BASIC NUMBER OF LANES AND LANE BALANCE: THEIR USE IN URBAN FREEWAY DESIGN

by

MICHAEL CHARLES CONNORS 4871

B.S., University of Nebraska, 1968

A MASTER'S REPORT

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Civil Engineering

Kansas State University
Manhattan, Kansas

1970

Approved by:

Bob L Smith
Major Professor

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

The urban traffic problem, like most problems, arises out of the frustration of trying to reconcile a number of partly imcompatible goals. Urbanites would like to move about their areas: a) quickly; b) comfortably; c) cheaply; d) mostly at the same time; and e) mostly to or from the same places. (4) Since a majority of trips, 80-90% during the peak hour (5) are to work and shop, time spent in transit is time lost from a productive activity. Urban movement, then, is largely an experience to be done with as quickly as possible. Minimum travel time becomes a prime objective and traffic congestion, which increases travel time, the main problem.

During the peak hour, almost all congestion is caused by traffic demands exceeding the capacity of a few bottleneck sections. In the bottleneck, traffic flow is smooth. However, when the arrival rate exceeds the service rate, a queue will form upstream from the bottleneck, i.e. congestion. Traffic flow in the system may be described as similar to sand in an hour glass. In the neck, the sand flows freely. However, the sand upstream from the neck flows very slowly, the last grain being delayed an hour. (3)

Removing these bottlenecks from the freeway would serve to reduce overall traveltime on the entire transportation system. Federally funded projects, such as TOPICS (Traffic Operations Programs to Increase Capacity and Safety) are presently being undertaken to eliminate existing bottlenecks.

The ultimate, however, should be the elimination of these bottlenecks during the initial design of the freeway.

At the 1965 Canadian Good Roads Association Convention, Jack Leisch presented a paper entitled "Lane Determination Techniques for Freeway Facilities." (1) In this paper Leisch introduced two new concepts into the field of freeway design: <u>basic number of lanes</u> and <u>lane balance</u>. These two concepts provide a systematic method to strategically provide additional lanes to a freeway which would serve to remove bottlenecks.

Leisch maintains that the number of lanes on a freeway facility cannot be determined by relating highway capacity to estimated traffic volume alone. To provide well-balanced freeway design, the following techniques must all be considered:

A. Volume-Capacity Relationships - to determine the number of lanes required to carry forecast traffic volumes.

B. Lane Balance - to ensure efficient operation and to realize the indicated capacity potential where merging, diverging, and weaving take place. The basic relationship used in determining lane balance is: $N_c \geq N_e + N_f - 1$

Merging Traffic   Diverging Traffic

Relationships of Lane Balance

(Figure 1)

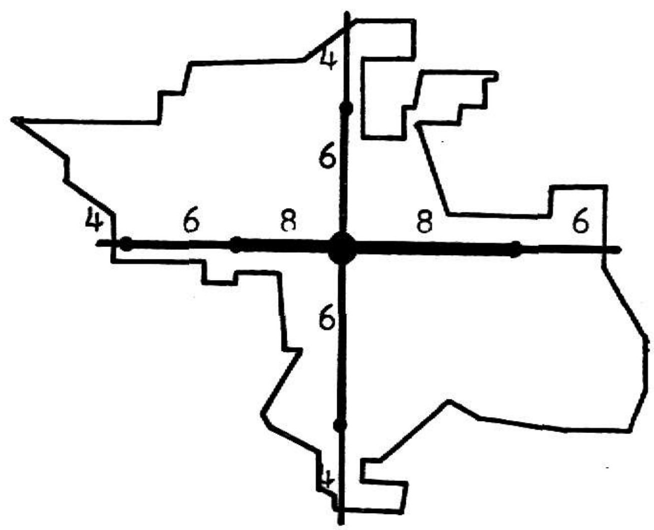
where: N_c is the number of lanes succeeding an entrance ramp or preceding an exit ramp;

N_e is the number of lanes on the entrance or exit ramp;

N_f is the number of lanes preceding an entrance ramp or succeeding an exit ramp.

That is, the number of lanes leaving a merging section is greater than or equal to the number of freeway lanes preceding the merge plus the number of lanes on the ramp minus one. Similarly, the number of lanes approaching a diverging section must be equal to or greater than the total number of lanes on the exit ramp and the freeway beyond the point of divergence, minus one.

C. Basic Number of Lanes - to maintain a certain consistency in the number of lanes provided along a route. The basic number of lanes is defined as a minimum number of lanes designated



Basic Number of Lanes Concept

(Figure 2)

and maintained over the whole of a freeway route or over a significant length of it, irrespective of changes in traffic volume and requirements in lane balance.

D. Special Auxiliary Lanes - Auxiliary lanes have three major purposes in freeway design:

1. to harmonize the techniques of lane balance and basic number of lanes by adding auxiliary lanes to, or removing them from, the basic number of lanes to achieve lane balance.

2. to improve the flexibility of a freeway by strategically adding an extra lane to the basic number of lanes.

3. to apply the principle of "one more lane going away" to interchanges. This principle of having an extra lane at the point of divergence is a form of escape hatch that would facilitate the necessary traffic operations to negotiate the interchange by providing greater exit capacity than entrance capacity.

