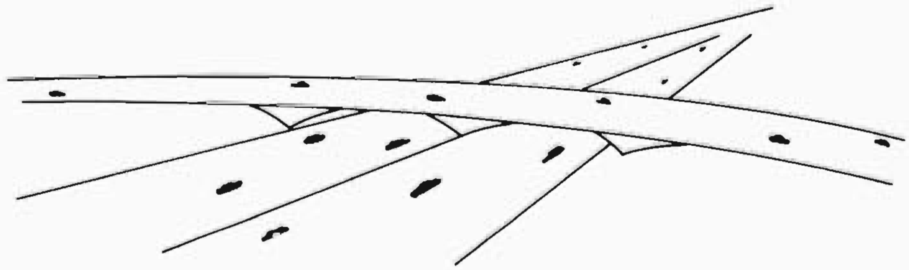

DEPARTMENTAL RESEARCH

Report Number SS 5.2

RECURRENT CONGESTION ON THE FORT WORTH WEST FREEWAY: ITS CAUSES AND REMEDIES

TEXAS HIGHWAY DEPARTMENT

RECURRENT CONGESTION ON THE FORT WORTH WEST FREEWAY: ITS CAUSES AND REMEDIES

by

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PREFACE

The automobile and the freeway system in the United States have given the American people a means of transportation few other people in the world will ever know or experience. Today the American motorist expects a facility to provide good service. However, on many urban freeways during peak periods, travel speeds are often no better than those experienced on major arterial streets. With today's understanding of freeway traffic flow, it is possible to remedy much of this congestion by placing some minor controls on the freeway system. This thesis is an attempt to prove this point on a freeway in Fort Worth.

The author would like to take this opportunity to express his gratitude to the many people that have given their time and encouragement during the preparation of this thesis. Many people within the Texas Highway Department, District 2, have been most helpful in discussing various aspects of this study.

The author is most grateful for the understanding, patience and support provided by his wife, Bonnie. Special thanks is offered for assistance in typing this thesis.

ABSTRACT

The traffic flow characteristics were evaluated on westbound I - 30 in Fort Worth during the afternoon peak period. The weaving movements were studied just upstream to the lane drop on this section of freeway. It was determined that weaving was not the cause of the recurrent congestion in this area. By closing two entrance ramps downstream from the lane drop, it was determined that the traffic entering at the second entrance ramp from Montgomery, produced most of the congestion. The demand placed on this two lane section is greater than capacity. The traffic entering the freeway from the Montgomery entrance ramp causes this excess demand, resulting in congestion. By closing this entrance ramp during the peak period, congestion can be eliminated and freeway speeds increased. It was also determined that the closing of an entrance does not insure better freeway flow conditions. The closing of the University entrance ramp did not produce better flow conditions. The diverted traffic traveled down the frontage road to the Montgomery entrance ramp and entered the freeway at this point. Congestion, similar to that with all ramps open, occurred when only the University ramp was closed.

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CHAPTER ONE

INTRODUCTION

A freeway system, composed of vehicles, their drivers and the roadway itself, represents many complex interactions between these various elements. This system can function either in a manner pleasing or annoying to the driver. A freeway system should provide a means of transportation that is rapid, safe and convenient. This is the expectation of every motorist. However, today in many metropolitian areas, many urban freeways fail to function as originally intended. There are many causes for this failure. These can be categorized into two basic classifications, the interaction of one vehicle with another and the interaction of the vehicle with the physical elements of the roadway.

When traffic volumes are low, the spacing or headway between vehicles is relatively large. Vehicular conflicts are infrequent or non-existent. As volumes increase the headways are reduced, thus the probability of vehicular conflicts increases. Each lane of a roadway has a limiting number of vehicles it can handle for any given time period. As the traffic volume increases, the average speed decreases until the volume reaches some maximum. Beyond this point, known as capacity, volume as well as speed will decrease. The end product is severe congestion.

Trucks have different and generally less favorable operating characteristics than smaller vehicles. Trucks by their very size and poor accleration characteristics produce a greater adverse effect on freeway flow than would an equal number of passenger cars. As the percentage of truck traffic increases, the capacity of the roadway decreases.

Another factor that can reduce capacity is what may be called maneuvering on the freeway. This can be entering or exiting traffic, weaving or lane changing. These types of maneuvers require additional space to be accomplished in a free flowing manner. This additional space requirement can be met by providing added lanes. If maneuvering becomes excessive, turbulence can develop resulting in further congestion.

The geometry of the freeway can affect the capacity. Lane width, lateral clearances, vertical and horizontal alignment have been studied in great depth and their effects on roadway capacity have been well documented. The main point that should be remembered is that each roadway by its very design has a limiting capacity. Under ideal conditions capacity has been established as 2,000 passenger cars per hour per lane in one direction (1).* Although most freeway designs today attempt to approach these ideal conditions, many older freeways have built-in deficiencies that produce a capacity something less than 2,000 passenger cars per hour.

Thus, there are many factors that affect freeway capacity. As volumes approach capacity, freeway flow becomes more sensitive to these factors. As

* Number in parentheses refer to references listed at the end of this report.

headways become reduced, there is less space and time for recovery from any detrimental effects that these factors may produce. When a freeway is operating near or at capacity this should be considered an unstable condition. Once freeway flow is interrupted even briefly, "stoppage waves" often develop. This often causes congestion to extend far upstream from the original interruption and recovery will not occur until there is a significant reduction in the demand, or "incoming vehicles".

When the flow of vehicles on a freeway approaches an unstable state, it may be necessary to place some type of controls on vehicles and motorists to insure that the freeway functions in an orderly and safe manner. Thus, freeway operation is described here as the manipulation and control of freeway vehicles in order to insure the orderly flow of traffic on freeways. In recent years much research has been conducted concerning the positive control of freeway traffic. This research (2, 3, 4, 5, 6) has shown that improved flow can be obtained by "operating" the freeway by controlling the amount of traffic on the freeway.

Freeway flow characteristics have been categorized in various "levels of service". Level of service is a qualitative measure of the effect of a number of the factors previously mentioned (1). There are six defined levels of service, "A" through "F". Level of service "A" denotes the best conditions, free flow, and level of service "F" identifies the worse driving conditions, stop and go traffic. Level of service "C" is considered acceptable and is the basis of most highway designs. Level of service "E" is either at or approaching capacity and is very unstable flow.

Since some older freeways are now operating at or near capacity level of service "E" during peak periods, it is particularly important to understand the various factors that affect the operational ability of the freeway. If one has an understanding of these factors, there are measures that can be implemented to increase the probability of safe and efficient operation. Often it is possible to improve freeway flow by imposing some minor restraints on the freeway operation.

The West Freeway, I-30, in Fort Worth is one of these older freeways that experiences a poor level of service, especially during the afternoon peak period. This freeway carries considerable truck traffic because this is the principal east-west freeway in Fort Worth. The westbound section, outbound, has thirteen ramps in a 2.5 mile length. This produces many freeway maneuvers. Because this is an older freeway, the vertical and horizontal alignment do not meet today's standards. The afternoon peak period produces a substantial volume of traffic. All of these factors in combination produce congestion each weekday afternoon.

CHAPTER TWO

FREEWAY PROBLEM SITE

OBJECTIVES

The scope and objectives of this study are as follows:

1. By using data collected for an existing freeway, determine the cause of congestion.
2. Determine alternative remedial measures based upon methods previously established.
3. Decide on one corrective measure that can be implemented with minimal cost on a temporary basis.
4. Implement this measure and compare actual results with those anticipated.
5. Based upon the study results, make final recommendations for solution.

PHYSICAL INVENTORY

The freeway selected for this study was the West Freeway, I-30, Fort Worth (Figures 1 and 2). Recurring congestion exists on the westbound lanes from Forest Park Blvd. to Clover Lane each weekday afternoon. This section was one of the first freeways constructed in Texas. It was designed in the mid-1940's and was opened to traffic in late 1951. This section has been classified as a First Generation Freeway (7). It has three twelve-foot lanes in each direction. There is a lane drop at the Montgomery exit ramp. From that point two twelve-foot lanes continue west. There is a raised median with eight

