Some Observations of Highway Traffic in Long Queues

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The arrival times of vehicles traveling southbound along a two-lane, bi-directional highway were recorded at eight neighboring locations upstream of a bottleneck caused by an oversaturated traffic signal. Cumulative curves constructed from these observations describe completely and in great detail the evolution of the resulting long queues. These queues formed directly upstream of the signal when the signal's service rate fell below the southbound arrival rates, and never formed away from the bottleneck. The predictability of bottlenecks like the one studied here can be exploited to manage traffic more effectively. The behavior of vehicles within the queue, however, was rather interesting. Although the flow oscillations generated by the traffic signal were damped out within 0.8 km (0.5 mi) of the bottleneck, it was found that other oscillations arose within the queue farther upstream, at varied locations, and then grew in amplitude as they propagated in the upstream direction. Thus, the queue appeared to be stable close to the bottleneck and unstable far away. Oscillations never propagated beyond the upstream end of the queue, however; that is, the unusual phenomena always arose after the onset of queueing and remained confined within the queue. Some of these findings run contrary to current theories of traffic flow. Because the data set collected in this study is unprecedented in scope and detail and so that it may be of use to other researchers, it has been posted on the Internet and is fully described here.

A better understanding of how queues form and propagate can lead to improved methods of managing highway traffic. Queue lengths and traffic spillovers, for example, depend on the spacing that drivers select in dense traffic, and this points to the important role that car-following theories can play in devising queue containment strategies. Although a number of such theories exist, the empirical evidence is scarce. Consequently, uncertainty surrounds even the most fundamental of issues. Especially telling in this regard is the lack of consensus as to why congestion (i.e., queues) arises (1); this is notable in that schemes for managing queues should stem from an understanding of their causes.

The study described here is part of an ongoing effort to identify the important and reproducible features of evolving traffic. To this end, the data collected have been posted on the World Wide Web (at http://www.ce.berkeley.edu/~daganzo/spdr.html). They describe queues that formed immediately upstream of a traffic signal, propagated several kilometers farther upstream, and eventually began to dissipate toward the end of the peak. Analysis reveals that the bottleneck pulses were damped out before they propagated through the entire queue and that other disturbances arose spontaneously at locations within the queue farther upstream. These disturbances never propagated beyond the upstream end of the queue.

The findings augment the observations of a few previous studies. Some of this earlier work, along with an overview of the present study, is summarized in the following section. The experiment and the resulting data are described next, the main findings from the analysis and their rationale are presented, and the final section presents some conclusions and suggestions for further work.

BACKGROUND

Some of the earliest car-following studies took place on test tracks (2,3). Although these efforts produced a wealth of very detailed observations, their realism is somewhat questionable since one cannot be sure that test track data really describe the behavior of drivers in highway traffic.

As an extension of these earlier efforts, researchers have more recently selected vehicles at random in real traffic and followed them in instrumented cars (4). These experiments, however, were not double-blind in that the subject drivers knew they were part of an experiment. Thus, it appears that these studies are also inconclusive.

Data taken in real traffic settings when drivers are unaware of their participation in an experiment can complement the earlier studies and shed additional light on the issues. Limited amounts of such data have been collected in past studies. In one widely cited example, researchers constructed time-space vehicle trajectories by comparing vehicle positions on consecutive aerial photographs (5). These trajectories revealed much detail, but the data were limited both in the observation duration and in the length of roadway examined. Video imaging methods have also been used as a (less laborious) means of extracting trajectories for longer periods of time (6). These methods, however, are still only capable of tracking vehicles over short distances.

In other studies, researchers have traced propagating disturbances over long sections of freeway using vehicle speeds and flows measured by loop detectors (7). This approach can yield much useful information, but it does not identify vehicles or their accumulation between detectors. Without these critical data, the results can be open to varying interpretations (1).

Fortunately, it has been demonstrated recently (8) that by working with cumulative curves of vehicle arrival number versus time, N-curves, it is possible to extract individual-vehicle information from loop detector data, provided that the road segments have simple geometries. The special insights derived from N-curves have been known to the transportation profession for years (9). Unfortunately, loop detectors are often located near freeway entrance and exit ramps, which makes it difficult to separate the effects of lane changing, merging, and diverging that occur at these access points from those of the pure car-following behavior that determines the lengths of queues.

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The approach used here was to find a location without the above-mentioned complexities and use the best available data collection techniques for the chosen location. The highway segment selected (a very simple two-lane, bidirectional highway) was ideally suited for the purpose because it had a downstream traffic signal that generated a bottleneck when vehicle arrival rates rose during the morning peak and because there were very little vehicle overtaking and almost no side traffic.

Since the site chosen was not instrumented with loop detectors, human observers equipped with laptop computers were deployed to record the arrival times (and classes) of all southbound vehicles at eight observation points on two separate mornings. The N-curves constructed from these data show the evolution of very long queues in a single traffic stream without the complications that arise from vehicle lane changing, merging, or diverging. In particular, it was possible to track the disturbances that propagated within these queues over their entire lives to their final dissipations. The relatively small measurement errors incurred by using human observers are described in a later section. From the authors' experience with experimental data, this procedure of manual data collection is believed to be comparable in accuracy with that of loop detectors.

THE EXPERIMENT

Presented in this section is a thorough description of the site chosen for the study and of the methods used to extract the data. As regards the former, the data were collected on the 6-km (4-mi) segment of southbound San Pablo Dam Road shown in Figure 1. The site, located immediately north of the intersection with Wildcat Canyon Road, is a two-lane rural highway connecting the cities of Richmond and Orinda, California. The highway serves as a commuter alternative to a congested regional freeway. It has a posted speed limit of 50 mph (80 km/h) (commensurate with its design standards), some gentle horizontal and vertical curves, and a slight uphill grade (for southbound traffic) near the intersection with Wildcat Canyon Road. Adequate shoulders exist throughout the segment.

