding interval on that link. Finally, after the density has been reevaluated, the speed of platoons on the link is not allowed to change abruptly. This is accomplished by modifying each platoon speed so as to switch gradually from the speed appropriate to the old interval to an updated speed for the new interval.

6. SIMULATION OF TEST NETWORK

A ninety-minute simulation was performed using the flows measured south of the first Mockingbird exit as the inputs to entry link 701,1. In addition, entry flows of the urban streets were input. Values of traffic volume, speed, and link occupancy were calculated and output was gathered every five minutes of simulated time. Input (Figure 2) values consisted of the link end points, number of lanes, link length, free speed, percentage of traffic turning, number of the next suceeding node for each turning direction, and in the case of the freeway, the parameters describing the speed-density curve. For the urban links, such as the parallel frontage road, information concerning queue discharge rates, pedestrian densities, and lane channelization were input. In addition, traffic signal data including interval durations, offsets and signal displayed to the approaching links were included. For the on-ramps to the freeway, the ramp metering control criteria were input with metering rates based upon queue length behind the signal and flow rates on the expressway.

The model was run and allowed to come to equilibrium before statistics were gathered. A zero net change of vehicles in the network from cycle to cycle was indicative of equilibrium. As the simulation progressed from subinterval to subinterval, input flow and turning rates were changed according to the measured data.

The output (Figure 3) basically consisted of flow, speed, and occupancy statistics for each simulated link. Delay times were calculated based upon the amount the speed was reduced below the free speed. In the operation of the model, cumulative statistics were output which were reduced to a subinterval basis for statistical analysis. The simulation output was then compared to the validation flows, densities and derived speeds (Table 1) that were measured as part of the data collection and reduction activity. Simulated results and the corresponding field quantities were then subjected to validation statistical tests.

TABLE 1. VALIDATION FLOWS (6)

SUBINTERVAL NUMBER	LENGTH OF SUBINTERVAL (SECS.)	TIME AT END OF PERIOD	ENTRY TOTAL FLOW	ENTRY TURNING FLOW	LINK 1 TOTAL FLOW	LINK 1 FINAL CONTENT	LINK 2 TOTAL FLOW	LINK 2 TURNING FLOW	LINK 2 FINAL CONTENT	LINK 3 TOTAL FLOW	LINK 3 FINAL CONTENT	ON RAMP FLOW	LINK 4 TOTAL FLOW	LINK 4 FINAL CONTENT	LINK 5 TOTAL FLOW	LINK 5 TURNING FLOW	LINK 5 FINAL CONTENT	LINK 6 TOTAL FLOW	LINK 6 FINAL CONTENT	LINK 7 TOTAL FLOW	LINK 7 TURNING FLOW	LINK 7 FINAL CONTENT	LINK 8 TOTAL FLOW	LINK 8 FINAL CONTENT
0	0	3:59:56	0	0	0	4	0	0	5	0	16	0	0	12	0	0	12	0	18	0	0	8	0	12
1	311	4:04:47	356	55	287	18	286	22	6	253	27	25	283	7	286	18	9	272	14	270	28	10	241	13
2	301	4:09:48	360	56	312	10	311	22	7	300	16	27	327	7	325	9	11	312	18	314	33	8	280	14
3	305	4:14:53	388	50	328	20	324	25	11	294	21	20	306	15	306	5	9	302	19	300	32	10	264	18
4	289	4:19:42	367	43	334	10	336	23	9	314	20	14	329	14	323	20	15	303	19	302	37	11	268	15
5	310	4:24:52	388	52	326	20	326	29	9	309	18	16	311	19	312	16	14	302	13	304	35	9	272	12
6	297	4:29:49	366	54	315	17	312	34	12	265	31	17	287	14	293	16	8	274	16	270	29	13	240	13
7	305	4:34:54	398	56	328	31	325	44	15	284	28	13	300	11	300	7	8	296	13	299	24	10	273	15
8	292	4:39:46	371	58	319	25	321	56	13	268	25	12	277	14	278	2	7	275	14	275	19	10	255	16
9	307	4:44:53	395	66	327	27	320	44	20	270	31	15	292	7	288	1	11	287	14	285	35	12	255	11
10	292	4:49:45	341	38	295	35	296	47	19	254	26	18	267	12	268	1	10	263	18	267	23	8	239	16
11	307	4:54:52	383	50	328	40	328	47	19	270	37	10	276	16	273	4	13	267	20	266	28	9	241	13
12	294	4:59:46	319	44	280	35	281	49	18	244	25	10	254	16	253	5	14	253	15	253	16	9	235	15
13	303	5:04:49	362	56	303	38	296	57	25	226	35	14	242	14	242	3	14	233	21	232	17	10	220	10
14	299	5:09:48	333	60	279	32	290	44	14	251	33	15	259	21	260	3	13	266	12	268	13	8	251	14
15	302	5:14:50	337	42	282	45	269	50	27	208	44	20	231	18	233	5	11	224	16	224	16	8	212	10
16	297	5:19:47	302	46	276	25	289	47	14	247	39	15	262	18	261	3	12	255	19	254	19	9	238	7
17	304	5:24:51	338	36	293	34	292	48	15	254	29	16	270	18	273	4	9	269	19	266	17	12	245	11
18	299	5:29:50	341	35	311	29	312	41	14	265	35	16	278	21	273	3	14	273	16	273	11	12	265	8

NOT REPRODUCIBLE

7. VALIDATION

The process of validation applied to this model consisted of testing the null hypothesis,

Ho: model output = empirical record

using the mean values or distributions both on a link by link and a subinterval by subinterval basis. If the model is successfully validated, the hypothesis is not rejected. The measures of effectiveness (MOE) tested were: vehicles discharged, average saturation and average speed. Saturation is defined as the average percentage of link area occupied by vehicles. Statistical tests were then conducted to check for significant differences between the field and simulation data at the 1, 2, and 5 percent levels. The tests applied to these MOE's were: paired Student t, Wilcoxon signed rank, Mann-Whitney U and one way analysis of variance.

