HSRI Report No. TrS-6

THE EFFECT OF RAINFALL ON FREEWAY CAPACITY

Karl L. Kleitsch and Donald E. Cleveland

Highway Safety Research Institute
The University of Michigan
Huron Parkway and Baxter Road
Ann Arbor, Michigan 48105

1971

Final Report

Contract NCHRP 20-3A

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Highway Research Board
National Cooperative Highway Research Program
National Academy of Sciences

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By

Karl L. Kleitsch
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OPTIMIZING FREEWAY CORRIDOR OPERATIONS
THROUGH TRAFFIC SURVEILLANCE,
COMMUNICATION AND CONTROL

Final Report
Task 3
1971

HIGHWAY SAFETY RESEARCH INSTITUTE
The University of Michigan
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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDIX C TABLES

SUMMARY OF FINDINGS

1. Rainfall decreases urban freeway capacity on the John C. Lodge Freeway in Detroit by about eight percent when the freeway is being regulated by a fully operational control system by means of ramp metering and variable message information signs. This value is approximately half that observed in a similar study recently concluded on a Houston Freeway.

2. The significance of the above findings is increased by the fact that at least one time in ten it will rain with enough intensity in Detroit to significantly reduce freeway capacity during one, or both of the peak periods.

3. Both the dry and rainy weather capacities were found to vary among the freeway detector stations and extensive data measurement systems are probably necessary to determine the appropriate reductions for a specific application.

4. Rainfall also appears to decrease the mean free speed of the freeway under the same conditions.

PART ONE

CHAPTER ONE

INTRODUCTION AND RESEARCH APPROACH

INTRODUCTION

The advanced control of freeway operations is based on relationships between demand on a section of freeway and the capacity (at the desired level-of-service) of that freeway section. The maximum observed traffic volume, together with results of speed and density studies, are used as a guide to establish a numerical value for the capacity of a roadway under ideal conditions (1). This value, quantifying the maximum number of vehicles which have a reasonable expectation of passing over the section of freeway, will vary depending on how roadway and traffic characteristics vary from ideal conditions. Thus capacity can be reduced for various reasons.

The Highway Capacity Manual identifies these reasons as belonging to two major categories--roadway factors and traffic factors. Roadway factors are physical features and are generally of a fixed nature and include: shoulder width, alignment, surface conditions, grades, lane width, number of lanes, and ramp spacing. Traffic factors act in addition to the roadway factors to determine the available capacity.

These include traffic mix, variations in traffic flow, lane use distribution, and traffic interruptions. All of these are variables when related to time. A third list could be developed to include dynamic environmental variables such as rain, snow, fog, and reduced visibility associated with these phenomena if the effects are large enough to be important. The Highway Capacity Manual identifies capacity variations as low as two and three percent, therefore, any change greater than this could be considered important. Since the effect of environmental factors have not been extensively studied, the main goal of this study is to determine how rainfall (in particular) affects capacity and performance at five consecutive freeway stations on the John C. Lodge Freeway in Detroit, Michigan.

A recent Texas Transportation Institute (TTI) study on a Houston freeway indicates that capacity was reduced to between 81% and 86% under rainy conditions (2). In a December 1968 report prepared by TTI on the John C. Lodge Freeway in Detroit (3), results of a similar but very limited study are presented. Their data were presented in diagram form relating speed with both energy (veh-miles/hr^2), and flow (veh/minute). Although only a few data points for dry weather days are shown, they are associated with a higher optimum speed for maximum energy than are rainy days. When maximum flow is considered, however, their plot indicates only one optimum speed. Since all efforts by researchers on this project have been directed toward maximizing flow on the Lodge Freeway, the result indicating no difference between rainy and dry days for capacity flow is more important.

The University of Michigan, in 1969, did an analysis similar to that of TTI of two representative dry days and two rainy days in an effort to confirm any significant differences in freeway capacity and theoretical free speed induced by weather changes (4). No consistent differences were found with regard to rain, but relatively consistent changes were found between the four freeway stations included in the study. The variability of the results indicated that a larger number of sample days was required to produce any definitive conclusions regarding individual station operations and the influence of rain.

Reports on studies dealing with incident detection indicate that the frequency of incidents (an incident being any stoppage of one or more vehicles either on the roadway or shoulder) is much greater during wet pavement conditions (5). In England it was found that spray sent up by cars is the biggest single cause of breakdown on roadways (6). Incidents may create bottlenecks which may further reduce capacity and this is another reason to study the problem of the effect of rain on capacity.

CONCEPT BEHIND STUDY

To effectively and efficiently control freeway operations, a value for the practical capacity for each section of freeway must be known. Since this numeric value assumes such a critical role in determining metering rates, it should be as accurate as possible. A value has been defined from the many years of study that have occurred on the Lodge Freeway. This study directed itself to the questions of how rainfall affects this value for capacity, and if it does, by how much. After determining the changes in the parameters due to wet pavement, more accurate control can be achieved. If the capacity of a freeway subsection is reduced, the demand should be more tightly controlled. This will thus prevent congested conditions from developing and will enable the freeway to operate "at capacity."

Demand for freeway sections can be controlled by utilizing a system of ramp metering and traffic control signs. Ramp metering consists of an ordinary stop-and-go traffic signal mounted approximately one-half way down an on-ramp.

The signal is controlled to give a green display to each vehicle on a one-at-a-time basis. During periods of heavy demand, queues build up on these ramps. Demand for ramps should, therefore, be controlled. This can be accomplished by means of traffic control and information signs (7), (8).

The difference between demand and capacity of a freeway section, and demand and storage on a ramp, dictate the control exercised. This control is based on real time traffic flow measurements rather than on a fixed time basis; a block diagram showing the system logic for control is shown in Figure 1. The introduction of the changed capacity parameter occurs in the processing and assessment phases of the control operation.