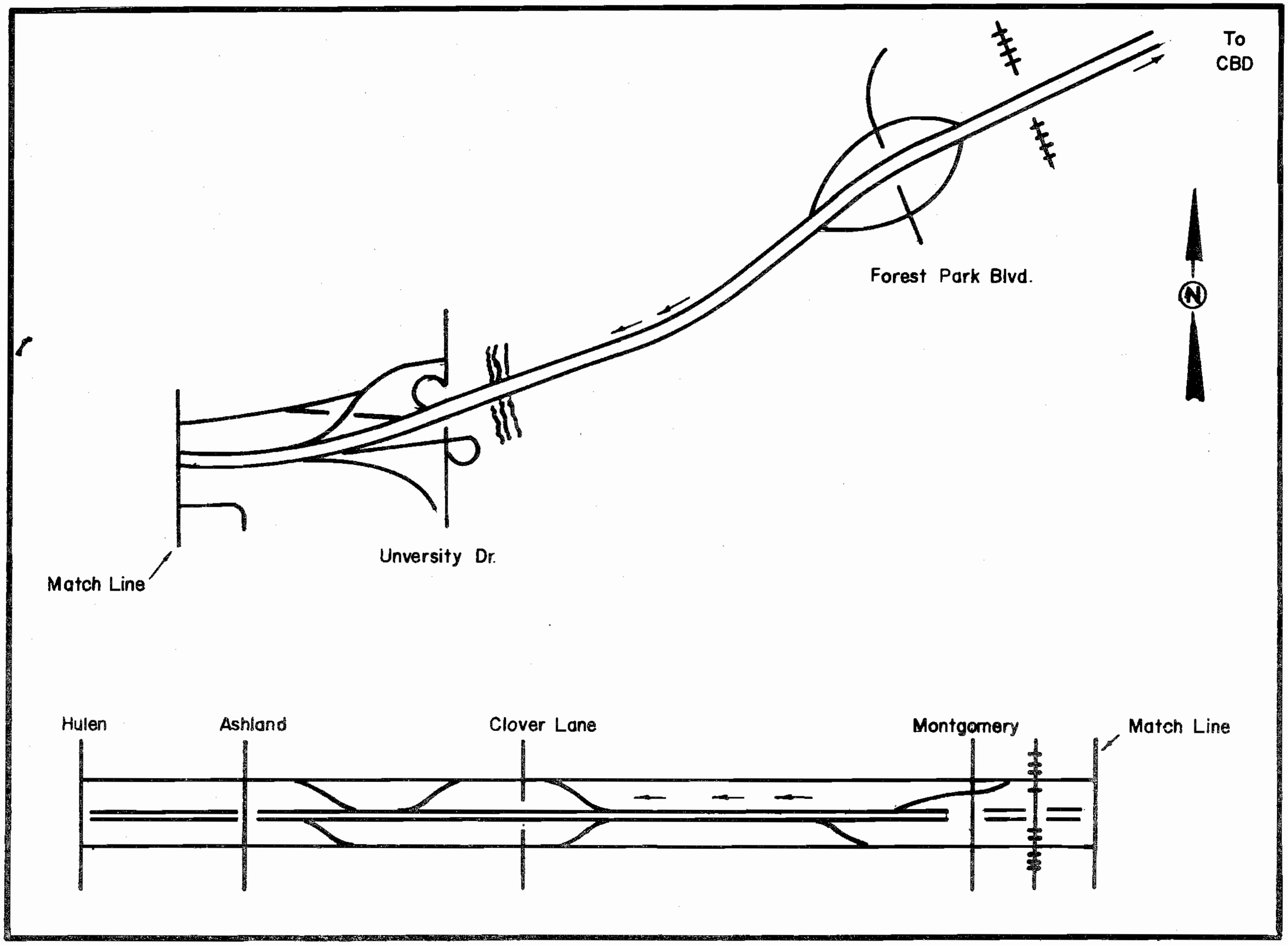

Figure 1: Schematic of I-30, West Freeway

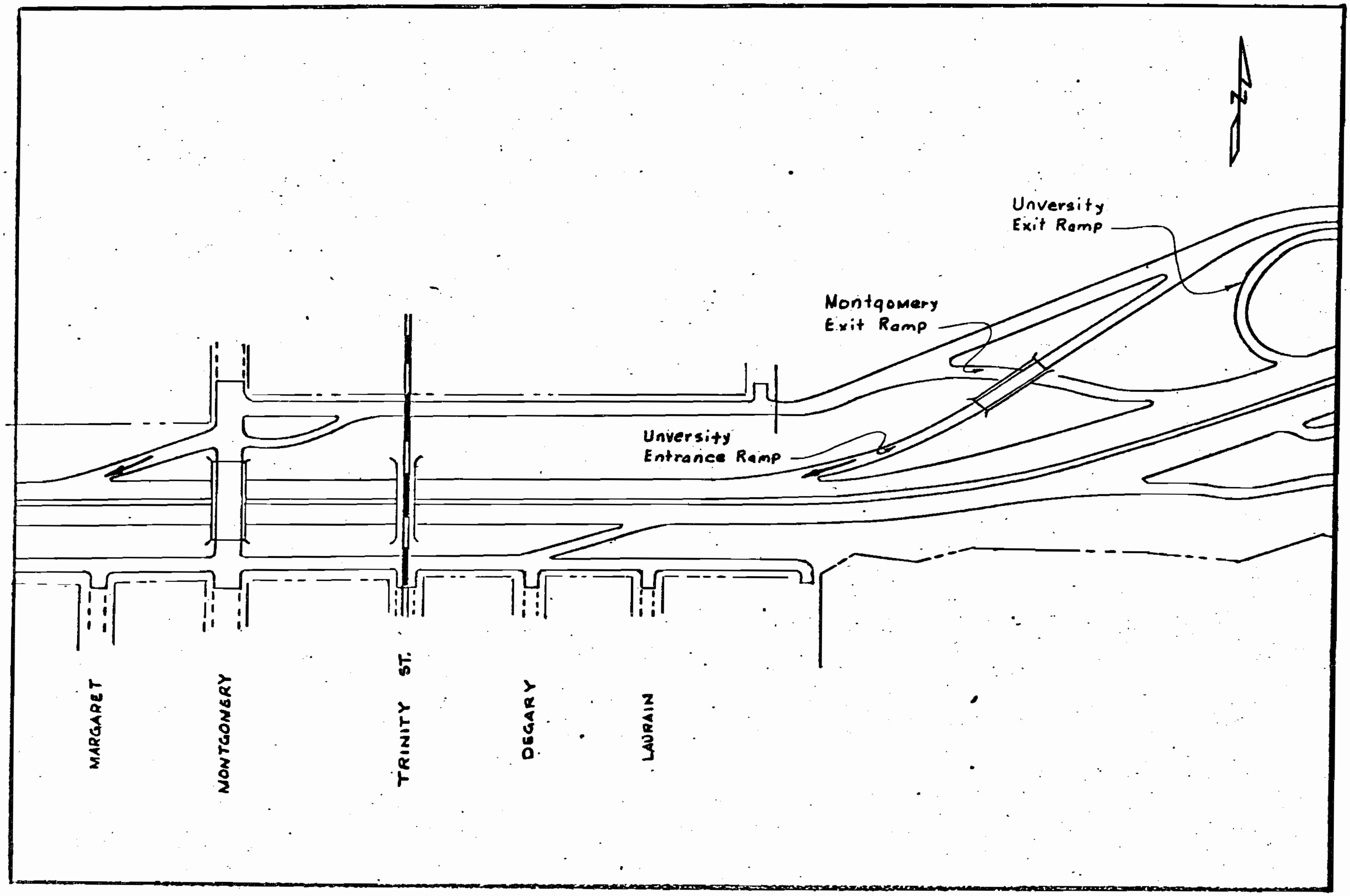

Figure 2: University and Montgomery Entrance Ramps

inch barrier curbs. The median width varies from 7.5 feet to 12.25 feet. Through lane vertical grades are limited to a maximum of four percent, which are less than 1000 feet in length. The maximum horizontal curvature is three degrees with 0.03 foot per foot superelevation. As originally constructed, entrance ramps had no acceleration lanes. Most of these ramps have been reconstructed to provide acceleration lanes. The right edge of the outside lane has a four inch mountable curb and a ten foot shoulder. Frontage roads exist, but they are not continuous.

REASONS FOR SELECTION OF SITE

There were several reasons for selection of this freeway section for study. As mentioned, recurrent congestion occurs each weekday afternoon. Congestion lasts approximately one hour. Congestion extends from Montgomery back to a point east of Forest Park Blvd. Although this freeway was designed some thirty years ago, for most hours of the day it functions without undue congestion. Although it has been recognized for the past few years that improvements are needed, no major reconstruction could be scheduled in the near future which could increase capacity. Therefore, there existed a need to determine what the exact causes of this congestion were and to implement some type of remedial measure to reduce or relieve this congestion.

The West Freeway serves the west and southwest portions of Fort Worth. This is one of the most rapidly developing regions of the city. This development continues to cause traffic volumes to increase. A permanent hourly traffic counter has been in operation for several years just east of Montgomery on the four lane freeway section. As can be seen in Figure 3, the average annual daily traffic (both directions) has increased in all years except 1971. Figure 4 shows that traffic on the two westbound lanes from 5 to 6 P. M. has increased to approximately 3,000 vehicles per hour and maintained that level for the last three years. It was anticipated that this pattern would maintain itself for the next several years because the recurrent congestion that exists limits the volume of traffic that this freeway section can handle.

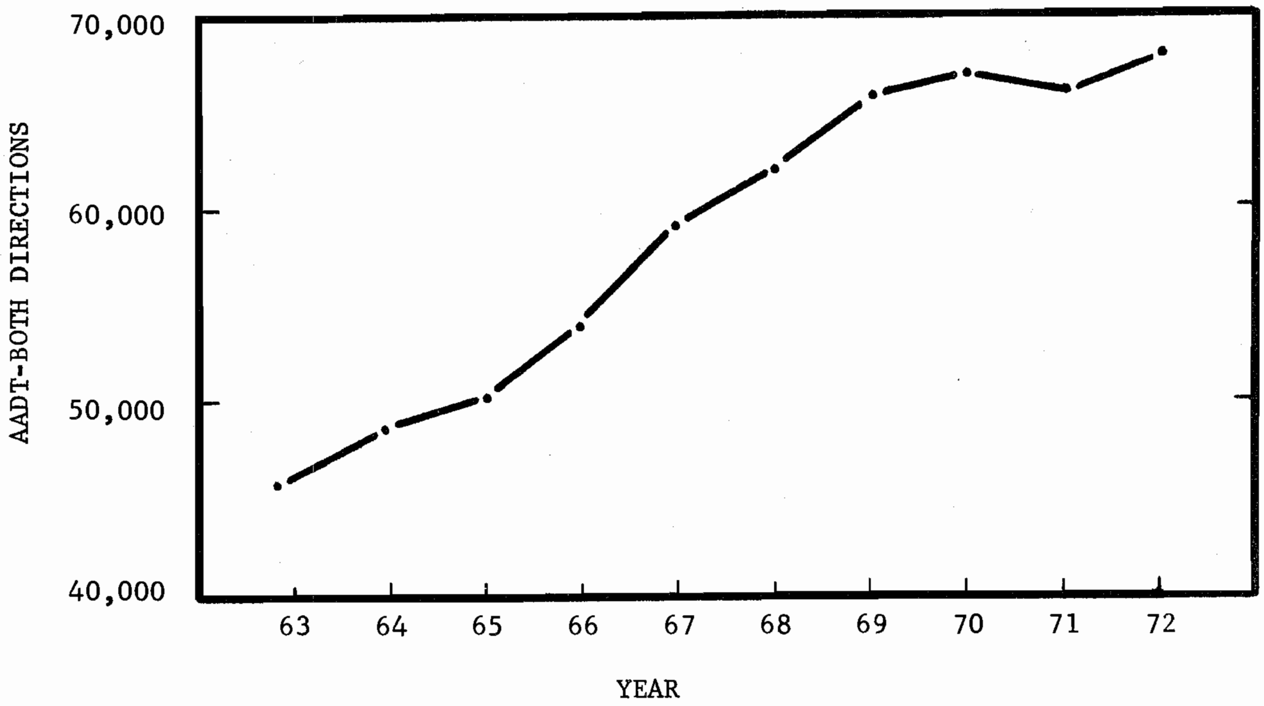

Figure 3: AADT on I-30, Two Lanes Each Direction

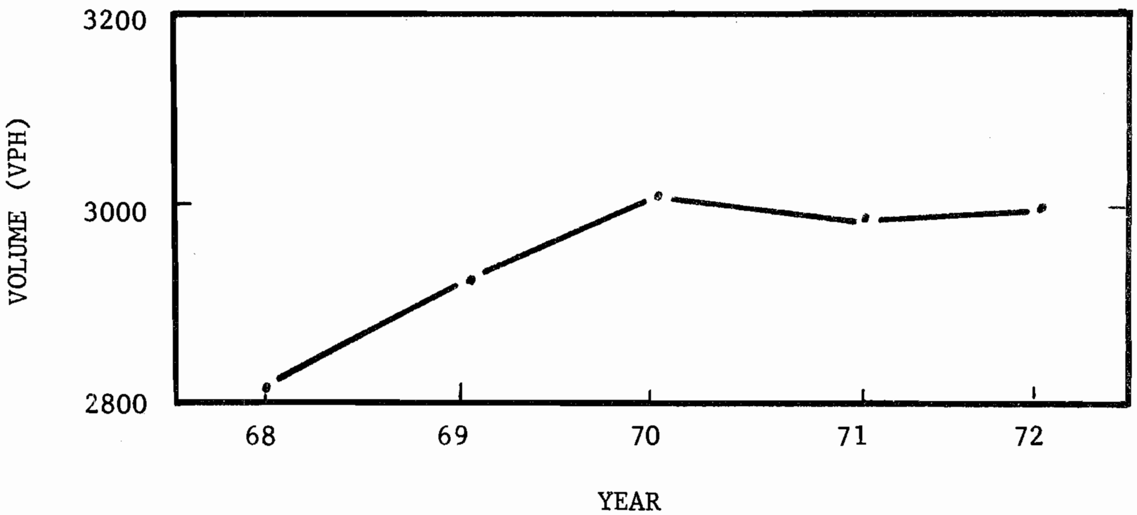

Figure 4: Average 5-6 PM Westbound Traffic, Two Lanes Upstream of Montgomery Entrance Ramp

CHAPTER THREE

REMEDIAL MEASURES TO BE IMPLEMENTED

EVALUATION OF EXISTING CONDITIONS

On Wednesday June 6, 1973, a traffic count was conducted on the West Freeway. The count was from 4 to 6 P.M. and flow rates were recorded at five minute intervals. The counts were made at the Forest Park Blvd., University, and Montgomery westbound entrance ramps. Individual lane and ramp counts were made at each of the three locations. No speed study was conducted on this day. Serious congestion began at about 4:40 and ended at approximately 5:32 P.M. There were no observed incidents such as accidents or stalled vehicles, that hindered traffic flow.

One of the first things discovered was that during this peak period of flow the Montgomery entrance ramp had a higher volume than the University entrance ramp. Twenty-four hour counts had shown University to have the heavier volume of the two ramps. Thus, the Montgomery entrance ramp had a higher K-factor, which is the peak hour traffic volume divided by the average daily traffic. The volume data collected is shown in Table 1 along with ADT at these locations.

Using methods outlined in the Highway Capacity manual, the capacity was calculated for the two-lane freeway section. The most significant reduction factor encountered in the calculations was that due to the truck traffic. From a previous

TABLE 1

TYPICAL VOLUMES ON WESTBOUND WEST FREEWAY

LOCATION	No. of Vehicles 4:30-5:30	No. of Vehicles 4:00-6:00	ADT-1972	K-Factor
Forest Park Blvd. Ent. Ramp	592	1,099	5,260	11.3
University Ent. Ramp	214	423	3,440	6.2
Montgomery Ent. Ramp	290	423	2,680	10.8
Forest Park Blvd. 3 Freeway Lanes + Ramp	4,527	8,221	43,820	10.3
University Drive 2 Freeway Lanes + Ramp	3,206	6,047	35,190	9.1
Montgomery 2 Freeway Lanes + Ramp	3,474	6,563	37,870	9.2

traffic count, it had been determined that there were about five percent trucks in a twenty-four hour period. During the afternoon peak period there were only three percent trucks, thus, three percent was used for calculation of capacity. The calculated capacity was 3, 640 vehicles per hour. Using this as the base, the various service volumes were computed. The results of these calculations are included in Table 2.

TABLE 2

SERVICE VOLUMES FOR THE TWO LANE SECTION OF THE WEST FREEWAY

Level of Service	Maximum Volume (PHF=. 88)	Maximum Volume (PHF=1. 0)
A	1, 275 vph	1, 275 vph
B	1, 820 vph	1, 820 vph
C	2, 400 vph	2, 730 vph
D	2, 880 vph	3, 276 vph
E	3, 640 vph	3, 640 vph

The peak hour factor is defined as the ratio of the whole peak hour volume to the highest rate of flow occurring during a five minute interval within the peak hour expanded to an hourly flow (1). The PHF when applied to the calculated service volumes takes into consideration the peaking effects of traffic within the hour when only hour volumes are used. The PHF in the Montgomery and University area averaged 0.88. Calculations based on a PHF of 1.0 were made to determine what the expanded peak five minute flow rates could ultimately be at the various service volumes.

A plot of the observed five minute flow rates expanded to hourly volumes versus time was made for the area just downstream of the Montgomery entrance ramp after the ramp traffic had merged with the freeway traffic. This volume included both through lanes and the ramp itself, which is shown in Figure 5. Also shown are the service volumes. Two points of interest are depicted in Figure 5. First, this section of freeway is operating in level of service "E" for seventeen of the twenty-four five minute time periods counted. For approximately one hour, the level of service should actually be considered "F" due to the high density and low travel speeds. Also, the best operating level of service was "C" during this two hour period. The second interesting point is that this plot shows the calculated capacity was close to the maximum volume actually measured during this day. Only one five minute time period showed an expanded flow rate greater than the calculated capacity.