Leisch concludes that by basing a freeway design strictly on the volume-capacity relationships, possible changes in the pattern and volume of traffic are being ignored. An unforeseen concentration of development, such as a shopping center or an industrial plant may significantly increase traffic volumes. Weekend travel may produce different traffic loadings than normal peak hour traffic. Stage construction or partial freeway network development may alter traffic patterns. Accidents or extensive maintenance operations either on the freeway or on intersecting or parallel facilities may cause increased traffic buildups. It is hypothesized that by incorporating the techniques of lane balance, basic number of lanes, and special auxiliary lanes into the design, the operational flexibility necessary to handle these unexpected developments will be built into the freeway system, usually at little increased cost.

To this author's knowledge, no testing of the hypothesis has been conducted on an existing freeway system. This report presents such a test on a section of freeway in Kansas City, Kansas. The purpose of this study was to determine if Leisch's concepts would have improved traffic operations had they been considered in the original design. It is hoped that this report will provide a basis for a new methodology in the design of urban freeways.

PROCEDURE

The basic plan of attack to test Leisch's method of design was to select a section of freeway in a metropolitan area and then incorporate the four techniques, volume-capacity, lane balance, basic number of lanes, and special auxiliary lanes, into a hypothetical design. This hypothetical design could then be compared to the existing freeway layout to determine if it would significantly improve traffic operations on the system.

The first step, the selection of a section of freeway, was dealt with after discussion with Kansas Highway Commission personnel who were familiar with the metropolitan regions of Kansas City and Wichita. The following criteria were used to judge a section's acceptability, listed in order of decreasing importance:

a) the original design information and plans were readily available;

b) more planned construction was to follow, to determine the effects of partial development of the freeway system;

c) traffic congestion was presently a reality;

d) a large, unforeseen industrial park, sports stadium, or shopping center, had been built near the freeway since it was constructed;

e) an extensive maintenance project was planned on or near the selected section in June, 1970;

f) the number of lanes in the section varied;

g) another freeway intersected the selected freeway section.

After the study section was selected, a search into the vaults at the Kansas Highway Commission uncovered the original design traffic volumes, as supplied by the Planning Department, and the final design, as conceived by the Design Department. Further discussion with personnel in the Highway Commission's Design, Planning, Construction, and Right-of-Way Departments and the Kansas City, Kansas Traffic Engineering Department unveiled further information useful for this study.

The study section was then analyzed using Leisch's method and the 1950 Highway Capacity Manual, the manual available at the time of the original design. Up to this point no use was made of the knowledge of existing traffic conditions. Every step was carried out as a designer in the 1950's could have proceeded if Leisch's methods had then been used.

When the hypothetical design was completed, the traffic operations on the existing freeway were analyzed and an attempt was made to predict what effect the additional lanes provided in the hypothetical design would have on existing 1970 conditions.