The vehicles discharged showed no significant differences at any level of significance on a link-by-link basis as shown on the upper portion of Table 2. Thus, no evidence was found to reject the null hypothesis at these levels. When the tests were performed on a subinterval by subinterval basis and all links are included, the t test indicated significant differences while the Mann-Whitney and analysis of variance test indicated no significant differences at all tested levels of significance. (See lower portion of Table 2). It was observed that these distributions had a bimodal shape due to the two classes of links considered i.e., freeway links and ramp links. However, the conclusion remains that no evidence exists to reject the null hypothesis when the statistics are compared on a subinterval basis.

The average speed indicated less agreement than the volume (Table 3). Two of the eight freeway links indicated significant differences at the one percent level for the t and Wilcoxon tests, however, the Mann-Whitney indicated no significant differences at the 1 percent level for all links. It should be noted that in both

TABLE 2. VEHICLES DISCHARGED ANALYSIS OF LINK STATISTICS

VEHICLES DISCHARGED
ANALYSIS OF LINK STATISTICS

LINK	NETWORK A MEAN	NETWORK A VARIANCE	NETWORK B MEAN	NETWORK B VARIANCE	T-TEST T	WILCOXON T/Z	U-TEST U/Z	ONE-WAY ANOVA SSW	ONE-WAY ANOVA SSB	ONE-WAY ANOVA F
(1, 2)	306.83	406.85	307.94	295.70	.37	75.50	159.50	11943.44	11.11	.03
(2, 3)	306.33	371.76	307.89	258.58	.41	67.00	149.00	10715.78	21.78	.07
(3, 4)	264.83	719.32	287.17	334.97	.49	83.50	146.00	17923.00	49.00	.09
(4, 5)	280.61	730.96	284.44	353.32	.72	73.50	143.00	18432.72	132.25	.24
(5, 6)	280.50	693.21	284.39	326.25	.75	69.50	140.50	17330.78	136.11	.27
(6, 7)	273.67	573.65	277.50	242.26	.75	76.00	144.00	13870.50	132.25	.32
(7, 8)	273.44	591.32	277.56	223.56	.82	74.50	144.00	13852.89	152.11	.37
(8, 9)	249.67	342.82	253.72	121.51	.87	67.50	142.50	7893.61	148.03	.64
(1, 11)	49.78	78.54	48.89	72.34	1.06	45.00	151.00	2564.89	7.11	.09
(3, 13)	40.00	138.82	40.89	133.63	1.03	43.00	150.50	4631.78	7.11	.05
) 14, 21)	16.28	25.51	17.44	26.50	1.56	43.00	138.00	884.06	12.25	.47
(21, 4)	16.28	20.33	17.44	24.85	1.39	47.50	144.50	768.06	12.25	.54
(6, 16)	6.94	37.74	6.67	34.00	.34	40.00	157.00	1218.94	.69	.02
(8, 18)	24.06	67.58	23.83	62.15	.43	69.50	156.00	2205.44	.44	.01
(19, 22)	25.58	24.38	26.33	42.00	.70	58.50	153.00	1128.44	5.44	.16
(22, 9)	25.72	23.62	26.39	45.90	.59	57.50	161.50	1181.89	4.00	.12

VEHICLES DISCHARGED
ANALYSIS OF LINK STATISTICS

SUBINTERVAL	NETWORK A MEAN	NETWORK A VARIANCE	NETWORK B MEAN	NETWORK B VARIANCE	T-TEST T	WILCOXON T/Z	U-TEST U/Z	ONE-WAY ANOVA SSW	ONE-WAY ANOVA SSB	ONE-WAY ANOVA F
1	151.56	15730.80	160.81	17555.23	4.38***	3.00***	109.00	499290.38	684.50	.04
2	169.06	21408.86	162.88	19665.72	2.85 **	9.00***	107.50	616118.69	306.28	.01
3	164.56	20783.33	167.81	21611.23	3.01**	12.00 **	119.50	635918.38	84.50	.00
4	167.81	22978.43	154.81	18948.16	3.41***	21.50 **	112.50	628868.88	1352.00	.06
5	166.38	21193.18	160.81	20085.90	2.16 *	25.00 *	112.50	619186.19	247.53	.01
6	154.56	17691.33	152.75	17981.13	2.46 *	16.50 *	120.00	535086.94	26.28	.00
7	163.06	20474.73	159.06	19195.13	3.14***	21.00 **	119.00	595047.88	128.00	.01
8	154.63	18175.72	148.75	16578.47	2.79 **	20.50 **	117.00	521312.75	276.13	.02
9	159.63	18710.92	150.50	18140.40	.10	48.50	122.00	552769.75	.13	.00
10	146.94	16060.46	149.88	17281.45	1.78	39.00	124.50	500218.69	69.03	.00
11	152.19	18309.23	161.06	19338.06	3.27***	15.50***	114.50	572209.38	630.13	.03
12	140.31	14674.90	152.00	17728.80	3.75***	12.00 **	108.00	485995.44	1092.78	.07
13	137.94	13872.20	158.94	17897.80	4.37***	1.00***	100.50	476549.88	3528.00	.22
14	145.88	15518.12	154.69	17734.36	3.35***	17.00***	105.50	498787.19	621.28	.04
15	131.00	12053.33	150.38	16391.18	3.81***	4.00 **	103.50	426667.75	3003.13	.21
16	142.69	14973.83	134.94	12898.46	2.88 **	23.00 **	114.50	418084.38	480.50	.03
17	146.63	16512.52	141.56	15513.73	2.44 *	30.50	116.50	480423.69	205.03	.01
18	150.75	18393.93	146.44	17134.93	3.00***	14.50***	113.50	532932.94	148.78	.01

* 5% Level
** 2% Level
*** 1% Level

TABLE 3. SPEED VALIDATION STATISTICS (6)

