The Environmental Influence of Rain on Freeway Capacity

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The capacity of a freeway is defined by physical factors of the roadway, traffic factors, and environmental disturbances. Physical characteristics of the roadway are fixed by design and construction and exert a constant influence on freeway capacity. Traffic factors are variable in their effect on freeway capacity, but they are also subject to control and regulation to some degree. Environmental factors cannot be controlled, and thus only their effect can be compensated for by preparation in advance of occurrence. Rain, the most common environmental disturbance to capacity, was studied in this research. Rainfall information for March 1968 through December 1968 in Houston, Texas, was correlated with traffic data records of the Gulf Freeway Surveillance and Control Center operation to obtain data indicating the effect of rain on freeway capacity. Rain was found to reduce the capacity of a freeway section to between 81 and 86 percent of the dry weather capacity with 95 percent confidence.

•CAPACITY OF A FREEWAY SECTION is a function of numerous variables. These variables can be classified into 3 groups defined by the roadway subsystem, driver-vehicle subsystem, and the environment of the highway operating system. Physical factors, related to the roadway subsystem, include lane width, horizontal curvature, grade, and condition of pavement. Traffic factors, related to the driver-vehicle subsystem, include composition of traffic stream, driver characteristics, and vehicular capabilities. Environmental factors (influencing capacity but not related to elements subject to control by design or operation) include light intensity, rain, fog, ice, and snow. Once a highway is constructed, the physical factors influencing capacity assume a constant value until reconstruction is initiated. The influence of traffic factors on capacity is subject to fluctuation as the characteristics of the traffic vary. To some extent, the effect of traffic factors on capacity can be reduced through regulation and control. Although it is possible through proper design to minimize the effect of environmental disturbances, no control can be exercised over their occurrence.

The effect of the physical and traffic factors on capacity have been extensively investigated and documented (1). Moskowitz and Newman reported in 1963 that the effects of weather and lighting were not treated at all in their research on freeway capacity and that this represented a deficiency in knowledge at that time (2). A survey of technical literature indicates that little has been done to fill this void in knowledge.

Design and/or control of a freeway may be based on normal environmental conditions. However, to have a comprehensive (system) design or control plan, the operation must be predictable under degraded environmental conditions. Therefore, this paper reports research undertaken to evaluate the effect of the most common environmental disturbance, rain, on the primary freeway operation parameter, capacity.

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RESEARCH METHODOLOGY

Study Site

Data were collected on the Gulf Freeway (I-45) in Houston, Texas. This facility was appropriate because it was available for research study; it had a fully operational freeway control system and an automatic detection system interconnected to a digital computer for data acquisition needs. The research was conducted by the Texas Transportation Institute for the Texas Highway Department in cooperation with the U. S. Department of Transportation.

Data Collected

The 3-lane, inbound portion of the Gulf Freeway from state highway 225 to the Houston central business district is divided into 4 subsystems as shown in Figure 1. Loop detectors, represented by dots in the figure, are located on all ramps and on the freeway lanes to define subsystem 2 (SS2) through subsystem 5 (SS5). A digital computer monitors these detectors for inputs to establish real-time freeway control during both the a.m. and p.m. peak-period flows. The computer also simultaneously accumulates traffic count information at each detector that can be converted into traffic flow and subsystem density measurements. Flow and density were recorded each minute for each of the 4 closed subsystems shown in Figure 1 during the period from 6:30 a.m. to 8:30 a.m. The one-minute traffic data collected for each subsystem in the 3.5-mile freeway section were converted into 5-minute flow rates and expressed as vehicles per hour (vph) across all 3 lanes. Average density was calculated in terms of vehicles per mile (vpm) for all 3 lanes in each subsystem. A typical sample of the data collected for one day is given in Table 1.

