Study of Freeway Bottlenecks in Texas

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Observations of flow rates much higher than 2,000 passenger cars per hour per lane and the recent revision of the multilane highway chapter in the *Highway Capacity Manual* have led to questioning the current value of freeway capacity and the speed-flow relationship. An analysis of free-flow and queue discharge flow rates at three freeway bottlenecks in Texas found less variability in queue discharge flow rates than in free-flow flow rates. Average free-flow flow rates ranged from 2,096 to 2,210 vehicles per hour per lane (vphpl) across all lanes, whereas queue discharge flow rates averaged approximately 2,175 vphpl for the study sites. In addition, higher flows did not occur in free-flow conditions in all cases. As a result of lane interaction, some lanes are prematurely transitioned into queue discharge without reaching high flow rates in free-flow conditions.

During the past decade, much attention has been given to freeway capacity and the relationship of speed, flow, and density for freeway bottlenecks. Freeway capacity plays a critical role in the planning, design, and operation of freeways in general and urban freeways in particular. As a result of steadily increasing congestion in urban areas throughout the United States, traffic engineers and transportation planners have identified problems associated with the freeway capacity numbers given in the 1985 *Highway Capacity Manual* (HCM) and the corresponding speed-flow relationship (*1*). Many studies have concluded that flows measured on freeways are frequently greater than the values given as capacity. A study by Hurdle and Datta (*2*) in 1983 concluded that the value of 2,000 passenger cars per hour per lane (pcphpl) was still a good estimate of capacity. A more recent study by Agyemang-Duah and Hall (*3*) concluded that the capacity flow rate was approximately 2,300 pcphpl. A study by Urbanik et al. (*4*) found peak 15-min flow rates between 2,100 and 2,300 vehicles per hour per lane (vphpl) at four sites in Texas.

In addition to the measurement of high flow rates, many studies have concluded that a reduction in capacity occurs once a queue forms. Hall and Agyemang-Duah concluded that the flow rate dropped from 2,300 to 2,200 pcphpl in queue discharge conditions (*3,5*). If two capacities exist, a possible problem exists with the use of the peak 15-min flow because it would give a flow that may not be sustainable at higher demand levels where queue discharge occurs.

Although many studies on freeway capacity have been done, a good understanding of the characteristics of flow during free-flow and queue discharge has not been achieved. The characteristics of flow at freeway bottlenecks, whether a reduction in flow exists once a queue forms, the shape of the speed-flow relationship, and recommendations regarding capacity are examined in this paper. Because the definition of

capacity plays a significant role in the determination of the value to use as capacity, the maximum sustainable flow will be the focus of this paper. Maximum sustainable flow is the maximum flow rate that can be maintained for an indefinite period with sufficient demand. For capacity to be useful, it is important that it be sustainable and repeatedly achievable.

STUDY SITES

Data were collected at three study sites. A schematic of each study site is shown in Figures 1, 2, and 3. The primary study site that was used to evaluate the operation at freeway bottlenecks was on US-290 in Houston, Texas. This study site was chosen because of the frequent occurrence of queues during the p.m. peak period.

The other two study sites were on I-410 in San Antonio, Texas, and at the merge of I-35 and US-67 in Dallas, Texas. These two study sites were chosen to validate the flow characteristics found at the US-290 site. These locations were chosen because of the occurrence of congestion during a.m. peak periods.

RESULTS OF ANALYSIS OF US-290

Data Collection

Data were collected for 15 days at the US-290 study site. The data were collected for 2 to 3 hr on each day using pairs of inductive loops in each traffic lane.

Analysis of Flows at US-290 Study Site

To be consistent with existing convention, 15-min peak flows were measured for each of the sample days. The average peak 15-min flow rates are given in Table 1. The flow rates in Table 1 represent the peak 15-min flow rates during the study period across all lanes for the 15 samples. Individual lanes can have higher peak 15-min flow rates occurring at different times.

Although truck traffic was present, no attempt was made to adjust for truck passenger car equivalents in the preliminary analysis. Truck percentages averaged 3.0 percent for all lanes combined. The highest percentages were in the outside lane (Lane 3), which averaged 5.3 percent trucks, whereas the inside lane (Lane 1) had the lowest average truck percentage, with 0.7 percent. These truck percentages reflect the truck traffic for the study periods.

Although peak 15-min flow rates are the existing convention detailed by the 1985 HCM, it is likely that they are not

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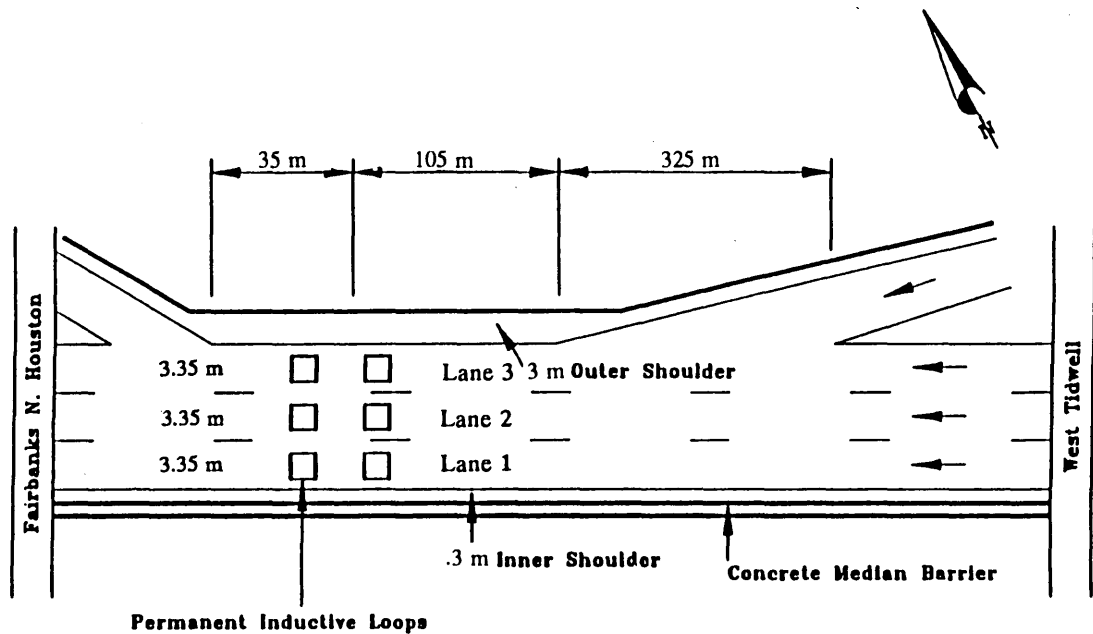
FIGURE 1 US-290 at Tidwell study site.

