Final Report

DESIGN OF ON-RAMP TRAFFIC CONTROL

ON THE BLACK CANYON FREEWAY

by

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INTRODUCTION

Stoppage of morning traffic flow on the southbound lanes of the Black Canyon Freeway is a frequent occurrence during the months of heaviest traffic flow. Such stoppages may be caused by an isolated incident involving a single vehicle. Or, they may be caused by traffic volumes which approach or exceed the carrying capacity of the freeway.

When freeway volumes approach capacity, any number of events may cause slowing or stoppage of traffic. Lane changes in the vicinity of interchanges, slowing to avoid exiting or entering vehicles, and differing performance characteristics of both drivers and vehicles, all contribute to freeway congestion. This can lead to a significant reduction in average freeway speed and may, in turn, cause traffic flow to 'grind to a halt' for periods ranging from seconds to several minutes and may occur repeatedly until the excess volume is finally dissipated and flow returns to normal.

Satisfactory speed-volume relationships can be maintained on the freeway if entering ramp volumes are controlled at each interchange to prevent freeway lane volumes from exceeding a critical level beyond which congestion and stoppage are likely to occur. The volume of ramp traffic entering the freeway can be controlled by metering the rate at which ramp vehicles are allowed to enter the freeway.

The ramp metering system already installed on the Black Canyon Freeway provides the essential hardware to experiment with different ramp metering rates to determine the effectiveness of ramp metering in maintaining satisfactory flow rates and speed on the freeway lanes.

Purpose of this Study

The purpose of this study was to develop a management strategy for controlling on-ramp traffic volumes which would minimize the chances of exceeding critical freeway lane volumes and the resulting congestion and stoppage on the freeway.

Scope of this Study

The scope of this study includes the analyses of data provided by Traffic Operations Services, establishing proposed metering rates for different volume-occupancy-speed relationships, testing and adjusting the metering rates in computer simulation to reduce the amount of on-site adjustment later, preparing a flow diagram of ramp metering strategy for subsequent adaptation to the existing hardware, and recommending hardware modifications as necessary to provide required information to drivers ramp vehicles.

BACKGROUND STUDY

In initial discussions the problem to be addressed was described as a study to detect non-recurring incidents on the Black Canyon Freeway which had caused, or were likely to cause, congestion or stoppage of traffic flow. The authors were provided with a copy of a freeway incident detection report of a study done for the California Department of Transportation (1).

While the California study reported the results of tests on many algorithms for incident detection it did not provide a strategy for controlling traffic volumes until traffic flow could be restored to normal. It soon became apparent that we had the opportunity to develop much more than the detection of non-recurrent incidents because of the ramp metering system which had already been installed. This led to the decision to develop a strategy for controlling the rate of flow of ramp vehicles onto the freeway as well as providing for ramp closure in the event of a non-recurring incident.

DATA ACQUISITION

Initial data were provided by Traffic Operations Services for Wednesday, January 28, 1981. The data included 15-minutes interval volume, occupancy and speed on the freeway lanes at each interchange location, for both Northbound and Southbound traffic, from midnight Tuesday until midnight Wednesday.

The January 28, 1981 data were acquired in mid-February, 1981, eleven months before the initiation of the project on January 15, 1982. The long lead time provided the basis for intensive study of the data which led to the formulation of the strategy for metering ramp traffic onto the freeway. Access to additional data has not changed the metering strategy although decision points have changed to reflect heavier volumes of traffic found in later data sets.

Once the project was under way, arrangements were made to obtain additional data on a much more intensive basis. Data were to be collected at one-minute intervals for all detectors at all ramp locations for Tuesday, Wednesday and Thursday in two consecutive weeks.

Initial delays in data collection resulted from the problem of incompatibility between the ADOT Nova 3 and the ASU Nova 2. This problem was resolved by locating and arranging for use of a Nova 3 in the Climatological Laboratory at ASU.

Further delay was encountered when the ADOT Nova 3 failed on March 26 and was not back in service until May 19. Difficulty in shifting from 15 min. to 1 min. summary tabulation, overflowing storage capacity, and starting and stopping the collection of data at desired times resulted in the loss of most of the AM and PM peak periods during which data collection was to have occurred. Useable data were obtained for one morning peak period and from two afternoon peak periods. Each set of data contained information form sixteen ramps which was judged to be sufficient for the purpose of establishing parameters for computer simulation runs.

The data were transferred from the Nova 3 disc to a computer tape using the Nova 3 at ASU. The intention was to reduce the data to graphical and tabular form in order to derive the necessary information for computer simulation. At this point this effort failed completely when, after repeated attempts, Dr. Lewis as unable to produce intelligible results from the computer tape.

At this point, Dr. Blackburn contacted Rolando Simeon at Traffic Operations Services, ADOT and asked if he had data for ramp, frontage road and freeway lane detectors from prior studies which we might use in the absence of other data. Mr. Simeon provided useable data for the southbound traffic during the morning peak period for Wednesday, November 18, 1981 and supplemental data for the northbound traffic during the afternoon peak period for Monday, November 30.

The Wednesday morning data contain 15-min. volume, occupancy, and speed from 5:30 until 9:30 A.M. for outside freeway lane, ramp, queue, and average freeway lane, for seven ramp locations.

The Monday afternoon data are for the period from 3:00 P.M. to 7:00 P.M. and are 15 min. tabulations of volume, occupancy and speed for outside lane and ramp only for eight ramp locations.

The significance of the November 18 and 30, 1981 data is that the freeway volumes were so much higher than those for the January 28, 1981 data. The increased volumes forced the shift from 1200 veh./lane per hour to 2000 veh/lane per hour as the upper boundary for heavy volume. In addition, the ramp volumes were much higher than had been assumed when working with the January 28, 1981 freeway lane data in the design of the original ramp metering strategy.

Fortunately, the November, 1981 data became available in time to be reflected in this report. They provide the basis for establishing much more realistic values of average headway in freeway traffic flow, minimum gap size acceptable to ramp vehicles entering the outside freeway lane, and average interval between arriving vehicles at the ramp metering signal.

TRAFFIC FLOW CRITERIA FOR SIMULATION

The Wednesday, November 18 data provided the basis for developing the criteria necessary for simulation. The data were used to establish values for: high, medium and low levels of outside freeway lane and ramp volumes average headway between vehicles in the outside lane and, average arrival rate for ramp vehicles.

Freeway Lane Volume

A study of the outside freeway lane data showed that congestion and slowing began when the volume exceeded the rate of 1400 veh./hr. at the four northernmost interchanges and 1600 veh/hr. at Bethany Home, Camelback and McDowell.

Maximum hourly volume rates for 15-minute intervals ranged from 2520 at Bethany Home to 1450 at Peoria.

Based on the above values the high, medium and low levels of freeway lane volume for which ramp metering should help maintain traffic flow at a satisfactory level is listed in the following tabulation.