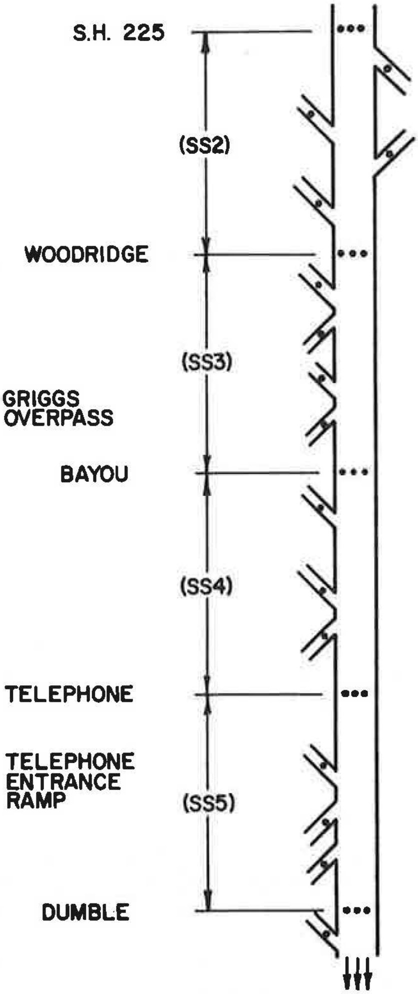

Figure 1. Location of vehicle detectors on inbound Gulf Freeway

Rainfall records were obtained from the U. S. Weather Bureau at Houston's William P. Hobby Airport and in downtown Houston. The Hobby Airport weather station is 4 miles southeast of the Freeway Surveillance and Control Center and the downtown Houston station is 4 miles northwest of the control center. Daily logs of observed weather conditions were also made at the Freeway Surveillance and Control Center.

The data did not provide information on rainfall intensity applicable to this study because the rainfall rate could vary throughout the length of the 3.5 miles of freeway and throughout the 2-hour peak period. Each day was simply classified as either "dry" or "rain." If unstable or inconsistent weather conditions existed during the peak period, or if no distinct classification was possible for a particular day, that data sample was discarded.

Capacity-Demand Considerations

The data collected on any given day will have a variation in the flow during the peak period. However, the maximum flow attained during the peak period on any given day is not always the capacity. The demand on a section must be great enough to exceed

TABLE 1

FLOW RATES AND DENSITIES ON THE INBOUND GULF FREEWAY, JUNE 25, 1968

5 MIN PERIOD ENDING	VPH AT 225	DEN IN SS2	VPH AT WOODRG	DEN IN SS3	VPH AT OVERPS	VPH AT BAYOU	DEN IN SS4	VPH AT TELEPH	DEN IN SS5	VPH AT MERGE	VPH AT CUMBLE	DATE
5	2184	18	2916	55	2256	1920	30	1296	19	1320	516	[illegible]
10	2304	22	3792	71	3792	3048	47	3576	56	3636	3216	68
15	2412	28	4320	83	4548	3888	56	3828	66	4032	3168	68
20	2844	27	4692	95	4668	4080	62	4272	78	4380	3552	2568
25	3612	46	5340	107	5220	4452	68	4728	95	4896	4116	62568
30	3600	49	5760	149	5844	5232	82	5544	118	5736	4392	62568
35	3852	54	5076	151	5388	4824	82	5352	119	5760	4704	62568
40	4200	62	5424	151	5688	5124	89	5304	112	5496	4656	62568
45	3816	70	5040	150	5664	5112	102	5472	131	5712	4920	62568
50	4152	71	5208	154	5736	5316	99	5640	138	5916	5004	62568
55	4452	78	5040	143	5808	5280	94	5760	160	6240	5364	62568
60	4488	94	4956	171	5496	5124	94	5376	158	5904	5376	62568
65	3780	101	4644	178	5700	5352	102	5460	171	5916	5124	62568
70	3516	104	4704	157	5472	5100	123	5184	186	5556	5232	62568
75	3816	102	4620	165	5220	4884	146	5208	192	5604	4992	62568
80	3588	115	4440	176	4980	4536	165	4776	176	5124	4992	62568
85	3264	110	4548	202	4812	4488	162	5076	177	5472	4668	62568
90	3948	112	3972	206	5208	4788	155	5208	189	5508	4764	62568
95	3228	99	4908	188	5316	4812	161	4896	183	5256	4800	62568
100	3804	91	4644	187	5184	4692	159	5280	178	5640	4932	62568
105	3180	84	4104	177	5196	4704	138	5208	175	5568	4656	62568
110	3480	70	4716	158	5160	4680	135	4944	192	5280	4464	62568
115	3324	42	5028	172	5136	4476	151	5052	181	5328	4392	62568
120	3732	46	4416	167	5256	4620	128	5472	182	5736	4740	62568
125	3264	35	5004	152	5316	4620	118	5316	178	5556	4392	62568
130	3374	30	4728	141	5304	4608	102	5028	197	5244	4080	62568
135	3264	28	4488	99	4884	4404	110	4920	171	5016	4320	62568
140	168	1	960	19	2064	1728	39	3576	109	3732	4536	62568