The near-absence of access and egress points and the minimal overtaking maneuvers at the site mean that vehicles maintained (approximately) their relative positions in the traffic stream; the amount of traffic that used the two access points at the San Pablo Dam reservoir was negligible and only a few vehicles, usually motorcycles, bypassed queues by driving on the shoulder. The downstream intersection at
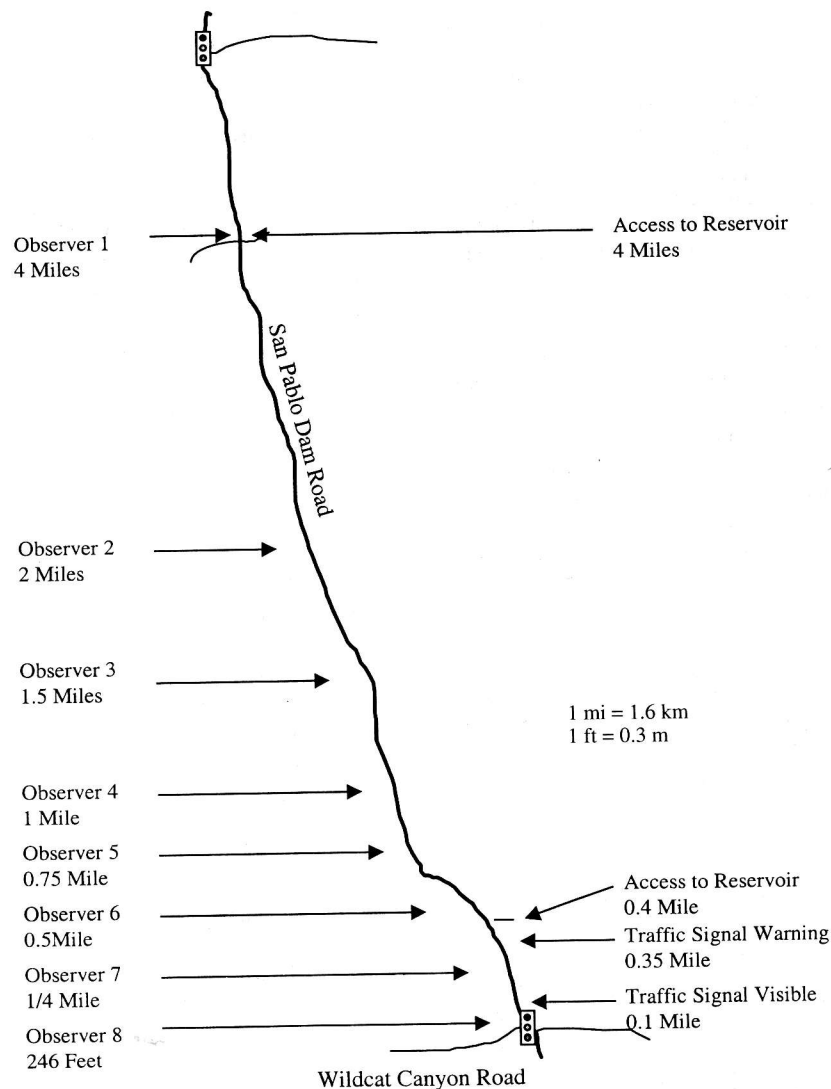

FIGURE 1   Experiment site (all distances measured from Wildcat Canyon Road).

Wildcat Canyon Road is controlled by a vehicle-actuated traffic signal, which causes a queue of southbound vehicles to grow steadily during much of the morning peak.

To collect the data, the eight observers were stationed along the site as shown in Figure 1. Obscured from the view of drivers, these observers used laptop computers to record the arrival times of individual vehicles at their respective observation points. The laptop computers' internal clocks were synchronized before the first day of observation, and a computer program was coded to append time values to keystrokes. The observers recorded each vehicle's arrival time and the vehicle class by pressing a specified key (e.g., A for automobile and T for commercial truck). The data format is explained in the following section.

Figure 1 shows that at the downstream end of the site, the observers were stationed in close proximity. This arrangement yielded a higher measurement resolution for viewing disturbances shortly after they emanated from the traffic signal where they were expected to be growing. To ensure a complete study of the queue, the observer farthest upstream was stationed 6 km (4 mi) from the signal since it was estimated that the effects of the queue would not be felt beyond this location. All distances shown in Figure 1 were carefully identified with a measuring wheel.

A pilot car, which was easily distinguished from other vehicles (in that it had a bicycle mounted on its roof rack), cycled through the site during the study periods. When the pilot car was traveling southbound, its arrival times at each observation point were recorded (i.e., the observers pressed B on their computer keyboards). To provide some redundancy, the driver of the pilot car recorded the approximate times that each of the eight observation points was passed while the car was traveling southbound. On each of the two observation days, the beginning and ending of the study period were marked by the first and last passages of the pilot car. Furthermore, the intermediate arrival times of the pilot car were useful in prorating any (small) measurement errors made by the observers, as described in the following section. A second car cycled through the site to provide the observers with any needed assistance, for example, to furnish observers with replacement computers when batteries had discharged.

Observations were collected from 6:45 a.m. to 9:00 a.m. on Tuesday, November 18, and again on Thursday, November 20, 1997. There was no precipitation on either day, and visibility on the road was good.

THE DATA

The data from this study have been posted on the previously mentioned World Wide Web site and are available in two forms: "raw" data, which have not been altered, and "final" data, which have been filtered in an effort to correct for measurement errors. This section provides a full description of these data, including the filtering processes used.