Table 1

Outside Freeway Lane Volume Levels
Used for Traffic Flow simulation

	Hourly Volume		15 Minute Volume	
Level	Mid Value	Range	Mid Value	Range
Low	1000	801 - 1200	260	211 - 315
Medium	1400	1201 - 1600	370	316 - 420
High	1800	1601 - 2000	475	421 - 525

The 15-min. volume values are based on a Peak Hour Factor of 0.95. This value was derived from the values for the seven interchange locations which ranged from 0.94 to 0.98 and averaged 0.957 with three at 0.95.

Ramp Volume

Values for high, medium and low levels of ramp volume were derived from a study of the data taken on Wednesday, November 18, 1981 for seven southbound ramps (excludes Indian School). Values selected for Peak Hour Factors for high, medium and low ramp volumes were 0.87, 0.91 and 0.95 respectively.

Values for high, medium and low ramp volumes are shown in the following tabulation.

Table 2.

Ramp Volume Levels Used for Traffic Flow Simulation

Level	Hourly Volume		15-Minute Volume	
	Mid Value	Range	Mid Value	Range
Low	555	486 - 625	140	116 - 165
Medium	695	626 - 765	190	166 - 215
High	835	766 - 905	240	216 - 265

Average Headway for Vehicles in Outside Freeway Lane

Outside freeway lane volumes of 2200 to 2500 veh/hr were observed over sustained periods of 30 to 45 minutes in the November 18 data for southbound traffic. The average headways for these high volumes are:

$$h = \frac{3600}{2200} = 1.64 \text{ sec/veh; and ,}$$

$$h = \frac{3600}{2500} = 1.44 \text{ sec/veh.}$$

These average headways for the highest observed volumes were considered to be the minimum achievable headway and were used to establish the minimum headway for constrained vehicles (discussed later) as $h_{min} = \delta_2 = 1.50$ sec/veh. (equivalent to a flow rate of 2400 veh/hr).

The minimum headway values for unconstrained (free-flowing) vehicles, δ_1, were established as 2.25, 2.00 and 1.75 sec/veh for low, medium and high levels of freeway traffic flow. These values correspond to per-lane traffic flow rates of 1600, 1800 and 2050 veh/hr.

Further explanation of minimum headways for constrained and unconstrained vehicles, δ_1, and δ_2, will be presented in the discussion of headway distribution in freeway traffic flow.

Average Arrival Rate for Ramp Vehicles

The average arrival rates for low, medium and high levels of ramp volume are derived directly from the mid values at each level and are shown in the following tabulation.

Table 3.

Level	15-Min. Vol. Mid Value	Avg. Arrival Rate, sec/veh
Low	140	6.43
Medium	190	4.74
High	240	3.75

The average arrival rates are required for calculating the probability distribution of arrival intervals between ramp vehicles from the equation

$$P\ (h \geq t) = e^{-\frac{t-2}{T-2}}$$

h = headway between vehicles, sec/veh

t = interval time, sec/veh

T = average arrival rate, sec/veh

e = base of natural logarithims, 2.71828

Two seconds is subtracted from interval time, t, and from average arrival rate, T, to impose a minimum headway of two seconds between ramp vehicles.

<u>Coefficients for Headway Distribution in Outside Freeway Lane</u>

After examining the results, obtained from several models for headway distribution, as described by Gerlough and Huber (2), the hyper-Erlang model was selected for use in this study.

The hyper-Erlang model was developed by Dawson (3) and provides for combined flow of constrained and free-flowing vehicles in the traffic stream and shifts the distribution to the right (away from 0 sec. headway) to adjust for a minimum headway consistent with those observed in freeway traffic flow.

The hyper-Erlang model may be written in the form

$$P(h \geq t) = \alpha_1 e^{-\frac{t-\delta_1}{\gamma_1-\delta_1}} + \alpha_2 e^{-\frac{t-\delta_2}{\gamma_2-\delta_2}} \times \sum_{x=0}^{K-1} \frac{\left(K\frac{t-\delta_2}{\gamma_2-\delta_2}\right)^x}{x!}$$

where $P(h \geq t)$ = The probability of headways being equal to, or greater than, any selected time t in seconds

α_1, α_2 = The percentages of free-flowing and constrained vehicles in the traffic stream

γ_1, γ_2 = The average headways for free-flowing and constrained vehicles, sec/veh

δ_1, δ_2 = The minimum headways for free-flowing and constrained vehicles, sec/veh

k = A factor that reflects the degree of non-randomness in the constrained headway distribution

A detailed study of the freeway and ramp traffic flow data led to the selection of the values shown in the following tabulation for the coefficients used in the hyper-Erlang headway distribution model. Note that nine different sets of results are obtained for low, medium and high ramp volumes for each of three levels (low, medium, high) of freeway outside lane volumes. 15-min. volumes are used since these are consistent with the intervals used in data collection.

Table 4.

Coefficients for the hyper-Erlang Headway Distribution Model Used in Computer simulation of Freeway Traffic Flow

15 Min.	15 Min.	% of Flow		Avg. Hdwy.		Min. Hdwy.		
Fwy Vol.	Ramp Vol.	α_1	α_2	γ_1	γ_2	δ_1	δ_2	k
	140	.55	.45	6.42	4.28	2.25	1.50	2.0
260	190	.55	.45	5.19	3.46	2.25	1.50	2.0
	240	.55	.45	4.29	2.86	2.25	1.50	2.0
	140	.28	.72	4.29	2.86	2.00	1.50	4.0
370	190	.28	.72	3.65	2.43	2.00	1.50	4.0
	240	.28	.72	3.21	2.14	2.00	1.50	4.0
	140	.10	.90	3.21	2.14	1.75	1.50	6.0
475	190	.10	.90	2.84	1.89	1.75	1.50	6.0
	270	.10	.90	2.57	1.71	1.75	1.50	6.0

SIMULATION OF OUTSIDE FREEWAY LANE AND RAMP TRAFFIC FLOW

The simulation of outside freeway lane traffic flow is achieved by generating successive random values ranging from 0.00 to 1.00. These random values then represent the probabilities of a randomly selected succession of vehicle headways on the outside freeway lane. The hyper-Erlang equation is solved for each probability value to find the headway in seconds per vehicle between successive vehicles in the traffic stream.

At the same time headways are being generated, ramp vehicle arrivals are being generated using the negative exponential equation to obtain random intervals between successive ramp vehicles. Ramp vehicles are processed in two steps. First, they arrive on the ramp at the ramp metering point, or they join the queue of ramp vehicles waiting to be released to the acceleration lane. Second, the vehicles are released to the acceleration lane and enter an available gap between two vehicles in the outside freeway lane, or they join the queue of vehicles on the acceleration lane waiting for acceptable gaps.

The simulation logic allows one or more vehicles on the acceleration lane to enter the outside freeway lane based on length of gap in seconds. The minimum acceptable gap for one vehicle was chosen as 2.5 sec. with one additional vehicle allowed to enter for each additional 3.0 sec. of gap time. The justification for these criteria is contained in the following paragraph.

