EFFECT OF RAIN ON FREEWAY CAPACITY

by

E. Roy Jones
and
Merrell E. Goolsby

Research Report Number 24-23

Freeway Surveillance and Control
Research Study Number 2-8-61-24

Sponsored by
The Texas Highway Department
in cooperation with the
U.S. Department of Transportation
Federal Highway Administration
Bureau of Public Roads

August 1969

TEXAS TRANSPORTATION INSTITUTE
Texas A&M University
College Station, Texas

ABSTRACT

Capacity of a freeway is dependent upon physical factors of the roadway, traffic factors, and environmental factors. The effect on capacity of physical and traffic factors has been extensively investigated. However, little study has been devoted to the effect on capacity of environmental factors. This investigation determined the effect of rain, one of the most common environmental disturbances, on freeway capacity.

Rainfall records and extensive traffic flow data of the Gulf Freeway Surveillance and Control Center were used to define the effect of rain on capacity. Rain was found to reduce freeway capacity to between 81% and 86% of dry weather capacity with 95% confidence.

SUMMARY

Capacity, the ability of a roadway to accommodate traffic, is one of the primary parameters Highway and Traffic Engineers must consider in the design and operation of traffic facilities. Freeway capacity is dependent upon physical features of the roadway, traffic factors, and environmental factors. The investigation described in this report quantifies the effect on freeway capacity of rain, one of the most common environmental disturbances.

The study was conducted on the Gulf Freeway in Houston utilizing extensive traffic flow data from the Data Acquisition and Control Computer System of the Gulf Freeway Surveillance and Control Center. Rainfall records from the U.S. Weather Bureau were merged with traffic data to determine the effect of rain.

Two bottlenecks of the inbound freeway were selected for analysis. Flow and density data for five-minute periods for a single peak period are adequate for fitting a mathematical traffic flow model relating flow, density, and speed. Maximum flow rate from the fitted curve is considered to be the capacity for that peak period. It was found that the capacity of the freeway during rain was between 81% and 86% of dry weather capacity with 95% confidence.

IMPLEMENTATION STATEMENT

The quantitative measurement of the capacity-reducing effect of rain has several possible applications in a freeway control system. Since freeway control systems are based, in some fashion, on the capacity-demand relationship of the freeway, refinements in the determination of capacity will be reflected in greater effectiveness and reliability of control.

An automatic freeway control system should be able to sense a change or impending change in the environment and through appropriate strategy, immediately react to the change. This form of control is preferable to that form which relies solely on measuring the effect of the environmental conditions on the traffic flow. The disadvantage in sensing the environment indirectly in this manner by sensing its effect are:

(1) The cause of the change in flow is not known and inappropriate corrective action may be taken to restore equilibrium.

(2) Some loss of efficiency will already have been suffered due to the delay in waiting for a measurable change in traffic operation.

(3) The need to take corrective action rather than providing precautionary measures in advance means that a larger margin must be used to avoid a breakdown in operation.

Flexibility in control strategies to compensate for the effect of rain on capacity can be designed into simple control systems which are based on historical traffic data as well as the more complex systems using real-time traffic inputs and digital computers. The use of digital computer easily utilize real-time inputs of environmental conditions, thence control modifications based on these inputs. Such a system might have instrumented rain detectors to transmit the presence of rain in the control area, at which time immediate control modifications based on predicted capacity reductions would be made in the controller.

Drew, et. al.[1] considered freeway control systems using a multilevel approach. An application of these findings could be applied at the highest level of control, called the "self-organizing function." It is at this level that self-learning by the computer can occur. Given adequate inputs of environmental conditions and bottleneck flow rates the computer can re-evaluate, update and actually "learn" the capacities of the bottlenecks under each environmental category. The values could be applied to modify control when environmental changes occur.

TABLE OF CONTENTS

INTRODUCTION

Capacity of a section of freeway is dependent upon a number of variables which fall into three classifications: (1) physical factors, such as roadway width, clearance, and grade; (2) traffic factors, such as distribution of vehicle types or driver characteristics; (3) environmental factors, such as lighting conditions, rain, fog, and ice. From these classifications it can be seen that capacity is not a fixed value dependent upon physical constraints alone, but varies with temporal changes in traffic and environmental factors. Only the physical factors contributing to capacity remain constant.

The effect on capacity of the physical and traffic factors has been extensively investigated.[2] Moskowitz and Newman reported in 1963 that the effects of weather and lighting conditions were not treated at all in their research on freeway capacity and that this represented a deficiency in knowledge at that time.[3] A survey of technical literature indicates little has been done to fill this void in knowledge.

The advent of freeway control as an operational reality has emphasized the need for a clear, quantitative determination of freeway capacity under all conditions. Although no unified approach to the design of freeway control systems has been generally accepted, the basic control techniques are not likely to change appreciably. The fundamental purpose of freeway control is to limit the traffic demand on the facility to some percentage of the capacity. If the demand exceeds the capacity, even for a short period of time, a breakdown in flow occurs, congestion sets in, and the rate of flow reduces to a value lower than that which the facility could support under free flow conditions. Thus the success of a control system depends to some extent on its ability to respond to changes in the environment which affect its capacity.

The objective of this investigation is to determine the effect on capacity of rain, which is one of the most frequently experienced environmental disturbances.

STUDY OUTLINE

The facility chosen for this capacity study was the Gulf Freeway in Houston, since it is the only facility in existence capable of the extensive data collection desired. The Gulf Freeway Surveillance and Control system is a product of six years of research. It now serves as both a research facility and as an operational freeway control system. This research was conducted by Texas Transportation Institute for the Texas Highway Department in cooperation with the Bureau of Public Roads, U. S. Department of Transportation.

Central control equipment includes a digital computer (Process Control and Data Acquisition System) and ancillary equipment. The computer is used for real-time control of the freeway during peak periods of the day, and to collect and store records of traffic flow and density. These records are collected by minute for each of four closed subsystems of detection on the inbound roadway during the morning peak period, 6:30-8:30 AM.

Measures of flow and density for a single peak period are adequate data for fitting a mathematical traffic flow model relating flow, density and speed. Statistical methods were used to fit and test the acceptability of the model. The model yields a maximum flow value which is defined, for the purpose of this report, as the capacity for that day. Identifying the peak of the curve relating flow rate and density to capacity is valid only if demand was sufficient to exceed capacity. This condition would be satisfied if the data points used to obtain each curve of best fit included points at or near the peak with densities higher than "cricital" or optimum density. This requirement was satisfied by the data used.

Rainfall records were obtained from the Weather Bureau Station at William P. Hobby airport, located four miles southeast of the control center and from the station in downtown Houston, four miles northwest of the control center. These data were used to estimate the likelihood of precipitation during peak periods to determine the degree of application of results of this study. In addition, logs kept in the control center were used to verify weather conditions for each day.

The relationship of rainfall intensity to capacity could not be identified because of the limitations created by varying rainfall rates both in time and space. Only an extensive long term study could hope to reveal this relationship. For this reason, days were simply classed as dry or rain. Where no clear-cut classification was possible, the data were not utilized. Further, the statistical tests applied to the data tended to discount those days where consistent weather conditions did not prevail through the entire peak period.

ANALYSIS AND RESULTS

Processing of the data consisted of two main steps. The first was the processing of traffic data for a particular section of freeway with the objective of estimating the capacity of that section on each morning of operation. The second stage was the linking of this capacity to the weather condition prevailing during the collection of data to determine if there was any significant effect of rain on capacity.

Basic Traffic Data

The collected data consisted of one minute vehicle detector counts taken in a 3.5-mile section of the inbound freeway. The location of these detectors and the subdivision of the freeway into four subsystems numbered 2 to 5 are illustrated in Figure 1.