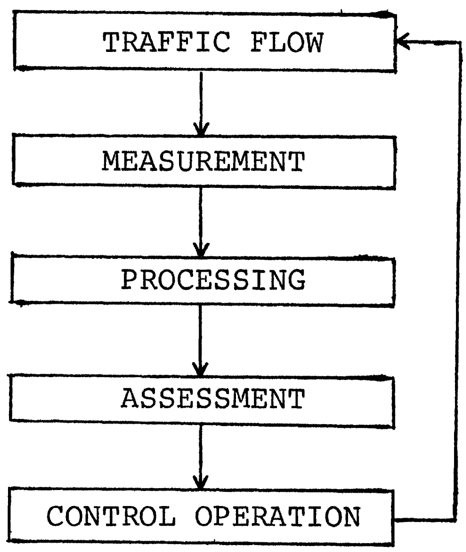


FIGURE 1

BLOCK DIAGRAM SHOWING REAL TIME SYSTEM LOGIC

RESEARCH APPROACH

The study was performed by the Highway Safety Research Institute (HSRI) of The University of Michigan on a northbound section of the John C. Lodge Freeway having a length of about 2 2/3 miles. This site was chosen since it contained an active traffic research facility that provided the necessary capabilities for data collection and analysis. The National Proving Ground for Freeway Surveillance, Control, and Electronic Traffic Aids facility and local agencies have been actively performing research work on the Lodge Freeway since 1955. At the time of this study, it was being utilized as a fully operational freeway control system for the purpose of maximizing flow through the Lodge corridor. Thus, this experiment took place in the appropriate environment of an advanced control system where, in application, the results and knowledge gained would be merged. It was to further refine the control parameters utilized in the ramp metering and information sign system that this study was initiated.

The freeway control system necessarily has a large number of vehicle detectors utilized for traffic flow measurements as well as exclusive use of an IBM 1800 computer system. These items were utilized for data acquisition, summary, and analysis during this study. Five separate consecutive freeway detector stations were employed to collect data and their locations are shown in Figure 2. Stations 3, 4, 6, and 7 each have three northbound lanes while station 5 has four lanes. As the figure depicts, stations 4, 5, 6, and 7 are each located on straight alignments; while station 3 is located midway through a reverse curve. Each lane at each station is counted individually by an ultrasonic vehicle detector. These units are mounted on bridges and pedestrian overpasses over the freeway. These lane counts are then summed to provide station counts. Occupancy is measured as the percentage of time that vehicles are detected by the detectors and averaged.

The first step in the study was to determine on which days it rained during the period 2:30 to 6:30. This four hour duration corresponds to the time the freeway control system was operational and, therefore, to the time data could be collected. The rainy days were determined by reviewing figures from the United States Environmental Data Service (9), and choosing days generally having more than 0.04 inch precipitation during this peak traffic flow period. Local climatological data for Detroit City Airport (about 4 miles from the project) are published monthly; a sample copy is