The raw data are contained in a total of 16 text files, each holding the measurements made by a single observer on one of the two observation days. For example, File 1_A.txt holds the measurements of the observer farthest upstream (i.e., Observer 1) on the first day, and File 8_B.txt, the measurements of the observer the farthest downstream on Day 2. A small portion of data File 5_A.txt is shown in Figure 2. Each vehicle arrival time is recorded in hours, minutes, seconds, and hundredths of seconds and is presented along with the vehicle's arrival number and class.

Hours	Minutes	Seconds	Hundredths of Seconds	Vehicle #	Vehicle Class
8	21	28	24	1678	A
8	21	29	99	1679	A
8	21	31	97	1680	A
8	21	35	43	1681	A
8	21	36	69	1682	A
8	21	37	74	1683	A
8	21	41	42	1684	A
8	21	43	83	1685	A
8	21	46	96	1686	A
8	21	50	37	1687	A
Computer Failure					
8	25	40	12	1688	A
8	25	43	31	1689	A
8	25	46	38	1690	A
8	25	49	52	1691	A
8	25	55	72	1692	A
8	26	0	83	1693	A
8	26	2	92	1694	A
8	26	4	78	1695	A
8	26	8	46	1696	A
8	26	12	25	1697	A

FIGURE 2 Sample from File 5_A: original vehicle count files (uncorrected); location: 15,602 ft (4755 m) from Observer 1, Tuesday, November 18, 1997 (Day 1).

The comment "Computer Failure" shown in Figure 2 was used to flag one particular type of measurement error. Measurement errors came from several sources, and they are described below so that other researchers may use the raw data with their own filtering processes. From the following discussion, however, it should become apparent that given the nature of the measurement errors, all reasonable filtering processes would yield practically indistinguishable results. It should also be clear that these errors did not erode the integrity of the final data in any substantial way; that is, despite the errors described in the following paragraphs, the data are arguably the most detailed and accurate of their kind.

Filtered in the following way, the final data were stored in two Excel spreadsheets named D1Final.xls and D2Final.xls, for Days 1 and 2, respectively. A portion of File D1Final.xls is shown in Figure 3. In the evaluation of these data and the findings that resulted, presented in the next section, it will become apparent that the changes made by the filtering process are very minor.

Hardware Malfunctions

In a few instances, records were apparently not entered by a human observer but were due instead to some type of computer malfunction. These entries were easily identified because they gave rise to unduly small vehicle headways and were often accompanied by a rectangular symbol rather than an A, B, or T in the field designated for vehicle class. The raw data files include comment statements to flag each of these errant records, and they have been purged from the final data.

Clock Synchronization Problems

Measurement errors also arose because the laptop computer internal clocks were not always well synchronized. The clocks in two of the

Tuesday, November 18, 1997 (Day 1)

mini-dataset	1	2	3	4	5
Start	1	402	1008	1588	2058
Average Count	401	607	579	471	268
Maximum Count	403	609	582	474	271
Minimum Count	396	605	575	389	241

Field Descriptions

A	Vehicle Class
B	Recorded Arrival Time (cor.)
C	Recorded Arrival Count
D	Adjusted Arrival Count

Distance	Distance from Observer 1 (ft)
Total Count	Number of Vehicles in Mini-dataset
Adj Factor	Adjustment Factor for the Mini-dataset

Field: A = class, B = time, C = act, D = adj

Observer 1 — Distance 0, Total Count 403, Adj Factor 0.9938

class	time	act	adj
B	6:47:46	1	1
T	6:47:51	2	2
A	6:47:52	3	3
A	6:47:53	4	4
A	6:47:54	5	5
A	6:47:56	6	6
A	6:47:57	7	7
A	6:47:58	8	8
A	6:48:00	9	9
A	6:48:01	10	10
A	6:48:02	11	11
A	6:48:05	12	12
A	6:48:06	13	13
A	6:48:09	14	14
A	6:48:14	15	15
A	6:48:15	16	16
A	6:48:16	17	17
A	6:48:19	18	18
A	6:48:22	19	19
A	6:48:23	20	20
A	6:48:25	21	21
A	6:48:27	22	22
A	6:48:28	23	23
A	6:48:30	24	24
A	6:48:31	25	25
A	6:48:32	26	26
A	6:48:34	27	27
A	6:48:37	28	28
A	6:48:38	29	29
A	6:48:40	30	30
A	6:48:41	31	31
A	6:48:42	32	32

Observer 2 — Distance 9504, Total Count 402, Adj Factor 0.996

class	time	act	adj
B	6:49:57	1	1
A	6:50:01	2	2
A	6:50:03	3	3
A	6:50:04	4	4
A	6:50:05	5	5
A	6:50:09	6	6
A	6:50:11	7	7
A	6:50:13	8	8
A	6:50:15	9	9
A	6:50:16	10	10
A	6:50:19	11	11
A	6:50:22	12	12
A	6:50:23	13	13
A	6:50:26	14	14
A	6:50:34	15	15
A	6:50:35	16	16
A	6:50:36	17	17
A	6:50:38	18	18
A	6:50:42	19	19
A	6:50:43	20	20
A	6:50:45	21	21
A	6:50:48	22	22
A	6:50:49	23	23
A	6:50:50	24	24
A	6:50:51	25	25
A	6:50:53	26	26
A	6:50:54	27	27
A	6:50:57	28	28
A	6:50:58	29	29
A	6:50:59	30	30
A	6:51:00	31	31
A	6:51:01	32	32