THE STUDY AND IT'S RESULTS

Selection of the Study Area

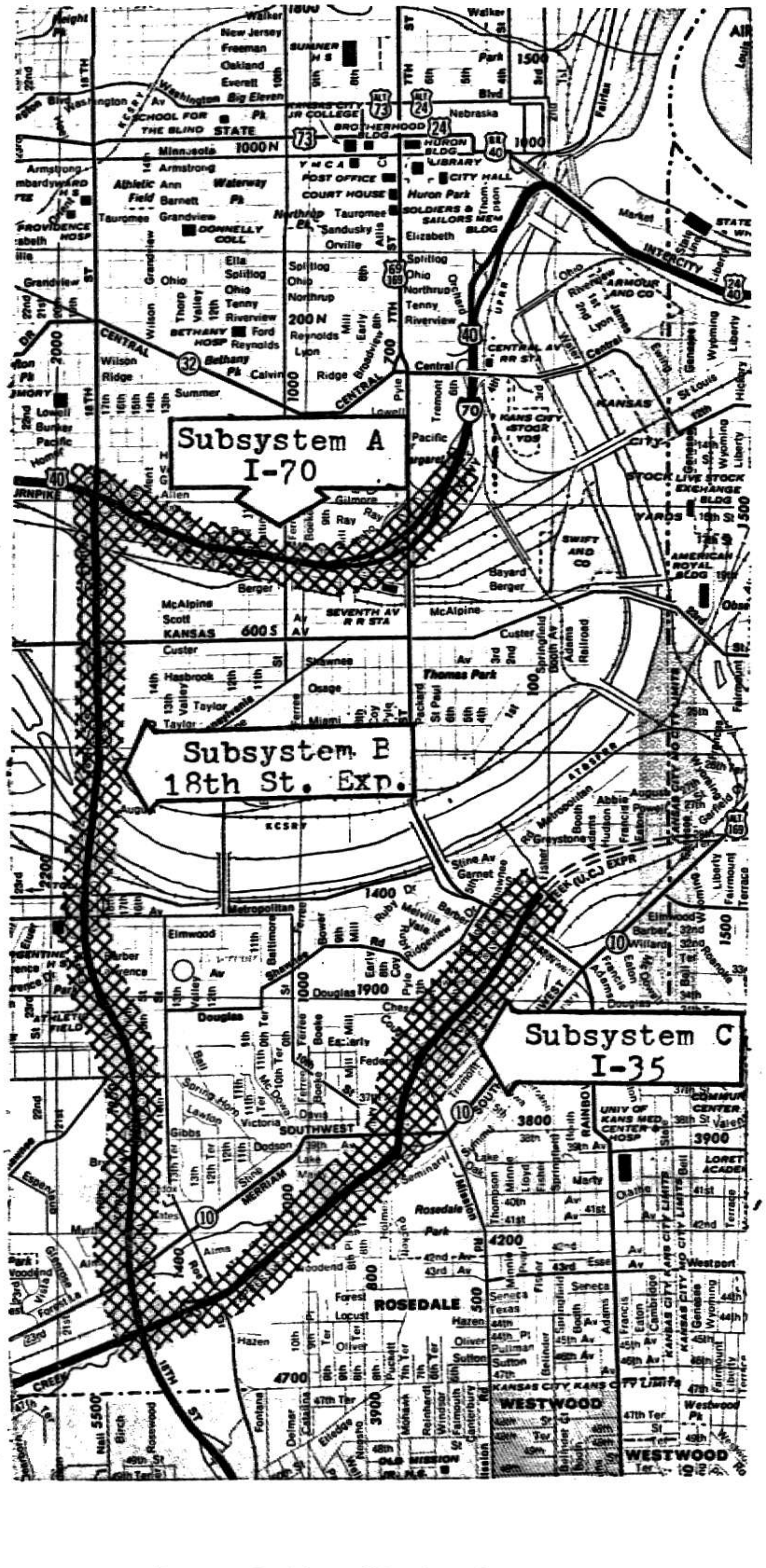
The cross-hatched areas in fig. 3 show the selected study system. The system provides service from downtown Kansas City, Kansas and Missouri to Kansas City, Kansas to the West and Johnson County to the South. For study, the system was divided into three subsystems. Subsystem A was defined as Interstate 70 (the Kansas Turnpike) from 7th Street to 18th Street Expressway. The 18th Street Expressway from I-70 to I-35 was denoted Subsystem B, and I-35 from 7th Street to 18th Street Expressway was defined as Subsystem C.

The selected system satisfies 5 of the 7 selection criteria, including the 3 most important. Criteria d and e, unforeseen development and maintenance operations, were not satisfied. The desirable, for this study, traits:

a) The original design information and plans were available from the Kansas Highway Commission.

b) Partial development of the freeway system could be very effectively studied. I-35, East of 7th Street was not opened until March, 1970. Therefore, current information was available on the operating characteristics of the system both partially and fully developed.

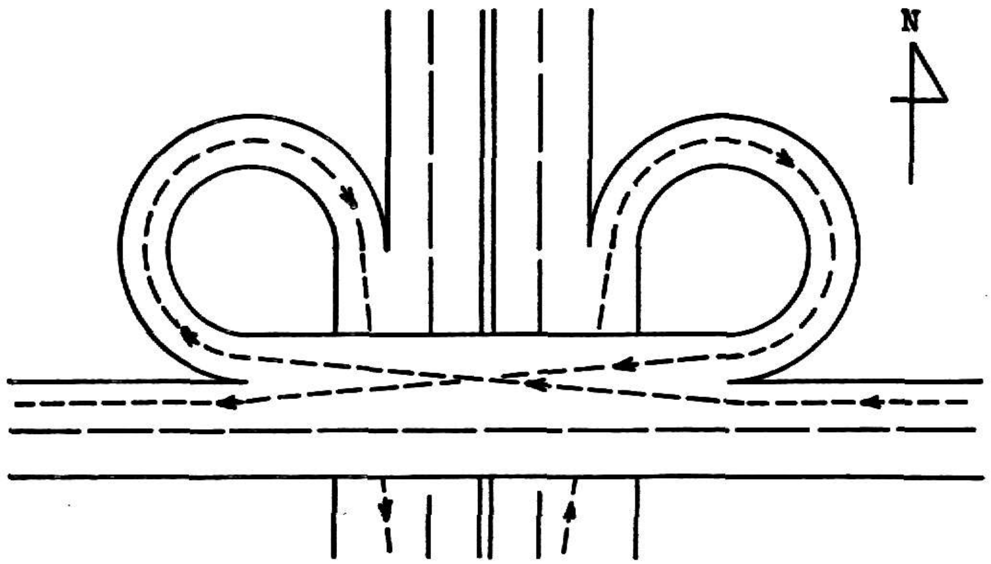
c) Traffic congestion is definitely a problem. Before I-35 opened a bottleneck at the intersection of 18th Street Expressway and I-70 during the afternoon peak hour created serious traffic congestion. The intersection is a clover-



Map of the Study Area

(Figure 3)

leaf. The P.M. peak produces very heavy traffic volumes leaving downtown Kansas City, Kansas Westbound on I-70. Many of these vehicles desire to turn South on the 18th Street Expressway towards Johnson County, which means they must traverse a leaf of the intersection after weaving with vehicles making a South to West turn. (see fig. 4) The opening of I-35 siphoned some of the



Bottleneck at I-70 and 18th Street Expressway

(Figure 4)

traffic off I-70 but at the same time created a problem similar to that of I-70 and 18th Street Expressway at the I-35 and 18th Street Expressway intersection, also a cloverleaf.

f) The number of lanes in the section varies from 2 to 4.

g) The system includes 2 intersections of urban freeways.