AVERAGE SPEED

ANALYSIS OF LINK STATISTICS

LINK	NETWORK A		NETWORK B		T-TEST	WILCOXON	U-TEST	ONE-WAY ANOVA		
	MEAN	VARIANCE	MEAN	VARIANCE	T	T/Z	U/Z	SSW	SSB	F
(1, 2)	21.86	113.51	27.53	210.98	1.60	64.00	132.00	5516.20	289.72	1.79
(2, 3)	27.73	195.55	28.75	185.01	.27	80.00	159.00	6469.62	9.45	.05
(3, 4)	27.45	92.19	30.30	174.63	.69	73.00	144.00	4536.05	73.00	.55
(4, 5)	26.65	65.48	30.47	176.70	.90	69.00	137.00	4117.11	131.08	1.08
(5, 6)	28.33	49.89	33.81	101.48	1.53	51.00	106.00	2573.29	269.90	3.57
(6, 7)	34.95	14.21	39.86	10.02	3.64***	17.00***	56.00**	411.81	217.57	17.96***
(7, 8)	40.30	17.06	38.98	6.38	1.05	71.00	127.00	398.46	15.65	1.34
(8, 9)	39.50	5.63	43.38	4.12	5.83***	5.00***	39.00**	165.72	136.13	27.93***
(1, 11)	44.78	376.10	33.94	17.29	2.18 *	48.00	101.00	6687.77	1057.99	5.38 *
(3, 13)	75.31	7154.35	18.10	75.59	2.82 **	9.00***	33.00**	122908.95	29454.78	8.15***
(14, 21)	3.42	8.31	15.14	202.84	3.45***	32.00 **	88.00**	3589.58	1236.44	11.71***
(21, 4)	19.40	193.22	18.76	12.58	.20	84.00	117.00	3498.57	3.63	.04
(6, 16)	5.37	139.03	21.54	126.39	4.72***	6.00***	63.00**	4512.22	2355.28	17.75***
(8, 18)	29.02	645.29	23.82	30.53	.85	77.00	159.00	11489.83	243.42	.72
(19, 22)	7.47	107.66	28.19	17.91	7.81***	4.00***	36.00**	2134.64	3866.31	61.58***
(22, 9)	16.69	99.59	15.58	2.23	.46	83.00	159.00	1731.01	11.07	.22

AVERAGE SPEED

ANALYSIS OF LINK STATISTICS

SUBINTERVAL	NETWORK A		NETWORK B		T-TEST	WILCOXON	U-TEST	ONE-WAY ANOVA		
	MEAN	VARIANCE	MEAN	VARIANCE	T	T/Z	U/Z	SSW	SSB	F
1	28.86	322.27	32.46	138.56	1.23	33.00	110.00	6912.38	103.72	.45
2	36.42	490.69	31.17	128.65	1.17	63.00	111.00	9290.12	220.28	.71
3	29.78	278.93	28.28	105.43	.49	45.00	105.00	5765.52	18.13	.09
4	27.86	461.26	27.17	101.67	.15	62.00	114.00	8443.88	3.79	.01
5	27.14	184.90	25.46	132.96	.55	56.00	110.00	4767.85	22.50	.14
6	27.31	308.94	24.73	138.95	.78	52.00	112.00	6718.34	53.01	.24
7	44.96	7319.43	23.59	141.04	.98	57.00	114.00	111906.93	3653.76	.98
8	25.12	296.48	22.53	135.62	.57	58.00	117.00	6481.46	53.95	.25
9	30.15	772.68	21.46	136.52	1.27	48.00	104.00	13637.96	605.19	1.33
10	25.00	287.02	22.03	169.33	.82	43.00	109.00	6845.35	70.25	.31
11	25.38	321.12	24.80	132.20	.12	57.00	112.00	6799.77	2.68	.01
12	36.46	2482.20	25.95	98.52	.79	55.00	117.00	38710.87	883.98	.69
13	20.78	172.57	27.84	135.06	1.78	33.00	88.00	4614.50	398.41	2.59
14	20.11	185.50	29.70	117.10	2.81**	17.00***	71.00*	4538.88	736.56	4.87*
15	24.67	751.01	31.43	116.93	.85	32.00	72.00*	13019.11	365.57	.84
16	23.41	221.79	33.18	248.16	1.87	30.00	75.50	7049.25	763.79	3.25
17	24.65	275.27	38.04	172.74	2.30 *	26.00 *	64.00**	6720.13	1433.25	6.40*
18	26.17	274.10	34.36	157.76	1.62	40.00	80.00	6477.84	536.92	2.49

* 5% Level
** 2% Level
*** 1% Level

NOT REPRODUCIBLE

Table 2 and 3 levels of significance are designated by asterisks. Blank spaces indicate no significant differences at the 5 percent level.

The two links which did not perform well according to the t test are both downstream of the bottleneck link and are calibrated based upon a restricted data set. The characteristic speed at 100 vehicles per lane mile, which must be specified for calibration purposes, was only roughly estimated because of a lack of data points near this density. Thus, the calibration for these links may be questionable. In addition, the scatter of data points about the curves for these links is rather pronounced, indicating greater driver speed selection at a given density. All tests performed, except the Wilcoxon, for all links on a subinterval by subinterval basis indicated no significant difference at the 1 percent level for all subintervals.

Average saturation performed in the same manner as the speed. The same two freeway links indicated significant differences for the t and Wilcoxon tests, but no significant difference was noted for all links at the 1 percent level.

The ramp statistics indicated some significant differences from the field data due to data taking and model related causes. The field data, especially that of content, was taken at one-minute intervals with considerable variance exhibited due to the nature of ramp operations, i.e., several cars turning off in sequence followed by a period of an empty ramp. The speed, which is calculated from this content and volume likewise exhibits considerable variance.

The second reason for the discrepancies is the inability of the surface street model to represent the interface between off-ramps and the connecting surface street.

The lower portions of the on-ramps indicated good agreement between field data and simulation output. No statistical differences were observed for these two links. The upper part of the ramp, which is metered by signals, revealed differences between the field and simulation results. At present, no satisfactory explanation is available for this discrepancy.