From visual observations, the initial congestion seemed to first develop just west of Montgomery and then it backed upstream from that point. There appeared to be no erratic lane changing immediately upstream of the lane drop at the Montgomery exit ramp. It was assumed that most of the traffic entering the freeway at the Forest Park Blvd. entrance ramp desired to travel past the Montgomery exit. If this were true, there would be considerable weaving required in this area which would contribute to some of the congestion observed.

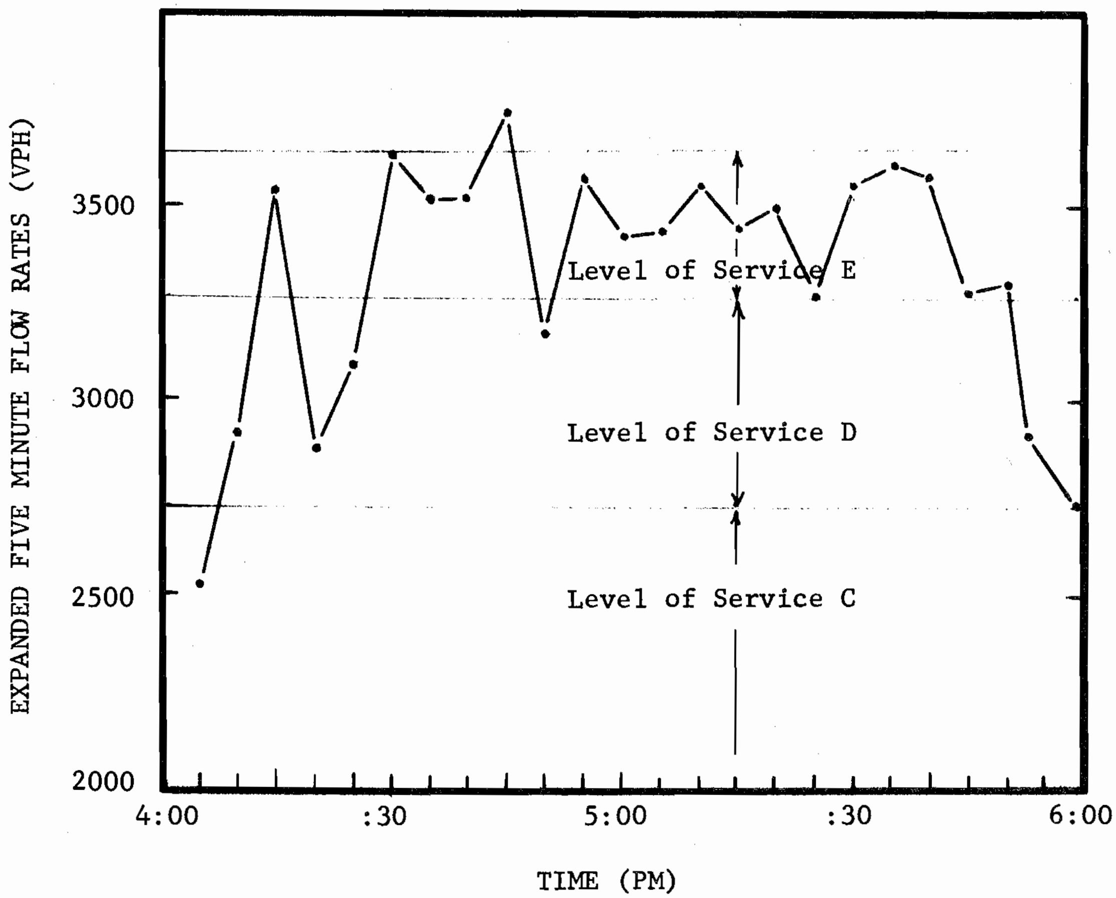

Figure 5: Expaned Five Minute Flow Rates Downstream of Montgomery Entrance Ramp

The highest traffic volumes are obtainable on freeways when traffic is moving in a fluid, orderly manner. This highest level of traffic flow can be maintained only if no interference occurs in the traffic stream to cause the large volume to "break speed" and thus result in a volume reduction. As volumes increase on a freeway, average headways (between vehicles) also become reduced. Eventually a state of flow is reached in which average headways are so small that when any small interference occurs there is not enough "elasticity" in the traffic stream headways to permit sufficient adjustment without causing a speed reduction to other traffic. This set of circumstances creates what is known as a "shock wave" (2).

Since the initial congestion appeared to begin just downstream from the Montgomery entrance ramp, an analysis was made of this section. Figure 6 shows a plot of flow rates versus time. The lane one plus ramp volumes indicate a merging level of service of "D" or "E" for one hour. Level of service "C" is the best that was ever obtained in the two hour counting period.

Entrance ramp vehicles are one of the greatest causes of disturbance in through lanes. When vehicles enter a freeway, they will merge into a gap between other vehicles, but they will not maintain this close merging distance. The vehicle that has just entered a freeway will slow down to provide a greater gap between itself and the preceding vehicle. Thus, as more and more vehicles enter the freeway during these peak periods of freeway flow, there results a general slow down on the freeway. If the total volume is great enough, subsequent

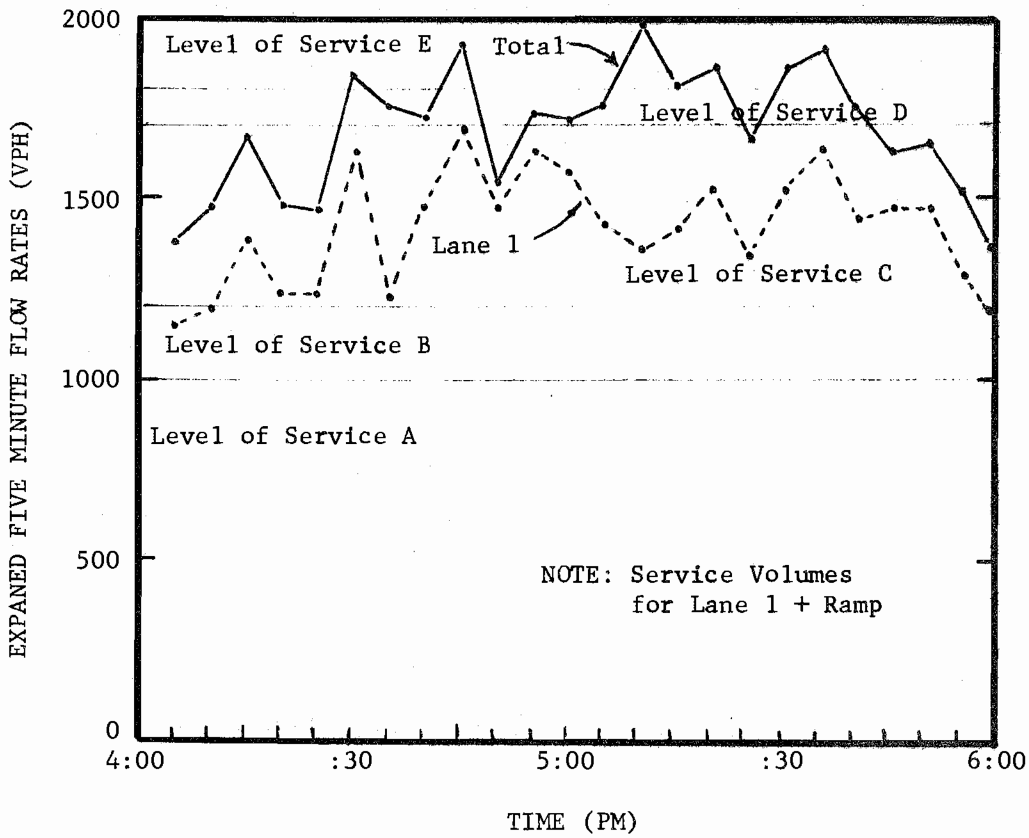

Figure 6: Lane One Plus Ramp Traffic at Montgomery Entrance Ramp

stoppages often occur on the through lanes (2).

The through lane (Figure 5) and ramp (Figure 6) calculations show that this section of freeway is operating at or near capacity. Most freeways cannot operate at capacity for any appreciable length of time. Eventually some "incident" will occur that causes a breakdown. Once this breakdown occurs, the freeway can never fully recover until the demand is greatly reduced. Such a situation appears to be what was happening on the West Freeway and especially in the vicinity of the Montgomery entrance ramp. Thus, the basic problem in this freeway section appeared to be that of demand being greater than capacity.

From both visual observations and a rudimenty analysis of the freeway count, there seemed to be two major problems on this freeway. First, demand was greater than capacity for one section of this freeway. It did not appear to be caused by the lane drop at the Montgomery exit. Shock waves or congestion never originated from this point. Downstream from this lane drop there are two entrance ramps on to the freeway before there is an exit ramp. The first entrance ramp, University, did not appear to cause any problems. The initial shock waves started in the area of the Montgomery entrance ramp. It appeared that the second problem, based solely on visual observations, was that caused by weaving traffic between Forest Park Blvd. and the lane drop, a distance of some 2,700 feet.

The traffic count on June 6 did not provide enough information to adequately determine if the foregoing observations truly represented the nature of the problem. It was thus necessary to conduct a more thorough study of this freeway section and at the same time institute some temporary remedial measure and determine its effectivness.

POSSIBLE REMEDIAL MEASURES

There are basically two remedial measures available for any congested freeway; reduce the demand or increase the capacity. The two most obvious ways to increase capacity on this freeway are to add a lane to the freeway or to eliminate all truck traffic. Neither of these options were available. To reduce demand on the freeway itself, motorists must be persuaded, in some manner, to use an alternate route or to use the freeway at some time other than the peak period. Ramp closure for a specific time period and ramp metering can accomplish the latter.

SELECTION OF MEASURE TO BE IMPLEMENTED

The choices available on a temporary basis were either ramp metering or ramp closure. Since ramp closure would produce a much more dramatic impact on freeway flow patterns and would require less cost, it was decided to use this measure. From past research (4, 5, 6) ramp closure had proven an effective tool in reducing freeway congestion. Also, this measure would force all ramp traffic to use the existing city street system. This would provide the opportunity to visually determine how well the street system could handle this additional traffic.

The study consisted of two separate parts. The first part concentrated on the weaving movements between Forest Park Blvd. to the lane drop at the

Montgomery exit. The second part of the study concentrated on the freeway section downstream of the lane drop. Flow rates and speeds were the principal factors studied.

The ramps selected for closure were the Montgomery and University entrances to the freeway. Closure was to be Monday through Friday from 4:30 P. M. to 5:30 P. M. Due to the heavy volume of traffic on the Forest Park Blvd. entrance ramp and since there was no good alternate route for most of these motorist, it was decided not to include this ramp in this phase of the study.

There were several reasons for selecting the Montgomery and University ramps for closure. There is a continuous frontage road from University to Montgomery. From Montgomery there are several city streets that parallel the freeway. The reduction of the impact from the two ramps during the peak hour was expected to raise the level of service for this section of freeway as demonstrated in Figure 7 which shows the expected volumes with the ramps closed. Also, by the closure of these two ramps, any problems associated solely with the lane drop could better be determined.

The ramp closings were to cover a three week period. During the first week, only the Montgomery ramp was closed. The second week both ramps were closed. During the last week, the Montgomery ramp was opened and only the University ramp closed. By sequencing the closings, it was anticipated that it would be possible to determine the different effects under various conditions.

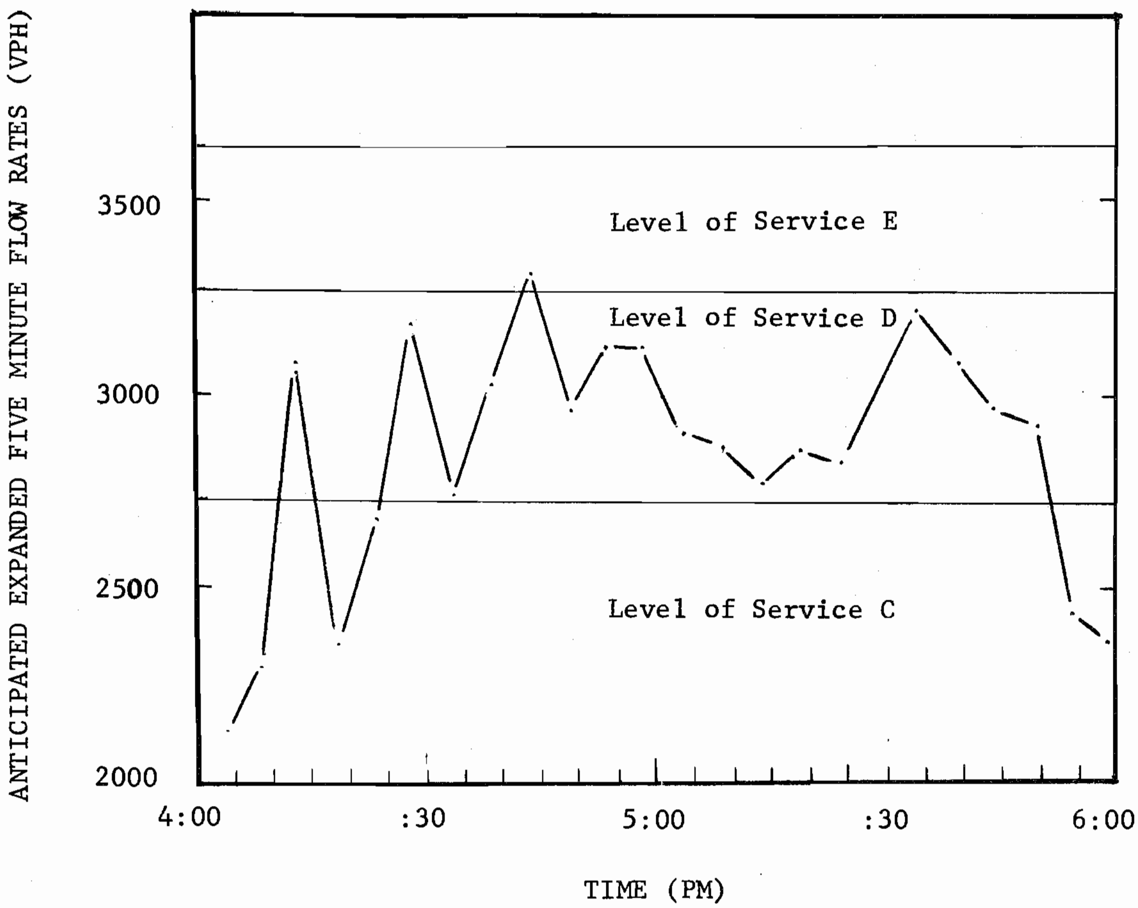

Figure 7: Anticipated Expanded Five Minute Flow Rates Downstream of Montgomery Minus Inputs From Montgomery and University Entrance Ramps