Since the major congestion in this system occured during the afternoon peak, Westbound design of I-70 and I-35 and the Southbound design of 18th Street Expressway were selected for detailed study.

Design Criteria

The original design volumes were obtained from the plans. Most were forecast for 1975. Figure 5 shows the forecast volumes together with the 1968 and 1970 traffic counts. With each forecast the following information was given:

(Design Hourly Volume) DHV = 10% of ADT (Average Daily Traffic)

(Trucks) T = 5% of DHV

(Directional Split) DS = 60-40 during the peak hour

The following are design criteria used from the 1950 Highway Capacity Manual:(2)

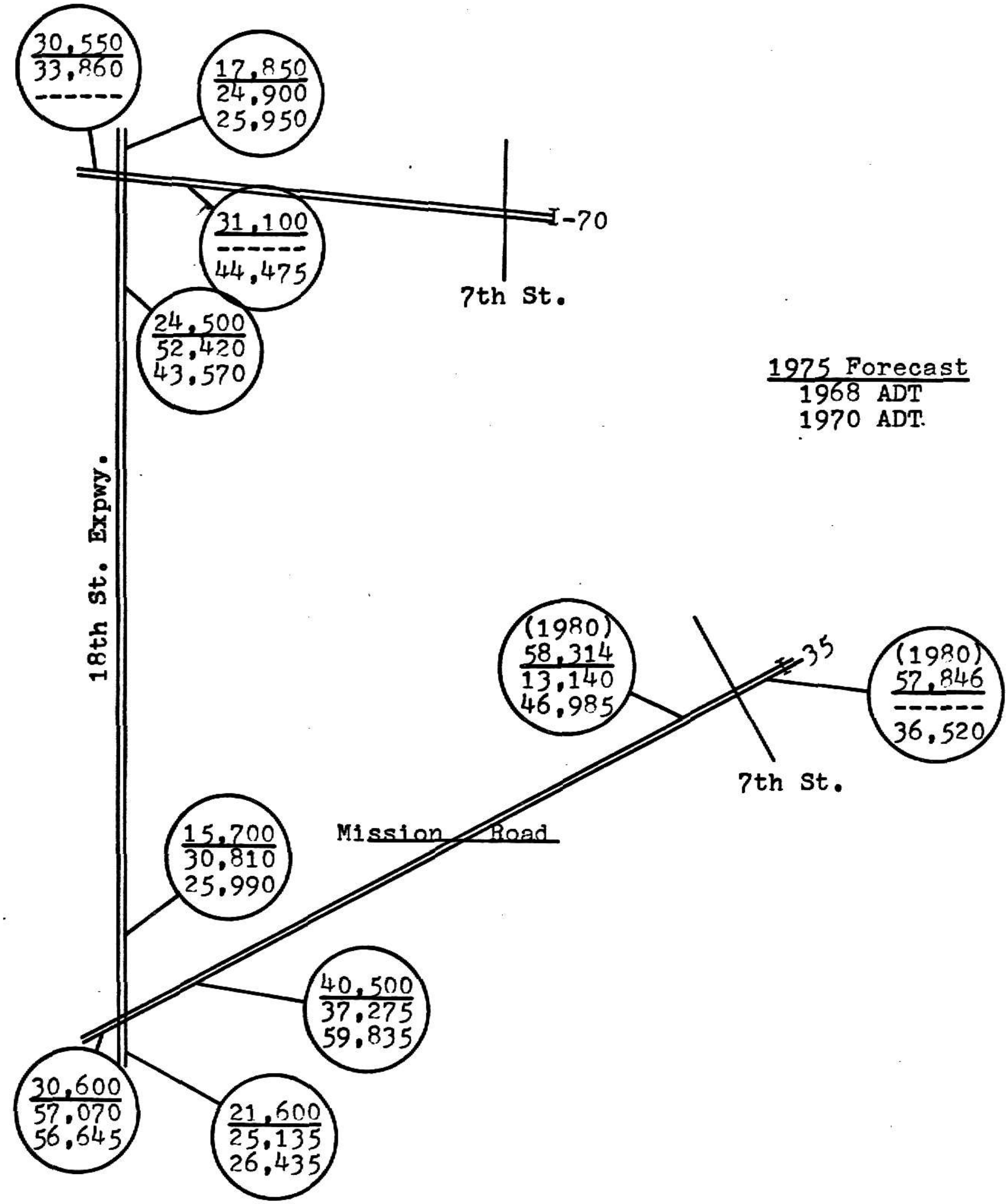
a) A 450 foot weaving section will accomodate 1500 passenger cars per hour at 30 miles per hour.

b) A truck can be considered as 2 passenger cars. Forecast volumes must be properly adjusted.

c) A normal ramp will accomodate 1200 to 1500 passenger cars per hour.

d) The basic capacity for uninterupted flow is 2000 passenger cars per lane per hour. This assumes adequate sight distance, adequate lateral clearance, no commercial vehicles, at least 2 exclusive lanes for use in one direction, and minimum speeds of 30 to 40 miles per hour.

e) With 20 to 25% of the traffic leaving the freeway, it can be assumed that the traffic is split 50-50 between the two lanes.



