CHARACTERISTICS OF FREEWAY TRAFFIC AND OF FREEWAY LANE-CHANGING BEHAVIOR

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This paper gives a detailed account of important freeway traffic characteristics based on an analysis of aerial photographic data obtained on the Long Island Expressway and the Ventura and the Santa Ana freeways. These freeway traffic characteristics include time headway distribution, time speed distribution, space headway distribution, space speed distribution, space relative speed distribution, and bivariate histograms of space speed and relative space speed with space headways. This information was obtained for every lane and for various levels of traffic service and is presented both in graphical and in summary table forms. The report also gives an account of the nature of various traffic characteristics distributions and relates the bivariate histograms to safe driving rules. Also reported are microscopic aspects of lane-changing behavior obtained from the Long Island data. Discussions and summary statistics were made for the speeds, space headways, and relative speeds of the lane-changing vehicle and its neighboring vehicles. This was done for each lane and for levels of service B and C; some interesting relations were found among the different variables. Three risk criteria were applied that provided hazard measures of lane changes.

•IN THIS paper we shall present some important freeway traffic characteristics and discuss their relations and usefulness. Traffic data used are all aerial photographic data. Each filmed period (usually a few minutes) is considered as a constant flow period. By this we mean that the flow is influenced only by natural fluctuations of traffic rather than the change of actual flow level (say, from service level A to service level B). We shall first analyze in detail the headway, speed, relative speed, and the bivariate relations between the headway and speed and between the headway and relative speed and then follow the analysis of freeway lane-changing behavior. These terms as well as other terms used in the paper are defined as follows.

L is the stretch of the road section, and T is the time period in which we are interested. $C_i(x, t)$ is the i th vehicle passing x at time t such that x is in L and t is in T.

The time headway is the time difference of successive vehicles passing a fixed point x in L during the time period T. Or, we may write that

$$h_{ti} = t_i - t_{i-1}, \quad i = 1, 2, \ldots, M(T, x) \qquad (1)$$

is the time headway of vehicle C_i at point x, where M(T, x) is the total number of vehicles passing x in T, and t_i is the instant that C_i passes x.

The space headway is the distance between two successive vehicles at a given time instant t in T [measured from front-to-front bumper (1)].

$$h_{si} = x_i - x_{i-1}, \quad i = 1, 2, \ldots, N(t, L) \qquad (2)$$

is the space headway of vehicle C_i at time t where N(t, L) is the total number of vehicles in L at the instant of time t.

The traffic is time-homogeneous (constant flow) in T at x if the time headways (h_{ti}) form an independent and identically distributed random sequence during all time arrival epochs t_i at point x.

The traffic is space-homogeneous in L at t if the space headways form an independent and identically distributed random sequence for any pair (x_{i-1}, x_i).

The time speed v_{ti} of C_i is the speed of C_i at a fixed point x in L.

The space speed v_{si} of C_i is the speed of C_i at a fixed time t in T.

The time relative speed r_{ti} is the difference in speed of successive vehicles passing a fixed point x in L, or

$$r_{ti} = v_{ti} - v_{t,i-1} \tag{3}$$

The space relative speed r_{si} is the difference in speed of successive vehicles at a fixed time t in T, or

$$r_{si} = v_{si} - v_{s,i-1} \tag{4}$$

For time-homogeneous traffic, we define the flow q(x) at any point x in L to be

$$q(x) = \lim_{T\to\infty} \frac{M(T,x)}{T} \tag{5}$$

We also define the instantaneous concentration k(t, L) at time t in L to be

$$k(t, L) = N(t, L)/\|L\| \tag{6}$$

where $\|L\|$ is the length of the road stretch L.

The concentration over L is defined as the mean of k(t, L) over all t in T, or

$$k(L) = \lim_{T\to\infty} \frac{1}{T} \int_0^T k(t, L)dt \tag{7}$$

and the instantaneous average speed at fixed time t in L is given by

$$v(t, L) = \frac{\sum_{i=1}^{N(t,L)} v_{si}}{N(t, L)} \tag{8}$$

The time mean speed at x is

$$\bar{v}_t(x) = \lim_{T\to\infty} \sum_{i=1}^{M(T,x)} \frac{v_{ti}}{M(T,x)} \tag{9}$$

The space mean speed over L is defined by

$$\bar{v}_s(L) = \lim_{T\to\infty} \frac{\int_0^T v(t, L)k(t, L)dt}{\int_0^T k(t, L)dt} \tag{10}$$

It can be shown that, in time-homogeneous traffic flow,

$$q(x) = \bar{v}_s(L) \times k(L) \tag{11}$$

For space-homogeneous traffic flow, we define concentration and space mean speed in the usual way, i.e.,

$$k(t) = \lim_{L \to \infty} k(t, L) \tag{12}$$

and

$$\bar{v}_s(t) = \lim_{L \to \infty} v(t, L) \tag{13}$$

For time- and space-homogeneous traffic, $k(t)$ and $\bar{v}_s(t)$ in Eqs. 12 and 13 are independent of t and equal to $k(L)$ and $\bar{v}_s(L)$ respectively. We refer to Breiman (2) for detailed discussions and proofs of all the preceding relations.