PUBLIC NOTICE OF PROPOSED CHANGES

In order to reduce the inconvience to motorists, an extensive publicity campaign was conducted by the Texas Highway Department the week prior to the beginning of the study. News releases were sent to local newspapers, radio and television stations describing the purpose of the study and especially the locations and times for ramps to be closed. Both Fort Worth daily newspapers carried the story, in addition to the four major television stations in the area. As a final measure, a brochure was prepared giving a schedule of ramp closures with a map showing possible alternate routes. This brochure was distributed to motorists using the ramps to be closed on the Friday afternoon prior to the first closing on the following Monday. Motorists were asked to call the Texas Highway Department if they experienced any excessive delays.

CHAPTER FOUR

METHODS USED TO MEASURE TRAFFIC CONDITIONS

The ramp closure study phase was made during a four week period in August. The first week of the study concentrated on existing conditions; no ramps were closed during this period. Of primary interest during this week was the study of the weaving movements between Forest Park Blvd. and the lane drop, a distance of about 2,700 feet (Figure 8).

Several field methods were considered in attempting the study. Time-lapse photography was rejected due to the expense and the tedious manual work required in reducing the data. The license plate method (8), which involves the recording of license numbers of those vehicles entering on the ramp and recording at some point further downstream, was rejected due to complexity and time required to reduce the data. A modification of the "lights-on" study technique (9) was rejected because of suspected poor driver compliance with this method. In this method motorists are asked to turn their headlights on as they enter the freeway. These ramp vehicles are counted on a five minute interval. Further downstream, in our case the area of the lane drop, an observer would note which lane or ramp was used by the "lights-on" vehicles. This information would also be recorded on five minute intervals.

The method finally decided upon was the interview method (8). This method gave the maximum amount of information with the least amount of data

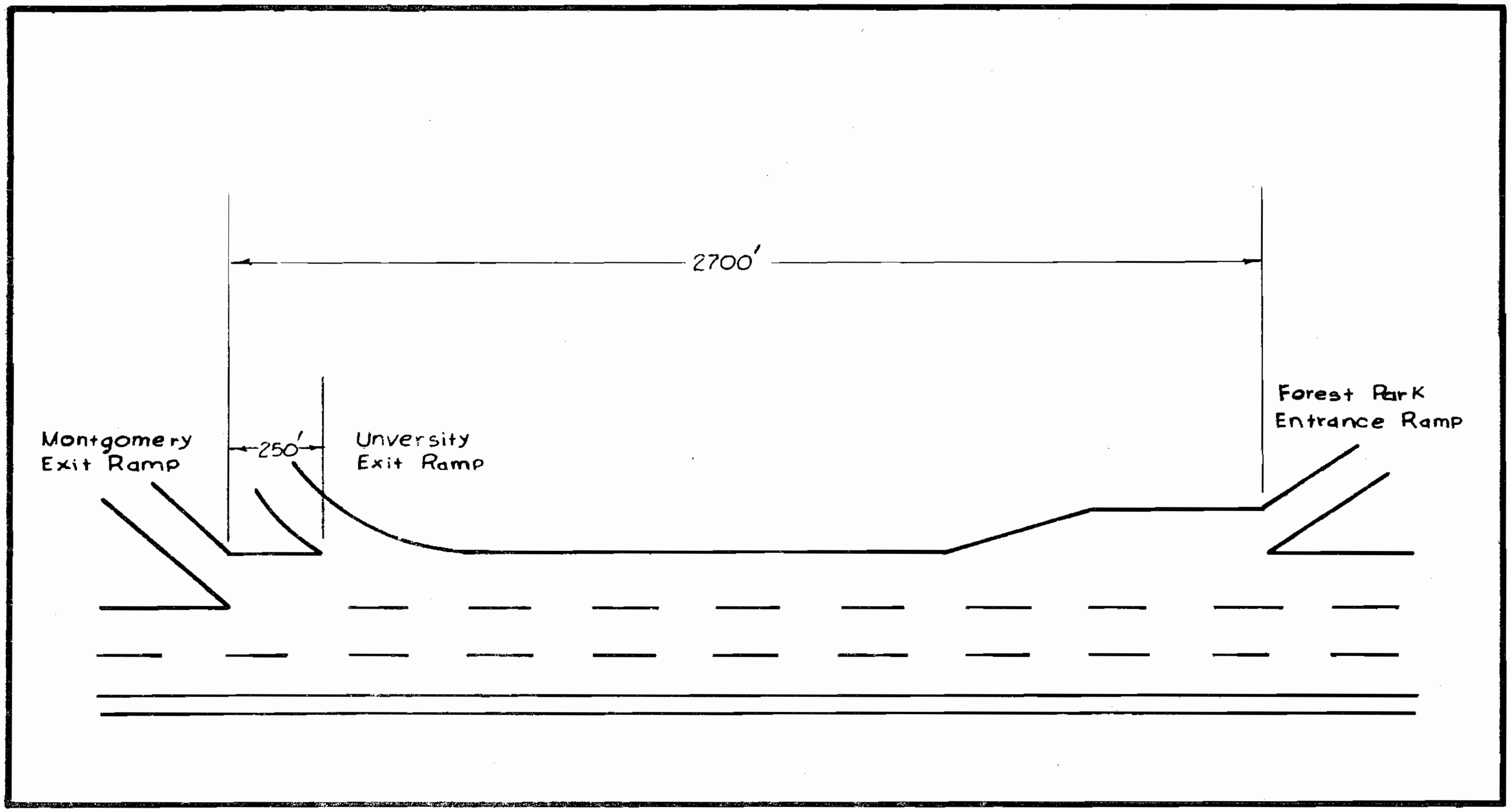

Figure 8: Section Between Forest Park Blvd. and Montgomery Exit Ramp

reduction. Motorists entering the westbound Forest Park Blvd. entrance ramp were stopped before they entered the freeway. Three motorists could be interviewed at a time. The interview consisted simply of asking, "What exit are you going to take when you leave the freeway?" Only the first six exits were tabulated. Any exit further west than Camp Bowie was listed as OTHER. About 88% of the motorists using this ramp from 4-6 P.M. were interviewed. If traffic began to back up into the intersection, motorists were waved through until the intersection was cleared.

The principal focal point of the interviews was the determination of the number of vehicles entering at Forest Park Blvd. and exiting at either University or Montgomery. These motorists are required only to make a merging maneuver. The remainder of the motorists entering at Forest Park Blvd. wished to travel further down the freeway, in other words, past the lane drop. These motorists are not only required to merge with lane one traffic, but also must make a weaving maneuver before they reach the lane drop, a total distance of 2,700 feet.

While the interviews were being conducted, there were four other counts being conducted. The number of vehicles entering the Forest Park Blvd. ramp was recorded at five minute intervals. The lane one flow rates were tabulated at the nose of this ramp. Also, the University and Montgomery exit ramps were counted on five minute intervals.

It was planned to conduct all volume studies on Wednesday of each of the four weeks of the study. The volume counts were made at the University, Montgomery and Clover Lane entrance ramps, which included individual freeway lane counts and ramp counts at each location (Figure 9). Just downstream from the Clover Lane entrance ramp is the Ashland-Hulen exit ramp. The distance from the nose of the entrance to the nose of the exit ramp is approximately 460 feet. Since it was predicted that much of the diverted traffic would be using this entrance ramp, it was decided to include this ramp in the traffic counts. Also, while at this location, the Ashland-Hulen exit ramp volume was counted. Two men were placed at the University entrance ramp, two at the Montgomery ramp and three at the Clover Lane ramp. Individual through lane flow rates as well as the ramp flow rates were tabulated on five minute intervals. Data were collected from 4-6 P. M. All volume data were collected on Wednesdays, except during the last week. On that Wednesday an accident occurred at about 4:20 P. M. Counting was ceased shortly thereafter. This count was then conducted the next day. It had been decided beforehand not to do any traffic counts on rainy days or if any incident occurred that would disrupt traffic flow.

Speed data were collected by use of a Tachograph Model TCO-15-6-03. This is a speed recording instrument mounted in a vehicle. It plots speed versus time. This instrument also marks each 0.05 mile on the graph. Each disc records for twenty-four minutes, and there is a seven disc capacity. Thus, this instrument can record continuously for two hours and twenty-four minutes. The instrument is also equipped with an "event" marker which enables the driver to place a mark on the graph as he passes pre-determined reference points. A typical recorded disc is shown in Figure 10.