These one-minute counts were converted into flow rates and average densities for five-minute periods. The average densities were determined in units of vehicles per mile for all three lanes in each subsystem. The average 5-minute rates of flow were expressed as vehicles per hour. An example of the 5-minute average densities and flow rates is shown in Table 1.

The validity of equating maximum flow rates with capacity depended upon the use of traffic data containing densities high enough to force the flow rate downward. To increase this likelihood, the traffic operations at two potential bottlenecks were selected for study. The first bottleneck, known as the "Griggs overpass" is located in subsystem 3, and the second,

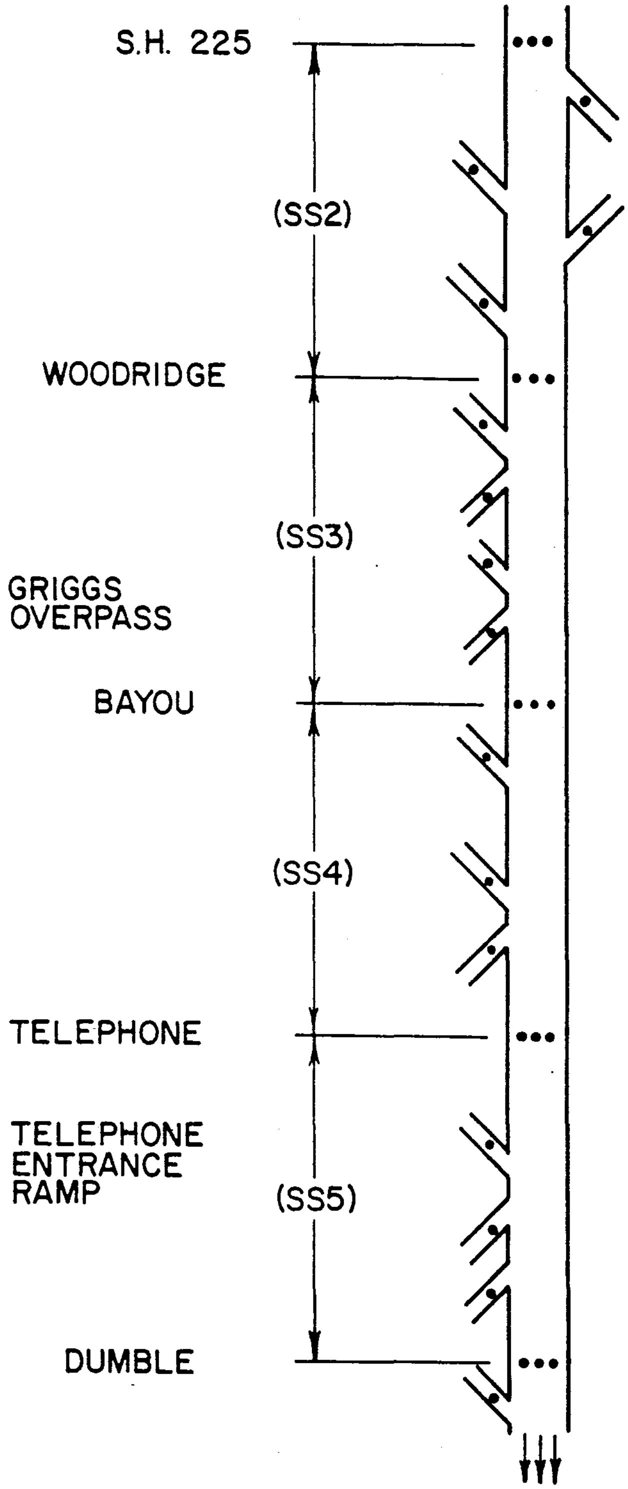

FIG. I. LOCATION OF VEHICLE DETECTORS ON INBOUND GULF FREEWAY

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	62568
10	2304	22	3792	71	3792	3048	47	3576	56	3636	3216	62568
15	2412	28	4320	83	4548	3888	56	3828	66	4032	3168	62568
20	2844	27	4692	95	4668	4080	62	4272	78	4380	3552	62568
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	39	5004	152	5316	4620	118	5316	178	5556	4392	62568
130	3324	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

TABLE 1. FLOW RATES AND DENSITIES ON THE INBOUND GULF FREEWAY, JUNE 25, 1968.

known as the "Telephone merge" is situated in subsystem 5 in the vicinity of Telephone Road.

Model

For each of the two subsystems a pair of values representing flow rate, q, and density, k, was available for each five minutes of operation. The first and last two pairs of points were discarded to avoid errors due to starting and stopping of the system counting, leaving 24 to 30 pairs of q and k values in each subsystem on each day of records. The space-mean-speed, u, corresponding to each pair of values was then calculated as:

$$u = q/k \qquad (1)$$

The model chosen for this analysis is the generalized macroscopic traffic flow model.[4] Detailed development of the model is provided in the cited reference. This model is stated as:

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

or

$$u = u_f \{1 - (k/k_j)^{(n+1)/2}\} \qquad n>-1 \qquad (3)$$

For a value of the exponent, n, this model relates the flow rate q, or speed, u, to density, k. The two parameters, u_f, and k_j, are known as the "free-speed" and "jam density" respectively. The value of the exponent parameter is restricted to be greater than -1.

The model was used in the following manner. A value of n was selected as an initial value and a least-squares regression analysis was performed with equation (3) to give the value of u_f and k_j for the best fit to a particular day's data. The residual mean square of the fitted curve to the data was calculated. A second value of n was then selected and the regression analysis repeated. If this value of n resulted in a closer fit, as indicated by a smaller residual mean square value, that value of n was chosen as preferable to the first value. This process was repeated using a Fibonacci Search Technique[4] until the optimum value of n was determined.

Substituting the values of n, u_f, and k_j thus determined in equation (3) provides the optimum flow-density model for the particular freeway subsystem and day. The maximum value of q in equation (2) was determined and reported as the capacity. The ratio of the highest observed 5-minute flow rate to the capacity was determined to provide a subjective comparison of the model capacity to the maximum observed flow rate.

Acceptability of Model

The model error was statistically tested to provide an indication of how closely the optimum model fitted the data. Under the hypothesis that the model error was zero, the probability of the occurrance of the data was determined and reported as the acceptance level. This probability value is in effect, the significance level, or level of confidence, at which the model would be accepted. The variance of speed for a fixed density used in this determination was determined on a very large sample of data from which a few very divergent results were excluded. This resulted in a rigorous test with 231 degrees of freedom. The level at which the model was selected as acceptable was chosen as 10%, but the sensitivity of the final conclusions to this choice was investigated.

Example of Traffic Model Output

Tables 2 and 3 show the result of fitting models to the data for the morning of June 25, 1968, in subsystem 3 and 5 respectively. The variable names used in these computer print-outs are:

EN = The n value used in the model equation.

RSMS = Residual mean square, a measure of how closely the model fitted the data. A smaller value indicated a closer fit, with the optimum model having the smallest value.

DJ = Jam Density

UF = Free Speed. (This is theoretically infinite when n = -1.)

QM = Maximum Flow Rate, or the crest of the model curve. This is the capacity.

A-Level = Acceptance level as described above. A measure of the acceptability of the model.

Ratio = Ratio of max observed 5-minute flow rate to QM.

In the case of subsystem number 3 (Table 2), the equation of the optimum model would be:

$$q = k \cdot 89{\cdot}02 \ \{1 - (k/319{\cdot}96)^{0.7}\}$$

or

$$u = 89{\cdot}02 \ \{1 - (k/319{\cdot}96)^{0.7}\}$$

DATE= 62568   SUB-SYSTEM NUMBER 3

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=	5442.36	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=	1.066
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=	82.90	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=	1.058
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) IS AS SET OUT BELOW

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

TABLE 2. TRAFFIC MODEL FIT FOR SUB-SYSTEM 3, JUNE 25, 1968.