Time statistics are fundamental statistics that are obtained directly from aerial data (with only data reduction and smoothing). On the other hand, space statistics are difficult to obtain even with the aid of aerial data. This is because we have neither an infinite length of road stretch with homogeneous traffic nor a means of photographing it—even if it were to exist. However, space statistics are more important than time statistics in describing traffic flow conditions and in analyzing relations among traffic characteristics with regard to freeway traffic operations and control. Approximate methods to obtain space mean speed and concentration from time statistics are given in Eqs. 14 and 15 respectively:

$$\bar{v}(x) = \frac{n}{\sum_{i=1}^{n} \frac{1}{v_{ti}}} \tag{14}$$

$$k(x) = q(x)/\bar{v} \tag{15}$$

where n is the number of vehicles passing the point x per unit time, and q(x) is the hourly flow at x.

In traffic engineering the operating characteristics are generally described in terms of level of services, i.e., operating conditions that are related to driving speed, comfort, convenience, economy, and safety. Detailed procedures are given in the Highway Capacity Manual (1) for the determination of level of service.

The Long Island Expressway aerial data showed little effect of either an on- or an off-ramp traffic flow; the Ventura Freeway and Santa Ana Freeway data showed an off-ramp traffic flow effect. Detailed descriptions of the physical sites and summary of data collected are given in the next section.

DESCRIPTION OF FREEWAY SITES AND DATA

Aerial data from three different locations are being presented in this report. The first is the three-lane westbound Long Island Expressway in New York. Various factors that affected the selection of this site were the level grade, free of curvature, nonsignificant effects of on- and off-ramps, and medium to high flow of traffic. The section of the Long Island Expressway between the interchange at Guinea Woods Road and Jericho Turnpike was the best possible site found after an extensive search.

The second is the four-lane westbound Ventura Freeway at White Oak Avenue in Los Angeles. The third is the three-lane southbound Santa Ana Freeway at Washington Bou-

levard in Los Angeles. Both Los Angeles sites have exit-ramp effects. All three sites are unidirectional with six, eight, and six lanes respectively in both directions.

Data Collection and Reduction

Aerial data of the Long Island Expressway were analyzed by U.C.L.A. and SDC for the purpose of a freeway analytical model study. The Santa Ana and Ventura Freeway data were analyzed by U.C.L.A. for a separate study of freeway exit-ramp effects.

Details of the photographic instruments, film-reading equipment and techniques, and the associated computer software used to develop trajectories of vehicles relative to an actual ground-based coordinate system are given by Tashjian and Knobel (3).

Summary of Data Collected

We shall give a summary of the time, number of frames and vehicle trajectories, and other pertinent information for each filmed period on the three sites for those films that are completely processed.

In Table 1, the first character of the film number indicates the freeway site; i.e., L indicates Long Island, V indicates Ventura, and S indicates Santa Ana. They are ordered within each site according to increasing amounts of flow (number of trajectories per frame).

The flow, concentration, and space mean speed given in Table 1 are computed based on Eqs. 14 and 15, and the level of service in the table is explained in detail in the Highway Capacity Manual (1).

PROCEDURES FOR COMPUTING SPACE STATISTICS

If one were to look at a fixed section of road, e.g., a 1-mile section, then he would miss all headways larger than 1 mile and possibly many of those that are less than 1 mile. This obviously would bias samples of headways, speeds, and other statistics that are obtained from aerial photographic data. Thus, aerial photographic data directly provide samples that can only be regarded as time statistics. However, space statistics are regarded as being more important than time statistics. For example, the relation $q = k\bar{v}$ for homogeneous traffic holds only for $\bar{v} = \bar{v}_s$ (space mean speed). This is one of the relations that underly the flow of traffic.

In order to obtain $\bar{v}_s$, one must study the relations of speeds and headways in the space domain for utilization in space relations governing traffic. However, one can obtain a measure of $\bar{v}_s$, if one selects a point of origin and looks at selected sequences of speeds downstream. It is noted that $\bar{v}$ using Eq. 14 involving harmonic mean of the time speeds would be an alternate way of obtaining the space mean speed. However, Eq. 14 does not provide probability distributions of space speeds.

Time statistics are easy to obtain. Only a smoothing of trajectories is required to get speed, headway, and relative speed at any fixed point on the road stretch. However, the calculation of space statistics is far more than trivial. The difficulty, basically, is that our data do not cover a long enough stretch of homogeneous freeway to be space data. They are actually time data taken at a fixed point with a small extension (on the order of 1 mile) into space. A naive approach to the estimation leads to serious errors. For instance, suppose we want to estimate the distribution of space headways in the outer lane. The obvious thing to do is to measure all space headways in each frame of a given freeway stretch and construct a histogram from these. Then the histogram should resemble the density of the underlying space headway distribution. However, the conclusions reached using this approach will not have a sound statistical basis. The main reasons are that there is a strong dependence between the headways of any car on successive frames as well as the dependence between successive car headways on the same frame. Also, the data are strongly biased in favor of the smaller headways because of the finite stretch of freeway covered. We refer to Breiman (4) for detailed arguments. Therefore, we use the following procedures to calculate space statistics.