Observer 3 — Distance 11847, Total Count 396, Adj Factor 1.0114

class	time	act	adj
B	6:50:27	1	1
A	6:50:31	2	2
A	6:50:32	3	3
A	6:50:33	4	4
A	6:50:35	5	5
A	6:50:38	6	6
A	6:50:39	7	7
A	6:50:42	8	8
A	6:50:44	9	9
A	6:50:45	10	10
A	6:50:47	11	11
A	6:50:50	12	12
A	6:50:52	13	13
A	6:50:55	14	14
A	6:51:06	15	15
A	6:51:07	16	16
A	6:51:08	17	17
A	6:51:10	18	18
A	6:51:13	19	19
A	6:51:15	20	20
A	6:51:17	21	21
A	6:51:21	22	22
A	6:51:21	23	23
A	6:51:22	24	24
A	6:51:23	25	25
A	6:51:25	26	26
A	6:51:26	27	27
A	6:51:29	28	28
A	6:51:30	29	29
A	6:51:31	30	30
A	6:51:32	31	31
A	6:51:33	32	32

Observer 4 — Distance 14784, Total Count 403, Adj Factor 0.9938

class	time	act	adj
B	6:51:07	1	1
A	6:51:08	2	2
A	6:51:12	3	3
A	6:51:13	4	4
A	6:51:14	5	5
A	6:51:18	6	6
A	6:51:18	7	7
A	6:51:21	8	8
A	6:51:23	9	9
A	6:51:24	10	10
A	6:51:27	11	11
A	6:51:29	12	12
A	6:51:30	13	13
A	6:51:36	14	14
A	6:51:47	15	15
A	6:51:49	16	16
A	6:51:50	17	17
A	6:51:52	18	18
A	6:51:57	19	19
A	6:51:58	20	20
A	6:51:59	21	21
A	6:52:01	22	22
A	6:52:03	23	23
A	6:52:04	24	24
A	6:52:05	25	25
A	6:52:06	26	26
A	6:52:07	27	27
A	6:52:09	28	28
A	6:52:10	29	29
A	6:52:12	30	30
A	6:52:13	31	31
A	6:52:15	32	32

Observer 5 — Distance 15602, Total Count 399, Adj Factor 1.0038

class	time	act	adj
B	6:51:19	1	1
A	6:51:25	2	2
A	6:51:26	3	3
A	6:51:27	4	4
A	6:51:31	5	5
A	6:51:33	6	6
A	6:51:33	7	7
A	6:51:35	8	8
A	6:51:36	9	9
A	6:51:39	10	10
A	6:51:41	11	11
A	6:51:43	12	12
A	6:51:49	13	13
A	6:52:00	14	14
A	6:52:01	15	15
A	6:52:02	16	16
A	6:52:05	17	17
A	6:52:11	18	18
A	6:52:12	19	19
A	6:52:13	20	20
A	6:52:17	21	21
A	6:52:17	22	22
A	6:52:18	23	23
A	6:52:20	24	24
A	6:52:21	25	25
A	6:52:23	26	26
A	6:52:24	27	27
A	6:52:25	28	28
A	6:52:27	29	29
A	6:52:27	30	30
A	6:52:27	31	31
A	6:52:29	32	32

Observer 6 — Distance 17598, Total Count 402, Adj Factor 0.9963

class	time	act	adj
B	6:51:45	1	1
A	6:51:45	2	2
A	6:51:50	3	3
A	6:51:52	4	4
A	6:51:53	5	5
A	6:51:57	6	6
A	6:51:58	7	7
A	6:52:00	8	8
A	6:52:01	9	9
A	6:52:02	10	10
A	6:52:05	11	11
A	6:52:07	12	12
A	6:52:08	13	13
A	6:52:14	14	14
A	6:52:26	15	15
A	6:52:27	16	16
A	6:52:29	17	17
A	6:52:31	18	18
A	6:52:37	19	19
A	6:52:39	20	20
A	6:52:40	21	21
A	6:52:43	22	22
A	6:52:45	23	23
A	6:52:47	24	24
A	6:52:48	25	25
A	6:52:49	26	26
A	6:52:51	27	27
A	6:52:53	28	28
A	6:52:54	29	29
A	6:52:56	30	30
A	6:52:57	31	31
A	6:52:59	32	32

Observer 7 — Distance 18744, Total Count 399, Adj Factor 1.0038

class	time	act	adj
B	6:52:26	1	1
A	6:52:29	2	2
A	6:52:32	3	3
A	6:52:35	5	5
A	6:52:37	6	6
A	6:52:39	7	7
A	6:52:41	8	8
A	6:52:42	9	9
A	6:52:45	10	10
A	6:52:47	11	11
A	6:52:48	12	12
A	6:52:50	13	13
A	6:52:52	14	14
A	6:52:54	15	15
A	6:52:57	16	16
A	6:53:00	17	17
A	6:53:04	18	18
A	6:53:06	19	19
A	6:53:07	20	20
A	6:53:10	21	21
A	6:53:12	22	22
A	6:53:14	23	23
A	6:53:16	24	24
A	6:53:18	25	25
A	6:53:20	26	26
A	6:53:23	27	27
A	6:53:25	28	28
A	6:53:26	29	29
A	6:53:28	30	30
A	6:53:30	31	31
A	6:53:31	32	32

Observer 8 — Distance 19813, Total Count 400, Adj Factor 1.0013

class	time	act	adj
B	6:52:50	1	1
A	6:52:54	2	2
A	6:52:58	3	3
A	6:52:59	4	4
A	6:53:01	5	5
A	6:53:03	6	6
A	6:53:05	7	7
A	6:53:06	8	8
A	6:53:07	9	9
A	6:53:10	10	10
A	6:53:11	11	11
A	6:53:13	12	12
A	6:53:17	13	13
A	6:53:19	14	14
A	6:53:22	15	15
A	6:53:23	16	16
A	6:53:26	17	17
A	6:53:30	18	18
A	6:53:32	19	19
A	6:53:35	20	20
A	6:53:37	21	21
A	6:53:38	22	22
A	6:53:40	23	23
A	6:53:41	24	24
A	6:53:43	25	25
A	6:53:45	26	26
A	6:53:48	27	27
A	6:53:52	28	28
A	6:53:55	29	29
A	6:53:57	30	30
A	6:54:00	31	31
A	6:54:01	32	32

FIGURE 3 Sample from D1Final.xls: final vehicle count files (corrected): Tuesday, November 18, 1997 (Day 1).