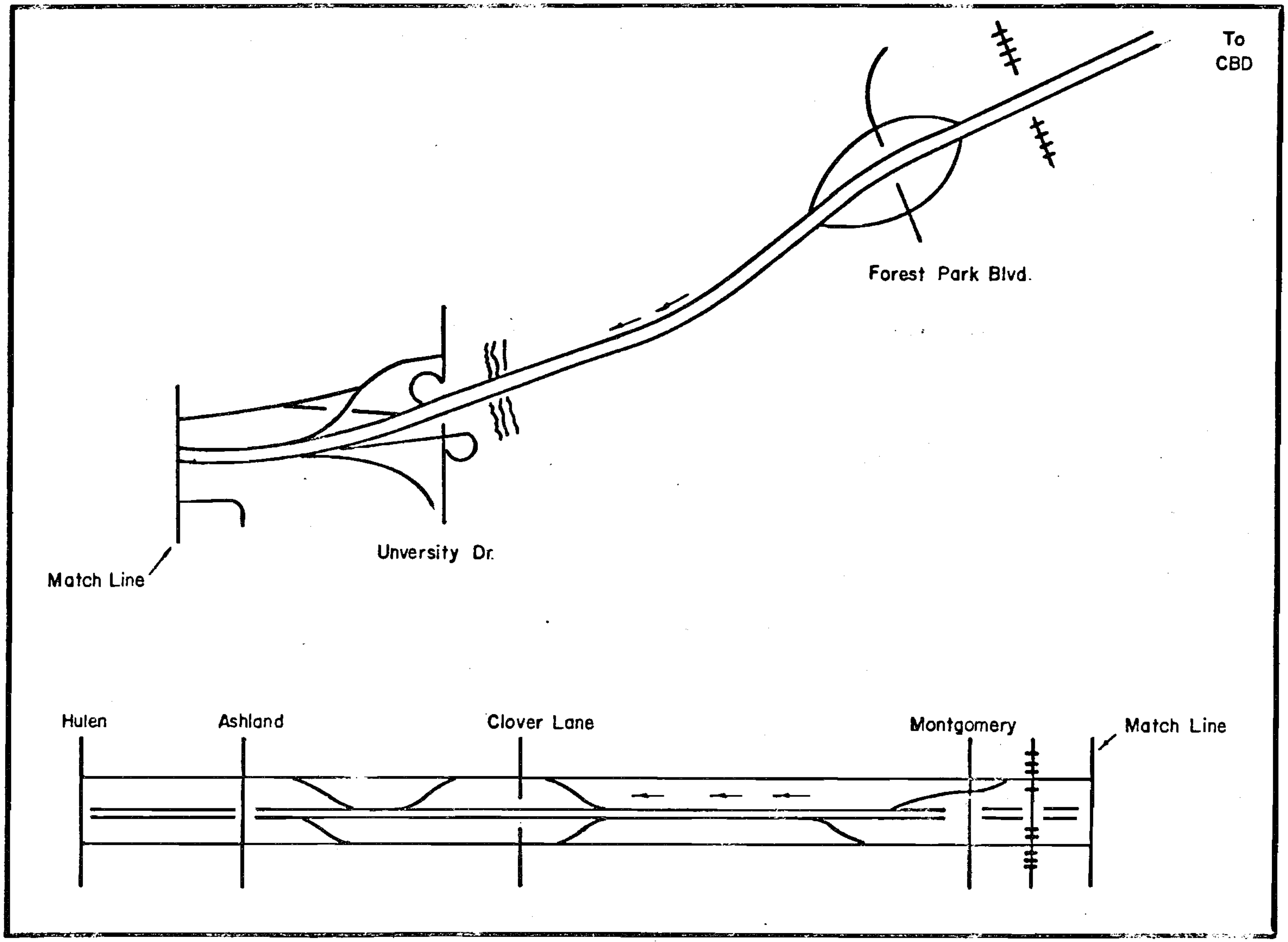

Figure 9: Schematic of West Freeway

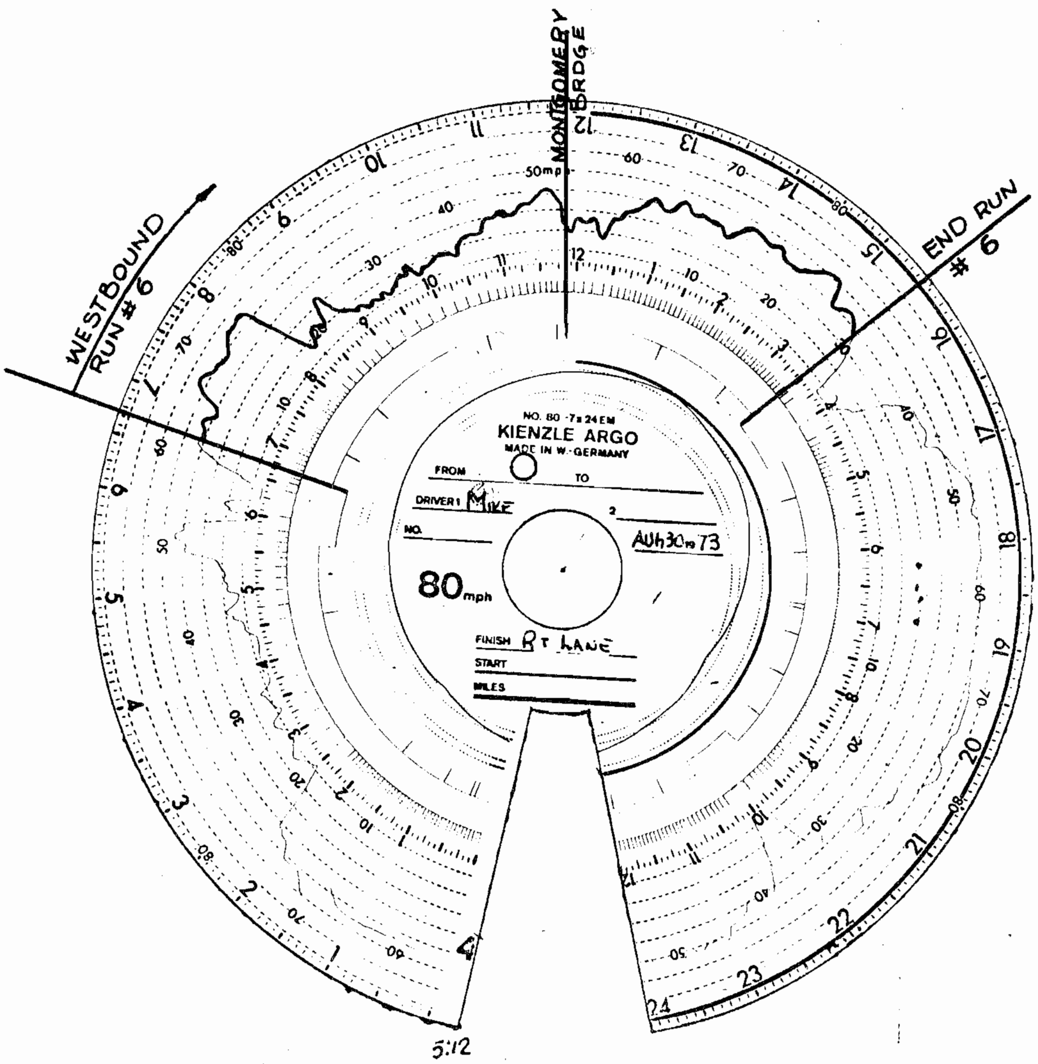

Figure 10: Typical Tachograph Recording Disc

Speed runs were conducted on Wednesdays and Thursdays of each week using two vehicles equipped with tachographs. Speed runs were started just east of Henderson Street and ended at Horne, a distance of approximately 4.6 miles. Each vehicle made runs in separate lanes on the freeway. Speed runs were made in the median lane and center lane (which becomes the right lane at the Montgomery exit). Runs were started at 4:00 P.M. and continued at fifteen minute intervals until 6:00 P.M. There were nine check points along the freeway at which the drivers marked the tachograph discs as they passed by. These speed plots were used to make speed contour maps of the West Freeway for each of the four weeks.

Video tapes were made during the last two weeks of the study, the week that both the Montgomery and University entrance ramps were closed and the week in which only the University ramp was closed. Most of these tapes were made from a bucket truck in the general vicinity of the Montgomery and University ramps. The bucket on this particular truck was elevated to a height of approximately seventy feet above the ground.

The tapes were made primarily for the purpose of demonstrating to various groups the results of the ramp closures. However, some data were collected using these tapes. Volume and speed data were collected from some selected tapes.

CHAPTER FIVE

ANALYSIS OF STUDIES

TRAFFIC MOVEMENTS BETWEEN FOREST PARK BLVD. AND THE MONTGOMERY EXIT RAMP

Using the data collected on June 6 and August 7, 1973, the level of service for the merging maneuver at the Forest Park Blvd. entrance ramp was computed. On both of these days, the peak hour for lane one and the ramp was from 4:30 - 5:30 P. M. Table 3 gives these volumes.

TABLE 3

PEAK PERIOD TRAFFIC AT FOREST PARK BLVD. ENTRANCE RAMP

	Peak Hour Volume			Peak Five Minutes		
	Ramp	Lane 1	Total	Ramp	Lane 1	Total
6 June '73 (Wed)	592	978	1570	65	91	156 (1872)
7 Aug. '73 (Tues)	555	945	1500	53	99	152 (1824)

In any description of levels of Service, "D" or "E", the effect of short-term fluctuations in volume must be taken into consideration (1). Thus, for these levels of service either the volume for the total hour with the appropriate peak hour factor or the peak five minute expanded volume can be used to compute level of service. Since flow rates were tabulated at five minute increments, it seemed appropriate to compute the level of service for this ramp based on the peak five minute volume. According to the Highway Capacity Manual (1), the upper limit for level of service "D" expanded from the peak five minutes is 1,800 vph. The upper limit for level of service "E" is 2,000 vph. Thus, the level of service, based on the merge volume, at the Forest Park Blvd. entrance ramp was "E" on both days.

Following the origin and destination (O and D) study on the Forest Park Blvd. entrance ramp, that data along with the data previously collected in June, were compiled in an effort to determine the weaving movement volumes that take place between this ramp to the lane drop, a distance of about one-half mile.

An attempt was made to compute the level of service for this weaving section. Due to the geometrics of this particular freeway section, in particular the lane drop, there is no direct method of computing level of service. Figure 11 is a schematic showing the minimum number of maneuvers possible. It is assumed that all those motorists in Lane 1 at the Forest Park entrance ramp are going to exit at either the University or Montgomery exit ramp. It is realized that this assumption is not entirely valid. There is some weaving that certainly takes place that is not shown in Figure 11. Most motorists are aware of the lane drop because they make this trip every day. Thus, it can be assumed that most motorists are in their desired lane by the time they reach Forest Park Blvd. Also, from the limited data available there is no way of determining anything but the minimum number of maneuvers possible between Forest Park Blvd.

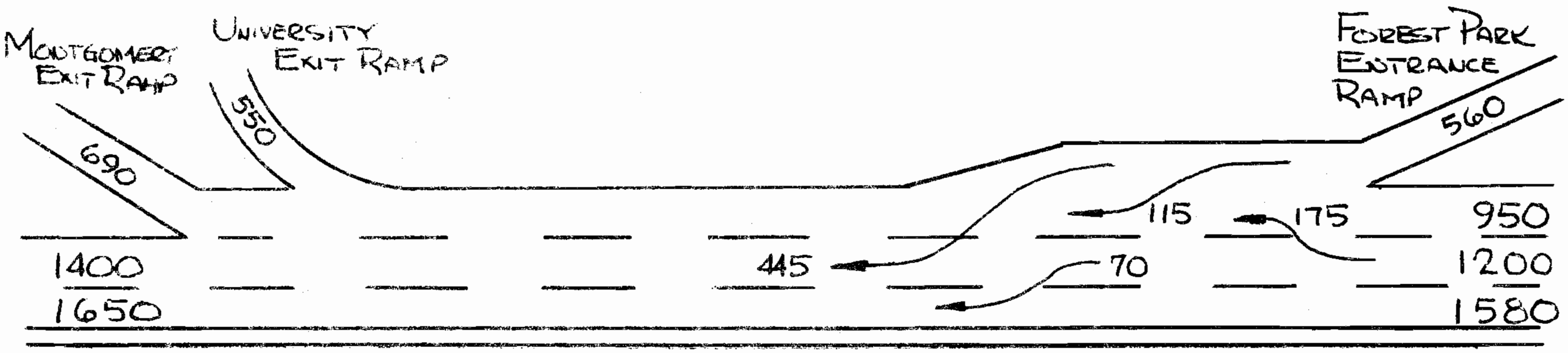

Figure 11: Typical Volumes During the Peak Hour and Possible Manuvers Between Forest Park Blvd. and Montgomery Exit Ramp.

and the lane drop. Anything more than the maneuvers shown would only worsen the level of service.

From Figure 11 the following data is available :

Length of weave	=	2, 500 feet
Total Volume	=	4, 290 vph
Total weaving volume	=	620 vph

Because this amount of weaving traffic is so small, this freeway section is "out of the realm of weaving". There would need to be approximately 1, 100 weaving vehicles for weaving to begin to effect the operation of the freeway in any significant manner.

Since weaving in this section does not appear to be the most critical factor, the best approach to evaluating this section of freeway appeared to be determining the individual level of service for each lane immediately down-stream of the Forest Park Blvd. entrance ramp, before any appreciable amount of weaving can take place, and just upstream of the University exit ramp, after most weaving has occurred. An analysis of the lane volumes at the above two locations gives the results shown in Table 4. The level of service for any lane at either location is either "D" or "E". The level of service across all three lanes was at the upper limits of "D". All of this is without considering any weaving. Any weaving or lane changing would only worsen the level of service.

TABLE 4

LANE VOLUMES AND LEVEL OF SERVICE

	Immediately after Forest Park Ramp Merge		Immediately upstream of Lane Drop	
	Volume	Level of Service	Volume	Level of Service
Lane 1	1580	E	1650	E
Lane 2	1200	D	1400	D
Lane 3	1510	E	1240	D
All Lanes	4290	D		

SPEED ANALYSIS

Freeway traffic flow was substantially improved by the closing of the Montgomery and the Montgomery and University entrance ramps. With the closing of just the University entrance ramp, little improvement was detected. The reason for this being that virtually all traffic using this ramp traveled down the frontage road to the Montgomery entrance ramp and entered the freeway there. The results of this caused congestion similar to that experienced prior to any of the ramp closings.

Speed contours (Figures 12-15) provide a means of representing average travel speeds over an extended length of freeway for the peak period. With all the ramps open, average speeds dropped below 15 MPH at about 5:15 in the vicinity of Montgomery to Forest Park as shown in Figure 12 . With the closing of the Montgomery entrance ramp, the lowest average speeds were just less than 25 MPH as shown in Figure 13 . With the closing of both entrance ramps, there was only