For space headways, we looked at the pairs consisting of the R th and (R + 1) st space headways downstream every other time that a car passed a fixed space origin

for the lane in question. Here R was taken as large as possible but fixed for every lane and for every run (in the range of 5 to 8, depending on lane and flow). These were recorded as space headways.

The distribution of space speeds was determined by looking at the sequence of speeds of the R th car downstream every time a car passed the origin.

The distribution of space relative speed distribution was determined by looking at the sequence of the differences of the speed of the (R + 1) st car and the speed of the R th car. The justification for this procedure is given elsewhere (4).

The mean and variances of the preceding statistics can be obtained by the standard procedures provided below:

$$\mu = \sum_{i=1}^{n} \frac{x_i}{n} \tag{16}$$

$$\sigma^2 = \sum_{i=1}^{n} \frac{(x_i - \mu)^2}{n} \tag{17}$$

where x_i is the i th sample of headway or speed (time or space), or space relative speed. The corresponding mean and variance are μ and σ^2.

GRAPHICAL REPRESENTATION OF FREEWAY TRAFFIC BEHAVIOR FOR SELECTED FILMS

For the Long Island Expressway data, there exist service levels A, B, and C. We have used films L1, L2, L6, and L8 as typical examples to represent the three service levels. Films L1 and L2 have an average flow of 2,213 vph, which is close to the maximum allowable volume in service level A. Film L6 has a flow of 2,852 vph, which is in the middle of service level B. Film 8 has a flow of 4,381 vph, which is at the maximum allowable volume in service level C for a peak-hour factor slightly higher than 0.91.

For the Ventura Freeway data, there exist service levels B, C, D, and E. Among them, B and C are chosen for detailed study because we are more interested in comparing them (four lanes with exit ramp) with the Long Island data (three lanes with no ramp). Films V1, V2, and V3 are used for service level B, and V4 and V5 are used for service level C. Films V1, V2, and V3 have an average flow of 4,533 vph, which is in the upper half of the volume range in service level B. Films V4 and V5 have an average flow of 5,453 vph, which is in the middle of service level C for a peak-hour factor of 0.91.

Because Santa Ana Freeway is also a three-lane freeway, it will also be interesting to compare its results with the Long Island and Ventura data. Unfortunately, only service level C is in common for all three sites. We thus select film S1 for detailed study. Film S1 has a flow of 3,808 vph, which is in the lower half of the volume range in service level C.

We note here that all probability density functions in the report are smoothed curves fitted over the empirical distributions. Only a limited number of density functions are presented graphically in this paper as examples because of space limitation. All others can be found elsewhere (5). However, our discussions are not limited to the examples.

Time Headway Distributions

Figure 1 shows the time headway distribution for the Long Island Expressway in service level C.

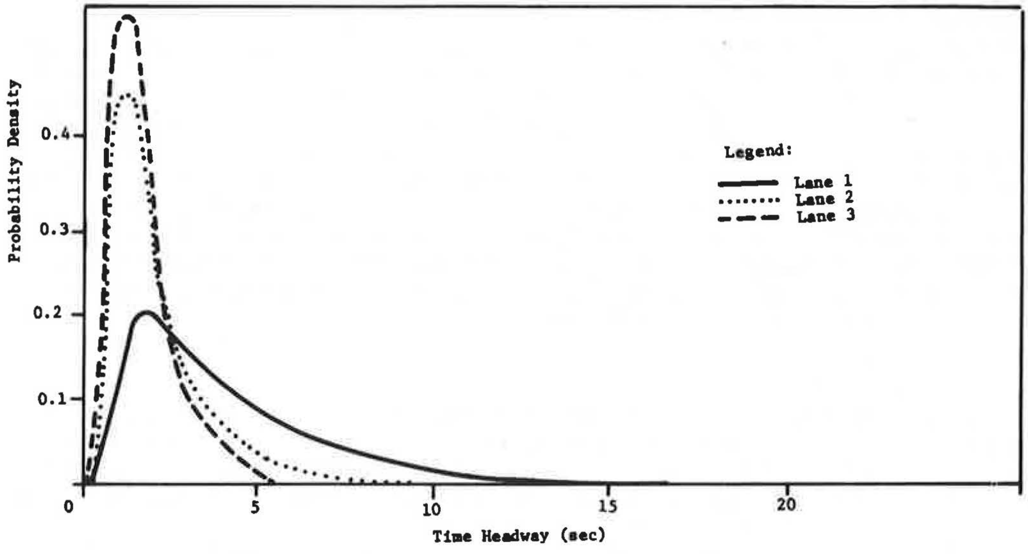
It was observed [for the Long Island Expressway data (6)] that, out of a total of 24 cases (three lanes, eight films), only 3 were rejected independence at the 5 percent level by the Spearman and Kendall rank correlation tests. This means that, for practical purposes,

Table 1. Summary of all films.