TABLE 1   Clock Synchronization Corrections, Tuesday, November 18, 1997 (Day 1) (min:s)

Tuesday, November 18, 1997 (Day 1)

Observer	Change
2	01:00 subtracted from all measured arrival times
3	01:00 subtracted from all arrival times measured between 6:44:33 and 8:42:14:82
	(the period when a computer with an asynchronized clock was used by observer 3)

laptops used on the first day of observation ran ahead of their counterparts by exactly 1 min. This error was made immediately evident by a comparison of the roadside data recorded with these two computers with the corresponding passage times measured (approximately) by the driver of the pilot car. The asynchronization was attributed to human error in setting the internal clocks, and in the final data set the vehicle arrival times measured with these two computers were adjusted (i.e., reduced) by 1 min. These adjustments are summarized in Table 1.

Regrettably, the computers' clocks were not resynchronized immediately before the second day of observation. As a consequence, by Day 2, the clocks of all the computers had drifted by varying amounts. To salvage the second day's data, the vehicle arrival times taken at observation points 2 through 8 were adjusted as follows. First, the average free-flow vehicle trip times between each pair of contiguous observation points were estimated for Day 1. These estimates were made using the arrival times for the first 25 vehicles observed on that day, since these vehicles did not encounter residual queueing at the downstream intersection. The average travel times and standard errors of the sample means are presented in Table 2. Notably, the standard error for each of these (seven) sample means never exceeded 1.2 s. The same calculations were then repeated for Day 2, with the results shown in Table 3. The large discrepancies between the measured averages on both days were attributed to synchronization error.

Thus, clock corrections that eliminated all the discrepancies between the recorded free-flow trip times on both days were chosen. (If no correction is assigned to Observer 1, the clock correction for Location $j > 1$ is simply the difference of the average trip times from Observer 1 to Observer j on both days.) These corrections are shown in Table 4. This adjustment method was deemed to be more reliable than using the approximate trip times measured on Day 2 by the driver of the pilot car.

Computer Failure

Figure 2 shows a gap in the observations that extended for almost 4 min and is labeled "Computer Failure." On occasion, a computer required replacement (while in the field) because its battery had fully discharged. The few replacements that resulted in the loss of recorded observations are flagged in the raw data as "Computer Failure."

To address the resulting loss of information, the observation days were partitioned into smaller datasets consisting of all the vehicular information collected between consecutive passages of the southbound pilot car. Ideally, each of the eight observers would measure the same number of vehicles in each minidataset. This was approximately the case except when a computer failure created large gaps in the recorded observations. Therefore, measurements taken (at the observation point) subsequent to a computer failure were removed from the minidataset if the gap in the records exceeded 1 min. In total, this truncation was performed only on two occasions, at two different observation points. On one of these occasions, which occurred during the penultimate minidataset of Day 2, the replacement computer could not be restarted in time to be useful for the last minidataset. Two counts were also truncated for the last minidataset of Day 2 because observations at these locations were terminated shortly before the final passage of the southbound pilot car.

Human Error

All other (small) discrepancies between the vehicle counts in a minidataset were attributed to human error, such as a missed observation or an unwarranted keystroke. The counting errors created by small glitches in computer exchanges were likewise placed in this category. Since these errors could not be individually identified, they were prorated equally over each minidataset by renormalizing the counts; that is, each vehicle's arrival number, as recorded by a jth observer, was multiplied by the ratio $\bar{N}/N^{(j)}$, where $N^{(j)}$ is the number of vehicles counted by Observer j in the minidataset and $\bar{N}$ is the average of the $N^{(j)}$ across observers. Of note, the four truncated counts discussed under "Computer Failure" were not adjusted and were not included in the computation of an $\bar{N}$.

On the second day, Observer 5 failed to record the second passage of the pilot car. It was assumed that the observer inadvertently logged this arrival by selecting an A, as if the pilot car were a passenger car. A record of vehicle class was subsequently changed from an A to a B. This record was chosen in the maximum likelihood way

TABLE 2   Free-Flow Travel Times, Day 1 (min:s)

Tuesday, November 18, 1997 (Day 1)

Segment	Estimated Average Free Flow Travel Time	Standard Deviation of the Population	Standard Error of the Sample Mean
1-2	02:16.6	00:03.7	00:00.7
2-3	00:30.3	00:01.6	00:00.3
3-4	00:40.5	00:01.7	00:00.3
4-5	00:15.2	00:02.5	00:00.5
5-6	00:24.1	00:03.2	00:00.6
6-7	00:36.2	00:06.1	00:01.2
7-8	00:25.8	00:01.0	00:00.2

TABLE 3   Free-Flow Travel Times, Thursday, November 20, 1997 (Day 2) (min:s)

Thursday, November 20, 1997 (Day 2)

Segment	Estimated Average Free Flow Travel Time	Standard Deviation of the Population	Standard Error of the Sample Mean
1-2	02:26.3	00:02.1	00:00.4
2-3	00:17.8	-00:01.0	00:00.2
3-4	00:45.3	00:01.9	00:00.4
4-5	00:19.4	00:01.3	00:00.3
5-6	00:11.2	00:01.8	00:00.4
6-7	00:31.0	00:01.1	00:00.2
7-8	- 00:10.4	00:01.5	00:00.3

so as to yield the same ratio of vehicle counts in the first and second miniruns as was typical of the other observers. The standard error in this procedure should be on the order of one or two vehicles.