sustainable. The two-capacity hypothesis asserts that two separate capacities exist: one during free-flow conditions and one when demand exceeds capacity, creating queue discharge conditions. Therefore, distinguishing between regions is necessary to ensure that a measurement does not contain data from both regions at the same time.

To compare the characteristics of flow before and during the period when demand exceeds capacity, the point at which

demand exceeds the service rate of the bottleneck was identified. Demand is considered to exceed the service rate when vehicle speed is controlled by the service rate of the bottleneck, thereby making vehicles wait to resume their desired speed. The excess demand generates queues and produces queue discharge flow. The point at which a rapid drop in 30-sec average speed occurs, which is shown conceptually in Figure 4, was determined to be the beginning of queue dis-
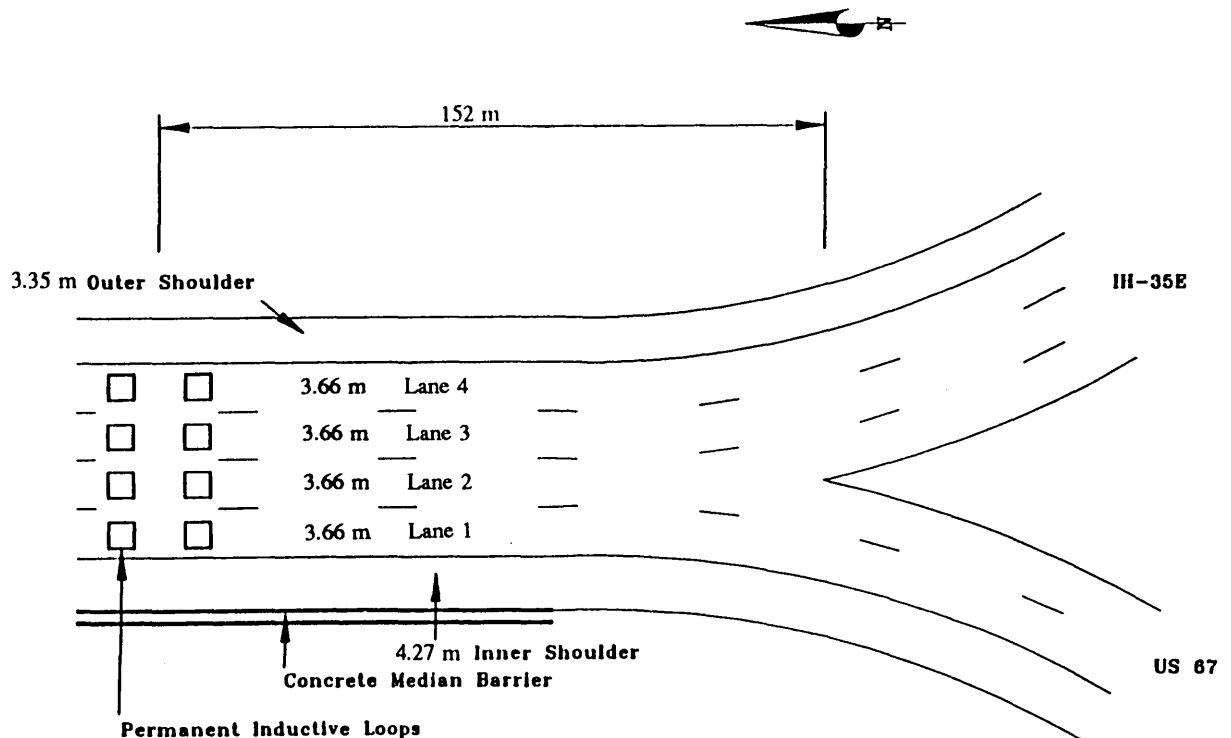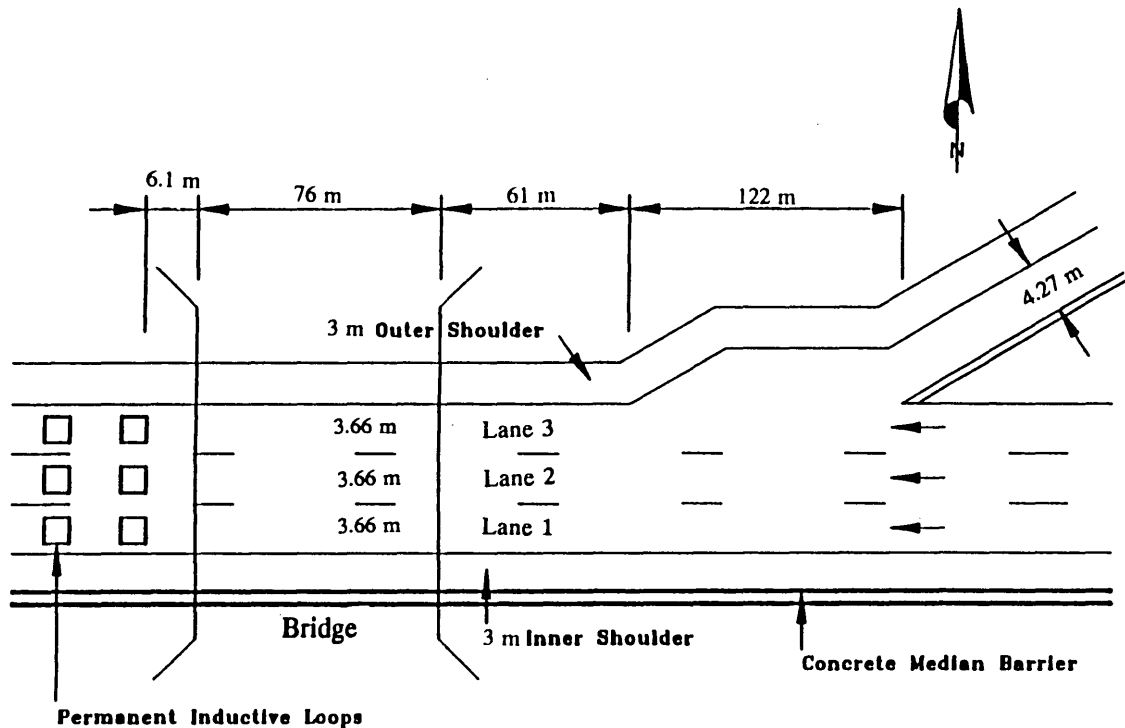