Film Number[a] (service level)	Date and Time	Number of Frames	Number of Trajectories	Flow (cars/hour)	Concentration (cars/mile)	Space Mean Speed (mph)
L1 (A)	6/10/69, 2:00 p.m.	297	340	2,135	35.7	59.9
L2 (A)	6/10/69, 10:30 a.m.	276	242	2,290	38.2	60.0
L3 (B)	6/10/69, 6:15 p.m.	351	508	2,633	42.0	62.7
L4 (B)	8/22/69, 9:20 a.m.	366	536	2,659	44.6	59.7
L5 (B)	6/10/69, 6:15 p.m.	176	268	2,839	47.3	60.1
L6 (B)	8/22/69, 5:55 p.m.	821	1,307	2,852	48.3	59.1
L7 (B)	8/21/69, 9:50 a.m.	849	1,393	2,953	51.1	57.8
L8 (C)	6/10/69, 8:15 a.m.	464	1,113	4,381	79.1	55.5
V1 (B)	4/21/70, 12:40 p.m.	492	661	4,443	69.9	63.6
V2 (B)	3/14/69[b]	515	715	4,532	73.1	62.0
V3 (B)	3/19/70, 12:40 p.m.	202	305	4,625	70.0	66.1
V4 (C)	9/18/68[b]	484	740	5,214	84.8	61.6
V5 (C)	3/25/69, 2:42 p.m.	478	823	5,691	89.6	63.6
V6 (D)	5/19/70, 4:00 p.m.	492	1,035	6,879	111.9	61.5
V7 (D)	3/31/70, 4:00 p.m.	406	896	7,170	118.2	60.7
V8 (E)	3/25/69, 4:35 p.m.	497	1,112	7,206	127.4	56.6
V9 (E)	9/18/68[b]	463	1,042	7,255	127.2	57.0
V10 (E)	5/5/70, 4:00 p.m.	477	1,063	7,369	126.9	58.1
V11 (E)	6/12/70, 4:25 p.m.	370	875	7,588	125.6	60.4
S1 (C)	7/9/68, 2:40 p.m.	404	652	3,808	64.0	59.5
S2 (D)	7/9/68, 1:30 p.m.	284	369	5,092	96.0	53.1

[a]L = Long Island, V = Ventura, and S = Santa Ana. [b]Times are unavailable.

Figure 1. Time headway distribution (Long Island Expressway, service level C).



we can assume the sequence of time headways to be independent. It was also observed (6) that the tail of the time headway distribution could be fitted to an exponential function. That is,

$$P(h_{t1} \geq t) = Ce^{-(t-t_0)/\beta} \qquad t \geq t_0 \qquad (18)$$

where C is the total proportion of the headways that are greater than or equal to t_0, and t_0 and β are constants that depend on flow levels. The general trend is that the smaller the flow is, the larger the value of C is. A better fit could be obtained by other probability density functions, e.g., a semi-Poisson function (7). However, its form is much more complicated than the exponential type of distributions.

The outer lane (lane 1) always has a longer tail than do the inner lanes. The mean and the standard deviation of headway decrease with an increasing lane number. The headway distribution of the Long Island site (no ramp) is quite different from the other sites (with exit ramp). The former has a larger mean and standard deviation. This phenomenon occurs because fewer cars are using lane 1 for exiting purposes.

Time Speed Distribution

Unlike time headways, the successive time speeds are heavily correlated, even at moderate flow. The correlation is lane-dependent, increasing with increasing lane numbers. It was found (6) that, for the Long Island Expressway data, time speeds in all lanes are normally distributed.

The mean and the standard deviation are heavily lane-dependent. Lane 1 has the smallest mean and largest standard deviation, and the inner lane (lane 3 or lane 4, corresponding to a three- or four-lane freeway) has the largest mean and smallest standard deviation.

Because the level of service C is common for all three freeways, we want to compare the speeds for this service level only. Except for lane 1, traffic on the Santa Ana Freeway moves faster than the traffic on the Long Island Expressway. This could be due to the different driving characteristics of the drivers on these two freeways. The exceptional case (lane 1) results from the exit-ramp effect, in which more cars are using lane 1 at the Santa Ana site and cause larger disturbances than at the Long Island site. In comparing the four-lane Ventura Freeway to the three-lane Santa Ana Freeway, we observed that the former has higher mean speeds for all lanes than the corresponding lanes in the latter. Because these two freeways are in the same metropolitan area, it is safe to say that a four-lane freeway has better performance than a three-lane freeway under the same volume/lane traffic.

Space Headway Distributions

It was observed that the space headway distributions are very similar to those of the corresponding time headways. For the Long Island Expressway data, it was observed (6) that, out of a total of 24 tests, independence of space headways was rejected at the 5 percent level only three times—the same as in the case of time headways, except the rejected cases were different.

In fact, when the speeds are constant, the space headway distribution is exactly the same as the time headway distribution (1). Small variations in speeds will not affect the space distribution in such a way as to make it significantly different from the time distribution.

Space Speed Distribution

Figure 2 shows the space speed probability density distribution of the Long Island Expressway in service level C.