In summary, based upon the tests utilized, the null hypothesis cannot be rejected at the 1 percent level of significance. The Mann-Whitney U test, which tests the frequency distributions is applicable because the sample sizes are adequate to insure normality of the statistic. The results are acceptable for designating the model as sufficiently validated and, if volume alone is the desired quantity, an extremely good indicator of traffic behavior.

8. ORIGIN-DESTINATION TRAFFIC ASSIGNMENT DEMONSTRATION

In addition to data collected for calibration and validation of the SCOT model, license plate data were gathered during the validation period for demonstration of the origin destination traffic assignment capability of the model. License plate data, the right most three alphanumeric characters of each license plate, were recorded in the frontage road and at each ramp of the test network. Hand recording was used at low volume data collection stations, and audio recordings were made at high volume stations. These audio recordings were later transcribed onto standard forms for manual counting. Time references were provided in order to permit the later identification of five-minute time period.

These license plate data were then analyzed to determine the origin destination frequencies present during the validation time period (8). These origin-destination frequencies were then converted into demand volumes for the first nine subintervals of the validation period. (Table 4) For each subinterval entry link the total volume was set equal to the corresponding demand volume. These entry volumes were then apportioned in accordance with the frequency distributions of the license plate data in order to obtain the origin destination volumes for the entry and exit links. These data were then used as input for the origin-destination assignment option of the SCOT model. The results for a nine subinterval simulation are shown in Table 5. Also shown is a comparison of these results with those obtained from the validation run for three measures of effectiveness, vehicles discharged, mean speed, and mean saturation percent.

When this O-D option is specified, the routing of traffic through the network reflects dynamically changing minimum time paths. Traffic is assigned via the minimum time route to its destination. The time interval between successive calculations of these paths is specified as input and in this case was specified as 78 seconds. The travel times along alternate paths are computed on the basis of data accumulated during the previous interval. Such

TABLE 4. SCOT ORIGIN - DESTINATION DEMONSTRATION INPUT VOLUME (6)

				Subinterval Volumes (Vehicles/Hour)								
Origin Link	Up stream Node	Down-stream Node	Destin-ation node	1	2	3	4	5	6	7	8	9
Freeway Entry	701	1	802	509	514	496	461	465	497	413	555	375
	701	1	803	116	203	189	199	174	255	331	333	293
	701	1	804	255	203	142	162	244	218	248	259	94
	701	1	805	267	323	354	548	418	267	342	321	399
	701	1	706	2973	3062	3398	3201	3205	3199	3364	3106	3471
Mocking-bird Entry	802	12	803	213	144	199	116	112	292	296	445	308
	802	12	804	71	32	54	58	13	87	66	61	26
	802	12	805	24	32	55	0	12	65	91	142	44
	802	12	706	248	199	199	212	188	162	90	141	185
Yale Entry	803	15	804	27	27	0	0	52	0	0	0	0
	803	15	805	13	34	0	0	11	0	0	0	0
	803	15	706	6	23	0	0	20	0	0	0	0
Univer-sity Entry	804	17	805	13	21	132	53	0	0	138	0	27
	804	17	706	10	15	57	9	0	0	39	0	8

TABLE 5. COMPARISON OF O-D DEMONSTRATION AND SCOT VALIDATION (6)

	Vehicles Discharged		Mean Speed		Mean Saturation Percent	
	O-D Demonstration	Validation Run	O-D Demonstration	Validation Run	O-D Demonstration	Validation Run
(1,2)	2824	2851	20.8	24.0	23	20
(2,3)	2802	2828	18.6	22.1	25	21
(3,4)	2594	2509	15.6	19.6	41	32
(4,5)	2675	2663	19.2	19.3	35	34
(5,6)	2671	2657	28.2	24.8	24	27
(6,7)	2602	2556	37.6	38.6	17	17
(7,8)	2600	2553	37.3	38.2	18	17
(8,9)	2387	2291	42.3	43.5	14	13
(1,11)	502	481	8.1	31.5	31	8
(3,13)	156	294	22.7	16.4	4	9
(14,21)	86	167	1.8	2.8	25	30
(21,4)	86	167	18.0	17.4	2	5
(6,16)	70	97	34.9	19.5	1	6
(8,18)	214	262	35.7	24.0	3	6
(19,22)	85	229	32.8	23.2	1	5
(22,9)	85	230	15.7	15.7	3	7

a strategy is known as a "capacity restrained" assignment (6).

The value of travel time along each link in the network is needed. The calculation of travel time for freeway links is simply the ratio of link length to current speed. For non-freeway links, the travel time is computed from intermittent calculations of occupancy.

At the present time, an "all-or-nothing" diversion strategy is employed. The following three assumptions are made:

1) "perfect knowledge" of conditions downstream is known,

2) the travel times previously calculated for each network link do not change radically during the current assignment time period as a result of the routing decisions being implemented, and

3) the network is of sufficient size and complexity to preclude the assignment of vehicles to a limited number of network links over any assignment period.

A review of the O-D simulation results (Table 5) indicates that the minimum time-path criteria has not been conclusively shown to be the correct criteria for origin-destination traffic assignments. Several possible explanations exist for these results. First, the third assumption has been violated in that the test network is small and few alternative paths exist. The second assumption was also compromised in that the "hunting" of traffic demand from one set of paths during one assisgnment time period to another set during the next time period was evident. Finally, the assignment time period of 78 seconds was too long for this test network as the mean vehicle travel-time was about 110 seconds.

One immediate suggesiton is to reduce the assignment time period commensurate with the network size, i.e., the computations of link specific travel-times be determined more frequently than once per signal-cycle. In this way, the "hunting" of traffic demand from one set of paths during one assignment time period to another set during the next time period will be reduced.

9. RAMP CONTROL

Analysis was made of freeway ramp control versus no ramp control for the Dallas test network. This was performed by representing the validation scenario without ramp metering control. The simulation results were compared with those of the validation run in which ramp control is simulated. A comparison of the statistical results for average speed is shown in Table 6 where network A represents "no Ramp Control" and network B represents "Ramp Control" (the validation results).