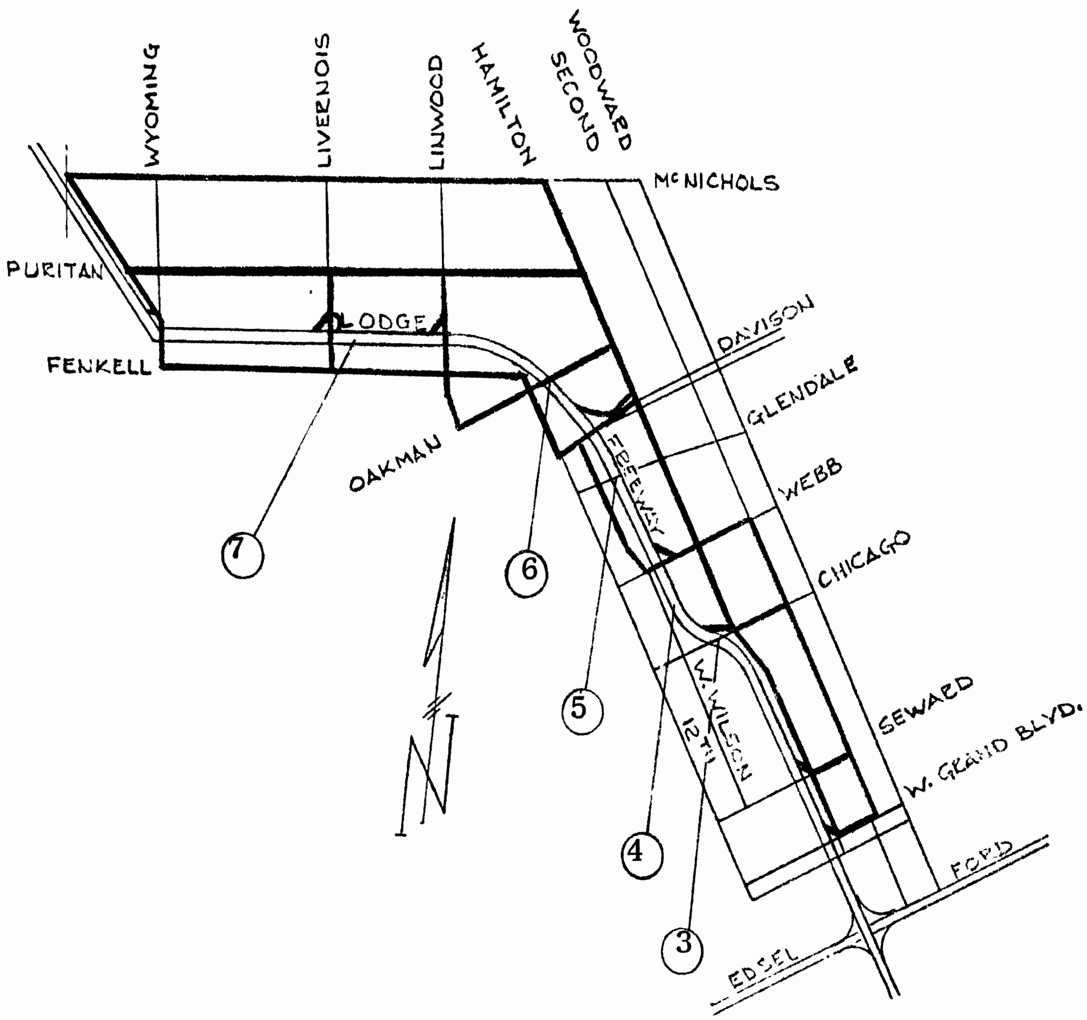


FIGURE 2

LOCATION OF FREEWAY DETECTOR STATIONS 3 THROUGH 7-
JOHN C. LODGE FREEWAY CORRIDOR

included as Figure 3. The monthly summaries were searched for rainy days and a similar quantity of dry days. The mean amount of rainfall on the days utilized in this study was 0.15 inch, while the highest value was 0.35 inch.

If possible, consecutive rainy and dry days were chosen to avoid possible changes in traffic patterns. Also, holidays, days preceding and following holidays, and days on which research experiments were conducted were not chosen. In addition, there were other days not available for selection because the computer was not operational due to software and/or hardware changes, as well as days when detector stations were not operating properly for any of a variety of reasons. Within these limitations, 34 station-days of dry data; and 21 station-days of rain data were compiled for the full four hour control period. Since the data collected daily on the project is stored on computer punch cards, there was no difficulty in recovering the desired days and reducing the data for analysis. The specific data utilized was among a larger assemblage collected routinely every day and consisted of 240 one-minute values for volume and occupancy at each of the five consecutive freeway stations previously described.

A program was prepared to plot volume versus occupancy data on a coordinate plane for each day for each station; see Figure 4 for plots of two days at station 5. Additionally,

LOCAL CLIMATOLOGICAL DATA

U S DEPARTMENT OF COMMERCE - MAURICE H. STANS, Secretary

ENVIRONMENTAL SCIENCE SERVICES ADMINISTRATION -- ENVIRONMENTAL DATA SERVICE

DETROIT, MICHIGAN
CITY AIRPORT
MARCH 1969

Latitude 42° 25′ N Longitude 83° 01′ W Elevation (ground) 619 ft Standard time used EASTERN

Date	Temperature (°F) Maximum	Minimum	Average	Departure from normal	Average dew point	Degree days (Base 65°) Heating	Cooling	Weather types shown by code 1-9 on dates of occurrence (1 Fog, 2 Heavy Fog X, 3 Thunderstorm, 4 Sleet, 5 Hail, 6 Glaze, 7 Duststorm, 8 Smoke, Haze, 9 Blowing Snow)	Snow, Sleet, or Ice on ground at 07AM (In)	Precipitation Water equivalent (In)	Snow, sleet (In)	Avg station pressure (In) Elev 626 feet m s l	Wind Resultant direction	Resultant speed (m p h)	Average speed (m p h)	Fastest mile Speed (m p h)	Direction	Sunshine Hours and tenths	Percent of possible	Sky cover (Tenths) Sunrise to sunset	Midnight to midnight	Date
1	2	3	4	5	6	7A	7B	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
1	43	29	36	6	17	29	0	8	0	0	0		05	9.3	9.9	14	02					1
2	44	25	35	5	17	30	0	8	0	0	0		04	6.4	7.6	13	07					2
3	46	23	35	5	14	30	0	8	0	0	0		02	5.4	5.5	13	03					3
4	40	22	31	0	11	34	0	8	0	0	0		35	5.7	5.8	17	36					4
5	43	20	32	1	12	33	0	8	0	0	0		27	3.6	5.9	14	29					5
6	40	24	32	0	20	33	0	8	T	T	T		31	6.0	8.3	14	36					6
7	34	19	27	-5	9	38	0	8	0	0	0		30	14.3	15.4	23	29					7
8	40	27	34	2	14	31	0	8	T	T	T		32	1.6	6.9	14	06					8
9	36	19	28	-5	14	37	0	8	T	T	T		34	9.0	10.2	14	33					9
10	34	15	25	-8	14	40	0	8	T	T	T		32	13.4	13.7	23	33					10
11	24	12*	18	-15	0	47	0	89	0	.01	.4		31	16.7	17.1	24	30					11
12	39	17	28	-6	7	37	0		0	T	T		30	13.3	13.8	23	30					12
13	42	21	32	-2	9	33	0		0	0	0		30	11.8	12.2	20	30					13
14	35	26	31	-3	13	34	0	8	0	T	T		27	12.3	12.5	18	28					14
15	44	24	34	-1	12	31	0	8	0	0	0		27	14.4	14.5	25	28					15
16	46	27	37	2	12	28	0	8	0	0	0		26	11.2	11.9	17	27					16
17	63	36	50	14	23	15	0	8	0	0	0		24	13.1	13.2	23	24					17
18	68*	44	56	20	30	9	0	8	0	0	0		21	6.4	7.3	16	24					18
19	63	37	50	14	31	15	0	8	0	T	0		04	5.3	7.8	14	07					19
20	63	36	50	13	33	15	0	3 8	0	.10	0		19	7.1	14.2	29	25					20
21	44	37	41	4	24	24	0	8	0	T	T		27	21.7	22.4	35	28					21
22	51	28	40	3	20	25	0		0	0	0		23	5.6	8.8	12	17					22
23	65	36	51	13	24	14	0		0	0	0		19	11.3	11.7	18	19					23
24	50	42	46	8	35	19	0	1 8	0	.88	0		09	10.3	10.6	17	10					24
25	42	29	36	-2	35	29	0	1	0	.37	.3		36	9.6	12.2	23	33					25
26	29	25	27	-11	22	38	0	1	1	.04	.8		31	11.6	11.9	17	30					26
27	38	19	29	-10	15	36	0	8	1	0	0		28	11.3	11.8	17	28					27
28	49	33	41	2	30	24	0	1 8	T	.05	T		21	12.2	12.9	23	29					28
29	39	22	31	-8	13	34	0		0	0	0		30	13.3	14.7	20	30					29
30	30	17	24	-16	8	41	0	8	0	T	T		28	17.3	17.4	29	28					30
31	34	17	26	-14	6	39	0		0	0	0		26	11.8	13.2	29	28					31
	Sum	Sum				Total	Total			Total	Total	For the month						Total	%	Sum	Sum	
	1358	808				922	0	Number of days		1.45	1.5		29	6.5	11.7	35	28		for			
	Avg	Avg	Avg.	Dep	Avg.	Dep	Dep.	Precipitation		Dep						Date	21	Possible	month	Avg	Avg.	
	43.8	26.1	35.0	0.2	17	-14		≥ .01 inch	6	-0.97												