The minimum acceptable gap time was based on the assumption that a driver would enter a gap if there were at least 2 car lengths (40 ft.) between the rear of the lead vehicle and the front of his vehicle, and 5 car lengths (100 ft.) between the rear of his vehicle and the front of the following vehicle. The total length of the gap is then 100+20+40+20 = 180 ft. At an average speed of 50 MPH (73.33 fps) in the outside freeway lane the headway would be 180/73.33 = 2.45 sec. between vehicles. This logic was the basis for the minimum acceptable gap of 2.5 sec. An additional 0.5 sec. for driver reaction was allowed for second and subsequent vehicles entering a long gap.

A maximum of 18 vehicles were allowed on the combined ramp-acceleration lane at any given time. Thus, once the queue totaled 18 vehicles, vehicles were accepted in the queue only as equal numbers of vehicles entered a gap in the outside freeway lane. Vehicles desiring to use the ramp when the queue totaled 18 vehicles were rejected and assumed to have found alternate routing.

Simulation runs were made for 75 minutes of real time with the first 15 minutes used to load the system and to achieve stable flow. Data were then obtained for the remaining 60 minutes for use in assessing the effectiveness of the simulation.

The effectiveness of the simulation for selected levels of freeway and ramp volumes (Tables 1 and 2) was measured by:

1. The average time between arrival of ramp vehicles and entry onto the freeway;

2. The number of vehicles in the ramp-acceleration lane queue at selected intervals, usually 15 min.

3. The total number of vehicles intending to use the ramp that were rejected.

RESULTS OBTAINED FROM TRAFFIC FLOW SIMULATION

The results from traffic flow simulation are presented in Tables 5, 6 and 7 for outside freeway lane volumes of 260, 370 and 475 vehicles per 15-min interval. These 15-min volumes are equivalent to the mid-values for low, medium and high hourly volumes of 1000, 1400 and 1800 vehicles.

Tables 5, 6 and 7 show what happened in simulation to ramp vehicles which arrived at rates of 140, 190 or 240 vehicles per 15-min when metered onto the freeway at intervals of 0, 4, 6, 8, 10 or 12 seconds. The simulation interval was 60 minutes so that the total for randomly generated ramp vehicles in each simulation run was approximately four times the 15-min ramp volume (15-min vol x 4 x PHF).

The results from these simulation runs form the basis for assessing the effect of different metering rates on potential ramp traffic. In general, the data show that the principle objective of ramp metering has been accomplished. That is, fewer ramp vehicles enter the freeway as the metering interval between vehicles is increased. Also, increasing numbers of ramp vehicles are rejected and must seek alternate routing as ramp vehicle volumes increase. From these data it is possible to evaluate ramp metering strategies as such strategies impact on ramp traffic.

RAMP MANAGEMENT STRATEGY

The purpose of any ramp management strategy is to control the entrance of ramp vehicles in such a way as to assure satisfactory performance of the freeway. it is therefore accepted that, before ramp volumes increase to the point of causing freeway traffic congestion or stoppage, some of the ramp vehicles must be delayed in entering the freeway and others must be rejected. The amount of delay and the number of rejections may be estimated by simulation, as in this study, for any ramp management strategy.

The ramp management strategy that has evolved from this study treats each ramp location separately and reflects only the freeway traffic conditions at a given location in decisions regarding ramp metering.

Table 5. Results from Freeway Ramp Metering Simulation

15-Min Fwy Lane Vol	15-Min Ramp Vol	Meter Rate	Total Ramp Veh	Ramp Veh Rejected	Ramp Veh Processed	Avg. Time in System	Avg Ramp Delay	Avg Acc Lane Delay	Speed Range On Fwy Lane
		0	540	0	540	1.2	0.0	1.2	
	140	4	557	0	557	3.9	2.9	1.0	52 - 70+
		6	544	0	544	13.9	13.0	0.7	42 - 52
260									
		8	578	128	450	139.2	138.5	0.7	35 - 42
	140	10	568	208	360	175.0	174.3	0.7	
		12	558	258	300	222.4	208.4	0.6	
		0	715	0	715	1.9	0.0	1.9	
	190	4	755	0	755	6.6	4.8	1.8	52 - 70+
		6	773	173	600	109.5	105.5	0.9	42 - 52
260									
		8	742	292	450	148.1	141.2	0.8	35 - 42
	190	10	763	403	360	186.5	176.4	0.9	
		12	767	468	301	224.6	210.3	1.0	
		0	965	35	930	55.4	0.0	55.4	
	240	4	945	46	899	67.2	57.9	8.2	51 - 70+
		6	938	338	600	110.9	106.4	1.3	42 - 52
260									
		8	941	491	450	149.5	142.3	1.2	35 - 42
	240	10	977	617	360	187.9	177.3	1.1	
		12	943	642	301	225.6	211.2	1.1	

Table 6. Results from Freeway Ramp Metering Simulation

15-Min Fwy Lane Vol	15-Min Ramp Vol	Meter Rate	Total Ramp Veh	Ramp Veh Rejected	Ramp Veh Processed	Avg. Time in System	Avg Ramp Delay	Avg Acc Lane Delay	Speed Range On Fwy Lane
		0	540	0	540	2.9	0.0	2.9	
	140	4	559	0	559	5.1	2.9	2.2	
		6	542	0	542	14.7	13.0	1.5	59 - 70+
370									
		8	578	128	450	138.1	136.5	1.6	48 - 59
	140	10	569	208	361	174.4	172.9	1.5	42 - 48
		12	558	258	300	222.7	207.9	1.6	37 - 42
		0	718	0	718	31.7	0.0	31.7	
	190	4	759	0	759	26.5	4.8	21.7	
		6	774	173	601	108.1	99.4	5.5	59 - 70+
370									
		8	743	293	450	147.7	139.4	2.7	48 - 59
	190	10	763	403	360	186.4	174.9	2.4	42 - 48
		12	768	468	300	224.5	208.8	2.6	37 - 42
		0	970	485	485	138.2	0.0	138.2	
	240	4	938	449	489	135.9	2.6	133.3	
		6	939	425	514	130.1	9.9	120.3	59 - 70+
370									
		8	941	488	453	148.7	126.0	17.9	48 - 59
	240	10	977	619	358	188.1	173.1	6.4	42 - 48
		12	942	642	300	225.4	207.5	4.7	37 - 42

Table 7. Results from Freeway Ramp Metering Simulation

15-Min Fwy Lane Vol	15-Min Ramp Vol	Meter Rate	Total Vehicles	Vehicles Rejected	Vehicles Processed	Avg. Time in System	Avg Ramp Delay	Avg Acc Lane Delay	Speed Range on Fwy Lane
		0	579	258	321	203.7	0.0	203.7	
	140	4	567	235	332	202.7	2.3	200.4	
		6	559	233	326	202.0	4.4	197.6	
475									
		8	541	219	321	206.2	8.5	197.7	61 - 70+
	140	10	557	215	342	192.2	31.0	161.2	53 - 61
		12	543	260	283	230.4	123.1	94.8	47 - 53
		0	742	633	109	620.8	0.0	620.8	
	190	4	763	653	110	578.1	1.9	576.2	
		6	748	635	133	510.8	3.5	507.3	
475									
		8	715	595	120	579.5	5.0	574.5	61 - 70+
	190	10	753	648	105	674.1	6.2	667.5	53 - 61
		12	774	657	117	562.0	8.8	553.4	47 - 53
		0	941	847	94	742.7	0.0	742.7	
	240	4	977	876	101	629.1	1.9	627.2	
		6	942	862	80	816.8	3.5	813.3	
475									
		8	970	881	89	767.5	4.1	763.3	61 - 70+
	240	10	938	844	94	772.0	6.3	759.7	53 - 61
		12	938	844	94	755.4	7.0	739.5	47 - 53

Decisions on metering rates are made at each ramp location on a minute-by-minute basis and depend on the volume, per cent occupancy, and average speed on the outside freeway lane for the past one minute.