SOME ANALYSIS

Figure 4 shows the conventional curves of vehicle count versus time, $N(j,t)$, for Day 2, where $N(j,t)$ is the (filtered) cumulative number of vehicles to pass stationary Observer j by time t, measured from the first passage of the southbound pilot car, $j = 1, 2, \ldots, 8$. Figure 4 indicates that the flow of southbound vehicles past $j = 8$ began to drop at around 7:04 a.m. [The reader may use a straight-edge to verify the change in the trend of $N(8,t)$ around this time.] This drop in flow is believed to have been caused by growth in the conflicting traffic streams at Wildcat Canyon Road because the stop-and-go features of $N(8,t)$ reveal that the drop is due exclusively to an increase in the duration and frequency of the episodes with zero flow (when the red signal was displayed to southbound traffic) and not to any significant change in the slope of $N(8,t)$ during the green.

Shortly following the overall flow reduction at $j = 8$, the slopes of some of the upstream N-curves dropped in sequence. Figure 4 includes labels indicating when these events took place at the various observation points. It should be noted that the drop in slope at an observation point j is simply the flow reduction brought about by the growing queue. As one would expect, after the drop at j, when the queue has grown beyond this location, the vehicle trip times (i.e., the horizontal displacements) and the accumulations (i.e., the vertical displacements) between observation points $j - 1$ and j are no longer minimum. It should also be noted that the queue never propagated to $j = 2$, and thus vehicles arrived at $j = 2$ without delay. This is evident because the horizontal displacements between the curves at $j = 1$ and $j = 2$ did not noticeably increase from what is displayed at the beginning of the observation period.

Downstream curve $N(8,t)$ continued to drop gradually until about 7:30 a.m. because of gradual growth in the conflicting traffic streams at Wildcat Canyon Road. Quite apart from this effect, a final flow reduction occurred at $j = 8$ when, at about 8:27 a.m., a queue from farther downstream spilled over. This result is evidenced by the reduced saturation flows at Wildcat Canyon road during the green periods, which are clearly visible in curve $N(8,t)$.

The slope of the upstream-most $N(1,t)$ dropped at about 7:23. It is clear that this slope change was due to a reduction in vehicle arrivals from farther upstream because curve $N(2,t)$ adopted the same slope (approximately) one trip time later. Similarly linked changes in the arrival rates at observation points 1 and 2 are visible form $N(1,t)$ and $N(2,t)$ at later times. It should be noted in particular how the wiggles in $N(1,t)$ are passed horizontally to $N(2,t)$. This is an additional indication of the absence of queueing (10).

The inset of Figure 4 shows that the pronounced stop-and-go patterns seen at $j = 8$ were damped out before they reached $j = 6$. Curve $N(6,t)$ is notably smoother than curve $N(8,t)$. Remarkably, however, new disturbances appeared farther upstream. In some instances, upstream traffic flow was reduced to zero as it completely jammed, and a few such examples are labeled in the inset. These jams propagated upstream and always died upon (or before) reaching the upstream end of the queue. Oscillations in flow near the tail end of the queue appeared to be softer, as evidence by curve $N(3,t)$, which exhibits a pattern of gradual slope changes. The observed fluctuations in flow never affected traffic upstream of the queue. There was no evidence that instabilities or jams occurred in freely flowing traffic well upstream of the signal. The latter finding should not be surprising; if flow collapses occur at all (and it is not certain that they do), they would not likely appear in a situation with a maximum flow of 1,500 vehicles/h. The interested reader may refer to the paper by Daganzo et al. (1) for more discussion of this issue.

Figure 5 shows the curves constructed with the final data from Day 1. Study of these curves reveals a queue evolution similar to

TABLE 4   Clock Synchronization Corrections, Day 2 (min:s)

Thursday, November 20, 1997 (Day 2)