DATE= 62568 SUB-SYSTEM NUMBER 5

EN= -1.00	RSMS= 4.611	DJ= 468.11	UF=********	QM= 5657.47	A-LEVEL= 0.077208	RATIO= 1.103
EN= -0.80	RSMS= 4.117	DJ= 432.54	UF= 373.48	QM= 5662.07	A-LEVEL= 0.143890	RATIO= 1.102
EN= -0.60	RSMS= 3.671	DJ= 404.73	UF= 209.25	QM= 5672.64	A-LEVEL= 0.241876	RATIO= 1.100
EN= -0.40	RSMS= 3.269	DJ= 382.40	UF= 154.53	QM= 5687.05	A-LEVEL= 0.368291	RATIO= 1.097
EN= -0.20	RSMS= 2.913	DJ= 364.07	UF= 127.18	QM= 5704.25	A-LEVEL= 0.509629	RATIO= 1.094
EN= 0.00	RSMS= 2.603	DJ= 348.77	UF= 110.77	QM= 5723.42	A-LEVEL= 0.646675	RATIO= 1.090
EN= 0.20	RSMS= 2.334	DJ= 335.80	UF= 99.84	QM= 5744.03	A-LEVEL= 0.763665	RATIO= 1.086
EN= 0.40	RSMS= 2.108	DJ= 324.69	UF= 92.03	QM= 5765.71	A-LEVEL= 0.850779	RATIO= 1.082
EN= 0.60	RSMS= 1.924	DJ= 315.06	UF= 86.18	QM= 5788.08	A-LEVEL= 0.908493	RATIO= 1.078
EN= 0.80	RSMS= 1.779	DJ= 306.64	UF= 81.63	QM= 5810.91	A-LEVEL= 0.928657	RATIO= 1.074
EN= 1.00	RSMS= 1.673	DJ= 299.22	UF= 77.99	QM= 5834.05	A-LEVEL= 0.948726	RATIO= 1.070

EN= 1.00	RSMS= 1.673	DJ= 299.22	UF= 77.99	QM= 5834.05	A-LEVEL= 0.948726	RATIO= 1.070
EN= 2.00	RSMS= 1.654	DJ= 272.40	UF= 67.06	QM= 5949.90	A-LEVEL= 0.951740	RATIO= 1.049
EN= 3.00	RSMS= 2.349	DJ= 255.77	UF= 61.56	QM= 6060.18	A-LEVEL= 0.757669	RATIO= 1.030
EN= 4.00	RSMS= 3.566	DJ= 244.56	UF= 58.22	QM= 6161.48	A-LEVEL= 0.271201	RATIO= 1.013
EN= 5.00	RSMS= 5.149	DJ= 236.55	UF= 55.95	QM= 6253.00	A-LEVEL= 0.037519	RATIO= 0.998
EN= 6.00	RSMS= 6.979	DJ= 230.58	UF= 54.29	QM= 6334.96	A-LEVEL= 0.001080	RATIO= 0.985
EN= 7.00	RSMS= 8.970	DJ= 225.99	UF= 53.00	QM= 6408.00	A-LEVEL= 0.000021	RATIO= 0.974
EN= 8.00	RSMS= 11.064	DJ= 222.36	UF= 51.97	QM= 6472.92	A-LEVEL= 0.000000	RATIO= 0.964
EN= 9.00	RSMS= 13.222	DJ= 219.44	UF= 51.10	QM= 6530.42	A-LEVEL= 0.000000	RATIO= 0.956
EN= 10.00	RSMS= 15.418	DJ= 217.05	UF= 50.36	QM= 6581.27	A-LEVEL= 0.000000	RATIO= 0.948

OPTIMUM (CLOSEST FITTING MODEL) IS AS SET OUT BELOW

EN= 1.50	RSMS= 1.561	DJ= 284.05	UF= 71.43	QM= 5892.25	A-LEVEL= 0.965336	RATIO= 1.059

TABLE 3. TRAFFIC MODEL FIT FOR SUB-SYSTEM 5, JUNE 25, 1968.

Figures 2 to 5 are computer plots of speed (u) against density (k) and flow rate (q) against density for both subsystems on the same day. The observed data points are shown, and the optimum model curve is also drawn on each plot.

Further examples of plotted traffic data output are shown in figures 6 to 9. These figures give an indication of the range of model parameters used and indicate that the optimum models did, in fact, fit the data well when the acceptance level was high.

Results

The condensed results of capacity, acceptance level of the model, and weather condition are shown in Table 4. Those capacities with an acceptance level greater than 10% are shown with an A for accept, and those with an acceptance level between 1% and 10% are shown with a D for doubtful. From an original source of 24 days, only 11 days in subsystem 3 and 10 days in subsystem 5 were acceptable at the 10% level.