The ramp management strategy is presented graphically in Fig. One. The concept is based on levels of service for volume and speed (4) and on observed volume, occupancy and speed data for southbound traffic on the outside freeway lane during the P.M. peak period on Wednesday, November 18, 1981.

The ramp metering is designed to maintain outside freeway lane volume and speed values at, or above, Level of Service D. Operation for up to 5 minutes is tolerated in a narrow range at Level of Service E for either speed or volume. If conditions have not improved after 5 minutes the ramp is closed until Level of Service D or higher has been re-established. The ramp is closed immediately if after any one minute a volume-occupancy-speed data point lies outside the monitor zone and further into the Level of Service E range or occupancy exceeds 16 per cent.

For convenient reference, speed and volume ranges for Levels of Service are presented in the following table.

Table 8. Ranges of Speed and Volume for Levels of Service

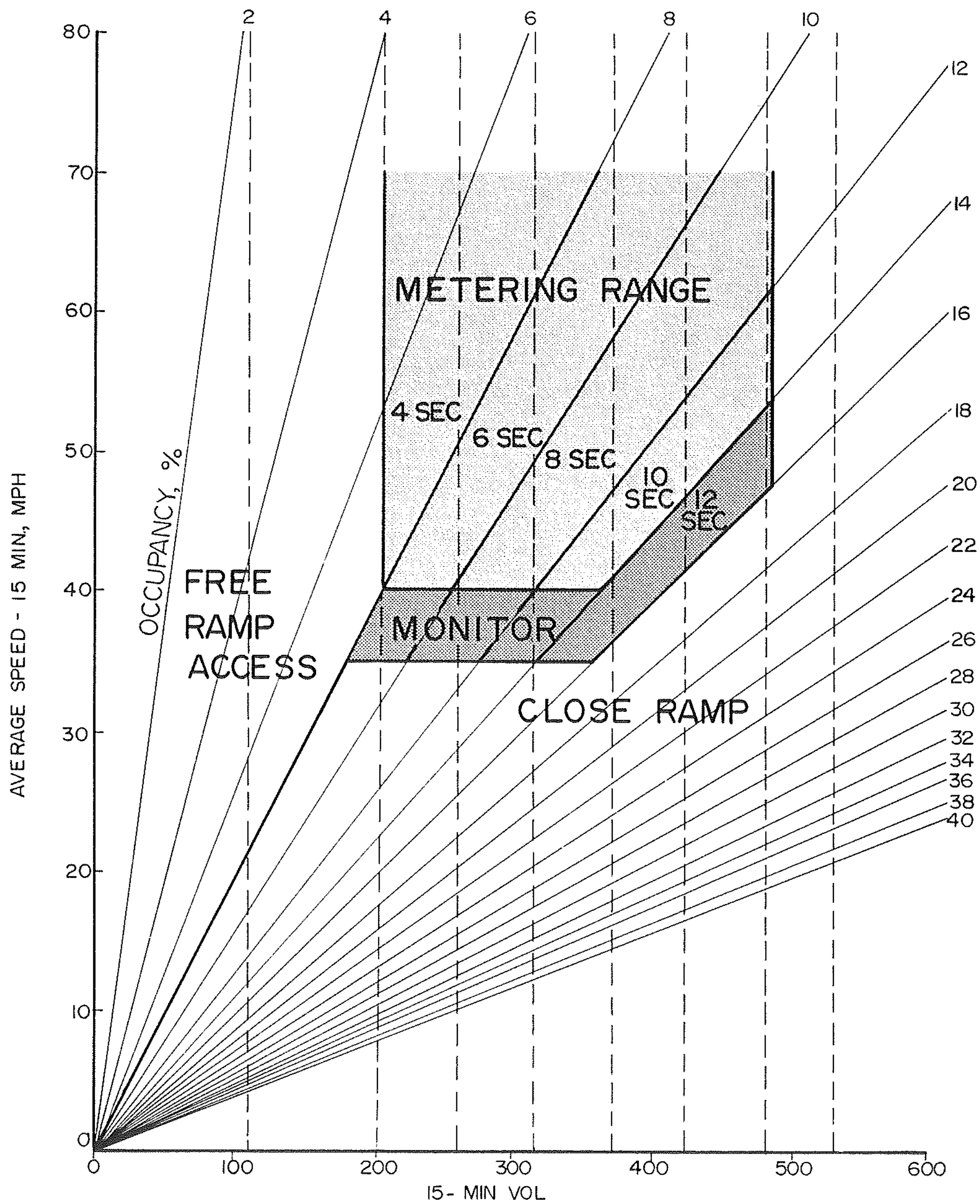
Level of Service	Speed, MPH	Volume,[1] Vol/Cap Ratio	Volume, Veh/Hr
A	60 - 70	0.00 - 0.40	0 - 800
B	55 - 60	0.40 - 0.58	800 - 1160
C	50 - 55	0.58 - 0.75	1160 - 1500
D	40 - 50	0.75 - 0.85	1500 - 1700
E	28 - 40	0.85 - 1.00	1700 - 2000
F	0 - 28	-- - --	-- - --

1. Based on 6-lane Freeway and Peak Hour Factor of 0.95

RESULTS OBTAINED FROM SIMULATION OF RAMP MANAGEMENT STRATEGY

The impact of the ramp management strategy on ramp vehicles can be judged from the data presented in Tables 5, 6 and 7 for low, medium and high outside freeway lane volumes respectively.

FIG. I OCCUPANCY, VOLUME, SPEED RELATIONS FOR RAMP MANAGEMENT STRATEGY.



EQUIV 15 MIN	0	105	200	263	316	368	421	474	526
EQUIV HOUR	0	400	760	1000	1200	1400	1600	1800	2000
EQUIV MINUTE	0	7	14	18	22	26	30	33	37

LOW/Outside Freeway Lane Volume - LOW Ramp Volume

The low outside freeway lane volume (Table 5) of 260 veh/15 min is equivalent to 1000 veh/hr. The average headway at this volume is 3.46 sec/veh for the 15 min interval. This average headway provides an adequate number of acceptable gaps for low ramp volumes (140 veh/15 min) to enter the freeway with little or no delay (0 to 14 sec/veh) for metering rates of 0, 4 and 6 sec between vehicles.