| Observer	Change
2	01:09.7 subtracted from all measured arrival times
	(includes 1 minute correction for original asynchronization of the clock)
3	00:02.8 added to all measured arrival times
4	00:02.0 subtracted from all measured arrival times
5	00:06.2 subtracted from all measured arrival times
6	00:06.8 added to all measured arrival times
7	00:12.0 added to all measured arrival times
8	00:48.2 added to all measured arrival times
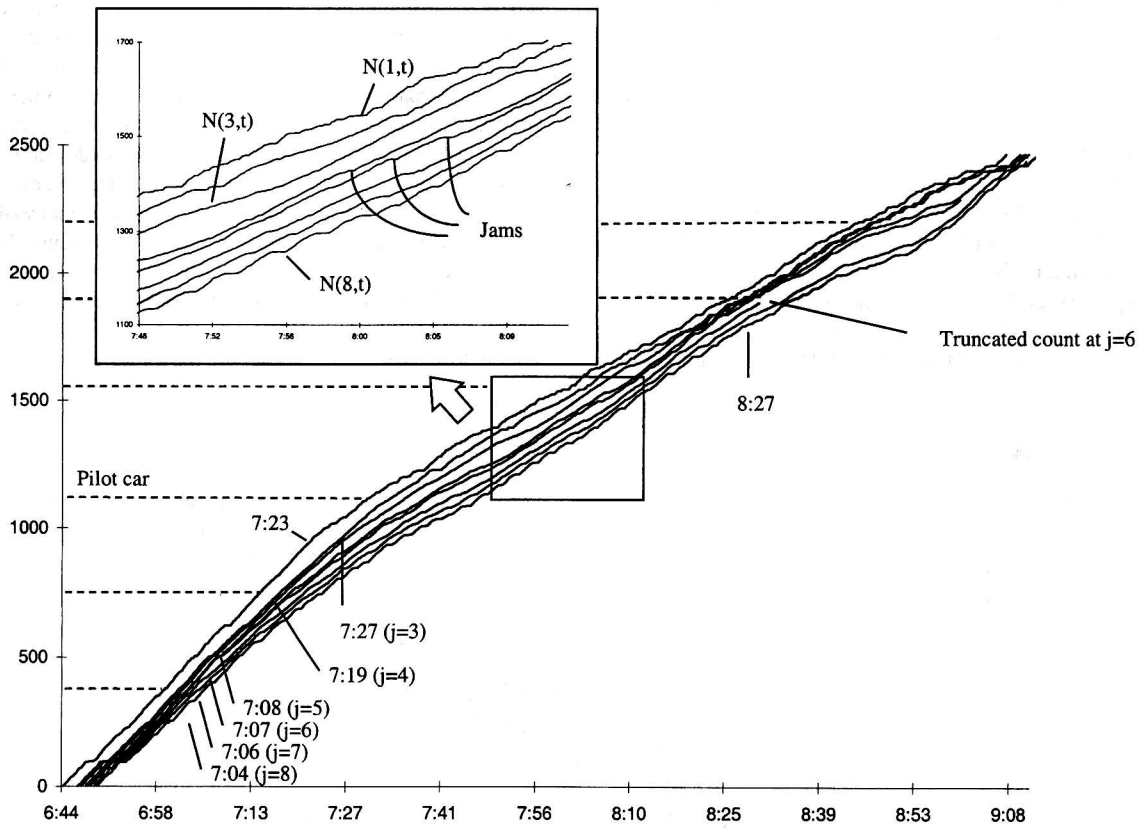
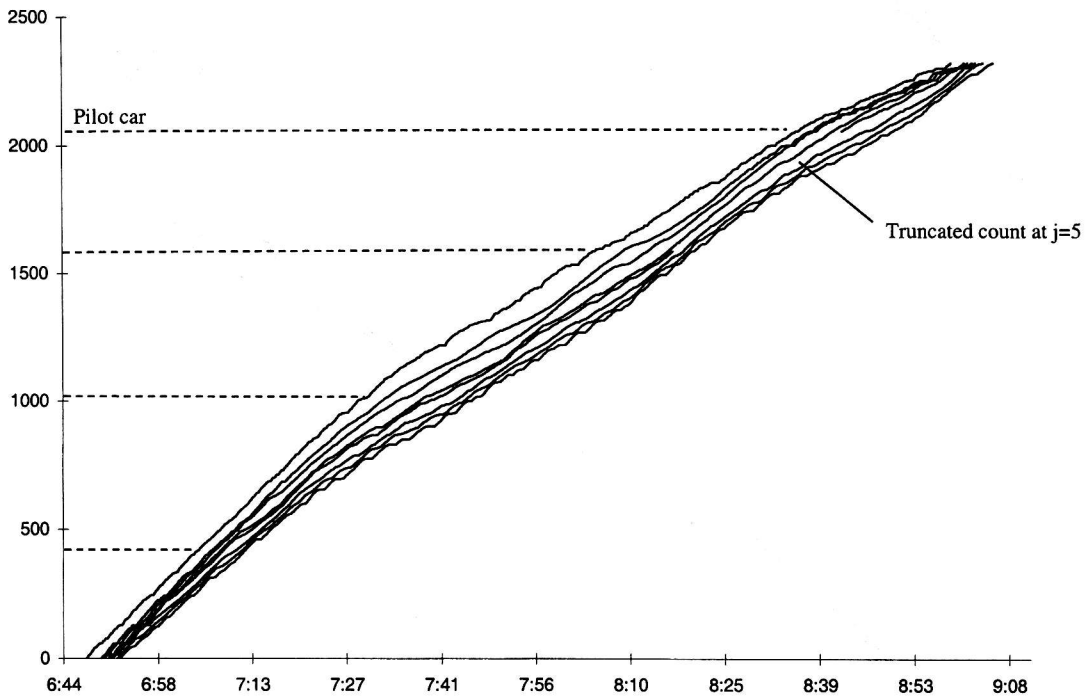**FIGURE 4** *N*-curves (adjusted), Day 2.

FIGURE 5 *N*-curves (adjusted) Day 1.

that observed on Day 2. Notable differences are that the queue on Day 1 appears to reach Observer 2 and to have dissipated more fully by the end of the observation period.

CONCLUSIONS

A study of queue evolution at a highway bottleneck has been described, and the sources of measurement error in the data collected were explained. The few large errors that arose (e.g., those due to failed battery exchanges) could be easily identified and corrected, thanks to the redundancy built into the experiment. The remaining errors were so small that they could be distributed evenly

across each minidataset with insignificant changes. As an illustration of this, Figure 6 presents the unadjusted *N*-curves for both observation days. The reader is invited to compare these curves with their counterparts in Figure 4 and 5 and to note the negligible differences. The authors believe that the accuracy of this experiment is comparable with that of experiments with loop detectors.

Visual inspection of the *N*-curves indicates that the queues formed in predictable ways at the most obvious inhomogeneity of this facility, the traffic signal. It was also found that the queues dissipated in predictable ways, for example, when vehicle arrival rates from farther upstream diminished, the bottleneck service rate increased, or both.