Examination of this figure shows a statistical reduction in speed with no ramp control for these freeway links in the vicinity of the on-ramp. Speed is shown to increase for the upper ramp, e.g., (link, 14, 21) and to decrease for the lower ramp, e.g., link (21, 4). This is consistent with the expected response of unregulated vehicle flow.

A calculation of travel time per freeway vehicle from node 2 to node 6 indicates an increase from 60.2 to 62.4 seconds to traverse this 2,700 foot section of freeway. Average ramp vehicle travel-time decreases from 22.0 to 17.2 seconds. In summary, at constant demand level, very little difference in travel time is seen by an individual driver.

TABLE 6. COMPARISON OF NO RAMP CONTROL VS. RAMP CONTROL: AVERAGE SPEED (6)

AVERAGE SPEED

ANALYSIS OF LINK STATISTICS

LINK	NETWORK A MEAN	NETWORK A VARIANCE	NETWORK B MEAN	NETWORK B VARIANCE	T-TEST T	WILCOXON T/Z	U-TEST U/Z	ONE-WAY ANOVA SSW	ONE-WAY ANOVA SSB	ONE-WAY ANOVA F
(1, 2)	27.17	210.63	27.53	210.98	1.68	50.00	157.00	7167.28	1.19	.01
(2, 3)	28.67	184.22	28.75	185.01	3.01***	30.00 **	155.00	6276.91	4.19	.02
(3, 4)	29.18	181.27	30.30	174.63	3.81***	10.00***	150.00	6050.30	11.35	.06
(4, 5)	29.14	183.85	30.47	176.70	3.87***	17.00***	150.00	6129.42	15.69	.04
(5, 6)	32.81	110.22	33.81	101.48	2.37 *	33.00 **	151.00	3598.81	8.86	.08
(6, 7)	39.80	8.54	39.86	10.02	.28	82.00	154.00	315.55	.04	.00
(7, 8)	38.91	5.78	38.98	6.38	.30	84.00	156.00	206.76	.05	.01
(8, 9)	43.36	3.37	48.38	4.12	.11	80.00	160.00	127.35	.00	.00
(1,11)	32.85	19.07	33.94	17.29	.77	64.00	137.00	618.15	10.53	.58
(3,13)	19.74	48.37	18.10	75.59	1.21	63.00	136.00	2107.24	24.18	.39
(14,21)	31.39	7.96	15.14	202.84	4.74***	14.00***	60.00 **	3583.58	2376.50	22.55***
(21, 4)	14.37	17.04	18.76	12.58	3.31***	22.00***	62.00 **	503.51	173.48	11.71***
(6,16)	27.99	118.46	22.87	100.86	1.45	50.00	110.00	3505.97	223.15	2.04
(8,18)	25.67	36.01	23.82	38.53	1.01	65.00	127.00	1165.11	31.01	.91
(19,22)	29.44	4.05	28.19	17.91	1.10	63.00	118.00	373.40	14.07	1.28
(22, 9)	15.34	4.06	15.58	2.23	.58	72.00	142.00	106.97	.62	.29

AVERAGE SPEED

ANALYSIS OF LINK STATISTICS

SUB-INTERVAL	NETWORK A MEAN	NETWORK A VARIANCE	NETWORK B MEAN	NETWORK B VARIANCE	T-TEST T	WILCOXON T/Z	U-TEST U/Z	ONE-WAY ANOVA SSW	ONE-WAY ANOVA SSB	ONE-WAY ANOVA F
1	33.65	89.72	32.46	138.56	.69	64.00	127.00	3424.08	11.47	.10
2	32.21	76.95	31.17	128.65	.56	64.00	127.00	3084.10	8.52	.08
3	28.74	83.76	28.28	105.43	.20	61.00	127.00	2867.98	1.72	.02
4	26.58	79.25	27.17	101.67	.26	23.00 **	113.00	2713.73	3.00	.03
5	28.33	91.59	25.46	132.96	.37	54.00	126.00	3368.24	5.98	.05
6	24.81	110.74	24.73	138.95	.04	49.00	125.00	3745.37	.05	.00
7	25.87	130.14	23.59	141.04	.83	68.00	124.00	4067.67	25.33	.19
8	24.59	150.88	22.53	135.62	.82	68.00	122.00	4296.61	34.14	.24
9	24.49	151.90	21.46	136.52	1.19	54.00	119.00	4326.23	73.74	.51
10	24.38	129.49	23.57	141.00	.43	51.00	109.00	3786.97	4.94	.04
11	26.31	124.47	24.80	132.20	.66	44.00	121.00	3850.05	18.28	.14
12	26.70	126.29	25.95	98.52	.64	63.00	120.00	3372.27	4.52	.44
13	29.29	111.38	27.94	185.06	.93	53.00	127.00	3695.45	16.90	.14
14	38.43	104.92	29.76	117.10	.46	56.00	126.00	3330.23	4.27	.04
15	31.40	115.79	31.43	116.93	.04	40.00	126.00	3490.88	.01	.00
16	33.92	159.59	33.18	248.16	.65	60.00	120.00	6116.25	4.37	.02
17	37.48	148.61	38.04	172.74	.35	67.00	126.00	4820.26	2.49	.02
18	37.69	106.92	34.36	157.76	2.77 **	18.00***	111.00	3970.15	59.40	.45

NOT REPRODUCIBLE

10. SUMMARY

The validation process described in this paper consisted of data collection, model calibration, and model validation. The data collection was implemented via ground-based time-lapsed photographic techniques supplemented by aerial photographs and manual counts. These techniques were found to be successful and economical.

Initial results of the model simulation runs revealed a sensitivity of the model to small parametric changes. This resulted in functional modifications to the SCOT model freeway logic in order to replicate freeway traffic more realistically. These revisions were: 1) increased resolution of the "a" parameter of the speed density relation, 2) an inter-link speed "look-ahead" feature to represent the interaction of continuous freeway links, 3) the addition of a 50 percent density smoothing factor after each density filtering period and, 4) a progressive speed change after the density has been reevaluated.