FIGURE 2 I-35/US-67 study site.

FIGURE 3 I-410 study site.

charge. Vehicles are forced to a lower rate of speed than previously desired under prevailing conditions. The following three time periods were used in the analysis:

- The 5 min immediately before the speed drop (free flow);
- The 5 min immediately after the speed drop (queue discharge); and

- The entire period after speed drop until end of queue discharge, formation of a downstream queue, or the end of data collection (queue discharge).

These time periods in relation to a typical speed profile are illustrated in Figure 4. The flow rates were calculated from the average headways during each interval. In most cases the

TABLE 1 Peak 15-min Flow Rates Across All Lanes at US-290 at Tidwell

| Highway	Observation	Peak 15-Minute Flow Rate (vphpl)			
		Lane 1	Lane 2	Lane 3	Average
U.S. 290	1	2336	2256	2348	2313
	2	2320	2200	2140	2220
	3	2300	2244	2456	2333
	4	2380	2240	2060	2227
	5	2288	2172	2180	2213
	6	2368	2204	2312	2295
	7	2260	2224	2120	2201
	8	2228	2196	2228	2217
	9	2220	2268	2132	2207
	10	2384	2256	2188	2276
	11	2496	2244	2172	2304
	12	2252	2220	2348	2273
	13	2408	2344	2156	2303
	14	2248	2356	2028	2211
	15	2312	2240	2068	2207
	Average	2320	2244	2196	2253
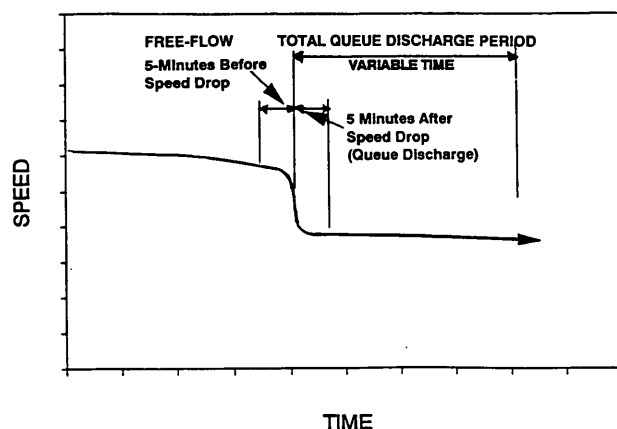
FIGURE 4 Time intervals used for analysis, typical speed profile.

speed drop occurred at the same time in all lanes, but for consistency between lanes the location of the speed drop for each sample was determined on the basis of highest flow lane (Lane 1 at the US-290 site).

Statistical Analysis of Speed Drop

A statistical analysis of the speed drop was performed in two steps. To determine whether a significant change in flow characteristics occurred after the speed drop, an F-ratio was calculated to compare the variances of headways during the 5-min intervals before and after the speed drop. A t-test was then performed to determine whether significant changes in mean headways occur after the speed drop. In using both the F-ratio and the t-test, it was assumed that the sample mean headways were independent and the headways within them have a normal distribution. These assumptions are considered valid because of the large sample of headways and the central limit theorem, which states that as sample size increases, the distribution of sample means approaches normality.

The F-ratio indicated that, for the most part, the two time periods have unequal variances. The variance before the speed drop was significantly higher than the variance after the speed drop for all 15 samples for Lane 1, for 9 samples for Lane 2, and for 10 samples for Lane 3. Because the variances were significantly different in several cases, the mean headways before and during queue discharge were compared using a t-test approximation for significance of difference between two means with different variances. The results of this t-test indicated that only three samples in Lane 1, two samples in Lane 2, and six samples in Lane 3 had statistically different mean headways before the speed drop compared with after the speed drop. Therefore, most samples did not experience a statistically significant change in mean flow after the speed drop. Because of the high variance in headways and corresponding flows, a large change is required to be statistically significant.

Average Flows for all Samples Combined

To evaluate the characteristics of flows between days, statistics were calculated for the mean flow rates for the 15 sample days. Individual flow rates for each sample were calculated from mean headways. The statistics for the sample flows are given in Table 2.

Table 2 gives the means, standard deviations, and a 95 percent confidence interval on the means for each time interval for the 15 days on which data were collected. The confidence interval assumes that the distribution of sample means follows a normal distribution, which should be applicable because a relatively large sample size was used.