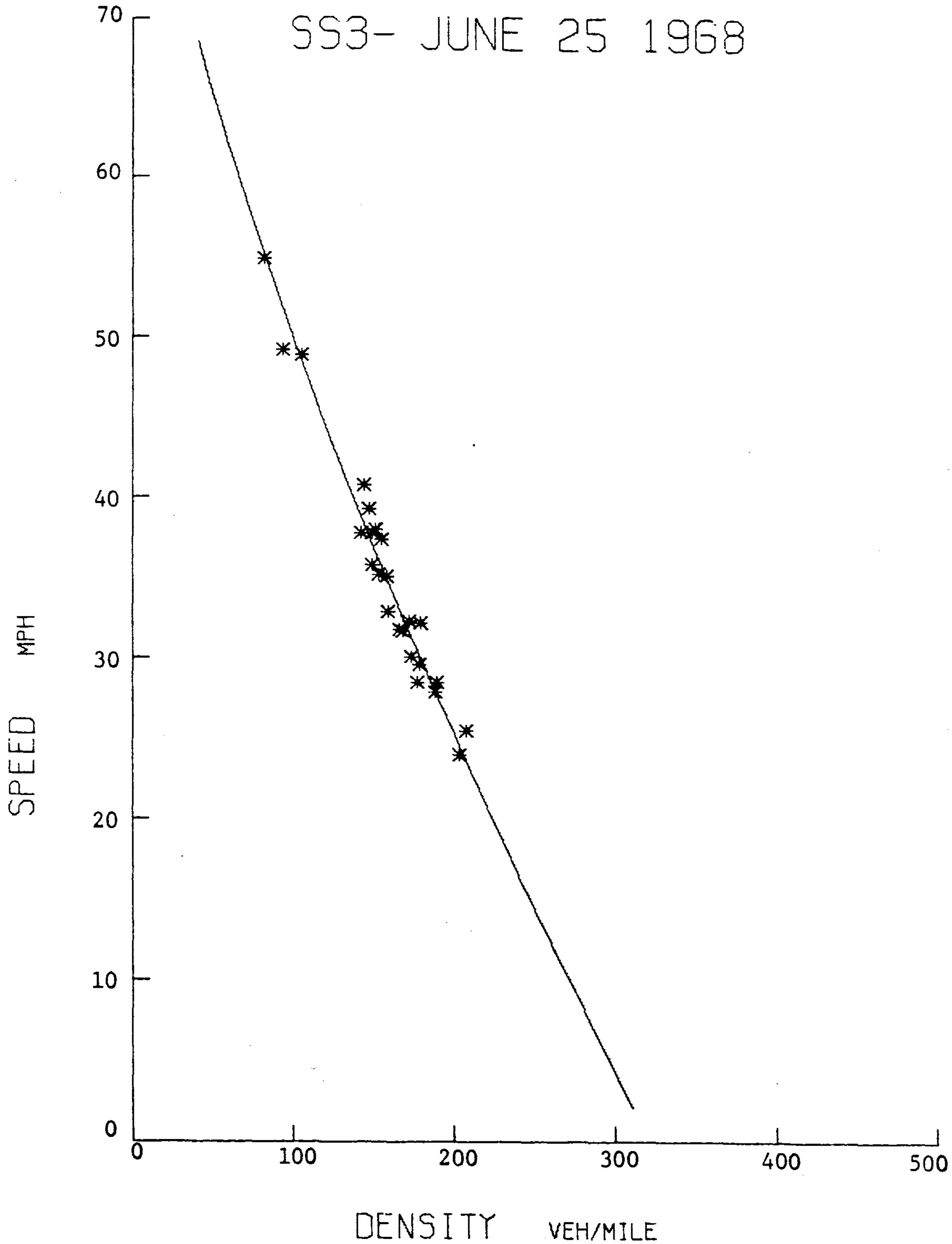

FIGURE 2. SPEED-DENSITY RELATIONSHIP FOR SUB-SYSTEM 3, JUNE 25, 1968.

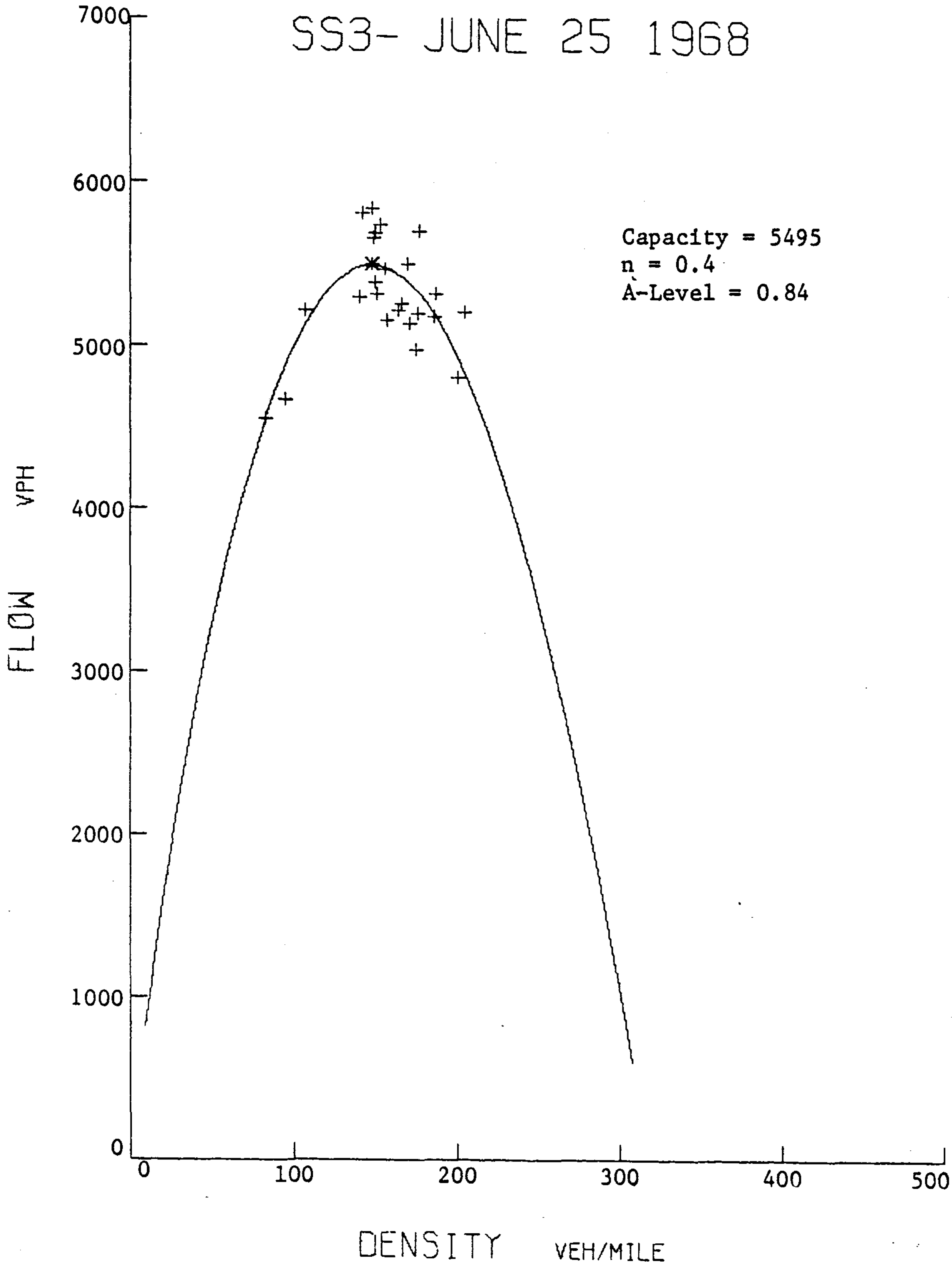

FIGURE 3. FLOW-DENSITY RELATIONSHIP FOR SUB-SYSTEM 3, JUNE 25, 1968.