After implementation of these modifications, the successful SCOT validation run was made. Mann-Whitney U tests showed no significant difference at the 1 percent level of significance between the field and simulation results for the basic measures of effectiveness: mean speed, flow, and saturation. Based on these statistical tests, the distributions of simulation results and field data have been demonstrated to agree well.

A review of the time history of percent difference of simulated volume from field volume shows volume differences up to 20 percent. The time history of percent difference of speeds exhibits marked differences in the transition area from forced-flow (congested) regime to the free-flow regime. In this transitional mode, freeway traffic is characterized by strong random fluctuations in speed over a range of density in the region of maximum flow. These time history comparisons show that congestion exists longer in the field than in the simulation model.

A review of the origin-destination traffic assignment demonstration results indicates that the minimum time-path criterion has not been conclusively shown to be the correct criterion. Comparison of simulation results of freeway ramp control vs. no ramp control shows a slight reduction in vehicle speed for those freeway links in the vicinity of the on-ramp with no ramp control.

It is not possible for simulated and field-time histories to match in detail for each short subinterval of the simulation run since traffic behavior is inherently a stochastic process. A true measure of the "goodness" of a macroscopic model is whether it represents the mean traffic behavior with an acceptable level of detail. For predicting mean traffic behavior, i.e., volume, speed, and density the SCOT model acceptably replicates freeway traffic performance with a sufficient level of detail and is a useful tool for assessing and comparing freeway traffic control strategies.

11. REFERENCES

1. E. Lieberman, "Dynamic Analysis of Freeway Traffic," ASME Paper 70-TRANS-42, Joint Engineering Conference, Chicago IL, 1970.

2. J. Bruggeman, E. Lieberman and R.D. Worrall, "Network Flow Simulation for Urban Traffic Control System", National Technical Information Service Report No. PB-207-268, Peat, Marwick, Mitchell and Co., June 1971.

3. P. Concannon, P. Connolly, and R. Ricci, "Simulation of Traffic Control Signal Systems," AIAA Paper No. 74-884, AIAA Mechanics and Control of Flight Conference, August 1974.

4. General Applied Science Laboratories, Inc., "Traffic Flow Simulation Study, the SCOT Model", Contract DOT-TSC-161, February 1972.

5. P. Concannon, L. McCabe, and R. Ricci, "Urban Traffic Corridor Study", Report No. DOT-TSC-FHWA-73-2, Transportation Systems Center, Cambridge MA, January 1974.

6. KLD Assoc. Inc., "Calibration and Validation of the SCOT Model", Contract DOT-TSC-740, November 1974.

7. C. Messer, R. Whitson and J. Carvell, "A Real-Time Frontage Road Progression Analysis and Control Strategy" 53rd HRB Meeting, Washington DC, January 1974.

8. KLD Assoc. Inc., "SCOT Model, Calibration and Validation, Data Acquisition and Reduction,"Contract DOT-TSC-740, June 1974.

9. E. Lieberman and R. Worrall, "Network Flow Simulation for Urban Traffic Control System - Phase II," Report No. FHWA-RD-73-86, Federal Highway Administration, Washington DC, May 1975.

APPENDIX A

FRONTAGE ROAD CONTROL STRATEGY

A Frontage Road Control Strategy (7) developed by Texas Transportation Institute has been tested with the SCOT program. This is a real-time, traffic responsive, frontage road progression analysis and control strategy which operates the roads adjacent to urban freeways as major arterials to relieve the congestion on the freeway especially at peak hours. Two continuous one-way frontage roads and diamond interchanges are combined to form a two-way signalized arterial. These roads are analyzed with the program selecting the phase sequence for each interchange yielding maximum progression. The four possible signal sequences are:

1. Basic Three-Phase Signal Sequence
2. Three Phase-Favoring West Side Frontage Road
3. Three Phase-Favoring East Side Frontage Road
4. Four Phase-Overlap Operation

An operating program deck containing this control strategy was sent to TSC by FHWA. This was successfully run on the CDC 6600 at Waltham. In order to interface this program with SCOT, several subroutines were written by G. Radelat of FHWA assisted by TSC personnel. These consisted of a driver subroutine for the Frontage Road Optimization Program (called the FRONT Program), a subroutine that converts the output of FRONT into values of the SCOT variables and a subroutine that converts the speed and volume data from SCOT into appropriate variables for use in the FRONT program. In addition, further modifications were made in the 8 FRONT subroutines and in 6 of the SCOT subroutines. Using the update version of SCOT, these new subroutines and modifications were then added to SCOT and the program successfully recompiled. Figure 6 shows the integration of FRONT into SCOT.

To test this updated program, a 10 intersection sample network (Figure 7) was created from the Dallas network. This network uses the frontage roads from Haskell St. through McCommas Ave. on either