Number of days				Season to date				Greatest in 24 hours and dates				Greatest depth on ground of snow, sleet or ice and date	
Maximum Temp.		Minimum Temp		Total	Total	Snow, sleet ≥ 1.0 inch	0	Precipitation		Snow, Sleet			
≤ 32°	≥ 90° ‡	≤ 32°	≤ 0°	5381	0	Thunderstorms	1						
3	0	23	0	Dep	Dep.	Heavy fog X	0	1.11	24-25				
				-67									

HOURLY PRECIPITATION (Water equivalent in inches)

Date	A. M. Hour ending at 1	2	3	4	5	6	7	8	9	10	11	12	P. M. Hour ending at 1	2	3	4	5	6	7	8	9	10	11	12	Date
1																									1
2																									2
3																									3
4																									4
5																									5
6						T	T	T	T		T	T	T	T	T	T		T	T	T	T				6
7																									7
8		T	T	T	T																				8
9																			T	T	T	T	T	T	9
10	T	T	T	T	T	T	T	T				T	T	T	T	T	T	T	T						10
11								T	T	.01															11
12	T	T																							12
13																									13
14													T	T	T	T	T								14
15																									15
16																									16
17																									17
18																									18
19							T	T																	19
20												.08	T	.01		.01								T	20
21	T									T	T	T	T	T											21
22																									22
23																									23
24								T	.08	.13	.11	.07	.09	.09	.06	.03	.03	.07	.06	.04	T	T	T	.02	24
25	.01	.09	.03	.04	.01	.01	.03	.01	.03	.02	.01	.02	.01	.01	T	.02	.01	.01	T	T	T	T	T	T	25
26	T	T	.01	T	.01	T	T	T	T	T	T	T	T	.01	T	T	.01	T	T	T	T	T	T		26
27																									27
28														T	.02	.02	.01			T	T		T	T	28
29																									29
30										T	T														30
31																									31

* Extreme temperatures for the month May be the last of more than one occurrence
– Below zero temperature or negative departure from normal
‡ ≥ 70° at Alaskan stations
+ Also on an earlier date, or dates.
X Heavy fog restricts visibility to ¼ mile or less.
T In the Hourly Precipitation table and in columns 9, 10, and 11 indicates an amount too small to measure
The season for degree days begins with July for heating and with January for cooling.
Data in columns 6, 12, 13, 14, and 15 are based on 8 observations per day at 3-hour intervals
Wind directions are those from which the wind blows
Resultant wind is the vector sum of wind directions and speeds divided by the number of observations
Figures for directions are tens of degrees from true North; i.e., 09 = East, 18 = South, 27 = West, 36 = North, and 00 = Calm. When directions are in tens of degrees in Col. 17, entries in Col 16 are fastest observed 1-minute speeds. If the / appears in Col 17, speeds are gusts.

Any errors detected will be corrected and changes in summary data will be annotated in the annual summary.

I certify that this is an official publication of the Environmental Science Services Administration, and is compiled from records on file at the National Weather Records Center, Asheville, North Carolina 28801

William H. Haggard

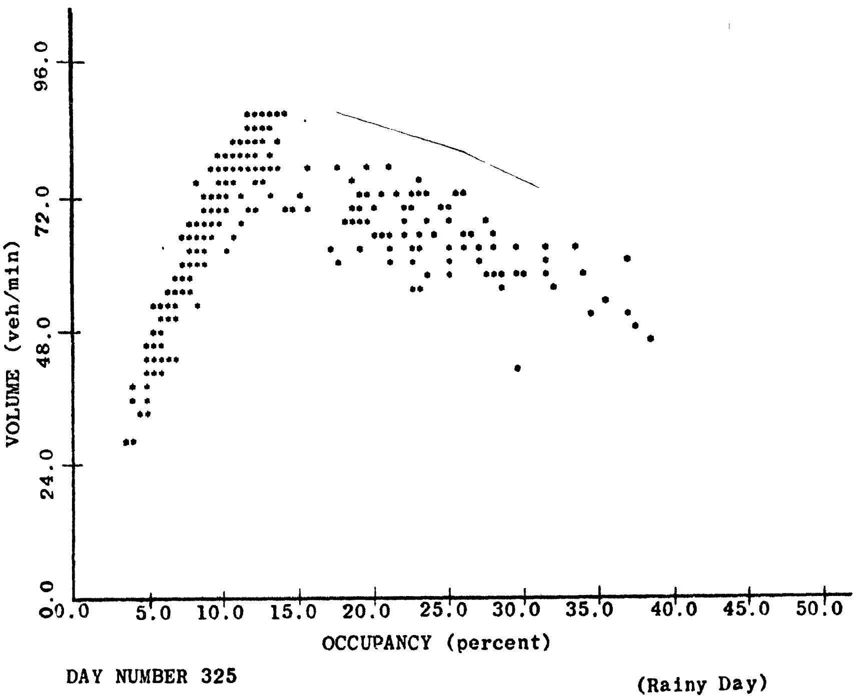
Director, National Weather Records Center