Traffic Forecasts and Counts

(Figure 5)

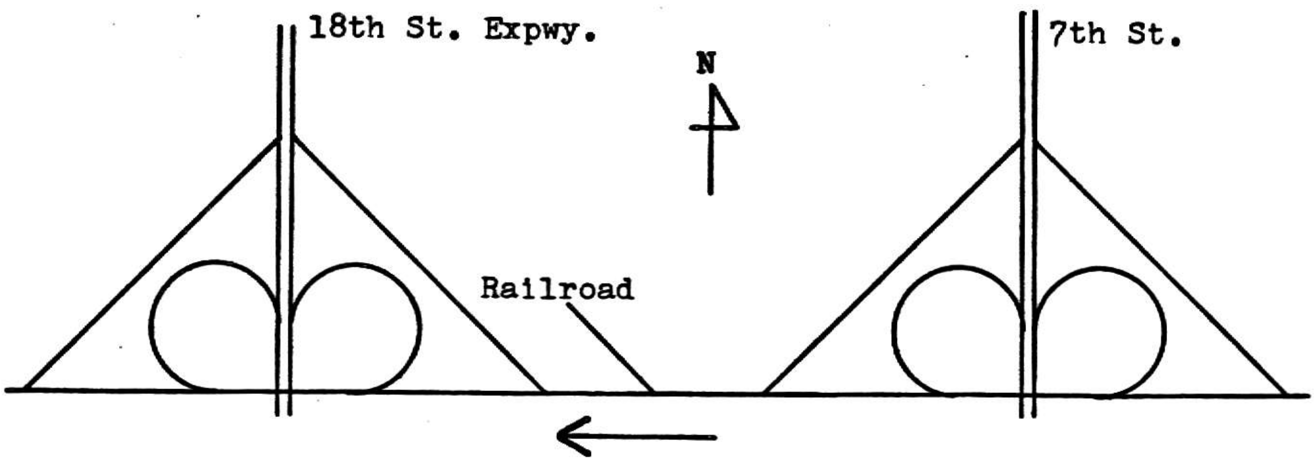
Design Procedure

To effectively analyze the study system, Subsystems A and C, I-35 and I-70, were analyzed separately. Then 18th Street Expressway was analyzed, incorporating the recommended designs of I-70 and I-35 at their respective interchanges.

The recommended design procedure has 5 steps: basic number of lanes, weaving, lane balance, ramps, and operational flexibility. These steps are detailed in the I-70 design procedure. The design of I-35 and 18th Street Expressway are given shorter, more general treatment than that of I-70.

I-70 Design

Figure 13, page 22, shows 5 schematic representations of I-70 between 7th and 18th, Westbound. This section consists of cloverleaf intersections at 7th and 18th and an access exit to



I-70 Westbound Layout

(Figure 6)

the railroad yard. The first 4 schematics of fig. 13, schemes A through D, show the number of lanes provided during various steps of the design procedure. The final scheme depicts I-70 as it is now operating. The following 5 step design procedure was done with forecast data for the original design made in 1956. The 1950 Capacity Manual was used.

A. Basic Number of Lanes

The basic number of lanes was determined by volume-capacity relationships. The following criteria were used:

ADT = 31,100 (fig. 5)

DHV = 10% of the ADT

T = 5%

DS = 60-40

1) The peak hour volume is 10% of the average daily traffic.

Peak Hour Volume = 31,100 x 0.10 = 3110 vph

2) The number of trucks during the peak hour is 5% of the peak hour volume.

Trucks = 3100 x 0.05 = 155

Each truck is equivalent to 2 passenger cars.

Equivalent Passenger Cars = 155 x 2 = 310

3) The design peak hour volume equals the peak hour volume minus the trucks, plus the passenger car equivalents.

Design PHV = 3110 - 155 + 310

= 3265 pcph (passenger cars per hour)

4) The design volume, traffic in the major direction, equals 60% of this number.

Design Volume = 3265 x 0.60 = 1960 pcph

One lane cannot carry this traffic since 2 lanes are required to carry 2000 vehicles per hour. Therefore, I-70 requires

2 basic lanes over the entire section. Scheme A shows the basic number of lanes as 2 in all sections except section 10, which requires 3 lanes, carried over from the design East of 7th Street.