The average flows show some interesting trends. Whereas the mean average flow rate across all lanes does not change much for the 5-min period before the speed drop compared with the 5-min period after the speed drop during queue discharge, the distribution of traffic across the lanes does change. In Lane 1 the mean traffic volume substantially increased in queue discharge. The opposite occurred in Lane 3, where the

TABLE 2 Statistics for Daily Averages for US-290 at Tidwell

Time Period	Statistic	Lane 1	Lane 2	Lane 3	Average
5-min Before Speed Drop (Free-Flow)	Average Flow (vphpl)	2076	2002	2210	2096
	Std Dev.	136	159	187	132
	95% CI (+/-)	ˋ75	88	104	65
5-min After Speed Drop	Average Flow (vphpl)	2266	2035	1989	2097
	Std. Dev.	145	134	193	115
	95% CI (+/-)	80	74	107	64
Total Queue Discharge	Average Flow (vphpl)	2246	2161	2090	2166
	Std. Dev.	81	68	101	67
	95% CI (+/-)	45	38	56	37

average volume decreased after the speed drop in queue discharge. This could be explained by the fact that in free-flow conditions Lane 1 has not reached its maximum flow and operates at very high speeds while Lane 3 is already becoming congested. When Lane 3 becomes congested and slows down even further, traffic merges into Lanes 2 and 1 and subsequently drops the speed and transitions the flow into queue discharge conditions. Therefore, if the maximum flow occurs in free-flow conditions, it would not be seen in Lane 1 because Lane 1 transitioned from free flow with a flow rate below maximum flow directly to queue discharge.

The analysis of means points out another problem with using free-flow conditions to obtain a maximum sustainable flow rate. Although a maximum flow rate in free-flow conditions exists, in certain lanes it may never be reached, and therefore it would be impossible to achieve. For example, suppose Lane 1 had a maximum flow of 2,400 vehicles per hour (vph), but because of the turbulence created by Lanes 2 and 3, the flow rate in Lane 1 transitioned directly from 2,076 to 2,266 vph in queue discharge as the data suggest. The flow rate of 2,400 vph would never be reached and therefore could not be considered the maximum flow rate.

Although it appears that for individual samples the variance decreased in queue discharge, the variance among samples (standard deviation squared) remained high in the 5-min period after the speed drop. One explanation for this occurrence is the way in which the boundary of the free-flow and queue discharge conditions was chosen. As shown in Figure 4, the boundary was determined on the basis of the speed drop. As can be seen in Figure 5 for Lane 1, a rapid speed drop into what appears to be queue discharge conditions does not occur in all samples. To investigate the effects of samples that did not appear to drop directly into queue discharge, the samples that appeared to drop directly into queue discharge were evaluated. The results of the evaluation of samples that had rapid speed drops into queue discharge indicate that the variance (and standard deviation) between samples decreases in the 5-min interval after the speed drop.

Speed-Flow Relationship

Figure 6 shows the speed-flow plots for all samples combined for each lane. Five-min averages were used for the plots. The lines represent the estimated shape of the speed-flow relationship on the basis of the data. The ends of the lines are equal to the average total queue discharge flow. Note that some data points include downstream congestion, also shown in Figure 6.

The hypothesized speed-flow relationship resulting from the analysis is plotted in Figure 7, showing that the operational characteristics of each individual site determine the capacity. Because of lane interaction, when Lane 3 transitions into queue discharge the other lanes quickly follow without reaching their theoretical maximum flow. As mentioned previously, this transition may be nearly instantaneous in some cases. The dashed lines show the hypothesized shape of the end section of the speed-flow relationships in Lanes 1 and 2, assuming Lane 3 does not break down and prematurely transition Lanes 1 and 2 into queue discharge.
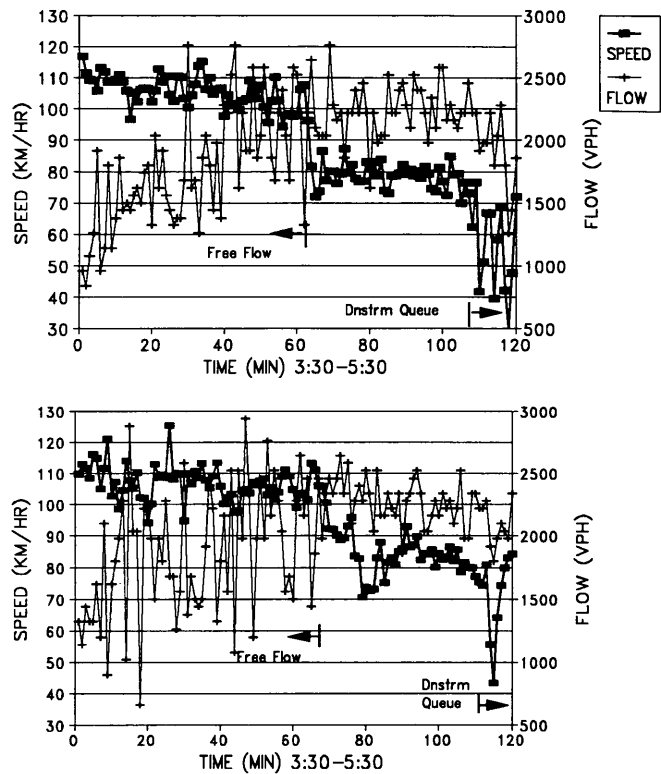

FIGURE 5 Types of speed drops during transition to queue discharge, 1 min, Lane 1: *top*, rapid transition (sample 2); *bottom*, unstable transition (sample 6).

Results of US-290 Analysis

From the analysis of the US-290 site the following observations can be made:

- The variance in flow decreases after the speed drop.
- The flow rate in Lane 3 decreased after the speed drop while flow rates in Lanes 1 and 2 increased, indicating that when Lane 3 transitions into queue discharge, Lanes 1 and 2 also transition to queue discharge.
- The transition to queue discharge can occur nearly instantaneously or over a longer period of time.
- Because of the variability and instability of flow during free-flow conditions and in the direct vicinity of the speed drop, use of these regions as maximum sustainable flow and capacity might not be practical.