SUMMARY BY HOURS

Hour (Local time)	Averages: Sky cover (In tenths)	Station pressure (In)	Dry bulb (°F)	Wet bulb (°F)	Rel hum %	Dew point (°F)	Wind speed (m p h)	Resultant wind: Direction	Speed (m p h)
01	5		32	27	55	16	9.8	29	5.7
04	5		29	25	58	16	9.3	29	5.7
07	4		29	25	61	17	9.6	29	5.9
10	5		35	29	54	19	12.7	30	7.4
13	5		40	32	44	18	12.7	29	6.2
16	6		42	33	44	19	14.4	29	7.7
19	5		37	30	48	17	13.2	29	7.1
22	5		34	28	52	17	11.5	28	6.3

USCOMM—ESSA—ASHEVILLE 500

FIGURE 3



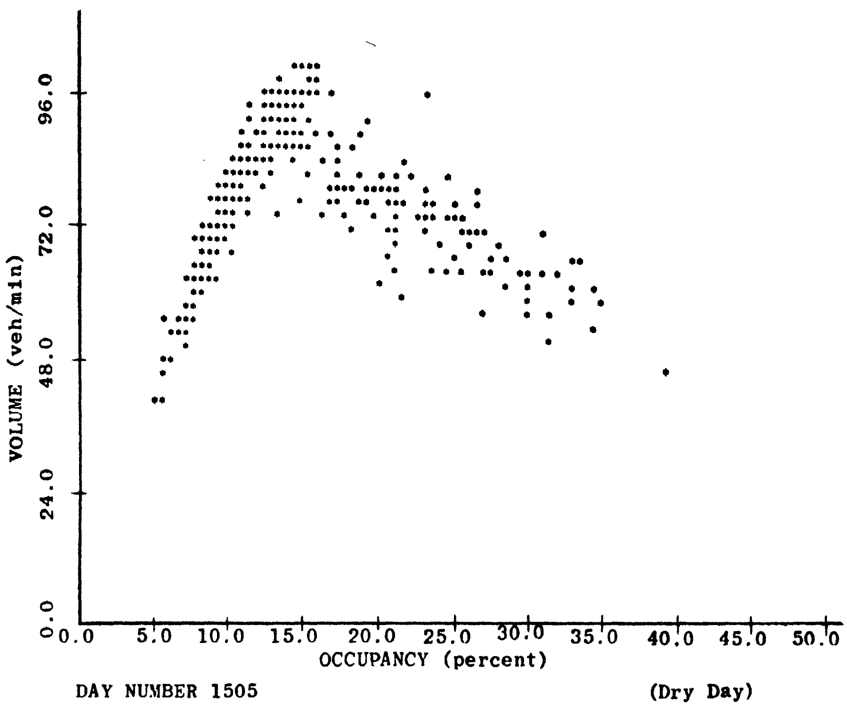


FIGURE 4

VOLUME-OCCUPANCY PLOTS, STATION 5

this program determined the least squares relationship for a parabola fit through these data points and forced through the origin, and these features correspond to the Greenshield's Model. A mathematical derivation of this model appears in Appendix A to this report. Appendix B contains a short description of the program logic as well as the method used to convert occupancy values to density values at each detector station.

From the least squares relationship developed for each station-day studied, the peak of the parabola can be determined. This vertex point will correspond to the maximum volume passing over a freeway section on that particular day. This value for maximum volume would equal the capacity of that section of freeway for that particular day since in all cases, demand was more than sufficient to achieve capacity and even congested flow levels. The inability of the control system to control demand and maintain it at capacity enabled the data to be judged acceptable. Since the Greenshield's Model was utilized, it was a simple matter to determine the jammed occupancy. Owing to the symmetrical properties of the parabola, the value for occupancy corresponding to the vertex of the parabola is one-half the value for jammed occupancy.

As derived in Appendix A, the free speed is equal to four times the capacity divided by the jammed density. By following the above procedures, values for free speed and capacity for each freeway station, and for each rainy and dry day, were determined. Each of these values have been arranged in tabular form and are shown in Appendix C, Tables C1 and C2, along with their respective mean values.

Statistical tests were performed on these sets of data for the two traffic descriptors for each station separately.

During an early period of this research a limited study was performed along the Lodge Freeway to confirm that the data reported on the official weather data summaries were in agreement with actual conditions observed on the freeway.

CHAPTER TWO

RESEARCH FINDINGS

The data presented in Tables C1 and C2 was examined statistically by utilizing the Students t Test. Results indicate that at three of the stations there was a statistically significant reduction in capacity (see Table 1). At these three stations the capacity on rainy days was reduced to about 92% of that attainable on dry days. There were no significant changes at station 6 or 7 and this is due in part to the smaller sample size of data gathered at these two sites. Also, this apparent contradiction at stations 6 and 7 was tested against the hypothesis that there is an 8 percent reduction in rainy weather capacity. Results indicate that values found at these two stations are not inconsistent within the range of normal sampling fluctuations.