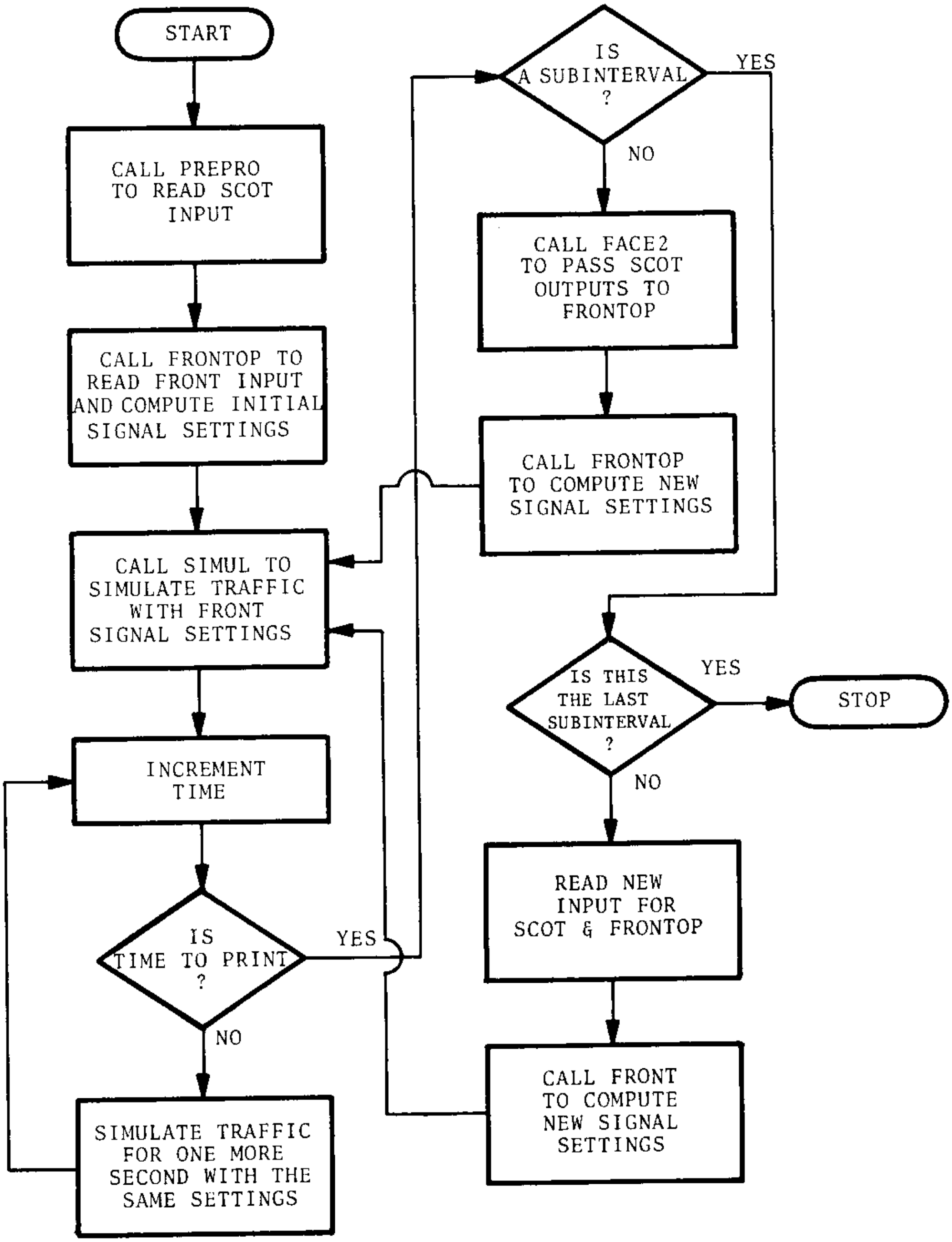

Figure 6. Integration of Front Subroutine

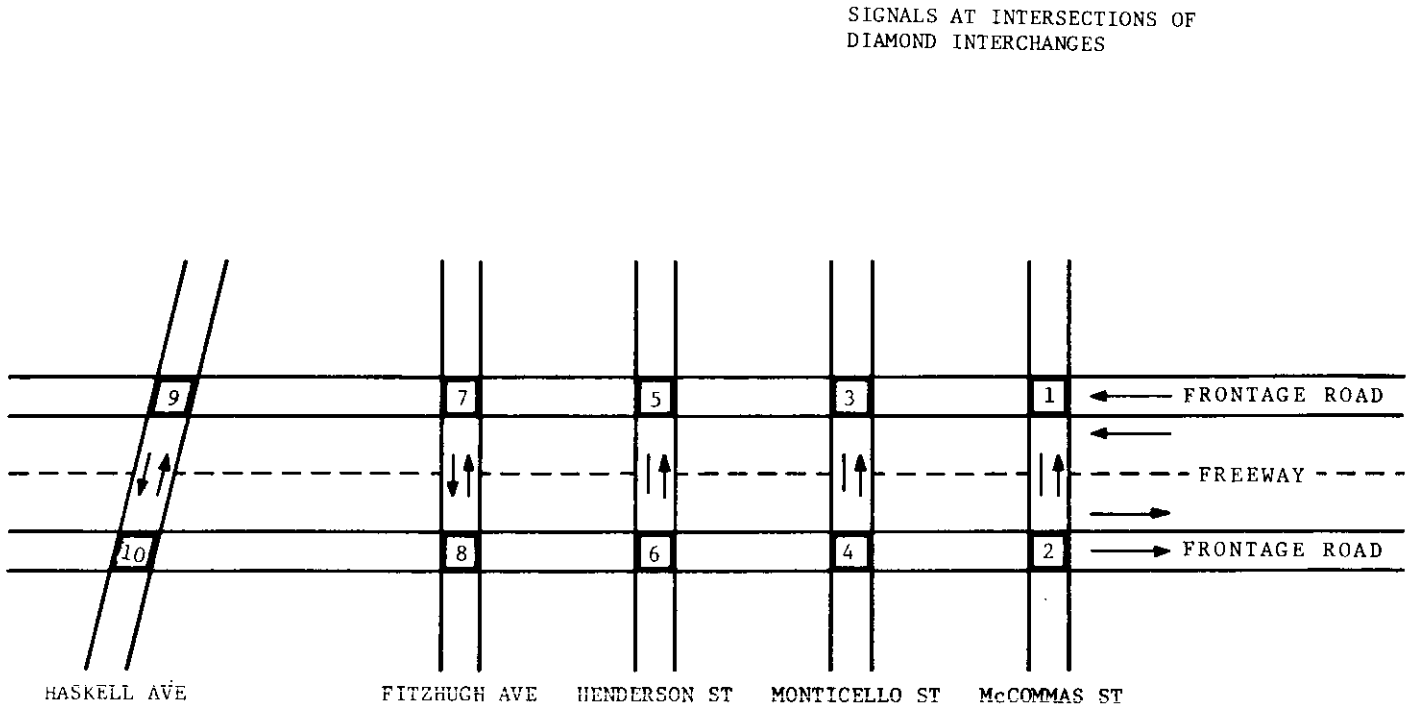

Figure 7. Frontage Road Control Strategy Test Network

side of the North Central Expressway as arterial roads with signals at each intersection as shown in Figure 2.