There were some unusual features in the data as well. For example, stop-and-go jams, uncorrelated with the traffic signal, were observed
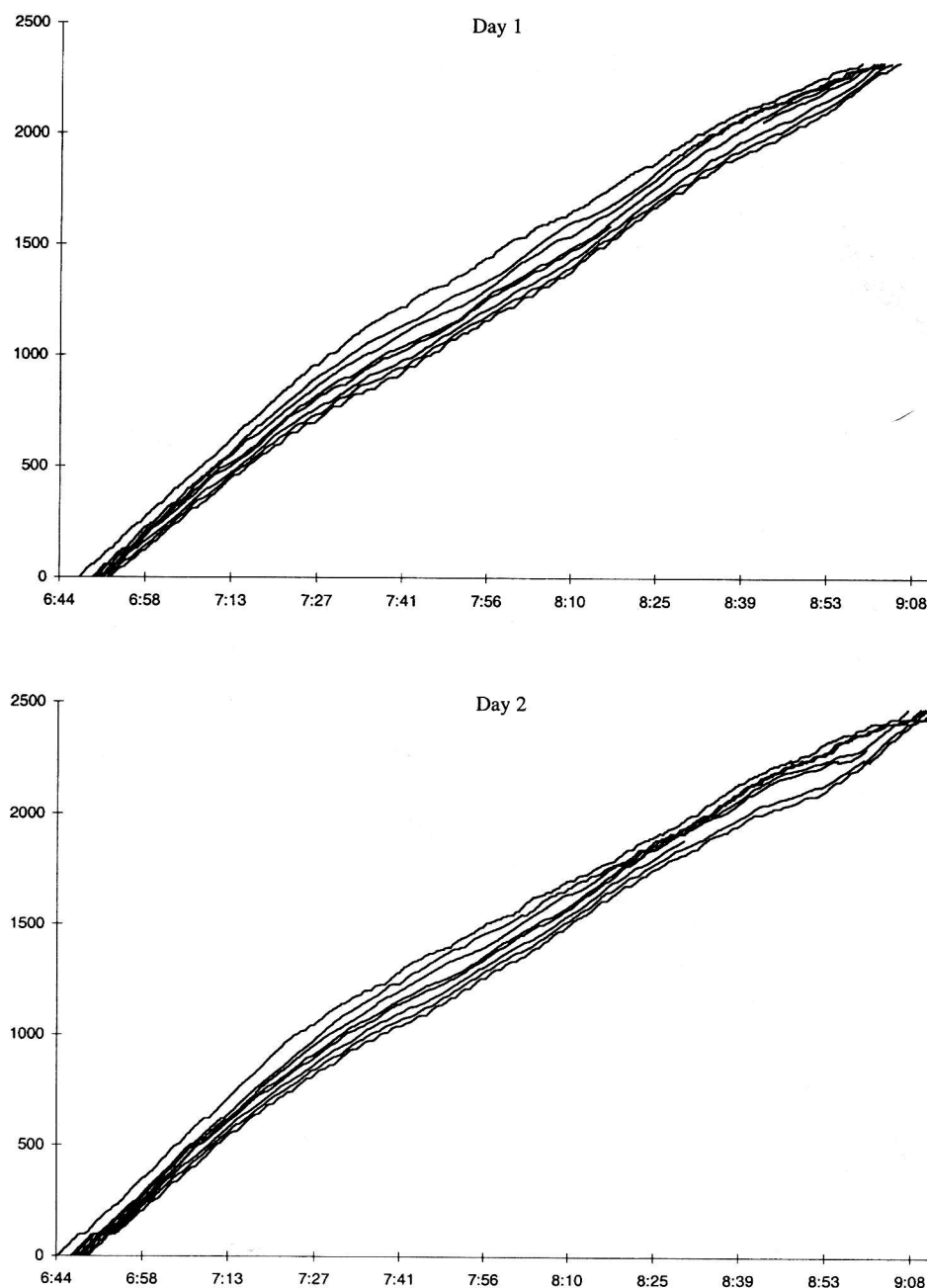

FIGURE 6   *N*-curves (unadjusted), Days 1 and 2.

in queued traffic without passing. This finding is interesting because the absence of passing means that traffic information is unlikely to overtake vehicles and that theories that include such possibility (kinetic theory, high-order fluid models, etc.) do not explain what is being observed here. A further puzzle is that although instabilities seem to grow in amplitude far from the bottleneck, the pronounced stop-and-go oscillations of the bottleneck itself were rapidly damped out within 0.8 km (0.5 mi) of it.

Perhaps these unusual observations are unique to the site studied here. For example, the predictability of the server (i.e., the traffic signal) or the low risk of being overtaken, or both reasons, may have motivated drivers to follow downstream vehicles in unusually relaxed ways. The authors hope that other researchers will attempt to replicate or disprove these observations at other sites. In any case, and even if stranger phenomena are observed at other sites, theories to predict these unusual features may not be needed. The usefulness of this research for practice will come from further research. From an engineering perspective, one is most interested in predicting approximately the time-dependent queue lengths (distances) due to control actions and the ensuing delays. To do this acceptably well, it suffices to predict the *N*-curves approximately at intermediate locations (e.g., given the curves at the highway's upstream and downstream boundaries) even if one cannot predict the detailed location of all the wiggles. This objective seems to have been behind Newell's simplified theory of kinetic waves (*11*), and it may be the desirable form for future theories of highway traffic flow. The authors believe that these data and similar data sets obtained elsewhere can be valuable for testing practical theories that would predict *N*-curves.

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