B. Weaving

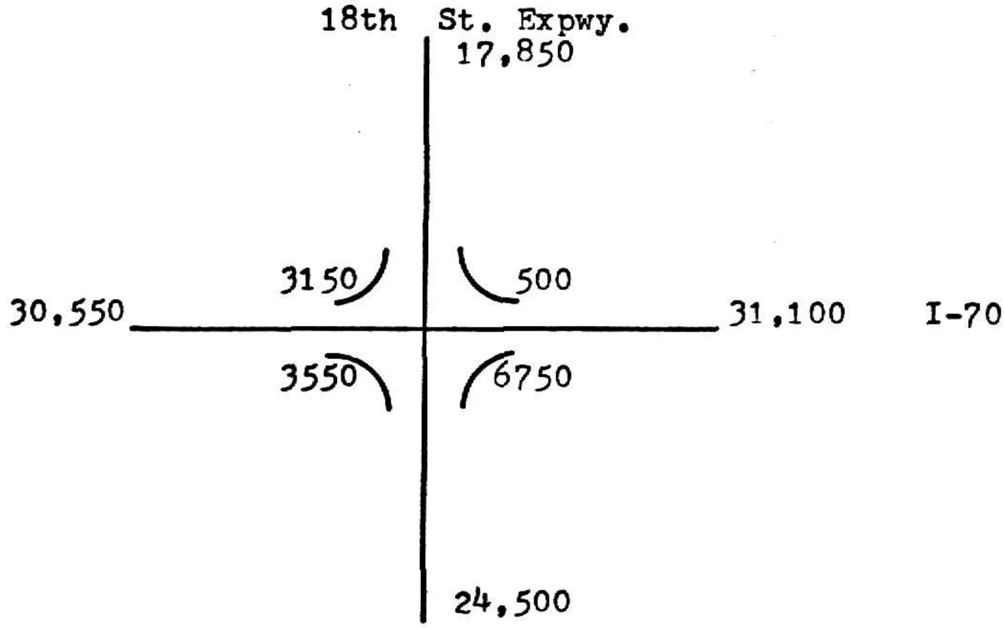
Examination of the schematic reveals 3 potential weaving sections. Table 1 (page 22) supplies the lengths of these sections:

Weaving Section	Length
3	400 ft
6	4400 ft
8	400 ft

Because of the length of section 6 and very few turns at the railroad yard exit, it can be considered as a simple merging and then diverging movement, and does not have to be considered as a weaving section. However, a weaving analysis must be conducted for sections 3 and 8.

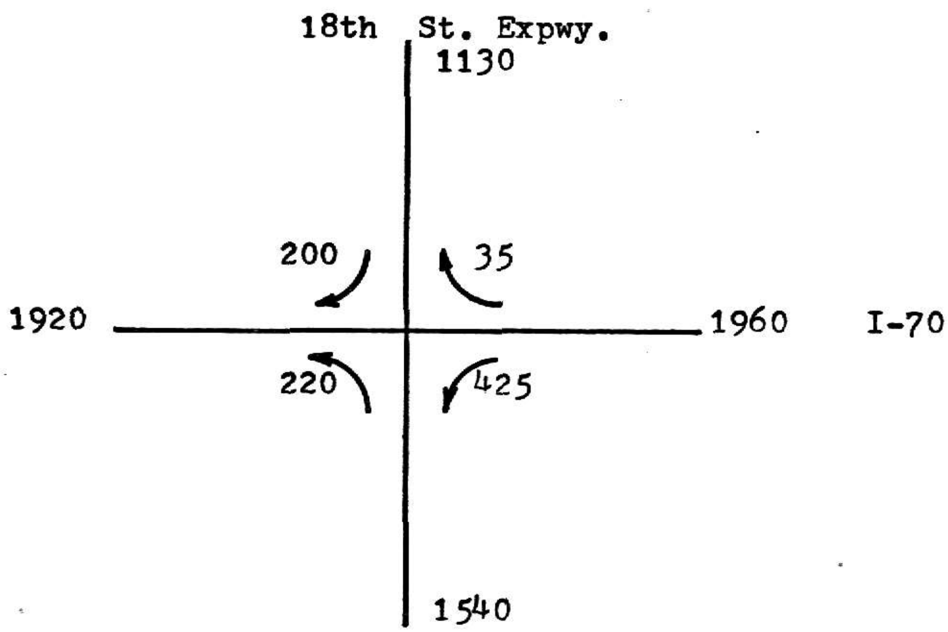
Section 3 is at the intersection of I-70 and 18th Street Expressway. Figure 7 shows the original traffic forecast for this intersection. The design volumes, fig. 8 were obtained by the same series of calculations outlined in part A of the I-70 design procedure.

The weaving section under study is represented in fig. 9. With 22% (425 of 1925) of the traffic leaving the freeway, it can be assumed that the traffic is split 50-50 in the 2 through lanes. Both lanes, therefore, carry 967 pcph (½ of 1925).