COMPARISON WITH OTHER BOTTLENECK SITES

Analysis of Flows at Validation Sites

To verify the results of the analysis for the US-290 site, data from the I-410 and I-35/US-67 sites were collected. Data were collected for 4 days at the I-410 site and 3 days at the I-35/US-67 site. Because one sample at the I-410 site was taken during a rainy morning, only three samples were used in the analysis. The peak 15-min flow rates for each of these sites are given in Table 3.
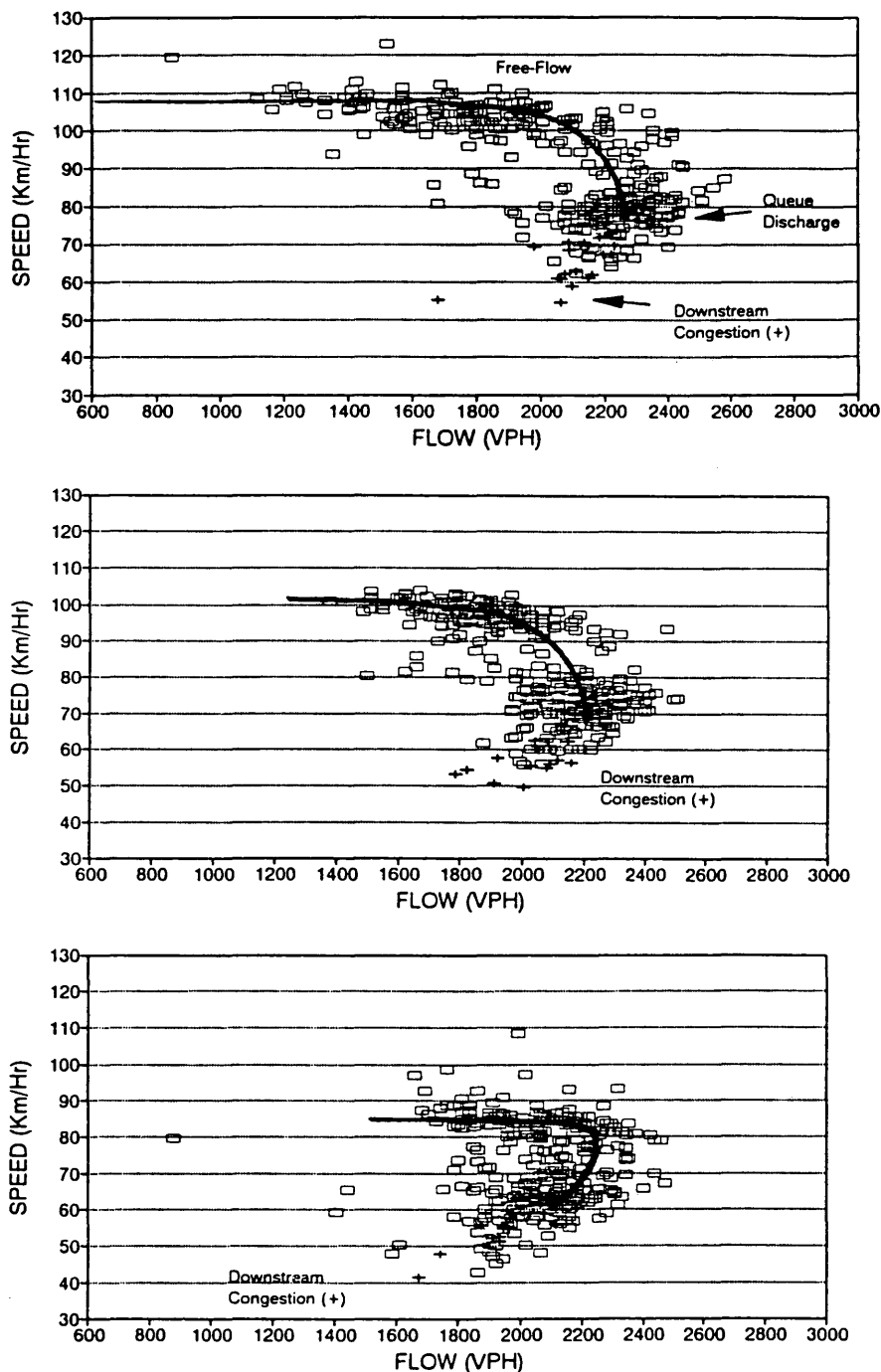
FIGURE 6 Speed-flow plots for US-290 study site, 5-min averages: *top*, Lane 1; *middle*, Lane 2; *bottom*, Lane 3.

The peak 15-min flow rates show some apparent differences between the two study sites as well as the US-290 study site. A comparison of flow rates for individual lanes indicated that the median lane (Lane 1) is the highest flow lane for all the sites and is predominant for the I-410 and the I-35/US-67 sites. These two sites have very large peak 15-min flows of 2,496 and 2,492 vph. The lowest flows tend to be in the outside lanes, which are merge lanes for the US-290 and I-410 sites but not for the I-35/US-67 site.

The average calculated flow rates for the 5 min before the speed drop, 5 min after the speed drop, and entire time during congested conditions are given in Table 4. Truck percentages averaged 1.7 percent at the I-35/US-67 sites and 2.1 percent at the I-410 site.