As in the case of time speed distributions, the sequence of space speeds is heavily correlated and normally distributed (6). However, because (1)

$$f_s(v) = \frac{\bar{V}_s}{V} f_t(v) \qquad (19)$$

where $f_s(v)$ and $f_t(v)$ are the density functions of speeds measured in space and time respectively, $f_s(v)$ and $f_t(v)$ cannot both be normal except when $\bar{v}_s = v$. But, when $\bar{v}_s/v$ is very close to one, the normality of $f_t(v)$ implies that $f_s(v)$ is approximately normal. In fact, because $\sigma/\bar{v}_s$ is generally less than 0.1, it follows that most speeds are in the range where $\bar{v}_s/v$ varies from 0.9 to 1.1, and we conclude that both $f_s(v)$ and $f_t(v)$ have approximately the same type of probability density functions, i.e., the normal distribution.

Space Relative Speeds

Figures 3 is the probability density function of the relative speed in space of successive pairs of cars on the Long Island Expressway for service level C.

As in the case of space speeds, the relative space speeds are all approximately normally distributed with close-to-zero mean and standard deviation decreasing with increasing lane number. For service level C, the standard deviation of the relative speed for the Long Island Expressway lane 3 is significantly smaller than those of the corresponding lanes in the Ventura and Santa Ana freeways. This difference is reduced with the reduction in the lane number. Because relative speed is an indication of freeway disturbances, the preceding results indicate that the freeway traffic disturbances decrease from outer lanes to inner lanes. However, at light to medium traffic, the general base value of these differences in the standard deviation of the relative speed merely indicates the differences in the desired speeds of the successive drivers in the various lanes. The lower values in the inner lane indicate that drivers in that particular case tend to have the same driving habits as those in the shoulder lanes. As the traffic concentration increases, different successive drivers are forced to give away their individual desired driving habits in favor of the average driving habits and safety. This results in the lower values of the standard deviations of the speeds of the successive cars as we encounter higher concentration of traffic.

The standard deviations of the relative speeds for lanes 2 and 3 of the four-lane Ventura Freeway are almost the same, and consequently the lane-3 values for this freeway are much larger than the corresponding values for this lane in the three-lane Long Island and Santa Ana freeways. Furthermore, the lane-4 values of the four-lane Ventura Freeway are comparable to the lane-3 values of the three-lane Santa Ana Freeway.

Bivariate Histograms

We may intuitively expect that either one or both of the following conditions hold: Space headway is positively correlated to the follower's speed, and relative speed of successive cars (speed of the leader and speed of the follower) is positively correlated to the space headway between them. However, the bivariate histograms of speed versus space headway and relative speed versus space headway do not appear to have any obvious correlations for all cases except that the higher the average speed is, the higher the average space headway. Therefore, we only present a bivariate histogram of the Long Island Expressway service level C as shown in Figure 4. The hazard region shown in Figure 4 is derived from the California safe-driving rule, which is discussed later in the paper. It is observed that the proportion of cars violating the California safe-driving rule increases from about 13 percent in lanes 1 and 2 to more than 50 percent in lane 3, and the average for the three lanes is 33 percent.

Summary Tables

The aforementioned probability density functions, plus others that are given elsewhere (5), are summarized in tabular form for easy comparison.

Tables 2 and 3 are the summary of mean and standard deviation of the time and space statistics respectively for the Long Island Expressway data, whereas Tables 4 and 5 are those for the Ventura Freeway data. Table 6 gives the mean and variances of time and space statistics for the Santa Ana Freeway data, and Table 7 gives the mean and standard deviation of relative space speeds for all three sites.

Figure 2. Space speed distribution (Long Island Expressway, service level C).

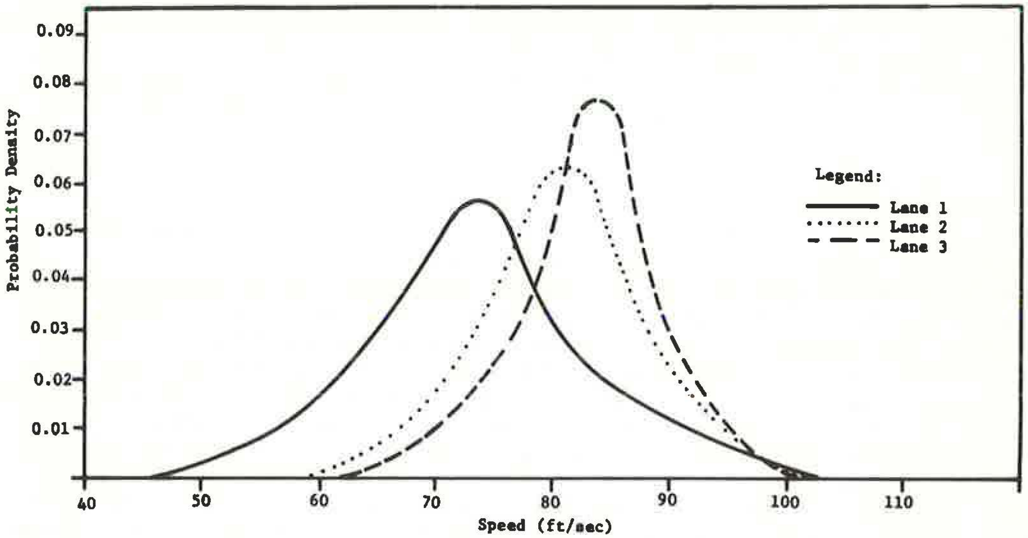


Figure 3. Relative speed distribution (Long Island Expressway, service level C).