Statistical examination of data on mean theoretical free speeds at each of the five stations presented in Table 2 shows that there was no statistically significant variation at four sites. Station 4 had a free speed reduction on rainy days of 10.9%. A sign test was performed on the free speed data and results showed there was a consistent reduction of the mean free speed at all five stations. Furthermore, only one time in thirty-two would results showing a decrease at all stations be obtained by chance. This indicates a

TABLE 1

COMPARISON OF CAPACITY FLOWS

DETECTOR STATION NUMBER	SAMPLE SIZE		CAPACITY FLOW (VEH/MIN)		DIFFERENCE		
	DRY	RAINY	DRY	RAINY	NUMERIC	PERCENT	SIGNIFICANCE LEVEL
3	10	5	88.0	82.0	-0.6	-6.8	0.01
4	10	6	93.9	86.0	-7.9	-8.4	0.001
5	9	4	94.9	87.1	-7.8	-8.2	0.001
6	3	2	89.4	87.9	-1.5	-1.7	---
7	2	4	97.9	94.4	-3.5	-3.6	---

TABLE 2

COMPARISON OF FREE SPEEDS

DETECTOR STATION NUMBER	SAMPLE SIZE		FREE SPEED (MPH)		DIFFERENCE		
	DRY	RAINY	DRY	RAINY	NUMERIC	PERCENT	SIGNIFICANCE LEVEL
3	10	5	79.3	69.9	-9.4	-11.9	---
4	10	6	84.5	75.3	-9.2	-10.9	0.01
5	9	4	76.0	67.4	-8.6	-11.3	---
6	3	2	76.5	74.4	-2.1	- 2.7	---
7	2	4	76.9	73.0	-3.9	- 5.1	---

significant effect attributable to rain. The magnitude of this reduction, however, cannot be determined at this time due to the limited data available. The decrease in free speed is consistent with the fact that the Greenshield's Model would predict a reduced free speed for a decreased capacity.

An investigation was undertaken to see if there was a relationship between the quantity of rainfall and the reductions in capacity values for these days.

When the six days were divided into two groups (one having the three days that it rained least and the other having the three on which it rained the most) each group had exactly one-half of the highest and one-half of the lowest values for capacity. Therefore, there is no apparent correlation between intensity of rainfall and the magnitude of capacity reduction.

A one-way analysis of variance was performed on the data at each station. Results showed that there is a statistically significant variation among the stations for both the rainy and dry data sets. This remained true even when the station having the largest mean differential was removed from the analysis.

FREQUENCY OF RAINFALL

Because the rain does have a decreasing effect on freeway capacity, the frequency of rainfall becomes an important question. Records for the period September 1960 through August 1970 for the Detroit area were received from the United States Environmental Data Service. This ten year span of data was examined for frequency of occurrence of rainfall during the periods of 7:00 to 9:00 a.m. and 3:00 to 6:00 p.m. These times would correspond to the morning and evening peak periods and would also be the time a freeway control project would be operational. Analysis shows that rainfall in excess of 0.04 inch can be expected 10% of the time for either one or both of the periods; and the rate jumps to 20% for a rainfall intensity of anything over a trace. These results are presented in Table 3. In this present study, all but one of the rain days had an intensity of 0.04 inch or more. The average amount of precipitation for the period 2:30 to 6:30 on the rain days studied was 0.15 inch.

TABLE 3

MEAN YEARLY RAINFALL AND SNOWFALL IN DETROIT, MICHIGAN SEPTEMBER, 1960 TO AUGUST, 1970 - FREQUENCY OF OCCURRENCE

AMOUNT Water Equivalent in Inches	7:00 to 9:00 a.m. Occurrences/ Year	3:00 to 6:00 p.m. Occurrences/ Year	Both Periods Cumulative Frequency/Year
NONE	283.7	272.1	555.8
TRACE	49.6	52.8	174.2
T - 0.03	16.6	17.8	71.8
0.04 - 0.09	9.6	10.9	37.4
0.10 - 0.49	5.4	9.9	16.9
0.50 - 0.99	0.1	1.4	1.6
1.00 - 1.99	0.0	0.1	0.1

CHAPTER THREE

INTERPRETATION, APPRAISAL, AND APPLICATION OF RESEARCH FINDINGS

Since limited information is available on this subject, the numerical findings of this extensive study must be viewed as tentative. The recent TTI study also shows that, on a Houston freeway, capacity was reduced by rain. However, their findings indicate the reduction to be somewhat greater, from 14% to 19%. The difference between this 16.5% and Detroit's 8% is statistically significant. The interpretation is that rainfall does appear to reduce the capacity of the Lodge Freeway by about 8%, a significantly less amount than that recorded on the Houston freeway.

The best application to be made from this knowledge in the operation of dynamic freeway control is to reduce the magnitude of the capacity value utilized for each of the Freeway substations on rainy days by the appropriate amount, tentatively appearing to be a constant for Detroit. This value change requires nothing more than a simple software alteration. Thus, a freeway section having a reduction in capacity due to rain by a known percentage would, on rainy days, incorporate a new threshold value for capacity. This would be the only change required in the entire real time freeway control and information system. In addition, this information can be applied in a ramp metering scheme utilizing pretimed metering rates by installing a companion dial having the appropriate reduction in metering rates and by energizing it on rainy days.

It is believed that a reduction of 8 percent in the available capacity of the Lodge Freeway, an occurrence that happens at least 10 percent of the time, is highly important. This is especially evident when it is compared with the fact that by constructing a fourth lane (which is a major undertaking) the capacity changes by only one-third. Other common physical and control changes such as one foot of lane width or variations in ramp design have impacts of less than 8 percent.

The consequences of not adjusting for reduced capacity would be, since the throughput is reduced, a lengthening of the period of capacitated freeway flow because the demand would be constant. Thus, there is extra delay to those motorists traveling during that period. The cost-effectiveness of this type of study and the application of results is very favorable. The cost was quite nominal since no new equipment was required for its execution. Hardware included existing ultrasonic vehicle detectors, and an IBM 1800 computer system. The need for such a study is obvious when the findings are considered as is the fact that the knowledge gained should be implemented into an operational freeway control system.

A further implication, particularly related to corridor control projects, is that on rainy days a large quantity of vehicles will be diverted from the Freeway due to reduced capacity. Thus, identification of attractive alternate routes becomes necessary.