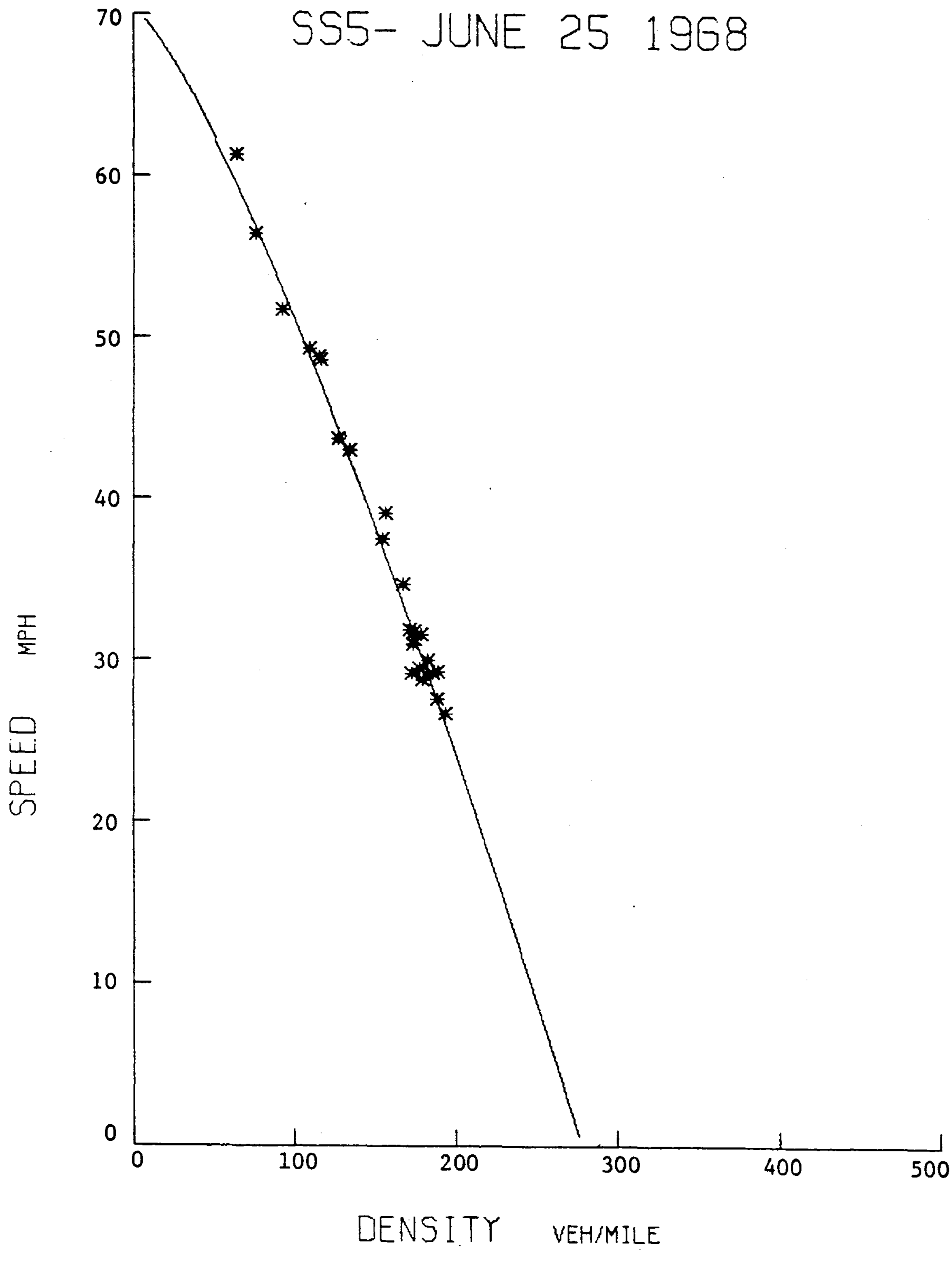

FIGURE 4. SPEED-DENSITY RELATIONSHIP FOR SUB-SYSTEM 5, JUNE 25, 1968.

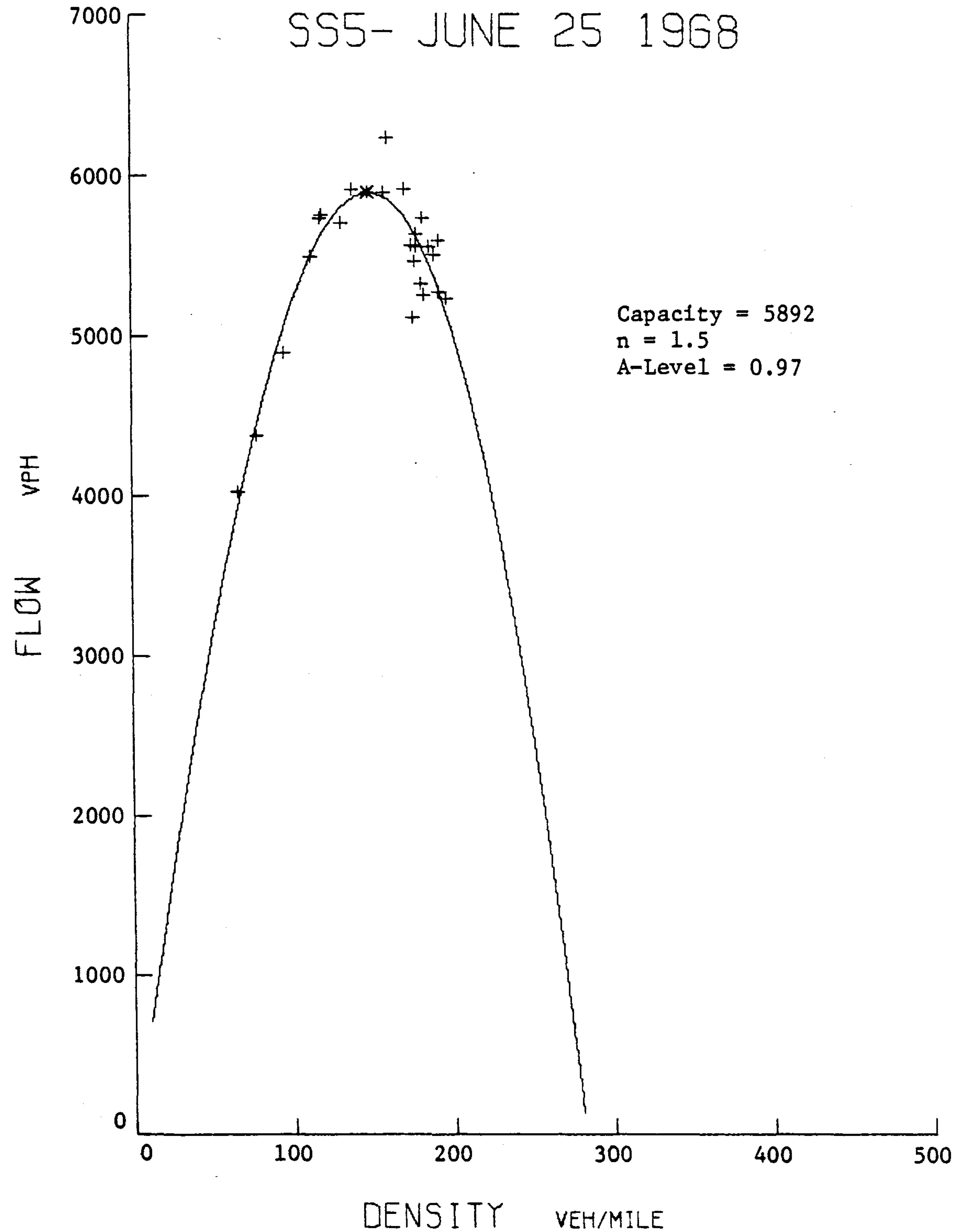

FIGURE 5. FLOW-DENSITY RELATIONSHIP FOR SUB-SYSTEM 5, JUNE 25, 1968.