For metering rates of 8, 10 and 12 sec the average delay per vehicle is greatly increased and ranges from 139 to 175 to 222 sec respectively. At these higher metering rates the ramp queue is full much of the time and 31, 51 and 65 of the 140 ramp vehicles are rejected and must find alternate routes.

The 260 veh/15 min average operating range for the ramp management strategy requires 4 and 6 sec metering and 8 sec metering in the monitor area. Operating speeds in the outside freeway lane are estimated to be 52-70+, 42-52 and 35-42 respectively. The system will work satisfactorily with rejections and significant delay occurring only in the monitor area. The speed of vehicles in the outside freeway lane will rarely drop below 50 MPH at a volume of 260 veh/15 min unless an incident has occurred.

LOW Outside Freeway Lane Volume - MEDIUM Ramp Volume

The outside freeway lane characteristics remain as discussed above. The increase in 15 min ramp volume from 149 to 190 results in an increase in the number of ramp vehicles rejected and an increase in delay for those vehicles that enter the freeway.

The ramp management strategy requires 4 and 6 sec metering and 8 sec metering in the monitor areas as before. At these metering rates 0, 43 and 75 of the 190 veh/15 min would be rejected. The average delay per vehicle is 7, 110 and 148 sec respectively for those vehicles that enter the freeway.

LOW Outside Freeway Lane Volume - HIGH Ramp Volume

At 240 ramp vehicles/15 min some ramp vehicles are rejected at all levels of metering. The metering rates of 4, 6 and 8 sec for the ramp management strategy result in 12, 86 and 125 of the 240 vehicles being rejected. Average delays for vehicles entering the freeway are 67, 111 and 150 sec respectively.

MEDIUM Outside Freeway Lane Volume - LOW Ramp Volume

The medium volume level of 370 veh/15 min in the outside freeway lane is equivalent to 1400 veh/hr. The average headway between vehicles is 2.43 sec/veh for the 15 min volume and is approximately equivalent to the minimum acceptable gap of 2.5 sec.

The ramp management strategy requires metering rates of 6, 8 and 10 sec and 12 sec metering in the monitor area. Expected speed ranges for each metering rate are 59-70+, 48-59, 42-48 and 37-42 respectively. Under normal operating conditions observed speeds do not fall below 40 MPH. When higher volumes have caused a breakdown in traffic flow, speeds below 20 MPH have occurred for intervals of 15 to 30 min during the peak period.

Rejections of ramp vehicles at ramp volumes of 140 veh/15 min are 0, 31, 51 and 65 for the respective metering rates of 6, 8, 10 and 12 sec. The average delay per vehicle for vehicles entering the freeway is 15, 138, 174 and 223 sec respectively. The data from 11/18/81 indicate that the metering rate will be 8 sec a majority of the time when the outside freeway lane volume averages 370 veh/15 min. As shown above this metering rate would result in an average delay of over 2 min/veh for the 109 ramp vehicles entering the freeway. This level of average delay suggests that it may be desirable to use a shorter metering interval. However, this decision could only be made after on-site study revealed the effect of the increased volume on freeway traffic flow conditions.

<u>MEDIUM Freeway Traffic Volume</u> - <u>MEDIUM Ramp Volume</u>

At the ramp management strategy metering rates of 6, 8 and 10 sec and 12 sec in the monitoring area, 42, 75, 100 and 116 of the 190 ramp vehicles/15 min would be rejected. For ramp vehicles entering the freeway, the average delay per vehicle is 108, 148, 186 and 225 sec. respectively. At the 8 sec metering rate this is over 2.5 min per vehicle. This amount of delay may be absolutely necessary to prevent congestion and traffic flow stoppage on the freeway. As before, only an on-site study of the effect of shorter metering intervals on freeway traffic flow conditions could provide the necessary data to make that decision.

<u>MEDIUM Freeway Traffic Volume</u> - <u>HIGH Ramp Volume</u>

At the ramp management strategy metering rates of 6, 8 and 10 sec and 12 sec in the monitoring area, 109, 124, 152 and 163 of the 240 veh/15 min are rejected. The average delay for those ramp vehicles that enter the freeway is 130, 149, 188 and 225 sec per vehicle. The high rejection and delay rates assure the satisfactory downstream performance of the freeway by maintaining the outside freeway lane volume at approximately the 1400 veh/hr flow rate.

<u>HIGH Freeway Traffic Volume</u> - <u>LOW Ramp Volume</u>

The high outside freeway lane volume of 475 veh/15 min is equivalent to 1800 veh/hr. Such a high traffic volume results in an average headway of only 1.89 sec/veh. This is substantially below the minimum acceptable gap of 2.5 sec which means that only occasionally does an acceptable gap occur to permit a ramp vehicle to enter the freeway. Under such circumstances it is best to discourage most, if not all, of the ramp vehicles from entering the freeway.

At such a high outside freeway lane volume the number of ramp vehicles rejected, and the average delay for vehicles entering the freeway, are both unafffected by ramp metering rate. Approximately 60 of 140 veh/15 min were rejected while the delay for the 80 ramp vehicles entering the freeway averaged 203 sec/veh for all metering rates.

HIGH Freeway Traffic Volume - MEDIUM Ramp Volume

The same insensitivity to metering rates is again evident. Of the 190 veh/15 min arriving at the ramp an average of 162 were rejected. The 28 vehicles which entered the freeway were delayed an average of 587 sec or nearly 10 minutes per vehicle.

These are obviously intolerable operating conditions for a freeway ramp but as long as outside freeway lane volumes are frequently observed in the 1600 to 2000 veh/hr range it will be necessary to severely restrict entering ramp traffic.

HIGH Freeway Traffic Volume - HIGH Ramp Volume

Again, metering rate has no effect on rejection and delay for ramp vehicles. Approximately 215 of the 240 veh/15 min were rejected. The 25 vehicles which did enter the freeway experienced delays averaging nearly 13 min/veh.

The very high penalty assessed to ramp vehicles is again required because of the extremely high volume in the outside freeway volume.

It is entirely possible that the ramp management strategy will be so effective in maintaining freeway volumes at lower levels that such high freeway volumes will be avoided in the future. This would be the ultimate payoff for this project.