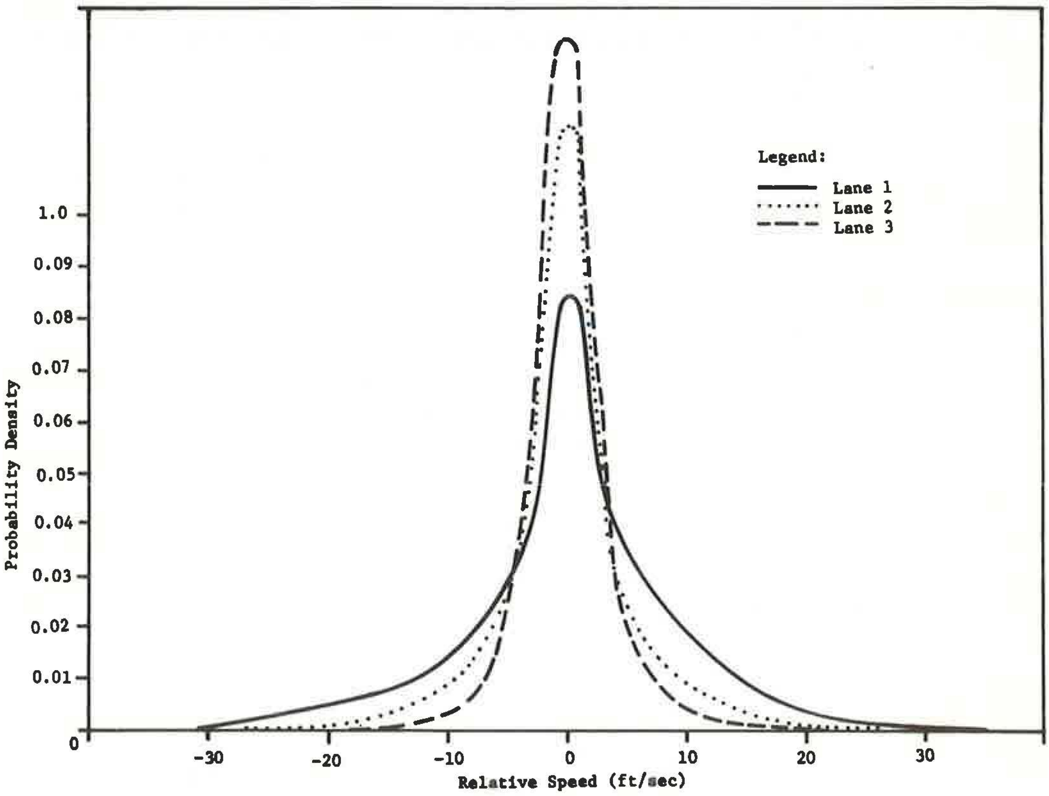


Figure 4. Speed versus space headway.