the capacity. To avoid collecting volumes of unnecessary data, the historical back-log of information on the Gulf Freeway operation was utilized in this study. Two bottlenecks were selected for this analysis. The first bottleneck, denoted Griggs overpass, is located in subsystem 3 (SS3), and the second, identified as the Telephone merge, is located in subsystem 5 (SS5).

Definition of Capacity

For a consistent basis of comparison among the days for which traffic data were determined to be suitable on the basis of weather conditions, a means of identifying the capacity for the total subsystem environment had to be established. Even with a known bottleneck in the subsystem under consideration, it would have been possible to measure demand as a maximum flow rather than capacity. It was decided to define the capacity of the freeway associated with the peak-period sample as the maximum ordinate of the best-fit flow-density curve.

For each of the 2 subsystems, a pair of values representing the flow rate, q, and the density, k, was available for each 5 minutes of operation. The first 2 and the last 2 pairs of data points were deleted to avoid bias in the sample while the computerized

TABLE 2

TRAFFIC MODEL FIT FOR SUBSYSTEM 3, JUNE 25, 1968

EN= -1.00	RSMS= 2.755	DJ= 432.26	UF=********	QM= 5408.11	A-LEVEL= 0.578729	RATIO= 1.081
EN= -0.80	RSMS= 2.597	DJ= 405.97	UF= 380.78	QM= 5418.16	A-LEVEL= 0.649487	RATIO= 1.079
EN= -0.60	RSMS= 2.461	DJ= 384.75	UF= 210.70	QM= 5429.86	A-LEVEL= 0.709336	RATIO= 1.076
EN= -0.40	RSMS= 2.349	DJ= 367.23	UF= 153.99	QM= 5442.35	A-LEVEL= 0.757408	RATIO= 1.074
EN= -0.20	RSMS= 2.261	DJ= 352.54	UF= 125.60	QM= 5455.39	A-LEVEL= 0.793474	RATIO= 1.071
EN= 0.00	RSMS= 2.197	DJ= 340.04	UF= 108.55	QM= 5468.73	A-LEVEL= 0.818542	RATIO= 1.069
EN= 0.20	RSMS= 2.158	DJ= 329.30	UF= 97.17	QM= 5482.26	A-LEVEL= 0.833101	RATIO= 1.065
EN= 0.40	RSMS= 2.142	DJ= 319.96	UF= 89.02	QM= 5495.86	A-LEVEL= 0.838861	RATIO= 1.063
EN= 0.60	RSMS= 2.151	DJ= 311.78	UF= 82.93	QM= 5509.40	A-LEVEL= 0.835471	RATIO= 1.061
EN= 0.80	RSMS= 2.185	DJ= 304.56	UF= 78.11	QM= 5522.80	A-LEVEL= 0.823025	RATIO= 1.059
EN= 1.00	RSMS= 2.243	DJ= 298.15	UF= 74.27	QM= 5536.05	A-LEVEL= 0.800473	RATIO= 1.056

OPTIMUM (CLOSEST FITTING MODEL)

EN= 0.40	RSMS= 2.142	DJ= 319.96	UF= 89.02	QM= 5495.87	A-LEVEL= 0.838841	RATIO= 1.063

Note: EN = n value used in calculations; RSMS = residual mean square (small value indicates a better fit); DJ = jam density; UF = free speed (theoretically it is infinite when n = -1); QM = maximum ordinate of Eq. 1 or calculated capacity; A-LEVEL = an acceptance level; and RATIO = maximum observed 5-minute flow rate to QM.

counting system was starting and stopping. From 24 to 30 pairs of flow-density values remained for each subsystem per record day.