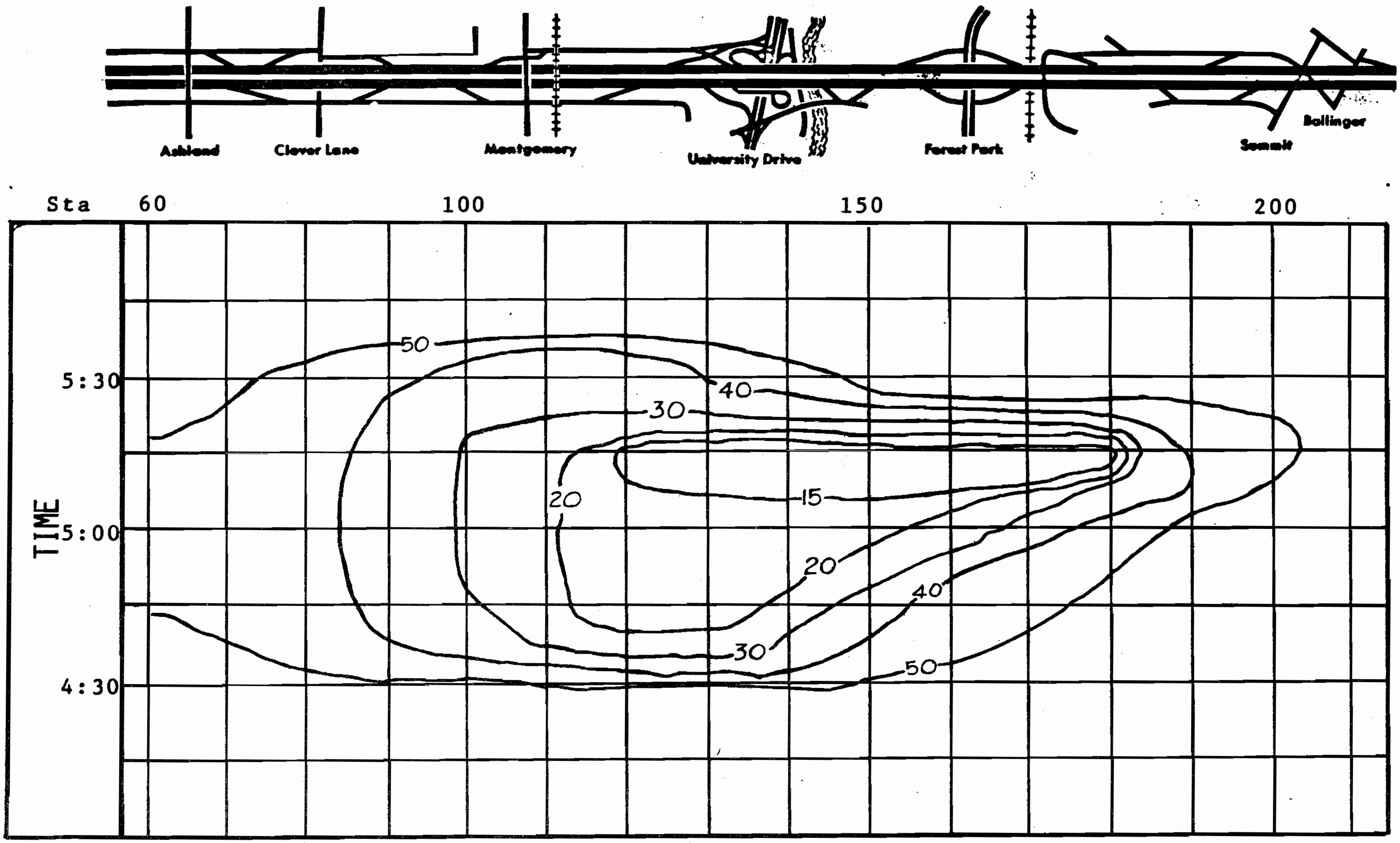

Figure 12: Speed Contours of West Freeway, Westbound With All Ramps Open

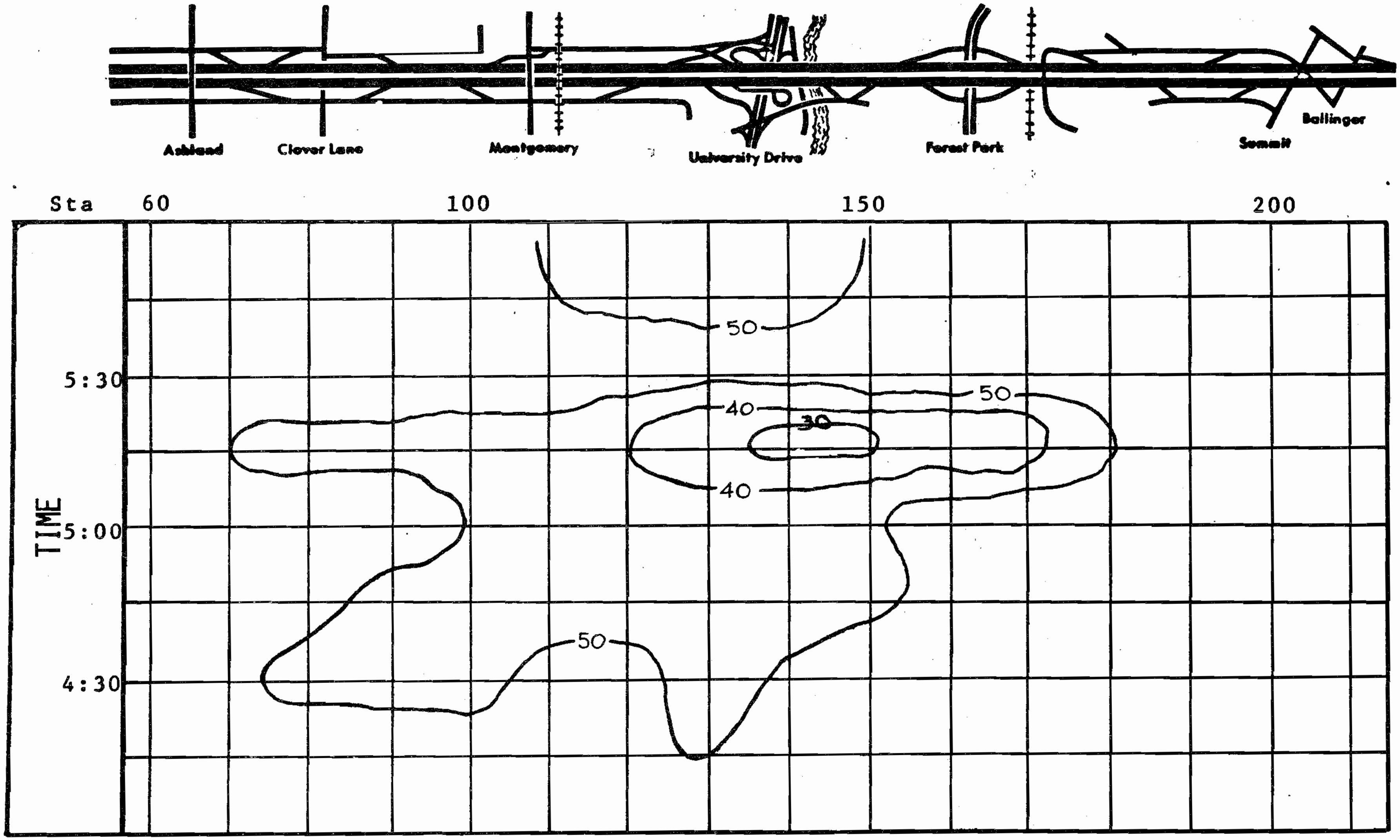

Figure 13: Speed Contours of West Freeway, Westbound With University and Montgomery Entrance Ramps Closed.

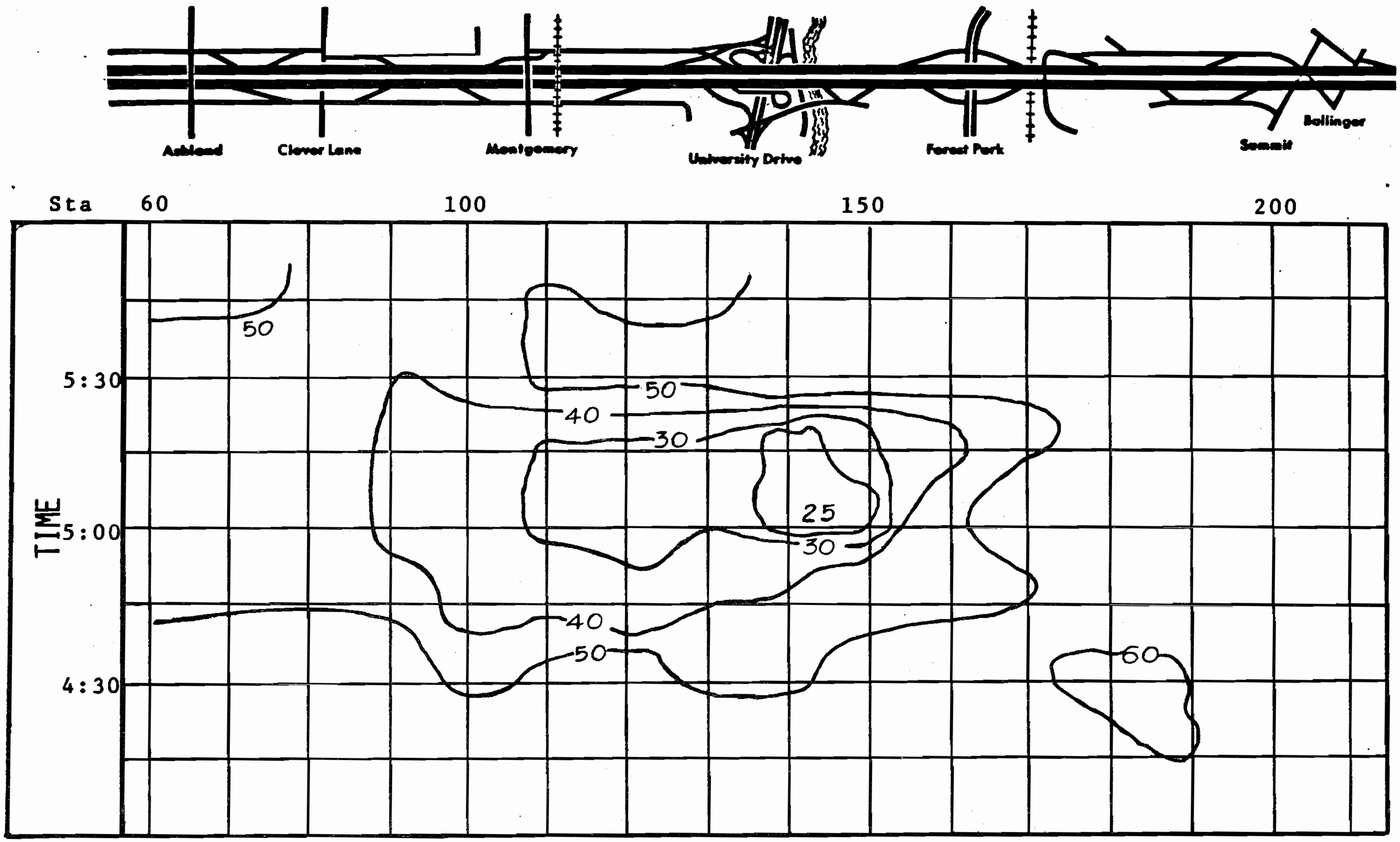

Figure 14: Speed Contours of West Freeway, Westbound With Montgomery Ramp Closed

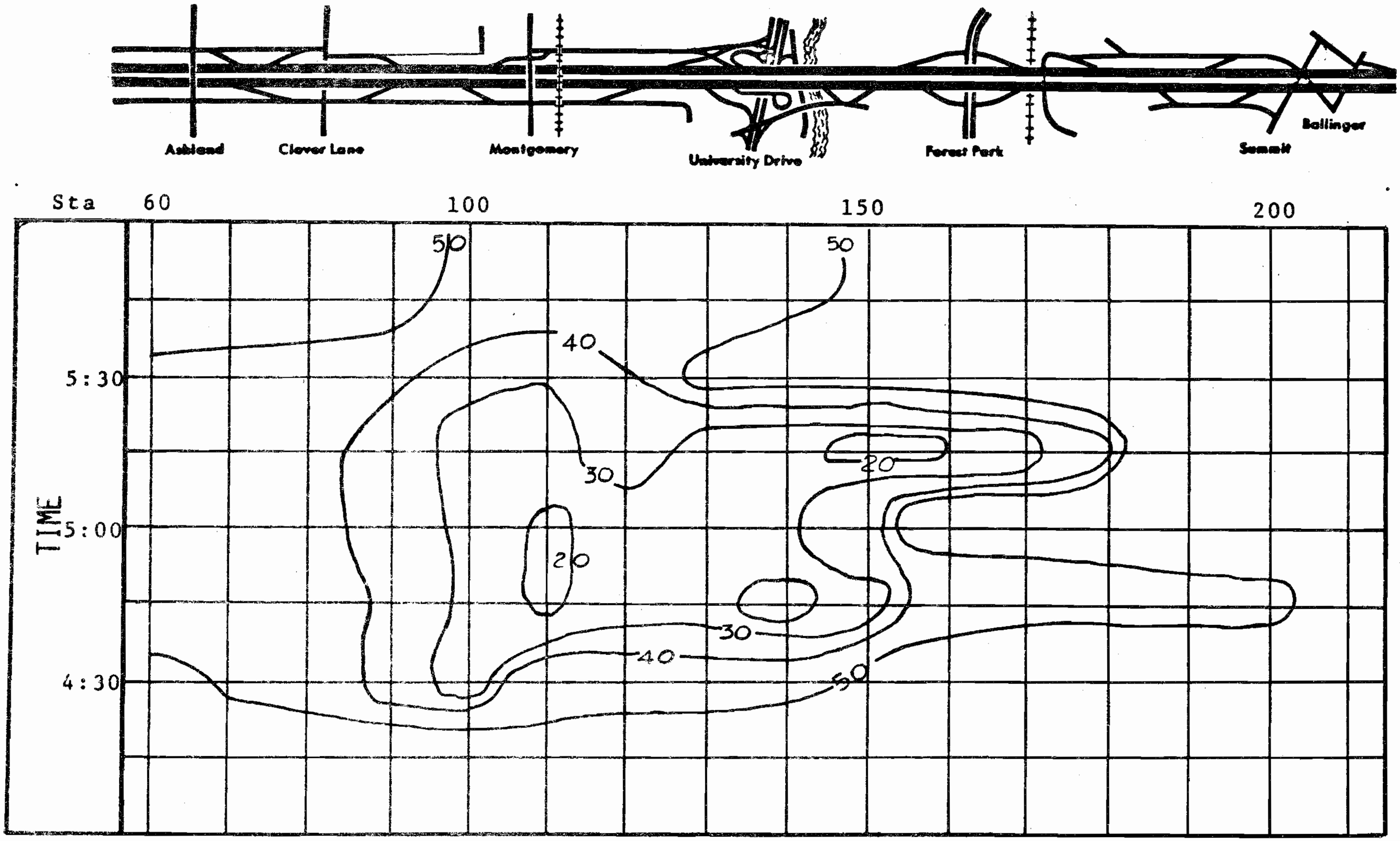

Figure 15: Speed Contours of West Freeway, Westbound With University Entrance Ramp Closed.

a short time period in which average speeds dropped below 30 MPH, which is shown in Figure 14. During the week of the University entrance ramp closing, speeds dropped to below 20 MPH for short periods of time and stoppage waves again appeared as shown in Figure 15. One point should be noted concerning the closure of both the University and Montgomery entrance ramps. During the week of this closure, freeway speeds were relatively high on all sections of the freeway for most of the peak period. The one exception to this was in the area downstream of the Forest Park Blvd. entrance ramp (Figure 16). Since the usual stoppage waves were not interfering with the traffic flow in the vicinity of the Forest Park Blvd. entrance ramp, the only reason offered for the slow down in this area was due to the high input of traffic from this ramp attempting to maneuver into the center lane before reaching the lane drop. This resulted in speeds dropping below 30 MPH for approximately ten minutes (Figure 13).