The I-410 site, which is similar to the US-290 site, had much different flow rates and distribution of traffic across lanes. At the US-290 site the outside lane had the highest volume before the speed drop, indicating that it reached its maximum flow
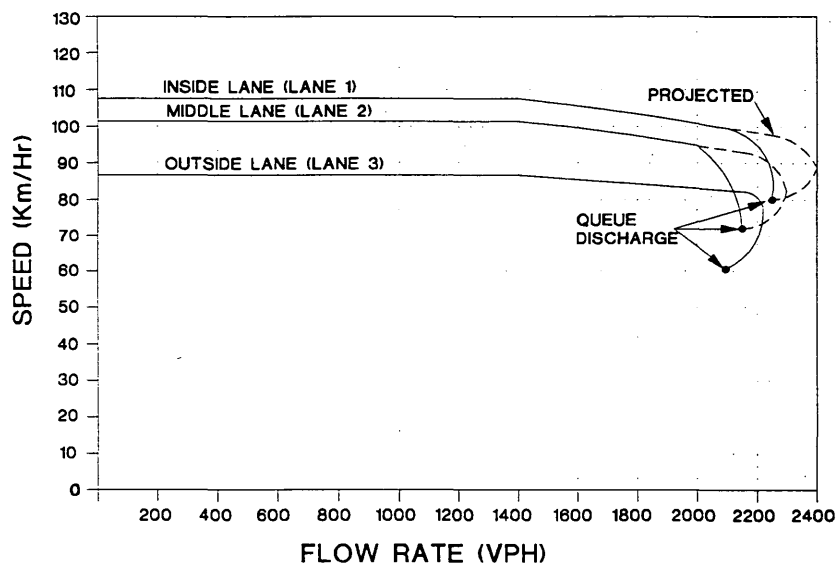
FIGURE 7   Speed-flow relationship for US-290 study site.

TABLE 3   Peak 15-min Flow Rates Across All Lanes

Highway	Observation	Peak 15 Minute Flow Rate (vphpl)				
		Lane 1	Lane 2	Lane 3	Lane 4	Average
U.S. 290	Average	2320	2244	2196	-	2253
I-410	1	2376	2212	1856	-	2148
	2	2476	2196	1856	-	2176
	3	2636	2096	1688	-	2140
	Average	2496	2168	1800	-	2155
I-35/US 67	1	2480	2180	2144	2124	2232
	2	2588	2320	2224	1856	2247
	3	2408	2240	2324	2172	2286
	Average	2492	2247	2231	2051	2255

TABLE 4   Comparison of Flow Rates Before and After Speed Drop at All Sites

Sample	5 Minutes Before Speed Drop (vphpl)					5 Minutes After Speed Drop (vphpl)					Entire Period After Speed Drop (vphpl)				
	Lane 1	Lane 2	Lane 3	Lane 4	Avg	Lane 1	Lane 2	Lane 3	Lane 4	Avg	Lane 1	Lane 2	Lane 3	Lane 4	Avg
U.S. 290															
Average	2076	2002	2210	-	2096	2266	2035	1989	-	2097	2246	2161	2090	-	2166
Std Dev	136	159	187	-	132	145	134	193	-	115	81	68	101	-	67
95% CI	75	88	104	-	65	80	74	107	-	64	45	38	56	-	37
I-410															
Average	2463	2166	1856	-	2162	1839	1790	1585	-	1738	1954	1864	1667	-	1828
Std Dev	285	89	188	-	153	164	14	49	-	46	180	95	46	-	68
95% CI	709	222	466	-	381	400	34	121	-	113	448	236	115	-	169
I-35/US 67															
Average	2679	2341	2134	1687	2210	2542	2238	2231	1856	2217	2396	2154	2172	2017	2185
Std Dev	128	79	254	182	137	90	75	56	86	70	47	56	41	80	47
95% CI	318	197	631	452	341	222	185	139	213	174	117	140	103	199	118

before the other lanes and broke down first. After the speed drop the inside lane increased in flow whereas the outside lane decreased in volume. A much different situation occurred at the I-410 site. All of the lanes decreased in flow after the speed drop. Further study found that the speed drop at the I-410 site was caused by downstream congestion that resulted in the flow reduction. Because of a downstream slowdown, the speed drop at the study site did not occur independently and the queue discharge flows were controlled by the downstream bottleneck. Although the site was affected by downstream congestion, the inside lane had a very high flow before congestion set in. This shows that it is possible to reach much higher flow rates under free-flow conditions than measured at the US-290 site in the inside lanes. This agrees with the hypothesis that the inside lane at the US-290 site prematurely dropped into queue discharge before reaching the maximum flow under free-flow conditions.

The most interesting results came from the I-35/US-67 site. At this site, traffic volumes were substantially higher than those measured at the US-290 site. The average flows before the speed drop were 2,679, 2,341, 2,134, and 1,687 vph for Lanes 1, 2, 3, and 4, respectively. After the speed drop the flow decreased in Lanes 1 and 2 and increased in Lanes 3 and 4, indicating that Lanes 1 and 2 broke down and transitioned Lanes 3 and 4 into queue discharge. This corresponds to the results and the model for US-290, which determined that once a lane or lanes break down, the other lanes are also subsequently broken down. Figure 8 shows the comparison of the flow rates between the I-35/US-67 site and the US-290 site for the 5 min before the speed drop and the total queue discharge period.