The flow-density model chosen was a generalized traffic flow model as given in Eq. 1 (3). The detailed development of the model is provided in the cited reference.

$$q = k \cdot u_f \left[1 - \left(k/k_j\right)^{(n+1)/2}\right] \quad n > -1 \qquad (1)$$

The corresponding relation for traffic stream speed is given by Eq. 2.

$$u = u_f \left[1 - \left(k/k_j\right)^{(n+1)/2}\right] \quad n > -1 \qquad (2)$$

The model is a 3-parameter model: the exponent constant, n; the free speed, u_f; and the jam density, k_j. As indicated in Eqs. 1 and 2, n is restricted to a value greater than -1. Because the traffic flow data yielded only flow-density points, a method of establishing the appropriate parameters was established as follows.

The space-mean speed, u, corresponding to each pair of flow-density data points was calculated as

$$u = q/k \qquad (3)$$

which produced pairs of speed-density points. A value of n was selected an an initial value, and a least squares regression was performed with Eq. 2 to give the value of u_f and k_j for the best fit to a particular day's data sample. The residual mean square of the fitted curve to the data was calculated. A second value of n was selected and the least squares regression repeated. If the second value of n provided a better fit to the data, as indicated by a smaller residual mean square, that value of n was selected over the previous one. The process was continued using a Fibonacci search until the optimum value of n was established (4).

Substituting the values of n, u_f, and k_j thus determined in Eq. 1 provides the optimum flow-density model. The maximum ordinate (flow) of this relation is considered to be the freeway capacity for a particular subsystem for the sampled day. The ratio of the highest observed 5-minute flow rate to the calculated capacity was noted and used for subjective evaluation of the procedure.

Table 2 gives an example of fitting the traffic model to the data collected on June 25, 1968, in subsystem 3. The acceptance level is the probability of obtaining the observed data sample from a process described exactly by the flow model used. This probability is the level of confidence at which the model would be accepted. The level at which the model was considered to be acceptable was 10 percent.

For the calculations given in Table 2, the optimum flow model would be

$$q = k \cdot 89.02 \left[1 - (k/319.96)^{0.7}\right] \qquad (4)$$

or in terms of speed

$$u = 89.02 \left[1 - (k/319.96)^{0.7}\right] \qquad (5)$$

Figure 2 shows an example of a speed versus density plot with both the observed data and the optimum model curve shown. Figure 3 shows an example of flow rate versus density with both observed data and the optimum curve shown. Both Figure 2 and Figure 3 are for the June 25, 1968, sample in subsystem 3.

Acceptability of Data Samples

The results of traffic flow model fitting and analysis of acceptability of model fit are given in Table 3 for all 24 peak-period samples available. All models that fit with an acceptance level greater than 10 percent were rated "accepted" and designated with an A in the table. All samples for which the model gave only an acceptance level of 1 to 10 percent were rated "doubtful" and designated with a D. Only 11 sample days for