The input data for this combined SCOT/FRONT program consists of the regular SCOT input data using dummy signal phasing data plus the FRONT input data which consists of the following:

1. Saturation Volume
2. Minimum Green Time
3. Link Distances
4. Possible Phase Sequence
5. For each cycle range devised:
   a. cycle range
   b. movement traffic demands
   c. link speeds

The FRONT subroutines calculate the most efficient cycle length, offset, phase sequence and green times and these are used in the SCOT portion of the program.

This test case ran successfully and the results plus a listing of all modifications and additions were sent to FHWA for further analysis.

APPENDIX B

CONVERSION OF THE SCOT 6600 PROGRAM TO THE IBM 360

A subordinate task of the urban traffic corridor study was the production of a version of the SCOT program executable on the IBM 360. [The SCOT program discussed here is the preliminary version before the changes mentioned in this paper were made.]

The 6600 update version of the Fortran SCOT program was converted to the IBM 360. Punched cards were produced as 6600 output and were used to create the 360 source tape. The update instruction used to produce these was as follows:

```
UPDATE (F, N, W, C = PUNCH)
```

The necessary modifications to convert the network size from 110 to 160 links, from 900 to 1600 vehicles and from 70 to 99 nodes were incorporated into the card deck. In addition, 43 integer variables were converted to I* 2 length specifications.

The following PL - 1 program developed by Draper Laboratory was used to convert the BCD cards to EDBDIC tape records. Records were sequenced in steps of 1000.

```
CONVERT: PROCEDURE OPTIONS (MAIN)

    DCL BUF CHAR (80);

    DCL BUFFA CHAR (80);

    DCL TEXT CHAR (72) DEF BUF POS (1);

    DCL NUMBER CHAR (5) DEF BUF POS (73);

    DCL ZIP CHAR (3) DEF BUF POS (78);

    DCL INT CHAR (8);

    DCL NUMBA FIXED DEC (5, 0);

    DCL ZEROS CHAR (3) INIT ('000');

    DCL SYSIN FILE RECORD INPUT EXTERNAL:

    DCL OUT FILE RECORD ENV (F (1680, 80) );

    DCL COUNT FIXED DEC (6);
```

```
OPEN FILE (SYSIN) TITLE ('SYSUT1');
OPEN FILE (OUT) OUTPUT TITLE ('SYSUT2');

ON ENDFILE (SYSIN) GO TO ENDJOB:
ZIP = ZEROS;
NUMBA = 1;
DO COUNT 1 BY 1;
     READ FILE (SYSIN) INTO (BUFFA):
     TEXT = SUBSTR (BUFFA, 1, 72);
     BUF = TRANSLATE (BUF,') :  !? + = ('", ' + " =   );
     INT = NUMBA;
     NUMBER = SUBSTR (INT, 4, 5,);
     WRITE FILE (OUT) FROM (BUF);
     NUMBA = NUMBA + 1;
END JOB

PUT SKIP (3) EDIT ('TRANSFER COMPLETE - COUNT = , COUNT)
(A, F, (6) ); PUT SKIP (2) EDIT ('LAST RECORD ..., 'BUF)
(a);
END CONVERT
```

The taped program was then compiled, executed and debugged using the JCL instructions as displayed in Reference 9, Exhibit 4.2.2. A slight modification of this arose because the input was produced from tape rather than cards. The input tape JCL instructions are as follows:

```
//FORT.SYSIN  DD UNIT = ...,
//LABEL = ..., VOL = (PRIVATE, RETAIN, SER = ...),
//DSN = ....., DISP = (,KEEP),
//DCB = (RECFM = FB, LRECL = 80, BLKSIZE * 1680)
```

In addition to the DD statement of Reference 9 exhibit 4.2.2., two files must be created. File 19 is a temporary file for storage of freeway flow and speed data during the execution of a given case. File 20 is a temporary file for storage of the array while least time paths for 0-D traffic assignments are calculated.

The DD cards for these files are:

```
//FT19F001  DD UNIT = SYSDA, SPACE = (301, (25, 25),, CONTIG),
//DCB = OPTCD = C
//FT20F001  DD UNIT - SYSDA,
//SPACE = (CYCL, (1, 1) ), DCB = (RECFM = VS, LRECL = 2044,
     BLKSIZE - 2098),
//DISP = (, DELETE)
```

Source tape corrections after debugging were corrected using the OS utility IEBUPDTE. The source program was copied from SYSUTI to SYSUT2 and the corrections which formed the data set were inserted. The instructions for this update are as follows:

```
//STEP A EXEC PGM = IEBUPDTE, PARM = MOD
//SYSPRINT DD SYSOUT = A
//SYSUT1 DD UNIT = ..., VOL = SER = ...,
//DSN = ..., DISP = (OLD, KEEP), LABEL = (01, SL)
//SYSUT2 DD UNIT = ..., VOL = SER ...,
//DSN = ..., DISP = (,KEEP), LABEL - (01, SL),
//DCB - (RECFM = FB, LRECL = 80, BLKSIZE = 1680)
//SYSIN DD DATA
   ./  NAME        CHANGE
       FORTRAN CARD #1          SEQUENCE NO.
       FORTRAN CARD #2          SEQUENCE NO.
          •
          •
          •
   ./  ENDUP
```

When recompilations of individual subroutines were required due to the correction or addition of FORTRAN instruction, the include statement as demonstrated in Exhibit 4.2.2 was utilized. A new load module is created by this instruction.

A set of instructions to run and edit the program, a source tape and a demonstration run with an identical output produced on the 6600 has been forwarded to FHWA. Compile time for this version required approximately 5.6 min. The load module required 448K bytes of core for execution.

B337
11