The flow rates for the I-35/US-67 site show the same statistical trends as the US-290 data. The standard deviations in mean flows between days tended to be lower after the speed
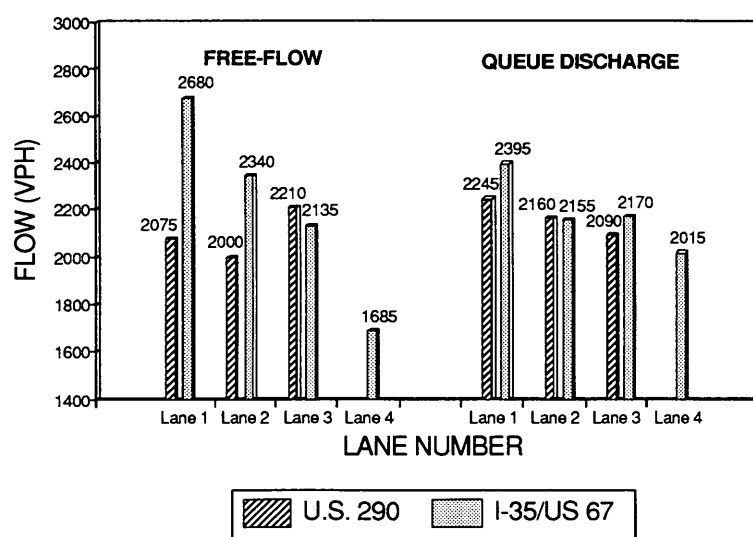

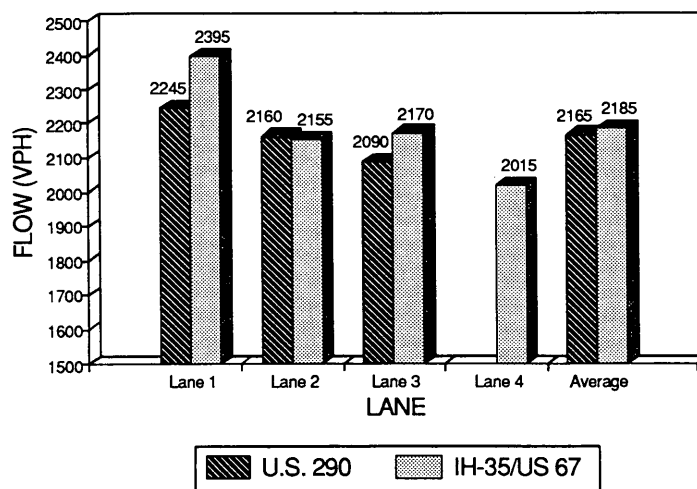FIGURE 8   Flow-rate comparison between I-35/US-67 and US-290 at Tidwell.

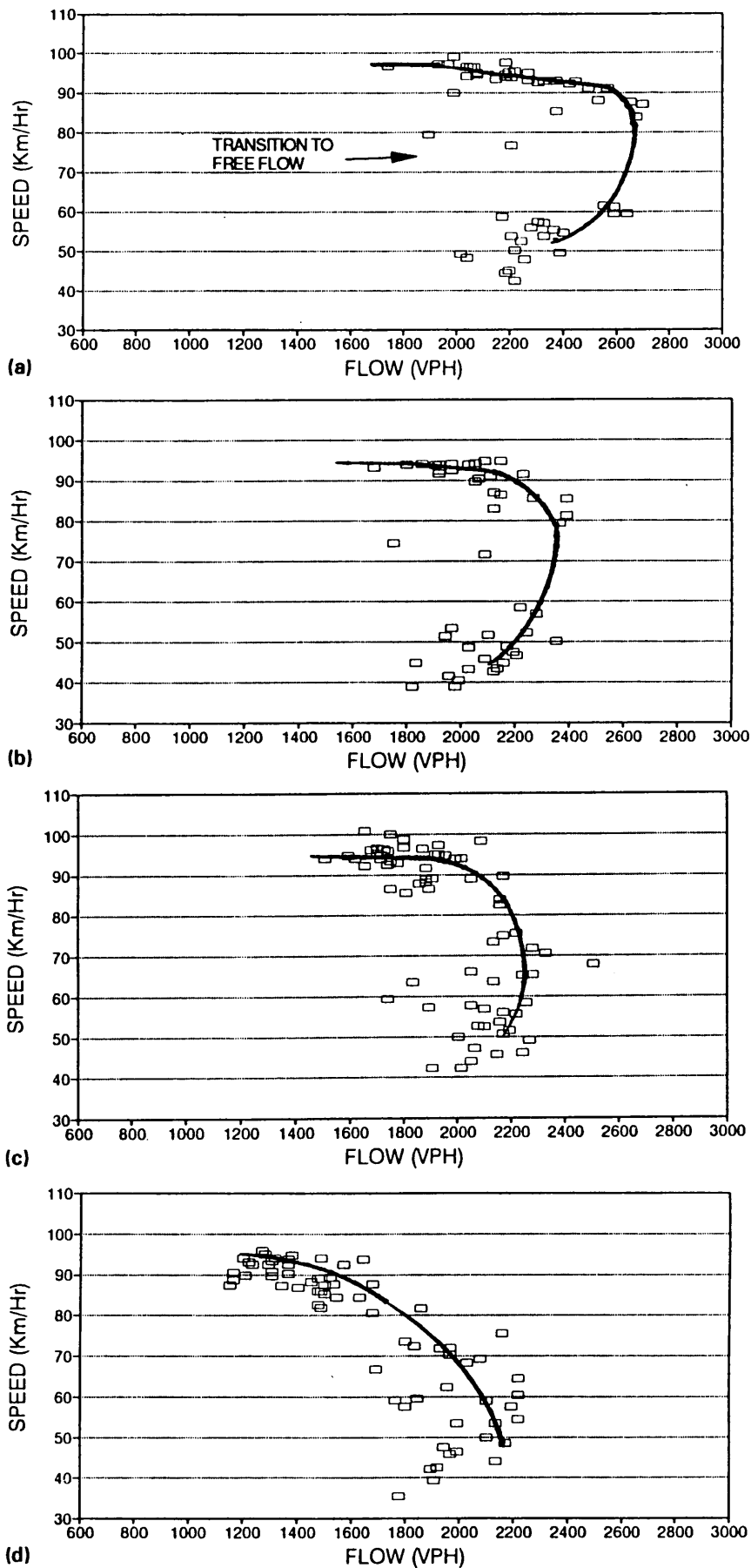FIGURE 9   Average queue discharge flow rates.