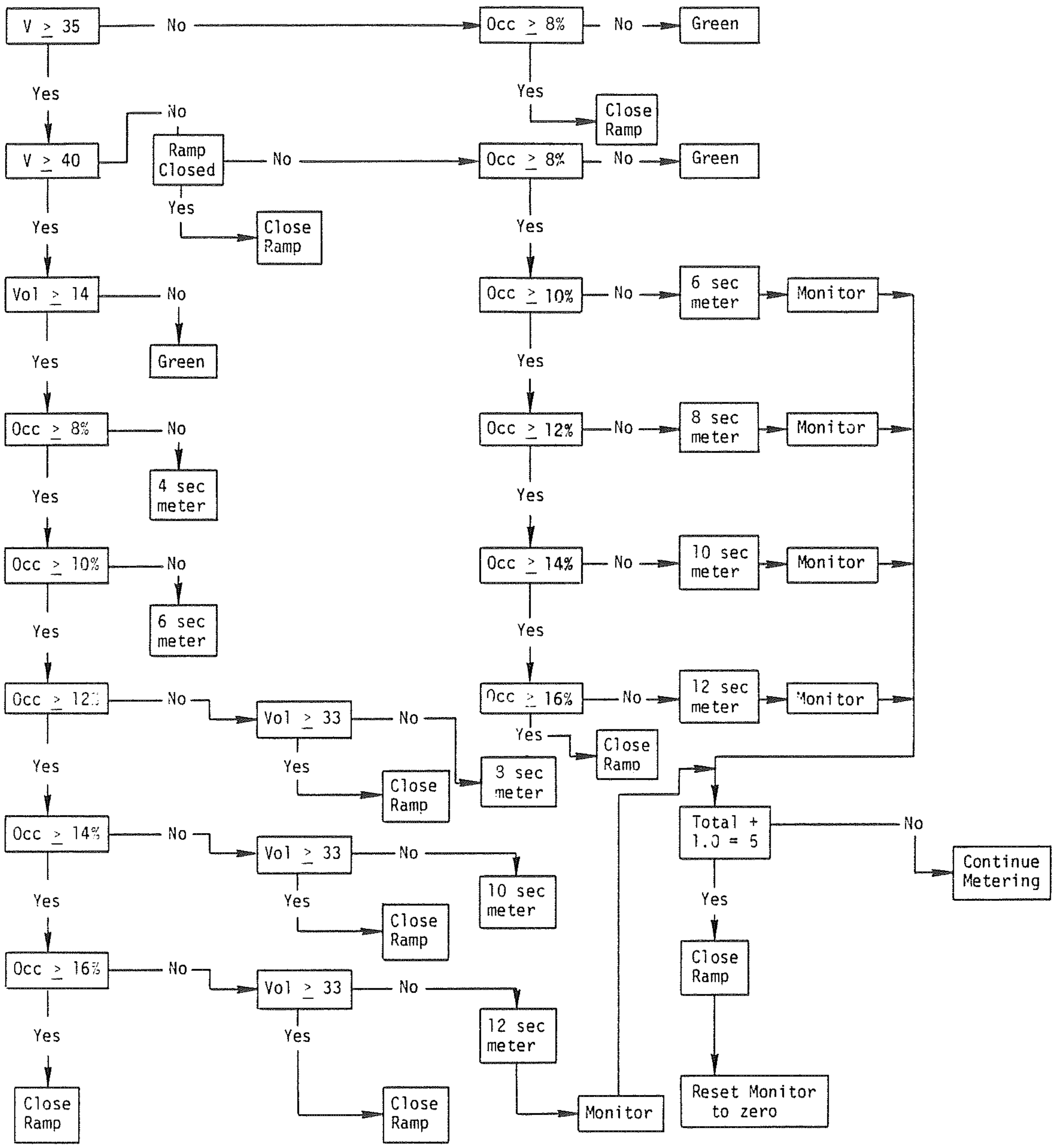
FLOW DIAGRAM FOR RAMP MANAGEMENT STRATEGY

The algorithm for ramp management strategy is shown in flow diagram form in Figure 2. This algorithm provides the logic necessary for the system to perform according to the criteria displayed graphically in Figure 1.

The development of a computer program from this flow diagram must be designed for ease of access to all numerical values on which decisions are based. Easy access will allow values to be changed as required, based on on-site study, to improve operating conditions.

It is believed that a single algorithm will work satisfactorily at all ramp locations. If, in operating the system, some ramp locations do not perform satisfactorily, different sets of criteria may be incorporated into the program package for those locations in order to improve performance.

Figure 2. Ramp Metering Strategy Flow Diagram



Retrieve last 1-min volume (outside fwy lane, P_1)

Retrieve last 1-min occupancy (outside fwy lane, P_1)

Compute last 1-min avg. speed, $\overline{V}$ mph (outside fwy lane, P_1)

$$\overline{v} = \frac{s}{t} = \frac{\text{Avg. Veh. Length}}{\frac{\text{1-min.occupancy}}{\text{1-min.volume}}} = \frac{\text{ft/veh}}{\frac{\text{sec/min}}{\text{veh/min}}} = \frac{\text{ft/veh}}{\text{sec/veh}} = \text{ft/sec}$$

$$\overline{V} = \overline{v} \times \frac{3600}{5280} = \text{MPH}$$

Compute last 1-min % occupancy, Occ %

$$\text{Occ, \%} = \frac{\text{sec of occupancy}}{60} \times 100$$

Early in this project a question was raised about the available time on the Nova III to execute the ramp management program. The question was whether there was enough time to bring in data from each ramp location, operate on the data, and send a command back to each location in less than 60 seconds total time for all locations. This is essential in order to maintain minute-by-minute control over ramp metering.

A tentative decision was made to explore the possibility of developing new firmware to be installed in each ramp controller. Dr. Bruce Towe and representatives from ADOT Traffic Operations and ATRC met with Dr. Blackburn for discussions of existing ramp controller hardware and programming. It was quickly established that the programming contained in the ramp controllers was written in assembly language which would be extremely difficult and time consuming to master in order to incorporate the ramp management programming. Dr. Towe strongly recommended against attempting to install the ramp management program into the ramp controllers.

Our attention then returned to the possibility of inserting the ramp management programming into the programming in the Nova III used as the central processing unit. This possibility was made more attractive by the knowledge that the Nova III programming was written in Fortran IV language and the insertion of added programming therefore much less difficult.

Dr. Towe then called Jim Goosman at Safe-Trans to discuss the amount of time required to execute the existing program and whether there was enough time remaining each minute to execute additional program steps in the Nova III and then send commands back to each ramp controller. Both Dr. Towe and Goosman were optimistic that the amount of additional time required was less than the time available. Since that time Dr. Towe has reviewed the flow diagram shown in Fig. 2 and is confident that there is sufficient time available each minute to do all ramp data processing, including ramp management strategy, in the Nova III.

Therefore, it is our recommendation that Safe-Trans be contacted and asked to prepare the Fortran IV programming. for down-loading into their existing program which, we understand from Ray Johnson must be processed through a Fortran V compiler for insertion finally in machine language. This appears to be the most expeditions way to implement the ramp management programming developed under this project.

CONCLUSIONS

1. A basic assumption of this study was that ramp metering at any level would benefit freeway traffic flow. Also, that the metering rate could be adjusted to prevent freeway traffic volumes from exceeding freeway capacity.

2. The effect of ramp metering on freeway traffic flow was not measured directly in this study. This would have required computer simulation of directional freeway and ramp traffic flow, for southbound traffic during the morning peak and repeated for northbound traffic during the afternoon peak.

3. In the absence of direct information on the effect of different metering rates on freeway traffic volume, final adjustment of criteria for satisfactory freeway operation cannot be made until such data can be obtained from on-site studies.