The findings of statistical variations among the freeway stations under both rainy and dry conditions has implications as to the number of detector stations required to acquire the data necessary to completely identify the magnitude of the capacity changes at each substation. It appears that measurements must be made at more than only one or two sites. On fully dynamic freeway control projects this would present no problem since adequate detector stations would of necessity be in existence. On projects employing other ramp metering strategies, detectors would have to be purchased, rented, or borrowed for a sufficient time to make complete measurement studies.

The variance obtained in the measured values in this study may provide a guide to the sample size necessary for additional studies of this type elsewhere.

In application, the presence of rain could be detected by simply looking out the window, by having automatic rain detection equipment in the field, or by contact from a nearby weather station. This last method may be superior because of the possibility of receiving information on duration and intensity of the storm. However, since the intensity of rainfall does not appear to be important, any of these methods would be acceptable.

CHAPTER FOUR

CONCLUSIONS AND SUGGESTED RESEARCH

This research report was concerned with determining if an environmental variable (rainfall in particular) had an influence on freeway capacity. In addition, it determined the magnitude of the variance found.

Analysis of data for one set of rainy days and another set of dry days for each of the five stations indicated that capacity was indeed decreased at three of the five stations. The magnitude of the reduction was 8 percent. Similar studies were accomplished on free speed data. There were no statistically significant changes in this traffic flow parameter, however, there was a consistent reduction in the mean free speed at each of the stations due to rain. It is believed that theoretical free speed is, in fact, reduced by rainfall.

Rainfall having enough intensity to produce an effect on capacity and free speed is a rather common occurrence in Detroit, Michigan, happening at least ten percent of the time.

Both the dry and rainy weather capacities were found to vary statistically among the five detector stations.

Since the influence of rainfall on traffic flow has, in many cases, an influence greater than some of the common physical and control changes that are commonly employed, there is an obvious conclusion that rainy weather influences should be examined completely.

The freeway operations and control project in the John C. Lodge Freeway Corridor in Detroit has identified viable alternate routes. Thus, when the capacity of the Freeway is reduced due to rain, motorists can be diverted to attractive alternate routes that have available capacity.

FURTHER RESEARCH

It is suggested that further research be performed on unmetered urban freeways to determine if rainfall has an influence on any of the traffic parameters under those conditions. It may be possible that metering helps to maintain a freeway's capacity nearer its full potential than if it were not metered. This could be because metering discourages the short trip which is often traffic disrupting. Also, smoother flow results because of the one-at-a-time merger that metering provides.

A second area for study could be to determine at what level rainfall intensity begins to have a significant effect. This study directed itself to days having an intensity in excess of 0.04 inch in a four hour period and an effect was discovered. Lesser intensities should also be studied.

Study results may be uniquely different in each city as the driving populations differ. However, each study could be performed as outlined in this report.

Although it had been originally planned to operationally employ the results of this study, other research having higher priority and time limitations made it impossible. It is suggested that operational freeway control systems introduce the recommended procedure and confirm these findings.

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PART TWO

APPENDIX A

MATHEMATICAL DERIVATION OF GREENSHIELD'S MODEL

APPENDIX A

MATHEMATICAL DERIVATION OF GREENSHIELD'S MODEL

We may express the linear relationship between speed and density as follows:

$$u = a - bk \tag{1}$$

u = speed

a = constant = u_m

b = constant of proportionality = u_m/k_j

k = density.

Speed is maximum (u_m) when $k = 0$ (or actually when only one car is present). Therefore,

$$u = u_m - bk. \tag{2}$$

Speed is minimum (zero) when $k = k_j$ or maximum density. Therefore,

$$0 = u_m - bk_j \text{ or } k_j = u_m/b. \tag{3}$$

Multiply both sides of equation (2) by k,

$$ku = u_m k - bk^2 .$$

Since $Q = uk$, we have

$$Q = u_m k - bk^2 .$$

To find Q_{max} we take the first derivative and set it equal to zero;

$$\frac{dQ}{dk} = u_m - 2bk \tag{4}$$

$$u_m - 2bk = 0 .$$

The optimum concentration (k_o) occurs when we have maximum volume, thus,

$$k_o = u_m/2b \tag{5}$$

and by substituting from equation (3) we have,

$$k_o = k_j/2 .$$

From equation (2) we have,

$$u_m = u + bk .$$

If we substitute this relationship into equation (4) we have,

$$\frac{dQ}{dk} = u + bk - 2bk = u - bk$$

and by equating to zero we find the speed for the maximum volume, or the optimum speed is,

$$u_o = bk_o .$$

By the relationship we have in equation (5), we obtain,

$$u_o = b(u_m/2b) = u_m/2 .$$

Maximum volume = $Q_{max} = k_o u_o$

$$Q_{max} = (u_m/2b)(u_m/2) = (2u_o/2b)(2u_o/2)$$

$$= (u_o/b)(u_o) = u_o{}^2/b = (bk_o)^2/b$$

$$= bk_o{}^2 = \frac{1}{4}(bk_j{}^2)$$

Since $b = u_m/k_j$

$$Q_{max} = \frac{1}{4}(u_m k_j) \quad \text{or,} \quad u_m = 4\, Q_{max}/k_j$$

APPENDIX B

DESCRIPTION OF LEAST SQUARES PROGRAM

AND

CONVERSION OF OCCUPANCY TO DENSITY VALUES

APPENDIX B

DESCRIPTION OF LEAST SQUARES PROGRAM AND CONVERSION OF OCCUPANCY TO DENSITY VALUES

This program computes equations for a least squares parabola, a parabola forced through the origin, and a least squares straight line forced through the origin based on volume and occupancy data. Additional output are values of capacity and occupancy at optimum values of the parabolas and a correlation coefficient for the straight line.