Speed contours provide an excellent means of representing speed characteristics over an extended length of freeway for any given period of time. As a means of comparing changes in speed characteristics over the same freeway section, speed contours have limitations. The only means of comparing two different set of speed contours is by making a visual comparison. In an effort to quantitatively represent the different speed characteristics for each week of the study, the area within the 30 MPH and 40 MPH contours was determined. The area within any speed contour has units of time-distance, in this case hours-miles. The larger the area of any given contour the greater the time and/or the greater the distance of speeds equal to or less than the value of the given speed

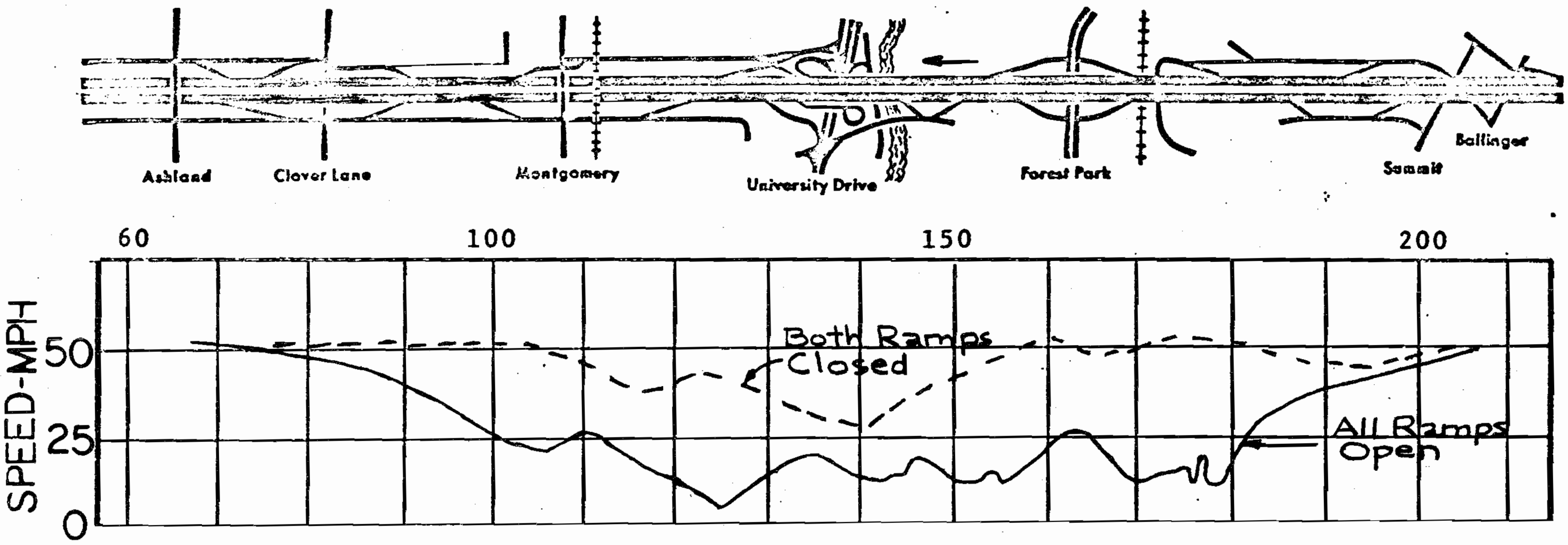

Figure 16: Typical Speeds on the West Freeway, Westbound

contour. Thus, smaller areas within a slow speed contour represent better flow characteristics. It should be noted that only areas within the same speed contour can be used for comparison. Areas within 30 MPH contours can only be compared to other areas within a 30 MPH contour. A comparison of the area within a 30 MPH contour to the area within a 40 MPH contour has little or no meaning.

Since the unit of hours-miles is not too meaningful in itself, the area within the 30 MPH and 40 MPH contours for the week in which both the University and Montgomery entrance ramps were closed may be used as a base equal to one. Thus, as can be seen in Table 5, the area within the 30 MPH contour is 7.7 times larger for the week when all ramps were open as compared to the week when both ramps were closed. This indicates there was significant improvement in freeway flow conditions with these two ramps closed for the peak hour.

TABLE 5

SPEED CONTOUR COMPARISON

Area Within Speed Contour (HR-Miles)

Speed Contour	All Ramps Open	Montgomery Closed	Both Ramps Closed	University Closed
30 mph	.92	.32	.12	.73
40 mph	1.51	.83	.21	1.33

During the week of the University ramp closing, little improvement was noted. Stoppage waves were a common occurrence. Video tapes were made on Tuesday, August 27, of the area in the vicinity of the Montgomery entrance ramp. Shortly after the University ramp was closed, the traffic diverted from this ramp began appearing on the Montgomery entrance ramp. From the video tape, one minute traffic counts and average speeds were calculated (Table 6). Congestion developed in a matter of two or three minutes due to a sudden increase in the flow rate of the through lanes as well as increase on the entrance ramp. This increase in the flow rate caused average speeds to drop from 50 MPH to below 30 MPH. Stoppage waves began occurring within four minutes from the initial slow down.

This particular incident offered a graphic example of the exact cause of congestion in this situation. Capacity for this section of freeway is approximately 3,640 vph. After the total flow rate exceeded this amount for a minute or two, speeds began to drop. The flow rate of the through lanes was less than capacity, but the input from the ramp caused the total flow rate to exceed capacity. The peak five minutes in this time resulted in a flow rate equivalent to 3,720 vph. Although a freeway can operate above capacity for short periods of time, this is an unstable condition. With the input of ramp traffic in this section, there is enough turbulence to cause the traffic flow to bread down. Drew (11) has stated that when the traffic volume reaches capacity of a bottleneck, velocities in the bottleneck are much less than that upstream of the bottleneck. A further increase in volume results in queuing just upstream of the bottleneck. This is almost a daily occurrence on the West Freeway. Congestion develops initially at the

TABLE 6

ONE MINUTE FLOW RATES AND SPEED
AT MONTGOMERY ENTRANCE RAMP

ENDING TIME	RAMP	RIGHT LANE		LEFT LANE		TOTAL
	EXPANDED VOLUME (VPH)	EXPANDED VOLUME (VPH)	AVERAGE SPEED (MPH)	EXPANDED VOLUME (VPH)	AVERAGE SPEED (MPH)	EXPANDED VOLUME (VPH)
4:28	180	1260	53	1380	57	2820
4:29	180	1440	53	1320	56	2940
4:30	600	1140	52	1560	58	3300
4:31	480	1440	49	2040	58	3960
4:32	480	1680	35	1740	39	3900
4:33	600	1260	30	1560	30	3420
4:34	780	1320	24	1680	34	3780
4:35	480	1560	23	1500	31	3540
4:36	540	900	-	1500	-	2940

Montgomery entrance ramp and the queue often extends as far as Summit Avenue, a distance of 1.6 miles (Figure 12). With the closing of the Montgomery entrance ramp, such congestion failed to develop.

Total travel time measurements within a freeway section provide a means to compare various operating conditions. Total travel time is the product of volume times travel time within a system. The total travel time is thus related to the speed analysis. Total travel time within the freeway system for the four phases of the study is shown in Table 7.

TABLE 7

TOTAL TRAVEL TIMES (VEH-HRS) FROM 4:30 - 5:30

	All Ramps Open	Montgomery Closed	Both Ramps Closed	University Closed
FREEWAY TRAFFIC	242	196	151	227
TRAVEL TIME FOR DIVERTED TRAFFIC	8	18	32	10
TOTAL SYSTEM TRAVEL TIME	250	214	183	237
VEH - HRS OF DELAY AS COMPARED TO WHEN BOTH RAMPS CLOSED	67	31	--	54

The ramp closing produced higher average freeway speeds, thus reduced trip times for freeway motorists. The ramp closings caused the motorists using these ramps to seek alternate routes. This produced longer trip times for these motorists. The trip times for the diverted ramp traffic were obtained by making trial runs on assumed alternate routes during closure periods. Even though trip times were increased for the diverted ramp traffic, the total system experienced a reduction in travel time. This means of evaluating the ramp closings compares similarly to that of the speed contour comparison (Table 5). Delay was greatest when all ramps were opened. The Montgomery closing showed significant improvement, but the closing of both ramps resulted in the most improvement. The University closing showed less improvement. Based on a cost of $4.50 for each vehicle-hour of delay (10), approximately $300 per day could be saved by closing both the Montgomery and University entrance ramps from 4:30 to 5:30 P.M. This represents an annual savings to motorists of approximately $75,000. Thus, even though some motorists were prevented from entering the freeway at their normal point of entry, the entire system experienced a significant improvement.

VOLUME ANALYSIS

The comparison of peak period volumes offers many insights into what effect ramp closure had on the freeway. Tables 8 and 9 show the peak hour volumes and the peak two hour volumes respectively. Table 10 gives a comparison of through lane volumes at three locations during each of the various ramp closure schemes. These percentages of the change in freeway flow are based on freeway volumes prior to any of the ramp closures. As can be seen, in the area

TABLE 8

VOLUMES FROM 4:30 TO 5:30 PM

	All Ramps Open		Montgomery Closed	Both Ramps Closed	University Closed
UNIVERSITY	JUNE 6	AUG 8	AUG 15	AUG 22	AUG 30
Ent. Ramp	214	233	234	3	0
Lane 1	1360	1319	1458	1424	1408
Lane 2	1632	1569	1705	1681	1569
Freeway Total	2992	2888	3163	3105	2977
Total	3206	3121	3397	3108	2977
MONTGOMERY					
Ent. Ramp	290	292	27	26	466
Lane 1	1470	1456	1632	1501	1449
Lane 2	1714	1670	1860	1702	1599
Freeway Total	3184	3126	3492	3203	3048
Total	3474	3418	3519	3229	3514
CLOVER LANE					
Ent. Ramp		98	196	228	120
Lane 1		1534	1562	1416	1534
Lane 2		1711	1809	1679	1770
Freeway Total		3245	3371	3095	3304
Total		3343	3567	3323	3424
Exit Ramp		274	316	320	258

TABLE 9

VOLUMES FROM 4:00 TO 6:00 PM

	All Ramps Open		Montgomery Closed	Both Ramps Closed	University Closed
UNIVERSITY	JUNE 6	AUG 8	AUG 15	AUG 22	AUG 30
Ent. Ramp	423	441	482	218	232
Lane 1	2511	2498	2637	2623	2615
Lane 2	3113	2940	3229	3202	3095
Freeway Total	5624	5438	5866	5825	5710
Total	6047	5879	6348	6043	5942
MONTGOMERY					
Ent. Ramp	517	474	226	182	672
Lane 1	2754	2775	2960	2812	2850
Lane 2	3292	3262	3467	3262	3180
Freeway Total	6046	6037	6427	6074	6030
Total	6563	6511	6653	6256	6702
CLOVER LANE					
Ent. Ramp		177	287	324	214
Lane 1		2970	2905	2799	2951
Lane 2		3261	3357	3291	3436
Freeway Total		6231	6262	6090	6387
Total		6408	6549	6414	6601
Exit Ramp		583	622	649	614

TABLE 10

PERCENT CHANGES IN FREEWAY VOLUMES AS COMPARED TO WHEN ALL RAMPS WERE OPEN

Percent Change In Peak Volume	Montgomery Ramp Closed	Both Ramps Closed	University Ramp Closed
Just Upstream of University Ramp	+7.6%	+8.6%	+1.3%
Just Downstream of Montgomery Ramp	+2.1%	-6.3%	+2.0%
Just Downstream of Ashland Exit	+5.9%	-2.2%	+3.2%

just upstream of the University entrance ramp there were large increases in the volumes of this two lane section during the first and second weeks of the ramp closings. These increased volumes were in addition to the higher speeds previously mentioned. The higher volumes were possible because congestion failed to develop and the freeway was able to operate with a demand just less than capacity for an extended length of time.