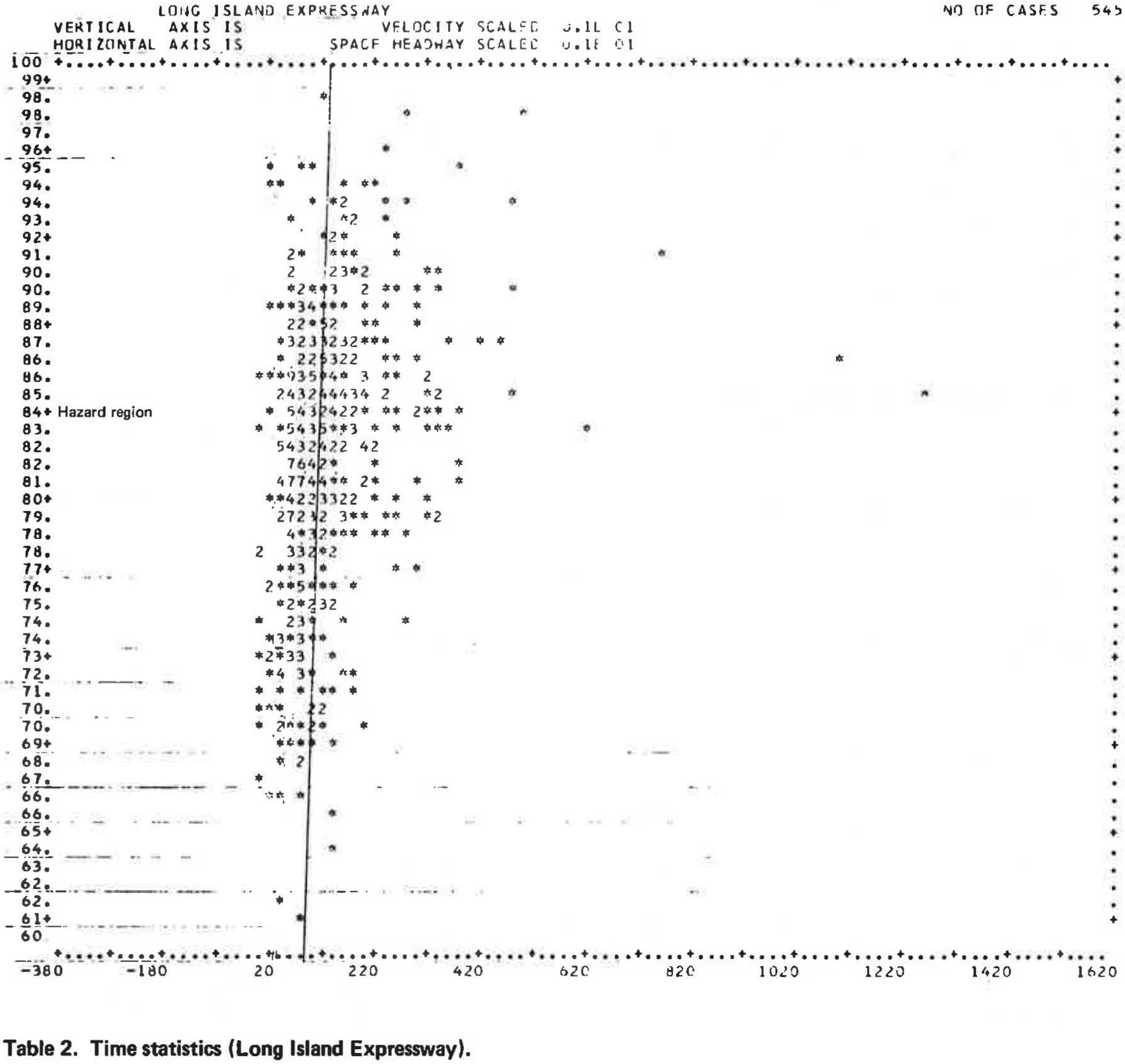


Table 2. Time statistics (Long Island Expressway).

Service Level	Lane 1 Speed (ft/sec)	Lane 1 Headway (sec)	Lane 2 Speed (ft/sec)	Lane 2 Headway (sec)	Lane 3 Speed (ft/sec)	Lane 3 Headway (sec)
A						
Mean	80.9	7.1	87.5	4.1	93.0	4.0
Standard deviation	9.6	5.3	6.6	4.1	5.8	4.1
B						
Mean	79.6	6.5	86.6	3.3	90.7	2.9
Standard deviation	10.1	4.9	7.1	2.5	5.4	2.8
C						
Mean	76.1	5.3	82.0	2.3	83.8	6.5
Standard deviation	10.8	4.4	7.2	1.8	1.7	1.2

Table 3. Space statistics (Long Island Expressway).

Service Level	Lane 1 Speed (ft/sec)	Lane 1 Headway (ft)	Lane 2 Speed (ft/sec)	Lane 2 Headway (ft)	Lane 3 Speed (ft/sec)	Lane 3 Headway (ft)
A						
Mean	79.2	572	86.0	338	91.4	393
Standard deviation	9.2	441	6.9	317	6.4	388
B						
Mean	78.3	460	85.5	286	89.5	257
Standard deviation	9.5	393	6.7	238	5.1	250
C						
Mean	74.4	343	81.9	182	82.5	152
Standard deviation	10.7	281	7.5	138	6.4	112

Table 4. Time statistics (Ventura Freeway).

Service Level	Lane 1 Speed (ft/sec)	Lane 1 Headway (sec)	Lane 2 Speed (ft/sec)	Lane 2 Headway (sec)	Lane 3 Speed (ft/sec)	Lane 3 Headway (sec)	Lane 4 Speed (ft/sec)	Lane 4 Headway (sec)
B								
Mean	81.2	4.3	91.7	3.2	100.6	3.0	105.2	2.9
Standard deviation	10.1	3.5	7.1	2.4	6.4	2.3	6.1	2.6
C								
Mean	83.8	3.1	91.4	2.8	98.1	2.5	102.3	2.3
Standard deviation	9.6	2.4	6.6	2.4	6.6	2.0	5.0	2.0

Table 5. Space statistics (Ventura Freeway).

Service Level	Lane 1 Speed (ft/sec)	Lane 1 Headway (ft)	Lane 2 Speed (ft/sec)	Lane 2 Headway (ft)	Lane 3 Speed (ft/sec)	Lane 3 Headway (ft)	Lane 4 Speed (ft/sec)	Lane 4 Headway (ft)
B								
Mean	79.3	334.9	90.6	296.2	99.3	294.0	104.1	294.9
Standard deviation	9.5	300	6.6	227	6.1	223	7.5	271
C								
Mean	80.8	253.1	90.0	247.9	97.2	248.0	101.2	237.6
Standard deviation	9.0	230	6.6	204	6.8	196	5.3	214

Table 6. Time and space statistics (Santa Ana Freeway, service level C).