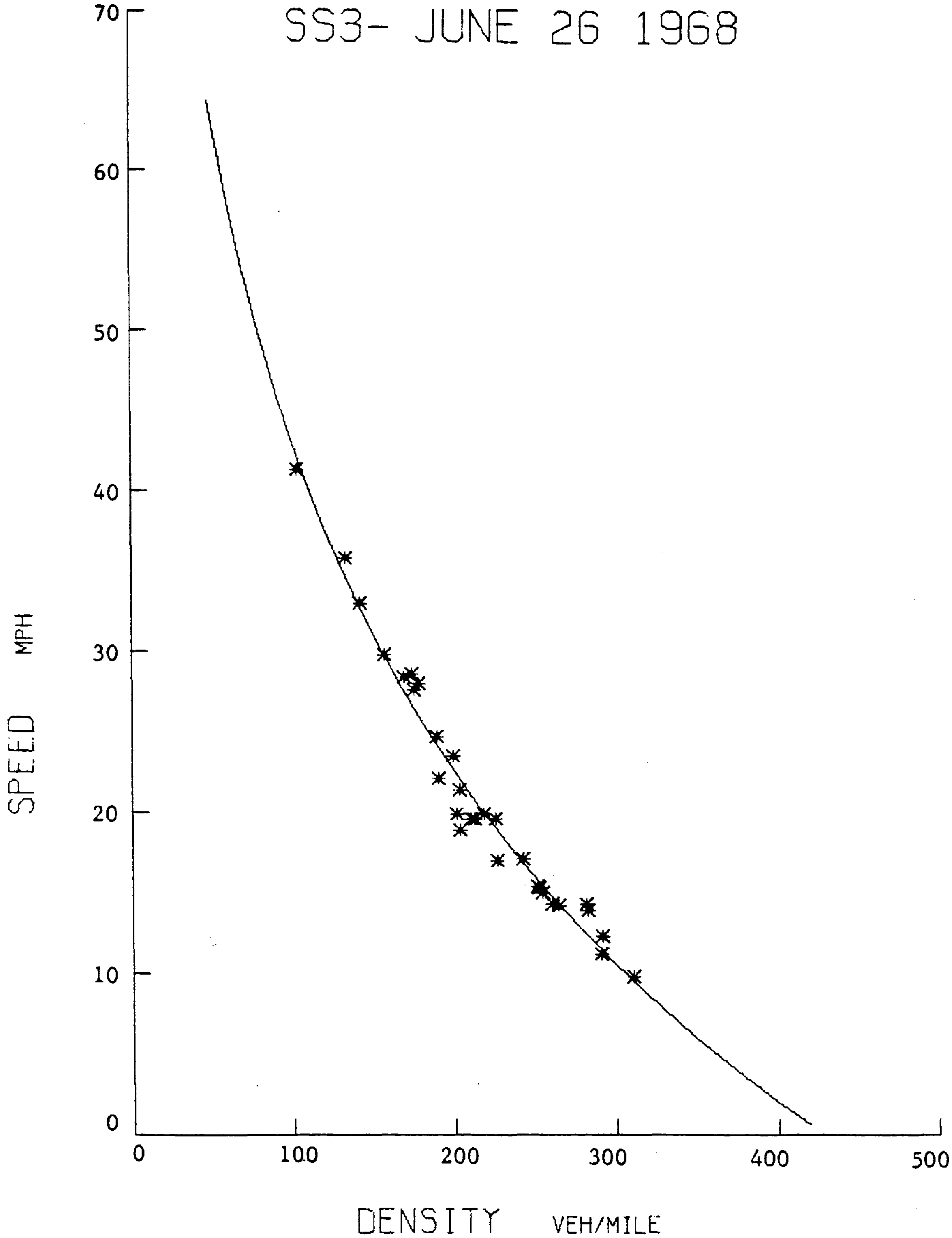

FIGURE 6. SPEED-DENSITY RELATIONSHIP FOR SUB-SYSTEM 3, JUNE 26, 1968.

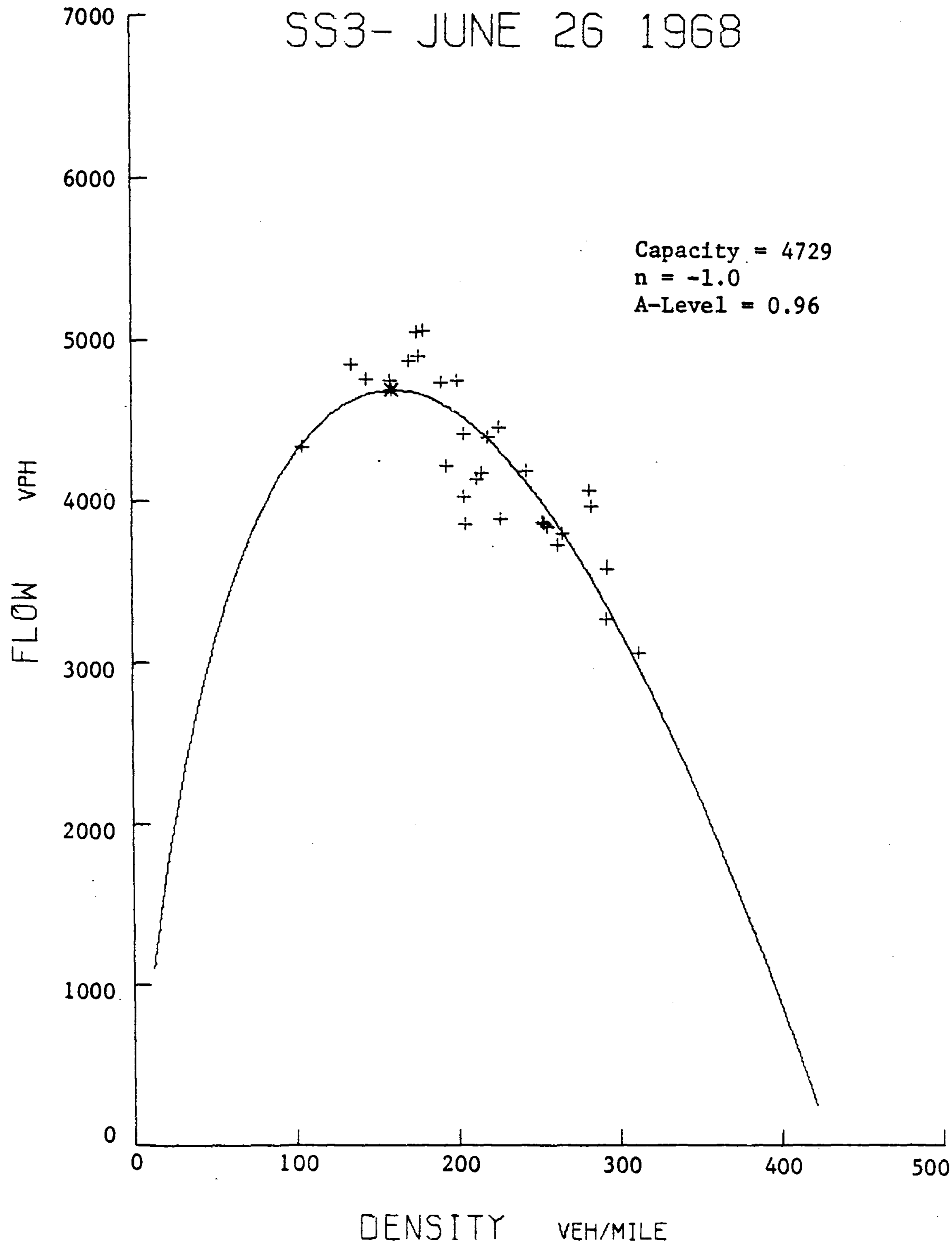

FIGURE 7. FLOW-DENSITY RELATIONSHIP FOR SUB-SYSTEM 3, JUNE 26, 1968.