The only actual decreases in volume were observed during the week when both entrance ramps were closed. These decreased volumes were downstream of these two entrance ramps. This reduced volume can be attributed to the fact that approximately 500 vehicles were diverted from this section of freeway.

During the week of the University ramp closure, the through lane volume upstream of the University ramp showed only a slight increase in volume. The principal reason for such a small increase in volume was because congestion once again developed on the freeway causing reduced speeds as well as reduced volumes. These various volumes can be best explained by use of Figure 17, which shows the relationship of levels of service to operating speed and volume/capacity ratio. Point 1 is typical of the condition when all ramps were open or when the University ramp was closed. In level of service "F", speeds are low and volumes are below capacity. Queues of vehicles are backed up on the freeway (1). Point 2 is typical of freeway conditions when the Montgomery and University ramps were closed, speeds increased and volumes increased. Even though freeway flow was improved, the freeway was still operating in level of service "E", which is an

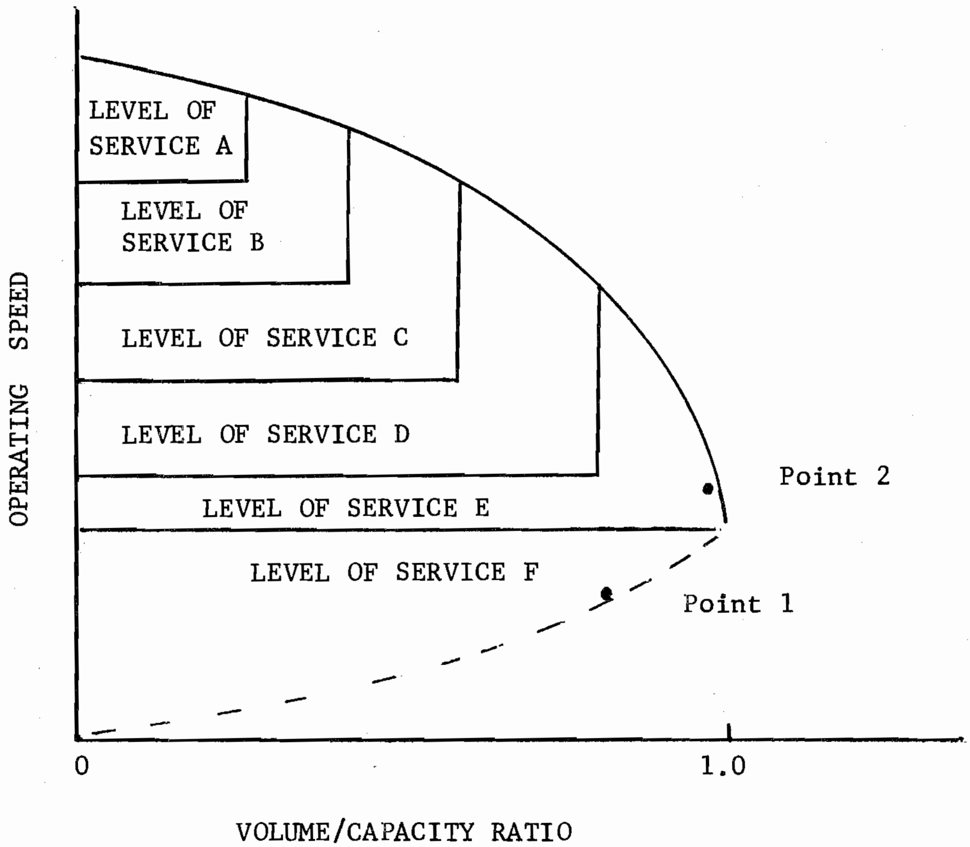

Figure 17: General Concept of Relationship of Level of Service to Operating Speed and Volume Capacity Ratio. (Taken from Highway Capacity Manual, 1965.)

unstable condition. Table 11 shows the levels of service during the four week study period in the vicinity of the Montgomery and University entrance ramps. The fact most apparent is that the best level of service obtained was "E". Even though this could not be considered good, it was a definite improvement when one considers that previously traffic flow in this area had been stop and go as level of service "F".

No attempt was made to quantitatively analyze the effect on the adjacent street system during the ramp closings except that the Clover Lane entrance ramp, the first downstream entrance ramp from Montgomery, was included in the traffic counts. The peak hour volumes of the Clover Lane ramp indicated that some of the diverted traffic entered the freeway at this point. As can be seen in Table 8 during the Montgomery ramp closure, the Clover Lane entrance ramp increased from 98 vph to 196 vph. This increase did not account for all of the 290 vehicles diverted during this hour. During the week of the closing of both the Montgomery and University entrance ramps, the peak hour volume for the Clover Lane ramp increased even more. Again, this left approximately 360 vehicles not accounted for. With the opening of the Montgomery entrance ramp, virtually all of the University ramp traffic proceeded down the frontage road and entered the freeway on the Montgomery ramp.

There are several possibilities as to what happened to those diverted vehicles that did not enter the freeway at the Clover Lane entrance ramp. Due to the advance publicity of the ramp closings, many motorists knowing of the

TABLE 11

LEVEL OF SERVICE, BASED ON VOLUME ONLY

	All Ramps Open	Montgomery Closed	Both Ramps Closed	University Closed
UNIVERSITY				
Ramp & Lane 1	E	E	-	-
Lane 1	E	D	D	D
Lane 2	E	E	E	E
Total	F	F	E	F
MONTGOMERY				
Ramp & Lane 1	E	-	-	E
Lane 1	D	E	E	D
Lane 2	E	E	E	E
Total	F	E	E	F

closings could have altered their trip in such a manner that the freeway was not even used. Some of the motorists whose trips were of short duration found that once they reached an entrance to the freeway they were almost to their destination. Therefore, they likely continued their trip on the adjacent street system. Finally, the Clover Lane entrance ramp has poor alignment and virtually no acceleration lane. The Hulen entrance ramp, approximately 0.5 miles further downstream has good alignment and grade with a fairly long acceleration lane. Thus many motorists may have elected to use this Hulen ramp because it offered a much easier means to enter the freeway.

PEAK HOUR FACTOR

The peak hour factor is defined in the Highway Capacity Manual (1) as the ratio of the whole peak hour volume to the highest rate of flow occurring during a five minute interval within the peak hour expanded to an hourly flow. Suggested peak hour factors to be used in case they have not been measured are based on metropolitan population only. These suggested peak hour factors are as follows:

over a million population - 0.91

from 1/2 million to 1 million - 0.83

under 1/2 million population - 0.77

These factors should be used with caution since there is much variation in individual cities at individual times. It has been noted that there is reduced peaking on those highways reported as non-free-flowing during the peak hour. This points out the damping effect of congestion (1).

The afternoon peak hour factor was measured for three different locations on the West Freeway. The afternoon peak hour varied slightly at the different locations. Under all circumstances it occurred within 10-15 minutes of the time period 4:30- 5:30 P. M. As can be seen in Table 12, on any given day there will be some variation in the peak hour factor. On August 15, the week in which the Montgomery ramp was closed, the peak hour factor varied from 0.78 to 0.95. During the week in which both entrance ramps were closed, the peak hour factor remained relatively constant at about 0.96. Due to the variations in peak hour factors observed, it would appear unwise to assume a peak hour factor for any existing freeway if it is at all possible to obtain this information from actual volume counts, since the PHF can produce substantial changes in the various service volumes.

TABLE 12

PEAK HOUR FACTOR

	Clover Lane		Montgomery		University	
	Freeway Lanes	Plus Ramp	Freeway Lanes	Plus Ramp	Freeway Lanes	Plus Ramp
All Ramps Open	--	--	.92	.90	.84	.85
All Ramps Open	.82	.82	.92	.88	.81	.80
Montgomery Closed	.78	.79	.94	--	.95	.93
Both Ramps Closed	.95	.91	.92	--	.91	--
University Closed	.81	.78	.97	.94	.93	--

SUMMARY

Freeway traffic flow is at best a complicated phenomenon. As volumes increase, each factor that affects traffic flow increases in importance and magnitude, thus increasing the complexity. A vehicle entering the freeway when volumes are light produces virtually no adverse effect on the freeway flow. If the same vehicle enters the freeway as volumes are approaching the capacity of the freeway, it produces an effect on the vehicles immediately surrounding it in terms of reduced headways. This in turn produces reduced speeds which again produces reduced headways upstream of the entering vehicle. If volumes and density are high enough this can produce a shock wave causing a series of slow downs a great distance upstream. Since there are many interelated factors that affect freeway flow, it is often difficult to determine the exact cause of freeway congestion. This study of the westbound peak period traffic on the West Freeway was an attempt to determine the cause or causes of recurrent congestion.

From visual observations of traffic flow on this freeway two probable causes were studied. One was the entering traffic at the Forest Park Blvd. entrance ramp and resultant weaving between that point and the lane drop some 2,700 feet downstream. The other area of interest centered around the University and the Montgomery entrance ramps just downstream of the lane drop.

The weaving volumes were determined by interviewing those motorists entering the freeway at the Forest Park Blvd. entrance ramp. The study of the University and the Montgomery entrance ramps involved closing these two ramps

during the peak hour. This covered a three week period which involved closing the Montgomery entrance ramp only; closing both ramps and closing the University entrance ramp only.

It was determined that weaving between Forest Park Blvd. and the lane drop was not one of the principal causes of congestion. The merging of the traffic from the Forest Park Blvd. entrance ramp with the lane one freeway traffic produced a greater reduction in level of service than did the weaving. The total freeway volume in this section also produced an adverse effect on traffic flow. The greatest factor that produced the most severe congestion was the entering traffic from the University and Montgomery entrance ramps. Upstream from these two ramps, freeway volumes were just below capacity. The additional input from these two ramps caused freeway volumes to exceed capacity which resulted in stoppage waves. The closing of these two ramps produced an improvement in traffic flow. The level of service was raised from "F" to "E", stoppage waves did not occur, volumes increased on the through lanes upstream of the ramps, speeds increased and total delay was reduced.

Major improvements can be achieved by placing minor controls on the freeway as was discovered in this study. Freeways that operate at capacity are at a delicate point. Any minor interference can result in congestion. Freeway controls do not increase capacity; they merely attempt to limit freeway volumes to a point slightly below capacity. This gives traffic on the freeway the opportunity to recover from minor interferences without causing a complete breakdown.

As was shown in this study, the closing of two entrance ramps increased the level of service from "F" to "E". Level of service "E" is not a desirable level, but it is much better than "F", as has been previously pointed out.

The West Freeway needs additional capacity. This can be achieved by the addition of more through lanes. The freeway is scheduled to be upgraded, but such improvements are scheduled for several years in the future. Until the upgrading, this freeway can be operated in a much more efficient manner by placing controls on several entrance ramps. This can be in the form of complete ramp closure during the peak period, ramp metering or a combination of the two. The best solution seems to be closure of the Montgomery entrance ramp during peak periods and metering of the University and Forest Park Blvd. entrance ramps. As demand volumes increase, additional ramps could be metered.

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

1. Peak period closure of the Montgomery and both the Montgomery and University entrance ramps produced substantial improvements in freeway flow.

2. Improvements were in the form of higher freeway speeds and an overall decrease in total travel time.

3. Improvements in flow were greatest with closure of both the Montgomery and University entrance ramps. The closing of just the Montgomery ramp was almost as effective. The closing of just the University entrance ramp produced little improvement. Thus, closure of just any entrance ramp does not insure improved freeway flow.

4. Diverted ramp traffic experienced no major problems.

5. Although the ramp closures produced better flow conditions (from level of service "F" to "E"), the freeway was operating at capacity and any minor incident could have again produced congestion.

6. All ramp closures resulted in increased freeway volumes upstream of the University entrance ramp.

7. The peak hour factor determination can vary considerably over a section of freeway which is operating at capacity.

8. Weaving and lane changing between Forest Park Blvd. and the lane drop were not the predominant factor in producing recurrent freeway congestion.

9. The cause of recurrent congestion on the West Freeway can be most simply explained by the fact that demand placed on the freeway is greater than capacity.

RECOMMENDATIONS

Many of the older urban freeways in this country experience recurrent congestion. This is caused because peak period vehicular demands exceed the capacity of the freeway. To increase capacity of a freeway in many cases means addition of a through lane or lanes. Addition of a lane often means a multi-million dollar project and many times the money is just not available for these projects.

An alternate to adding capacity is controlling the demand placed on the freeway to prevent congestion; in other words operating the freeway. This can be accomplished by ramp metering, ramp closure or a combination of both.

This study has shown that ramp closure can improve flow on the West Freeway. Ramp closure was done manually, but automatic closure would be preferable. Other ramp closure studies have been made recently (7), but as of this time the exact parameters needed to make the decision when to open and close a ramp due to freeway flow conditions have not been identified. Once these parameters have been identified, the closure of a ramp could be reduced to the minimum required time to prevent congestion. An automated system could be devised that would prove both effective and would improve freeway flow.

Although ramp closure or ramp metering is not new, no one has yet collected all the data necessary in this field to formulate some "design standards" for those engineers not familiar with this type of control. The questions often arise as to which ramp to control and how many ramps. Should control consist of closure or metering ? Although each situation is different, there should be some means developed to assist the practicing engineer in finding a starting point in his design.

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