FIGURE 10 Speed-flow plots for I-35/US-67 study site, 5-min averages; *a*, Lane 1; *b*, Lane 2; *c*, Lane 3; *d*, Lane 4.

drop than before the speed drop. This further supports the conclusion that flows in the free-flow regions contain a large amount of variability, whereas the flows during queue discharge are not nearly as variable. Even with only three samples the confidence intervals for the average queue discharge flow rates are low, with 2,396 ± 117, 2,154 ± 140, 2,172 ± 103, and 2,017 ± 199 for Lanes 1, 2, 3, and 4, respectively. The average across all lanes was 2,185 ± 118 for the three samples. Although the individual lanes differ significantly, the average across all lanes during queue discharge was not statistically different than at US-290, which had an average flow of 2,166 ± 37. Figure 9 shows the average queue discharge flow rates adjusted for heavy vehicles (assuming an E_t of 2.0) for the US-290 and I-35/US-67 sites. The flows ranged from 2,200 to 2,400 pcphpl for individual lanes except in Lane 4 at the I-35/US-67 site, which was observed to not be a preferred lane and had lower flows. The averages for both sites across all lanes were nearly identical, with 2,230 and 2,220 pcphpl. For these reasons, queue discharge appears to be the most consistent flow for estimating the maximum sustainable flow of a facility. Although much higher flows are obviously possible, they typically do not occur across all lanes and would be difficult to maintain.

Even in queue discharge, Lane 1 at the I-35/US-67 site continually had very high flows, averaging 2,396 vph. It is difficult to determine the reason for these very high queue discharge flow rates. One explanation for the high flow rates during queue discharge in Lane 1 could be the difference in the type of bottleneck at the I-35/US-67 site.

Speed-Flow Relationship at Validation Sites

Because the I-410 site was affected by downstream congestion, the relationship between speed and flow was not evaluated at this site. Figure 10 shows the speed-flow plots for each lane at the I-35/US-67 site. Also shown in Figure 10 are

the projected speed-flow relationships suggested by the data. The scattered points in the center of the relationship (low flow and higher speed) represent recovery to uncongested conditions. This phenomenon was not present in the US-290 data.

Figure 11 shows the speed-flow model for the I-35/US-67 site. As can be seen in this figure, Lanes 1 and 2 reach their peak flow rates during free-flow conditions while Lanes 3 and 4 are prematurely transitioned into queue discharge. One interesting aspect of this site is the relation of Lanes 2 and 3. Both have approximately the same free-flow speeds and transition into nearly identical queue discharge flow rates, yet Lane 2 reaches it peak in free-flow conditions and Lane 3 peaks after the speed drop in queue discharge. These two lanes illustrate the effects of lane interaction. Because Lane 2 broke down, the turbulence transitioned Lane 3 into queue discharge before it reached its maximum flow rate. The extremely high flows in Lane 1 make it difficult to determine if the turbulence created by Lane 1 restricted Lane 2 from reaching its maximum free-flow flow rate.

These results support the hypothesis that when one or more lanes break down the other lanes are prematurely transitioned into queue discharge conditions. The data from the I-35/US-67 site show that extremely high flows are possible in free-flow conditions and that relatively high flows also occur in queue discharge. Therefore, the measured flows are a function of the interactions between the lanes.

Although lane interaction is not a new idea, it seems to have been forgotten in many studies. One of the most significant problems is when lanes are combined to form an overall speed-flow relationship. In free-flow conditions all lanes operate similarly, and all lanes can be combined to produce average flows. Once the facility begins to break down, average flow rates and speeds are significantly different from the individual lanes, and combining all lanes to produce a single relationship is misleading. The interaction between lanes may help explain the variety of results obtained in earlier studies.
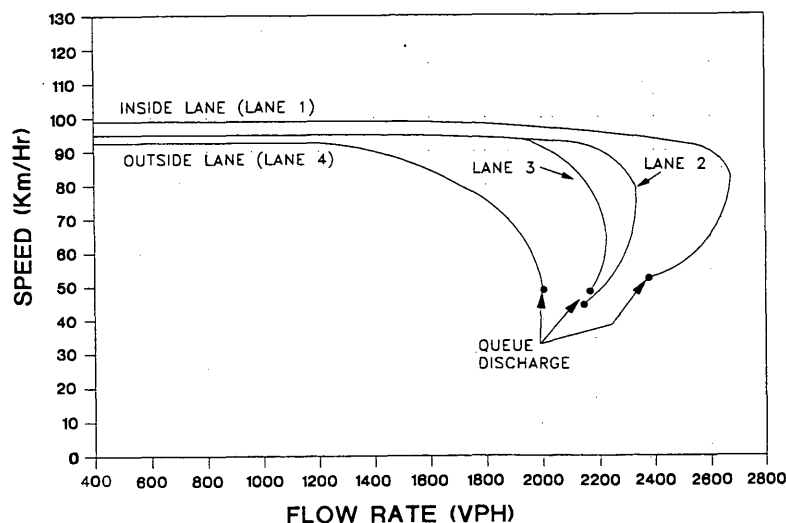

FIGURE 11   Speed-flow relationship for I-35/US-67 study site.

RESULTS AND CONCLUSIONS

On the basis of the analysis of the US-290, I-410, and I-35/US-67 study sites the following conclusions can be made:

- Variance in flow rate decreases after the speed drop to queue discharge.
- Peak flows for individual lanes occur in free-flow conditions before breakdown.
- Peak flows during free-flow conditions do not generally occur in all lanes on a facility because of an imbalance of flow rates between individual lanes. This prematurely transitions the flow from free-flow into queue discharge conditions.
- Bottleneck configuration may influence the maximum possible flow obtainable during free-flow and possibly queue discharge conditions.
- Queue discharge appears to be the best estimate for maximum sustainable flow and capacity.

ACKNOWLEDGMENTS

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