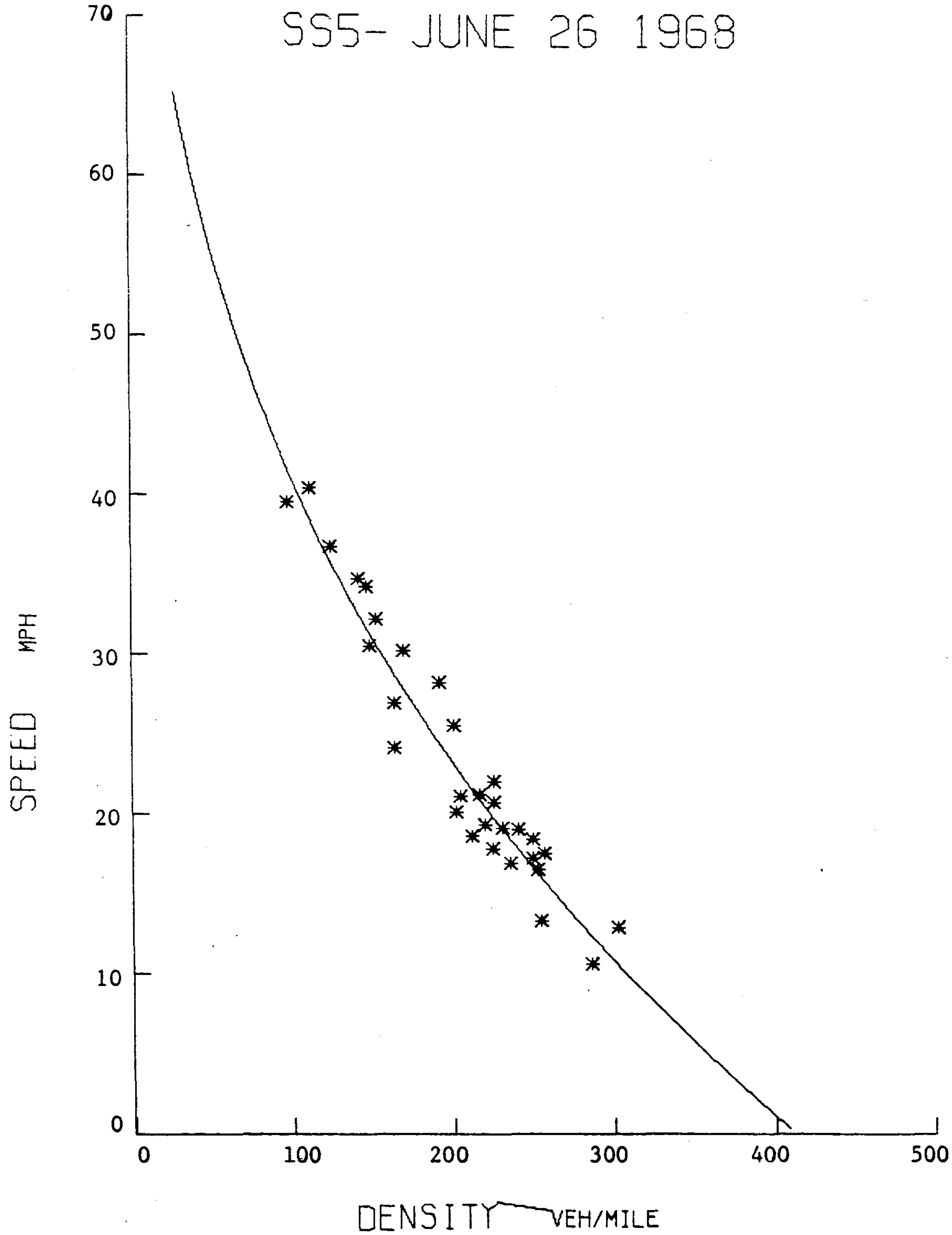

FIGURE 8. SPEED-DENSITY RELATIONSHIP FOR SUB-SYSTEM 5, JUNE 26, 1968.

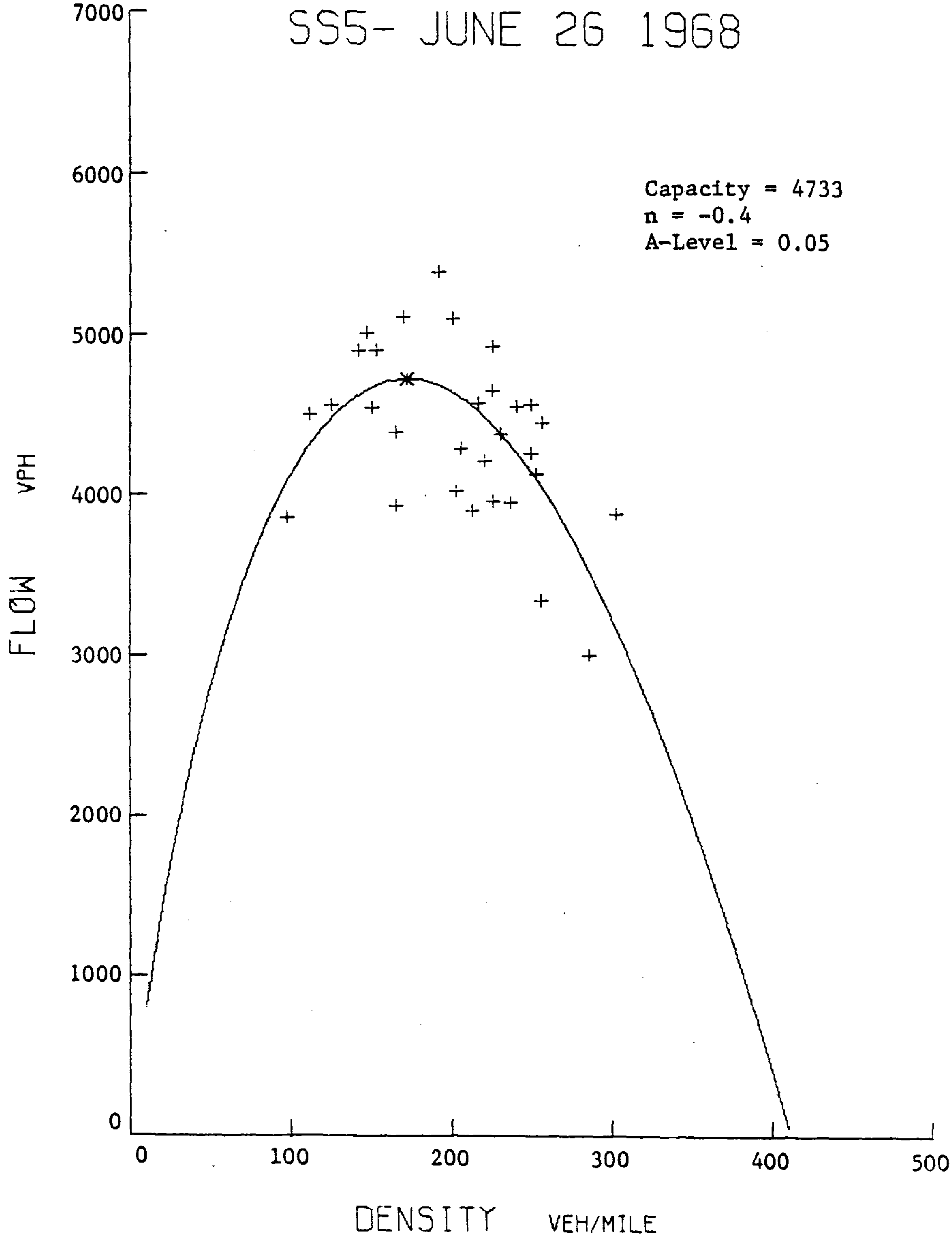

FIGURE 9. FLOW-DENSITY RELATIONSHIP FOR SUB-SYSTEM 5, JUNE 26, 1968.

TABLE 4. CAPACITIES AND MODEL ACCEPTANCE LEVELS

Date	Dry/Wet	SUB-SYSTEM 3 Capacity VPM	SUB-SYSTEM 3 Acceptance Level	SUB-SYSTEM 5 Capacity VPM	SUB-SYSTEM 5 Acceptance Level
Feb 13	Wet	4795 D	.0772	4817 U	.0000
Mar 21	Wet	5000 U	.0079	4932 U	.0001
May 6	Dry	5836 D	.0404	5917 A	.2903
May 7	Dry	5541 A	.2340	5883 A	.2342
May 8	Wet	5338 U	.0000	5792 D	.0350
May 9	Dry	5684 D	.0422	5688 D	.0180
June 6	Dry	5640 A	.5199	5933 A	.8764
June 12	Dry	5732 A	.3795	5883 A	.9195
June 21	Wet	4530 A	.9494	4685 A	.8022
June 25	Dry	5495 A	.8388	5892 A	.9653
June 26	Wet	4729 A	.9602	4733 D	.0542
Aug 14	Dry	5554 U	.0002	5710 A	.1134
Sept 12	Dry	5652 U	.0000	5762 D	.0241
Sept 23	Wet	5140 D	.0872	5359 D	.0702
Oct 17	Dry	5380 U	.0000	5520 U	.0000
Oct 21	Dry	5284 A	.8282	5689 A	.9901
Oct 29	Dry	5711 U	.0025	5853 A	.5382
Oct 30	Dry	5340 U	.0089	5619 U	.0003
Oct 31	Dry	5641 A	.4463	5708 U	.0000
Nov 5	Dry	5639 A	.1961	5829 U	.0000
Nov 6	Dry	5592 A	.1340	12092 U	.0000
Nov 7	Dry	5595 U	.0001	5675 U	.0000
Nov 8	Wet	5208 U	.0000	89554 U	.0000
Dec 12	Wet	4770 A	.9759	4995 A	.2576

(A denotes acceptable; D, doubtful; U, unacceptable)

DISCUSSION OF RESULTS

The general attrition of data due to its apparent unacceptability in fitting the model might lead the reader to the false conclusion that the theoretical model used is inappropriate. No mathematical model can perfectly describe the reality which it represents, and the sophistication of the model chosen will depend upon what aspects of reality it is desired that it represent.