USAGE

1. Operational Procedure: Use 11 XEQ LSP

2. Input: Data file on disk containing volume and occupancy data must be for a complete six hour period. This is checked before computation begins, if any data is missing the job is aborted.

MATHEMATICAL MODEL

Normal equations for a least squares parabola are:

$$\Sigma y = a_o N + a_1 \Sigma x + a_2 \Sigma x^2$$

$$\Sigma xy = a_o \Sigma x + a_1 \Sigma x^2 + a_2 \Sigma x^3$$

$$\Sigma x^2 y = a_o \Sigma x^2 + a_1 \Sigma x^3 + a_2 \Sigma x^4$$

Normal equations for a least squares parabola forced through the origin are:

$$\Sigma xy = a_1 \Sigma x^2 + a_2 \Sigma x^3$$

$$\Sigma x^2 y = a_1 \Sigma x^3 + a_2 \Sigma x^4$$

$$a_o = 0$$

Normal equations for a least squares line through the origin is:

$$\Sigma xy = a_1 \Sigma x^2$$

$$a_o = 0$$

Correlation coefficient for line is:

$$R = \frac{N\Sigma xy - (\Sigma x)(\Sigma y)}{\sqrt{[N\Sigma x^2 - (\Sigma x)^2][N\Sigma y^2 - (\Sigma y)^2]}}$$

The least squares parabola yields the following equation,

$$y = a_o + a_1 x + a_2 x^2$$

Occupancy is equal to x and volume to y, therefore, the value of occupancy when volume is a maximum is given by;

$$\frac{dy}{dx} = a_1 + 2a_2x = o$$

$$x = -a_1/2a_2 = \text{occupancy}$$

The corresponding value of y is the maximum volume or capacity given by;

$$\text{CAPACITY} = a_1(\text{OCCUPANCY}) + a_2(\text{OCCUPANCY}^2)$$

These values are computed for both parabolas.

CONVERTING OCCUPANCY TO DENSITY

The ultrasonic detectors used at the freeway stations measure both volume and occupancy. It is therefore necessary to determine a value for k (at each detector station) so the occupancy values can be converted to density. The point-slope formula (Y = mX) was utilized to obtain the relationship Volume = m Occupancy; giving,

$$m = \text{Volume/Occupancy}$$

Since Speed = k Volume/Occupancy, we have,

$$k = \text{Speed x Occupancy/Volume, or,}$$

$$k = \text{Speed}/m$$

To calibrate this relationship a speed of 55 mph (the speed limit on the Lodge Freeway) was utilized. Data points for various values of volume and occupancy were plotted on a coordinate plane. The slope of the line drawn through these data was then determined. With m known, and using 55 mph as the value for speed, k could be determined. Only data points for periods when the speed was at 55 mph were utilized. The value of k was then applied in the relationship; Density = Occupancy/k.

A more detailed description of this measurement and other relationships can be found in Reference 3.

APPENDIX C

TABLES OF MEASURED AND CALCULATED VALUES FOR CAPACITY AND FREE SPEED

TABLE C-1

DAILY MEASURED VALUES FOR CAPACITY

ON DRY AND RAINY DAYS

DATE 1969-1970	DAY OF WEEK	STATION NUMBER				
		3	4	5	6	7
March 27	Thursday	86.6	93.8	94.3		
April 23	Wednesday	93.7	98.4	94.9		
May 8	Thursday	93.1	95.9	94.9		
September 15	Monday	86.1	93.6	99.4		
November 20	Thursday	83.7	91.2	98.8		
November 21	Friday	86.3	94.9			
March 5	Thursday	87.6	95.6	93.8	94.7	
April 3	Friday	88.4	94.4	93.1	90.4	98.4
May 26	Tuesday	88.2	91.9	90.8		97.4
August 18	Tuesday	86.7	89.2	94.3	83.1	
MEAN OF DRY DAYS		88.0	93.9	94.9	89.4	97.9
March 24 (0.19 in.)	Monday	82.5	84.8	83.5		
March 25 (0.04 in.)	Tuesday	82.3	85.7	87.3		
March 4 (0.20 in.)	Wednesday	81.5	84.1	86.8	92.2	90.0
April 2 (T)	Thursday		85.5		83.7	96.5
May 25 (0.35 in.)	Monday	81.0	86.0			94.6
July 29 (0.14 in.)	Wednesday	82.9	90.1	91.0		96.7
MEAN OF RAINY DAYS		82.0	86.0	87.1	87.9	94.4

TABLE C-2

DAILY CALCULATED VALUES FOR FREE SPEED

ON DRY AND RAINY DAYS

DATE 1969-1970	DAY OF WEEK	STATION NUMBER 3	4	5	6	7
March 27	Thursday	85.9	77.4	74.2		
April 23	Wednesday	91.3	97.2	89.7		
May 8	Thursday	88.2	90.5	83.2		
September 15	Monday	68.2	84.2	80.2		
November 20	Thursday	90.1	79.0	74.8		
November 21	Friday	86.6	88.5			
March 5	Thursday	71.7	83.7	72.6	78.1	
April 3	Friday	72.4	83.0	71.6	74.8	75.9
May 26	Tuesday	72.7	82.9	60.8		77.9
August 18	Tuesday	65.0	78.1	76.9	76.7	
MEAN OF DRY DAYS		79.3	84.5	76.0	76.5	76.9
March 24	Monday	77.0	67.9	62.1		
March 25	Tuesday	81.8	75.1	68.5		
March 4	Wednesday	67.4	75.8	63.2	72.0	75.7
April 2	Thursday		83.8		76.9	72.1
May 26	Monday	65.2	73.1			76.9
July 29	Wednesday	57.9	76.1	76.0		67.2
MEAN OF RAINY DAYS		69.9	75.3	67.4	74.4	73.0