4. The ramp management strategy must be programmed so that criteria for ramp metering rate may be changed as the need is indicated from on-site experience and study.

5. The ramp management strategy programming must provide for branching on ramp location in order to use different criteria for ramps which do not function well when the criteria for ramp metering for the general solution are used.

6. Implementation of the ramp management strategy is contingent on Safe-Trans willingness to prepare programming and to install it into existing programming.

LIST OF REFERENCES

1. Payne, H.J., Helfenbein, E.D. and Knobel, H.C., "Development and Testing of Incident Detection Algorithms," Report No. FHWA-RD-76-20, Federal Highway Administration. April, 1976.

2. Gerlough, Daniel L. and Huber, Matthew J., 'Traffic Flow Theory," Special Report 165, Transportation Research Board. 1975.

3. Dawson, R.F. and Chimini, L.A., 'The Hyperlang Probability Distribution - A Generalized Traffic Headway Model," Highway Research Record 230, Highway Research Board. 1968.

4. "Highway Capacity Manual - 1965," Special Report 87, Highway Research Board. 1965. Pg. 264.

APPENDIX A

Volume, Occupancy and Speed Data

for

Outside Lane (P_1), Ramp (R) and Queue (Q) Detectors

for

Southbound AM Peak Period Traffic Flow

on the

Black Canyon Freeway

on

Wednesday, November 18, 1981

REPORT PREPARED ON 11 19 1981

TRAFFIC DATA SUMMARY REPORT

ATE: 11 18 1981 THRU 11 18 1981
AYS: WED
OLIDAYS: EXCLUDED
IME: 5:30- 9:30
ETECTORS: P1
ISPLAY MODE: TABLE

DIRECTION: SOUTH BOUND
INTERVAL: 15 MIN
DATA: VOLUME (VPH)

OC TIME	PEO	DUN	NOR	GLE	BET	CAM	IND	MCD	TST
5 45	391	423	480	495	471	511	--	519	--
6 0	607	583	639	727	935	851	--	831	--
6 15	595	679	671	739	1095	891	--	691	--
6 30	871	943	1020	1031	1699	1083	--	1059	--
6 45	1055	1091	1327	1500	2520	1635	--	1487	--
7 0	1339	1375	1311	1380	1911	1627	--	1431	--
7 15	1335	1255	1547	1555	2195	1623	--	1519	--
7 30	1551	1451	1431	1607	2215	1787	--	1543	--
7 45	1567	1403	1579	1603	2215	1747	--	1527	--
8 0	1527	1427	1643	1535	1959	1487	--	1519	--
8 15	1227	1063	1247	1467	1899	1759	--	1615	--
8 30	1131	1200	1227	1407	1967	1651	--	1467	--
8 45	1203	1223	1255	1307	1939	1463	--	1140	--
9 0	1007	1051	1211	1335	1823	1347	--	1051	--
9 15	1059	1175	1231	1311	1579	1183	--	923	--
9 30	851	875	987	1027	1131	1059	--	811	--

REPORT PREPARED ON 11 20 1981
TRAFFIC DATA SUMMARY REPORT

ATE: 11 18 1981 THRU 11 18 1981
AYS: WED
OLIDAYS: EXCLUDED
IME: 5:30- 9:30
ETECTORS: P1
ISPLAY MODE: TABLE

DIRECTION: SOUTH BOUND
INTERVAL: 15 MIN
DATA: OCCUPANCY (%)

OC TIME	PEO	DUN	NOR	GLE	BET	CAM	IND	MCD	TST
5 45	3	3	3	3	2	3	--	3	--
6 0	4	4	4	5	5	5	--	6	--
6 15	4	5	4	5	6	6	--	5	--
6 30	6	7	8	7	10	7	--	8	--
6 45	8	8	10	11	15	13	--	11	--
7 0	11	16	28	19	19	15	--	11	--
7 15	27	30	19	12	16	13	--	11	--
7 30	16	11	13	15	22	14	--	11	--
7 45	25	21	17	14	18	14	--	12	--
8 0	25	12	20	26	24	37	--	11	--
8 15	10	9	34	24	25	19	--	12	--
8 30	8	9	9	11	13	13	--	11	--
8 45	9	9	10	9	11	10	--	8	--
9 0	8	8	9	9	10	9	--	8	--
9 15	8	9	9	9	9	8	--	7	--
9 30	6	6	7	7	6	7	--	6	--

REPORT PREPARED ON 11 20 1981

TRAFFIC DATA SUMMARY REPORT

ATE: 11 18 1981 THRU 11 18 1981
AYS: WED
OLIDAYS: EXCLUDED
IME: 5:30- 9:30
ETECTORS: P1
ISPLAY MODE: TABLE

DIRECTION: SOUTH BOUND
INTERVAL: 15 MIN
DATA: SPEED (MPH)

OC TIME	PEO	DUN	NOR	GLE	BET	CAM	IND	MCD	TST
5 45	50	53	56	58	71	62	--	54	--
6 0	53	58	57	60	74	59	--	57	--
6 15	55	54	56	59	73	61	--	55	--
6 30	52	53	52	59	68	57	--	54	--
6 45	52	54	50	53	65	50	--	54	--
7 0	48	34	19	28	41	43	--	53	--
7 15	20	17	33	50	53	51	--	56	--
7 30	40	50	43	44	41	52	--	54	--
7 45	25	27	36	45	48	51	--	52	--
8 0	24	45	33	23	33	16	--	53	--
8 15	50	47	14	25	31	38	--	54	--
8 30	53	54	54	50	59	50	--	52	--
8 45	51	53	51	54	69	57	--	56	--
9 0	50	53	51	55	70	56	--	54	--
9 15	51	53	54	57	69	57	--	52	--
9 30	51	54	52	57	68	58	--	52	--

REPORT PREPARED ON 11 20 1981
TRAFFIC DATA SUMMARY REPORT

E: 11 18 1981 THRU 11 18 1981
S: WED
IDAYS: EXCLUDED
E: 5:30- 9:30
ECTORS: R
PLAY MODE: TABLE

DIRECTION: SOUTH BOUND
INTERVAL: 15 MIN
DATA: VOLUME (VPH)

TIME	PEO	DUN	NOR	GLE	BET	CAM	IND	MCD	TST
5 45	255	275	235	183	151	151	219	319	--
6 00	375	399	459	327	283	279	507	567	--
6 15	439	351	407	319	367	295	383	475	--
6 30	663	651	615	360	391	467	543	695	--
6 45	799	815	903	571	579	491	695	843	--
7 00	627	571	575	551	543	575	623	943	--
7 15	579	443	619	591	559	591	603	743	--
7 30	607	591	603	571	575	567	600	815	--
7 45	611	607	615	591	595	583	595	823	--
8 0	587	611	611	571	583	611	595	823	--
8 15	563	527	531	547	563	595	591	720	--
8 30	579	595	615	475	583	495	559	699	--
8 45	611	619	611	563	531	387	487	607	--
9 0	883	679	775	480	435	459	499	583	--
9 15	843	563	747	431	371	363	503	720	--
9 30	627	587	635	455	319	343	495	707	--