TABLE 3

CAPACITIES AND MODEL ACCEPTANCE LEVELS

Date	Dry/Wet	Subsystem 3		Subsystem 5	
		Capacity[a] (vpm)	Acceptance Level	Capacity[a] (vpm)	Acceptance Level
Feb. 13	Wet	4,795 D	0.0772	4,817 U	0.0000
Mar. 21	Wet	5,000 U	0.0079	4,932 U	0.0001
May 6	Dry	5,836 D	0.0404	5,917 A	0.2903
May 7	Dry	5,541 A	0.2340	5,883 A	0.2342
May 8	Wet	5,338 U	0.0000	5,792 D	0.0350
May 9	Dry	5,684 D	0.0422	5,688 D	0.0180
June 6	Dry	5,640 A	0.5199	5,933 A	0.8764
June 12	Dry	5,732 A	0.3795	5,883 A	0.9195
June 21	Wet	4,530 A	0.9494	4,685 A	0.8022
June 25	Dry	5,495 A	0.8388	5,892 A	0.9653
June 26	Wet	4,729 A	0.9602	4,733 D	0.0542
Aug. 14	Dry	5,554 U	0.0002	5,710 A	0.1134
Sept. 12	Dry	5,652 U	0.0000	5,762 D	0.0241
Sept. 23	Wet	5,140 D	0.0872	5,359 D	0.0702
Oct. 17	Dry	5,380 U	0.0000	5,520 U	0.0000
Oct. 21	Dry	5,284 A	0.8282	5,689 A	0.9901
Oct. 29	Dry	5,711 U	0.0025	5,853 A	0.5382
Oct. 30	Dry	5,340 U	0.0089	5,619 U	0.0003
Oct. 31	Dry	5,641 A	0.4463	5,708 U	0.0000
Nov. 5	Dry	5,639 A	0.1961	5,829 U	0.0000
Nov. 6	Dry	5,592 A	0.1340	12,092 U	0.0000
Nov. 7	Dry	5,595 U	0.0001	5,675 U	0.0000
Nov. 8	Wet	5,208 U	0.0000	189,554 U	0.0000
Dec. 12	Wet	4,770 A	0.9759	4,995 A	0.2576

[a]A denotes acceptable; D, doubtful; U, unacceptable.

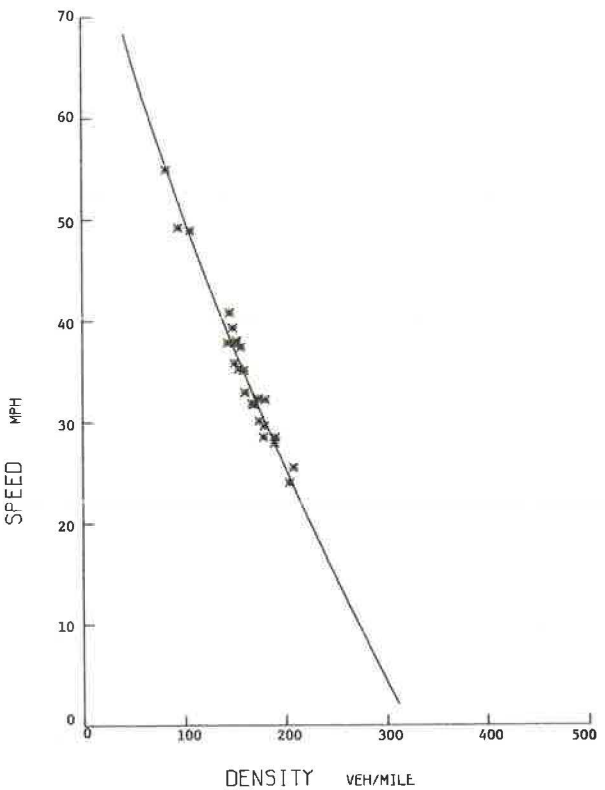

Figure 2. Speed-density relationship for subsystem 3, June 25, 1968.