Original Traffic Forecast - I-70 and 18th Street Expressway

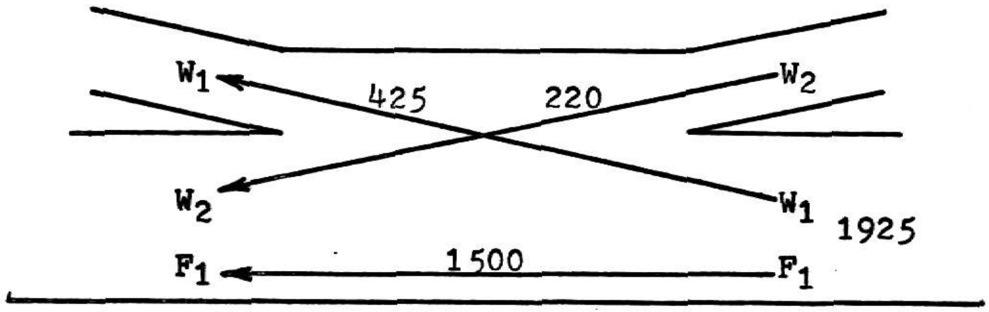
(Figure 7)



Design Volumes - I-70 and 18th Street Expressway

(Figure 8)

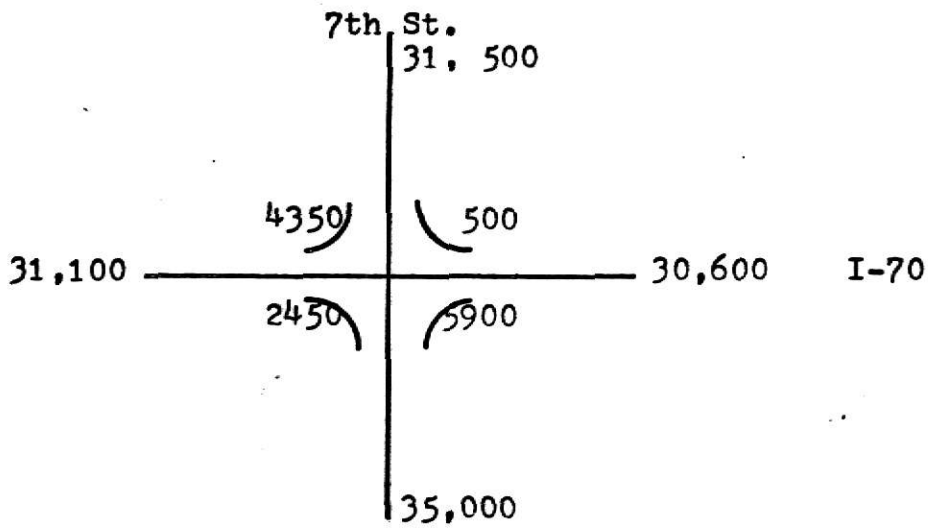
The 645 (425 + 220) weaving vehicles must contend with 542 (967 - 425) through vehicles. This is a total of 1187 vehicles in the weaving section. One additional lane should be adequate to handle the weaving traffic, although at a reduced speed from other portions of the freeway.



I-70 and 18th St. Expwy. Weaving Movements

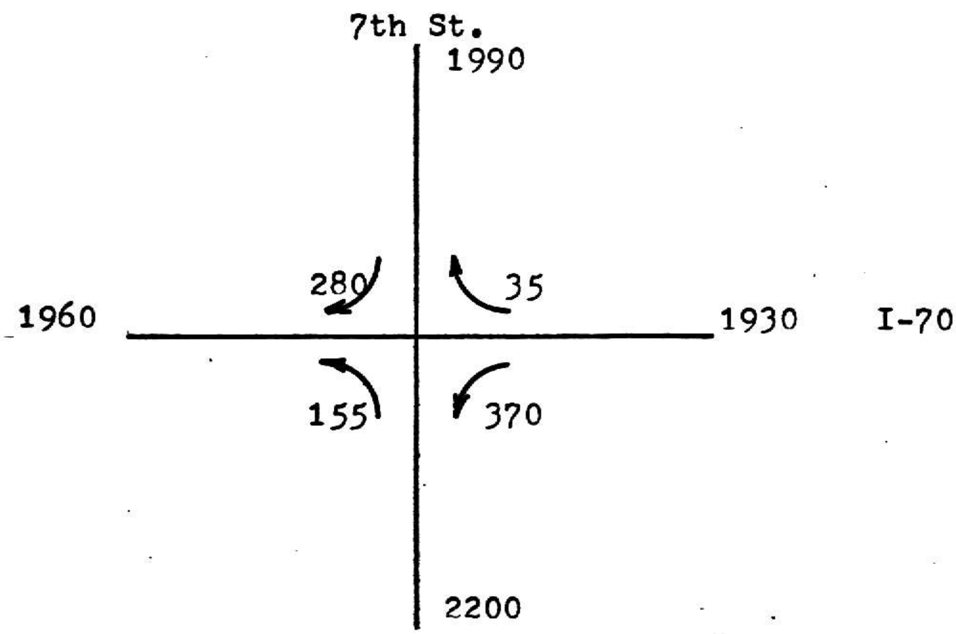
(Figure 9)

The forecast traffic volumes for section 8, the intersection of I-70 and 7th Street are shown in fig. 10, the design volumes in fig. 11 and the weaving movements are shown in fig. 12.