A model was desired in this study which would adequately permit the determination of capacity from the flow density relationship. Any model chosen to fit traffic data on such a plane is subject to certain limitations. The first limitation already mentioned when discussing rainfall intensity is that the model is required to fit points which represent traffic operation over a period of time, in this case approximately two hours. With records of vehicle flow rates and densities, even the most sophisticated model could not cope with a large change in, for example, truck percentages which alter the capacity. Similarly high intensity rain for a short period during the two hours could have the same effect. Accidents could also cause such a mixture of points for different conditions.

This resulted in the rejection of data where the conditions affecting flow rates were not uniform. This unacceptability of data applied irrespective of the degree of sophistication of the model chosen. A bias in favor of those data where conditions were uniform is exactly what is required by the objectives of this study. This study is interested only in data taken when the conditions affecting capacity could be related to the capacity itself. The fact that the model did not reflect reality when conditions were variable is part of the data screening process, and does not reflect upon the worth of the model.

The accepted capacity values, classified by subsystem and weather condition are shown in Table 5. It should be emphasized that these values are representative of an entire set of compatible data points, and that they have 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 conditions prevailing during the study period of approximately two hours during which the set of data was obtained.

To compare the dry weather and wet weather capacities, all the capacities in each subsystem were "normalized." This means that the capacities were all reduced by the factor necessary to result in a dry weather capacity mean of 100. The dry weather mean in subsystem 3 was 5570.5, and in subsystem 5 it was 5845.0. The subsystem 3 factor was therefore 100/5570.5 and the subsystem 5 factor was 100/5845.0. In this way all capacities could be compared to a dry weather mean of 100.

It can be seen that on the basis of a dry weather capacity of 100, the wet weather capacity is about 84. The sixteen dry weather capacities sampled fall within a range of 94.8 to 102.9, or a range of approximately 5% of the mean. Statistical methods were used on these

TABLE 5. ACCEPTED CAPACITIES

Sub-System	Date	CAPACITY V.P.H.	CAPACITY Normalized	Dry/Wet
3	May 7	5541	99.47	Dry
3	June 6	5640	101.25	Dry
3	June 12	5732	102.90	Dry
3	June 25	5495	98.64	Dry
3	Oct 21	5284	94.86	Dry
3	Oct 31	5641	101.27	Dry
3	Nov 5	5639	101.34	Dry
3	Nov 6	5592	100.39	Dry
3	June 21	4530	81.32	Wet
3	June 26	4729	84.89	Wet
3	Dec 12	4770	85.63	Wet
5	May 6	5917	101.23	Dry
5	May 7	5883	100.65	Dry
5	June 6	5933	101.51	Dry
5	June 12	5883	100.65	Dry
5	June 25	5892	100.80	Dry
5	Aug 14	5710	97.69	Dry
5	Oct 21	5689	97.33	Dry
5	Oct 29	5853	100.14	Dry
5	June 21	4685	80.15	Wet
5	Dec 12	4995	85.42	Wet

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% confidence, to be between 81.2 and 85.8% of dry weather capacity. The dry weather capacities were all very closely bunched, so much so, that tolerance limits of 93.1 to 106.9 were calculated, within which 95% 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.

The question of how much these results would differ if the model acceptance level were changed may now be investigated. Table 6 shows the additional results of capacity and weather conditions which would have to be considered if the acceptance level were changed from 10% to 1%. The capacity figures are normalized by application of the same multiplying factors for subsystem 3 and 5 which were used in Table 5.

It can immediately be seen that the inclusion of the additional capacity measurements in Table 6 results in a bigger scatter of capacity values for each weather condition. An analysis of variance test on the entire set of results shown in Tables 5 and 6 nevertheless shows a highly significant difference between dry and wet weather capacities.

Having established that rain has a significant and drastic effect on capacity, the question regarding the likelihood of rain during the peak hours may be considered. It is hardly worthwhile providing protective measures against an event which may occur with negligable probability.

TABLE 6. CAPACITIES OF DOUBTFUL ACCEPTABILITY
(Acceptance Level Between 1% and 10%)

Sub-System	Date	CAPACITY V.P.H.	CAPACITY Normalized	Dry/Wet
3	May 6	5836	104.77	Dry
3	May 9	5684	102.04	Dry
3	Feb 13	4795	86.08	Wet
3	Sept 23	5140	92.27	Wet
5	May 9	5688	97.31	Dry
5	Sept 12	5762	98.56	Dry
5	May 8	5792	99.09	Wet
5	June 26	4733	80.98	Wet
5	Sept 23	5359	91.69	Wet

From a ten-year rainfall record in Houston,[6] the number of occasions on which a certain amount of rain fell between certain hours was determined. The average frequency for various intensities of rain recorded during the hours 7-9 a.m. and 4-6 p.m. in Houston, is shown as Table 7. For example, the number of times that 0.25 inches or more of rain was observed during these hours was on the average of eight times per year.

Most of the rainfall recorded during the "wet" conditions for this research were greater than 0.02 inches. This amount is likely to occur about 50 times per year in Houston, summing morning and evening peak periods. This would seem to be a high enough frequency to warrant consideration in the design and control of Houston freeways.

TABLE 7. HOUSTON PRECIPITATION. FREQUENCY OF OCCURRENCE

	7 - 9 a.m.	4 - 6 p.m.	BOTH	
	Frequency/ Year	Frequency/ Year	Frequency/ Year	Cumulative Frequency/ Year
TRACE	42.7	34.4	77.1	150.6
.00 - .01"	7.8	12.6	20.4	73.5
.02 - .09"	15.8	18.2	34.0	53.1
.10 - .24"	5.7	5.6	11.3	19.1
.25 - .49"	2.3	1.5	3.8	7.8
.50 - .99"	1.3	2.0	0.6	4.0
1.00 - 1.99"	0.3	0.3	0.6	0.7
2.00 +		0.1	0.1	0.1

CONCLUSIONS

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

1. Rain significantly reduces freeway capacity.
2. The capacity of the freeway during rain can be expected to be 81% to 86% of the dry weather capacity with 95% confidence.
3. Dry weather capacity is very stable. Ninety-five percent of the dry weather capacity values can be expected to fall within 7% of the mean observed capacity 99% of the time.
4. The frequency of rain during the peak periods in Houston is on the order of fifty times per year.

REFERENCES

1. Drew, D., Brewer, K., Buhr, J., Whitson, R., "Multilevel Approach Applied to the Design of a Freeway Control System," Presented at 48th Annual Meeting of Highway Research Board, Washington, 1969.

2. Highway Research Board Committee on Highway Capacity, "Highway Capacity Manual," Special Report 87, 1965.

3. Moskowitz, Karl and Newman, Leonard, "Notes on Freeway Capacity," Highway Research Report 27, 1963.

4. Drew, Donald R., "Traffic Flow Theory and Control," McGraw-Hill, New York, 1968.

5. Wilde, Douglas J., "Optimum Seeking Methods," Prentice-Hall Inc. 1964.

6. U.S. Weather Bureau, "Climatography of the U.S. No. 40-41. Climatic Guide, Houston-Galveston, Texas Area," U.S. Government Printing Office.