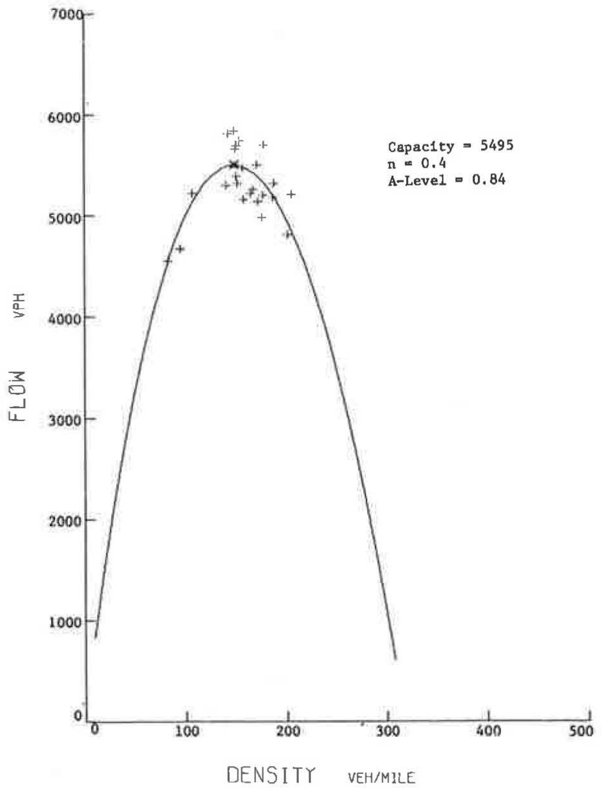

Figure 3. Flow-density relationship for subsystem 3, June 25, 1968.

subsystem 3 and 10 sample days for subsystem 5 were considered acceptable out of the original set of 24 sample days.

The high rate of disqualification of data samples may appear to indicate an inappropriate mathematical and statistical technique. However, this is not the case. The model developed was intended to provide a prediction of the capacity when only rain was a disturbance or when the weather was dry with a consistent traffic stream. Consequently, if the traffic composition changed suddenly producing a different capacity during the collection of a data sample, the increased variability would lower the acceptance of the data. Minor accidents along the freeway right-of-way, sharp variations in the intensity of rain during a peak period, or any unusual occurrence could produce fluctuations that the macroscopic flow model cannot adequately describe. Therefore, the test for acceptability was applied, and any nonuniform flow was discarded. The remaining samples could be taken to represent capacity flow under consistent comparable conditions.

ANALYSIS OF RESULTS

Results

The accepted capacity values, classified by subsystem and weather condition, are given in Table 4. It should be emphasized that these values are representative of an entire set of compatible data points, and that they survived a rigorous screening process. No value may be arbitrarily ignored as a freak, and each constitutes a very positive and definite representation of the capacity of the subsystem in question for the

TABLE 4

ACCEPTED CAPACITIES

Subsystem		Date	Capacity		
			Vehicles per Hour	Normalized	Dry/Wet
507	3	May 7	5,541	99.47	Dry
606	3	June 6	5,640	101.25	Dry
612	3	June 12	5,732	102.90	Dry
625	3	June 25	5,495	98.64	Dry
1021	3	Oct. 21	5,284	94.86	Dry
1031	3	Oct. 31	5,641	101.27	Dry
1105	3	Nov. 5	5,639	101.34	Dry
1106	3	Nov. 6	5,592	100.39	Dry
621	3	June 21	4,530	81.32	Wet
626	3	June 26	4,729	84.89	Wet
1212	3	Dec. 12	4,770	85.63	Wet
506	5	May 6	5,917	101.23	Dry
507	5	May 7	5,883	100.65	Dry
606	5	June 6	5,933	101.51	Dry
612	5	June 12	5,883	100.65	Dry
625	5	June 25	5,892	100.80	Dry
814	5	Aug. 14	5,710	97.69	Dry
1021	5	Oct. 21	5,689	97.33	Dry
1029	5	Oct. 29	5,853	100.14	Dry
621	5	June 21	4,685	80.15	Wet
1212	5	Dec. 12	4,995	85.42	Wet

conditions prevailing during the study period of approximately 2 hours during which the set of data was obtained.

In order to compare the dry weather capacities to wet weather, all the capacities were "normalized" for the 2 subsystems. This means that the subsystem 3 capacities were all reduced by the common factor necessary to result in a dry weather capacity mean of 100.00, and similarly for subsystem 5. It may be mentioned here that the dry weather capacity mean in subsystem 3 was 5,570.5, and in subsystem 5 it was 5,845.0. The subsystem 3 factor was therefore 100/5,570.5 and the subsystem 5 factor was 100/5,845. In this way all capacities could be compared to a dry weather mean of 100.00.