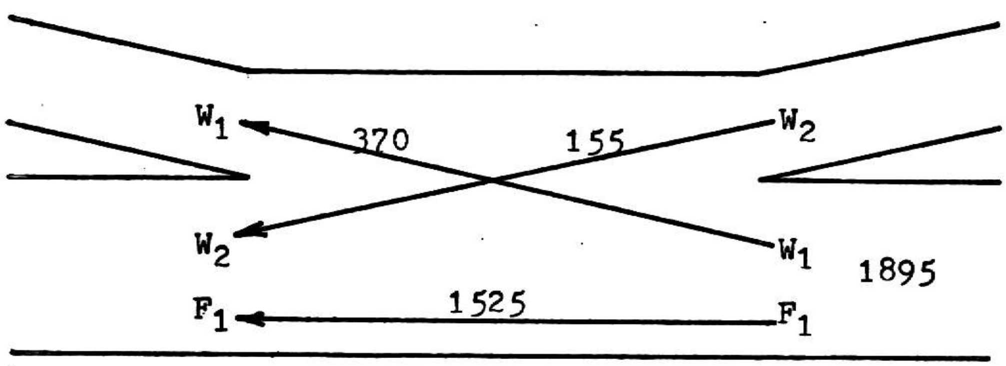
Original Traffic Forecast - I-70 and 7th Street

(Figure 10)



Design Volumes - I-70 and 7th Street

(Figure 11)



I-70 and 7th Street Weaving Movements

(Figure 12)

Following an argument similar to that above, a total of 1097 vehicles will use the weaving section, again requiring one additional lane. Scheme B shows the third lane added in sections 3 and 8.

C. Lane Balance

Reviewing the formula for lane balance:

$$N_c \geq N_e + N_f - 1$$

where: N_c is the number of lanes succeeding an entrance ramp or preceding an exit ramp;

N_e is the number of lanes on the entrance or exit ramp;

N_f is the number of lanes preceding an entrance ramp or succeeding an exit ramp.

The procedure of lane balance is not a cookbook method for lane determination. It requires that the designer be familiar with the study area and apply Engineering judgment to the positioning of the additional lanes.

The following analysis will start in section 10 and work from the right to the left in the direction of traffic flow.

Section 10 has 3 lanes. Therefore, section 9 plus ramp J must total at least 4 lanes:

$$N_c(10) \geq N_e(J)+N_f(9)-1$$

$$N_c(10)+1 \geq N_e(J)+N_f(9)-1+1$$

$$4 = 3+1 \geq N_e(J)+N_f(9)$$

A one-lane ramp is sufficient, therefore section 9 must have 3 lanes. (see scheme C)

Assuming ramp I needs 1 lane, plus the 3 lanes of section 9 minus 1 requires at least 3 lanes for section 8. Since the basic number of lanes and weaving analysis require 3 lanes, there is no change in section 8.

Section 7 plus ramp H must have a total of 4 lanes since section 8 has 3 lanes. Beyond 7th Street, the forecast traffic volumes do not require more than 2 lanes, therefore to satisfy the lane balance requirement of 4 lanes, 2 lanes will be assigned to both section 7 and ramp H.

Sections 4, 5, and 6 all require 2 lanes with one-lane ramps E, F, and G. However, section 3, although requiring only 2 lanes for lane balance needs 3 lanes to satisfy the basic number of lanes and weaving. These 3 lanes in section 3 dictate 4 lanes for section 2 plus ramp C. Again, because of no forecast need for more than 2 lanes on I-70, 2 lanes will be assigned to both section 2 and ramp C. Section 1 requires 2 lanes with a one-lane ramp B.

The inclusion of lane balance with the basic lanes and weaving has added 1 additional lane to section 9 and made all ramps 1 lane, with the exception of ramps C and H which require 2 lanes. The composite design is shown in scheme C, fig. 13.

D. Ramps

The 1950 Capacity Manual used as the only design criteria for ramps a volume of 1200 pcph/lane. No ramp is forecast to exceed this volume, therefore no additional lanes are needed on the ramps.

E. Operational Flexibility

The inclusion of operational flexibility involves the principle of "one more lane going away." This step again requires Engineering judgment and a feel for traffic operations on the freeway in it's application. When combined with all the other methods for determining the number of lanes, this step produces significant operational flexibility on freeways in handling traffic loads beyond design hourly volumes.

Scheme D shows the final recommended design based upon all factors. Extra lanes, beyond scheme C, are provided in sections 6, 7, and 8. The extra lane in section 8 is necessary to provide smooth traffic flow through the weaving section. With 3 lanes approaching in section 9 and the one-lane ramp I merging, an extra lane is desirable to enable sufficient weaving to take place before the 2 lane exit.

Lane balance dictates the extra lane in sections 6 and 7. Without the extra lane in section 7, traffic from ramp I would have to weave through 2 lanes of traffic in approximately 400 feet to avoid exit ramp H.

The final schematic of fig. 13 depicts I-70 as it is operating today. By comparing with scheme D, it is noted that the only additions brought about by Leisch's method are the addition of one lane to each of ramps C and H. The significance of this will be analyzed after the design of the other segments of the study system are discussed.

<u>I-35 Design</u>

The methodology for the design of I-35 Westbound between

OVERSIZED DOCUMENT

THE FOLLOWING DOCUMENTS ARE BEING FILMED IN SECTIONS.

THE FOLLOWING IMAGES WILL BE TAKEN FROM LEFT TO RIGHT, TOP TO BOTTOM. SEE EXAMPLE BELOW:

1	2	3
4	5	6
7	8	9