REPORT PREPARED ON 11 20 1981

TRAFFIC DATA SUMMARY REPORT

ATE: 11 18 1981 THRU 11 18 1981
AYS: WED
OLIDAYS: EXCLUDED
IME: 5:30- 9:30
ETECTORS: R
ISPLAY MODE: TABLE

DIRECTION: SOUTH BOUND
INTERVAL: 15 MIN
DATA: OCCUPANCY (%

OC TIME	PEO	DUN	NOR	GLE	BET	CAM	IND	MCD	TST
5 45	1	2	1	1	1	1	1	2	--
6 0	2	2	3	2	1	2	3	3	--
6 15	3	2	3	2	2	2	2	3	--
6 30	5	4	4	2	2	3	4	5	--
6 45	6	6	8	4	4	4	5	6	--
7 0	10	10	11	8	7	8	7	6	--
7 15	11	7	9	8	7	9	8	4	--
7 30	10	8	10	7	7	8	8	6	--
7 45	12	11	11	8	8	9	8	6	--
8 0	10	9	11	9	11	12	8	7	--
8 15	10	8	14	9	8	10	10	5	--
8 30	10	8	10	6	7	7	8	5	--
8 45	10	9	9	7	7	6	6	4	--
9 0	7	5	7	3	3	3	4	4	--
9 15	7	4	6	3	2	3	4	5	--
9 30	5	4	5	3	2	2	4	5	--

REPORT PREPARED ON 11 20 1981

TRAFFIC DATA SUMMARY REPORT

ATE: 11 18 1981 THRU 11 18 1981
AYS: WED
OLIDAYS: EXCLUDED
IME: 5:30- 9:30
ETECTORS: R
ISPLAY MODE: TABLE

DIRECTION: SOUTH BOUND
INTERVAL: 15 MIN
DATA: SPEED (MPH)

OC TIME	PEO	DUN	NOR	GLE	BET	CAM	IND	MCD	TST
5 45	56	57	52	63	57	50	59	64	--
6 0	56	61	52	59	60	55	54	65	--
6 15	54	60	53	60	59	53	55	64	--
6 30	52	56	52	62	62	51	53	53	--
6 45	49	51	46	56	55	48	51	57	--
7 0	25	22	21	27	30	27	32	56	--
7 15	20	24	27	29	30	27	31	62	--
7 30	23	27	23	30	30	27	28	52	--
7 45	19	22	22	27	29	25	28	52	--
8 0	22	28	21	24	20	20	28	47	--
8 15	22	26	15	23	26	23	24	52	--
8 30	23	28	25	31	31	27	25	53	--
8 45	23	27	25	32	30	26	31	55	--
9 0	47	52	45	55	57	48	49	56	--
9 15	49	53	50	49	55	46	50	53	--
9 30	51	50	47	56	58	48	49	50	--

REPORT PREPARED ON 11 20 1981

TRAFFIC DATA SUMMARY REPORT

ATE: 11 18 1981 THRU 11 18 1981
AYS: WED
OLIDAYS: EXCLUDED
IME: 5:30- 9:30
ETECTORS: Q
ISPLAY MODE: TABLE

DIRECTION: SOUTH BOUND
INTERVAL: 15 MIN
DATA: VOLUME (VPH)

OC TIME	PEO	DUN	NOR	GLE	BET	CAM	IND	MCD	TST
5 45	219	227	139	103	95	83	60	315	--
6 0	339	343	323	207	151	203	187	451	--
6 15	375	271	287	207	231	180	155	420	--
6 30	643	607	443	227	275	335	187	587	--
6 45	703	759	627	435	399	347	303	687	--
7 0	711	583	503	463	555	447	435	755	--
7 15	575	459	447	471	379	411	351	639	--
7 30	699	571	503	475	503	439	431	660	--
7 45	671	603	575	467	543	515	463	683	--
8 0	543	623	515	595	527	551	531	647	--
8 15	571	443	360	399	411	483	480	531	--
8 30	575	567	483	427	411	323	287	543	--
8 45	563	647	475	315	323	219	235	519	--
9 0	775	531	480	300	259	251	219	447	--
9 15	767	463	459	287	219	291	187	507	--
9 30	535	503	351	255	180	223	203	551	--

REPORT PREPARED ON 11 20 1981
TRAFFIC DATA SUMMARY REPORT

ATE: 11 18 1981 THRU 11 18 1981
AYS: WED
OLIDAYS: EXCLUDED
IME: 5:30- 9:30
ETECTORS: Q
ISPLAY MODE: TABLE

DIRECTION: SOUTH BOUND
INTERVAL: 15 MIN
DATA: OCCUPANCY (%)

OC TIME	PEO	DUN	NOR	GLE	BET	CAM	IND	MCD	TST
5 45	3	3	2	1	1	1	1	4	--
6 0	4	5	5	3	2	3	3	6	--
6 15	4	4	4	3	3	3	2	7	--
6 30	8	10	7	3	4	5	3	8	--
6 45	8	13	10	7	6	5	5	10	--
7 0	9	9	8	7	17	6	12	10	--
7 15	7	8	7	8	6	6	7	9	--
7 30	9	9	9	7	8	6	10	10	--
7 45	8	11	11	8	14	7	12	11	--
8 0	6	10	11	16	10	9	54	8	--
8 15	7	7	5	6	7	8	54	8	--
8 30	7	10	8	7	6	5	6	10	--
8 45	7	12	8	4	5	3	4	8	--
9 0	9	8	7	4	3	4	3	7	--
9 15	9	7	7	5	3	4	3	9	--
9 30	6	8	6	4	2	3	4	9	--

REPORT PREPARED ON 11 20 1981

TRAFFIC DATA SUMMARY REPORT

ATE: 11 18 1981 THRU 11 18 1981
AYS: WED
OLIDAYS: EXCLUDED
IME: 5:30- 9:30
ETECTORS: Q
ISPLAY MODE: TABLE

DIRECTION: SOUTH BOUND
INTERVAL: 15 MIN
DATA: SPEED (MPH)

OC TIME	PEO	DUN	NOR	GLE	BET	CAM	IND	MCD	TST
5 45	30	24	24	23	24	23	18	30	--
6 0	33	25	23	27	25	27	20	27	--
6 15	31	25	25	26	24	24	22	24	--
6 30	32	24	25	28	25	25	22	28	--
6 45	33	24	25	25	24	27	21	28	--
7 0	30	24	24	25	13	27	14	29	--
7 15	32	23	26	22	23	27	19	29	--
7 30	31	24	23	25	25	27	17	26	--
7 45	33	22	20	24	15	27	15	24	--
8 0	32	23	18	15	20	24	4	30	--
8 15	30	25	25	25	22	24	3	24	--
8 30	31	23	24	25	25	25	17	22	--
8 45	31	21	24	27	26	25	23	25	--
9 0	33	25	25	27	27	25	23	24	--
9 15	33	24	25	20	22	25	19	22	--
9 30	34	23	23	24	25	24	20	24	--