It can be seen that on the basis of a dry capacity of 100, the wet capacity is about 84. It is also obvious that the 16 dry weather capacities sampled all fall within a range of 94.9 to 102.9, or, a range of approximately 5 percent of the mean. Statistical methods were used on these data to establish the fact that rain has a highly significant effect on capacity, and that the wet weather capacity may be expected, with 95 percent confidence, to be between 81.2 and 85.8 percent of dry weather capacity. The dry weather capacities were all very closely bunched, so much so, in fact, that tolerance limits of 93.1 and 106.9 were calculated, within which 95 percent of the normalized dry weather capacities could be expected to lie. This provides some indication of the stability of capacity and its sensitivity to weather conditions. A range of ±7 percent of capacity is small, and it may therefore be concluded that capacity is sensitive to wet weather conditions.

Effect of Varying Acceptance Level

The question of how much these results would differ if the model acceptance level were changed may now be investigated. Table 5 gives the additional results of capacity and weather conditions that would have to be considered if the acceptance level were dropped from 10 to 1 percent. The capacity figures are normalized by application of the same multiplying factors for subsystems 3 and 5 that were used in Table 4.

It can immediately be seen that the inclusion of the capacities in Table 5 results in a bigger scatter of capacity values for each weather condition. An analysis of variance test on the entire set of results given in Tables 4 and 5 nevertheless show a highly significant difference between dry and wet weather capacities.

TABLE 5

CAPACITIES OF DOUBTFUL ACCEPTABILITY

Subsystem		Date	Capacity		
			Vehicles per Hour	Normalized	Dry/Wet
506	3	May 6	5,836	104.77	Dry
509	3	May 9	5,684	102.04	Dry
213	3	Feb. 13	4,795	86.08	Wet
923	3	Sept. 23	5,140	92.27	Wet
509	5	May 9	5,688	97.31	Dry
912	5	Sept. 12	5,762	98.56	Dry
508	5	May 8	5,792	99.09	Wet
626	5	June 26	4,733	80.98	Wet
923	5	Sept. 23	5,359	91.69	Wet

Note: Acceptance level between 1 and 10 percent.

TABLE 6

HOUSTON PRECIPITATION FREQUENCY OF OCCURRENCE

Rainfall (in.)	7-9 a.m.	4-6 p.m.	Both	
	Frequency per Year	Frequency per Year	Frequency per Year	Cumulative Frequency per Year
Trace	42.7	34.4	77.1	150.6
0-0.01	7.8	12.6	20.4	73.5
0.02-0.09	15.8	18.2	34.0	53.1
0.10-0.24	5.7	5.6	11.3	19.1
0.25-0.49	2.3	1.5	3.8	7.8
0.50-0.99	1.3	2.0	3.3	4.0
1.00-1.99	0.3	0.3	0.6	0.7
2.00 and over		0.1	0.1	0.1

Frequency of Occurrence of Rain

Because rain has been shown to have a significant effect in reducing freeway capacity, the chance that rain will occur during the peak period must be considered. It is doubtful whether any design or control planning should be modified for a capacity reduction that would rarely occur during the peak period. (Ample freeway capacity is assumed to exist in the off-peak hours.) General geographic location will be an important factor affecting frequency of rain. Most coastal areas will be subject to rain much more frequently than other inland areas. The Houston area weather records were examined to determine the frequency of peak-period rain.

From historical rainfall records, the number of times that a given amount of rain fell between specified hours in each month was calculated and accumulated for the entire year (5). Table 6 gives the average frequency for which various intensities of rain were observed during the hours from 7:00 a.m. to 9:00 a.m. and 4:00 p.m. to 6:00 p.m. in Houston. Most of the rainfalls recorded during the "wet" conditions for this research were on the order of 0.02 in. or more. Houston records indicate, then, that about 50 times per year the freeways will be operating under reduced capacity conditions due to rain. This would seem to be a high enough frequency to warrant consideration in design and control of the Houston freeways.

CONCLUSIONS

Based on the results of this research, the following conclusions can be made:

1. Rain significantly reduces freeway capacity.
2. The capacity of the freeway during rain can be expected to be between 81 and 86 percent of the dry weather capacity with 95 percent confidence.

3. Dry weather capacity is very stable as indicated by the fact that 95 percent of the dry weather capacity values could be expected to be within 7 percent of the mean observed capacity 99 percent of the time.

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