Statistics	Lane 1 Speed (ft/sec)	Lane 1 Headway	Lane 2 Speed (ft/sec)	Lane 2 Headway	Lane 3 Speed (ft/sec)	Lane 3 Headway
Time						
Mean	74.0	3.3 sec	85.4	2.6 sec	93.1	2.2 sec
Standard deviation	10.0	2.8 sec	7.8	1.9 sec	5.0	1.7 sec
Space						
Mean	69.6	226.7 ft	84.7	199.2 ft	90.2	193.2 ft
Standard deviation	10.5	193 ft	10.8	121 ft	15.9	148 ft

It is noted that, in all cases, the mean of space speeds in a lane is smaller than the mean of time speeds in the corresponding lane. This is not surprising because

$$\bar{v}_t = \bar{v}_s + \frac{\sigma_s^2}{\bar{v}_s} \qquad (20)$$

CHARACTERISTICS OF FREEWAY LANE-CHANGING BEHAVIOR

Lane changing is a common and important phenomenon in freeway traffic. It is the only operation that a driver can exercise other than the change in speeds. Both lane changing and speed changing are key traffic operations of multilane freeways; it is very important to understand them so that they can be predicted under various circumstances such as bottlenecks and other freeway disturbances. The extensiveness of lane changing has great impact on the quality of service and safety. In another study (8) we used aerial experimental data for freeway lane-changing model validation. In that study, we were more interested in the macroscopic aspects of the lane-changing behavior; that is, we are interested in the average frequency of lane changing for a given traffic situation. In this study, our focus is now on the microscopic aspects in order to understand various factors such as lane changer's speed relative to its neighboring vehicles, its clearance, etc., which may have caused lane-changing maneuvers. Use of Figure 5 can help us to define all the pertinent parameters. In this figure the circled numbers indicate vehicles that constitute the local environment of a lane changer. Vehicle 1 is the lane changer in its original lane, with the long arrow heading its destination lane. Vehicle 2 is the leader. Vehicle 3 is the accepted gap leader. Vehicle 4 is the accepted gap follower. Vehicle 5 is the opposing gap leader. Vehicle 6 is the opposing gap follower. Case A represents a lane change from lane 1 (the outer lane) to lane 2 (the middle lane), case B from lane 2 to lane 1, case C from lane 2 to lane 3 (inner lane), and case D from lane 3 to lane 2. Other variables shown in Figure 5 are defined in the following:

- v_i = speed of vehicle i, i = 1, 2, . . . , 6, at the instant, e.g., t, vehicle 1 is making a lane change;
- x_1 = the distance between vehicles 1 and 2 at t;
- x_2 = the length of the accepted gap at t;
- x_3 = the distance between the gap leader 3 and the lane changer 1 at t;
- x_4 = the distance between the lane changer 1 and the gap follower 4 at t;
- x_5 = the length of the opposing gap (x_5, x_6, and x_7 applicable in cases B and C only) at t;
- x_6 = the distance between the opposing gap leader 5 and the lane changer 1 at t; and
- x_7 = the distance between the lane changer 1 and the opposing gap follower 6 at t.

Aerial photographic data of the Long Island Expressway were used to obtain the aforementioned variables in a lane-changing process.

SUMMARY OF LANE-CHANGING STATISTICS

Because of space limitations we shall only present, in table form, all pertinent lane-changing statistics. Detailed graphical data are given elsewhere (9).

Gap Statistics

The mean values and standard deviations of gaps x_1 through x_7, for service levels B and C of the Long Island Expressway data, are given in Table 8. It was found that the type of distribution of the various spatial distances (x_i's) among the different vehicles during the lane-changing process are very similar to the space headway distribution of all vehicles (e.g., details are all negatively exponential), except that the mean and standard deviations are quite different.

Let us first look at service level B. The mean gap of x_1 in each lane is much lower than the mean gap of all vehicles in corresponding lanes. This shows that most lane changers are in a position too close to the leader prior to lane changing. The distribu-

Risk Criterion 1

The first criterion considered is based on measurement of the closing speed between a pair of car-following vehicles and the separation distance between them, namely v_{31} versus x_3 and v_{41} versus x_4. The pair would fall within the hazardous region if the separation distance between them was so small that the follower would have to decelerate at a rate greater than $a_c = 5$ ft/sec^2 to avoid hitting the leader. More precisely, for a pair of vehicles 1 and 3, we calculate

$$a = \frac{(v_1 - v_3)^2}{2(x_3 - 17.6)} u(v_1 - v_3) \qquad (21)$$

and compare a with a_c. The number 17.6 is the average vehicle length (ft) and $u(\cdot)$ is the unit step function. Vehicle 1 is in the hazard region if $a \geq 5$ ft/sec^2. This is similarly done for the vehicle pair 1 and 4.

Risk Criterion 2

This criterion was defined (10) by considering a driver's response to a rapid braking maneuver of the leader, including an allowance for a lag in his response time. For the vehicle pair 1 and 3, the hazard region is given by

$$v_1T - (x_3 - L) + \frac{1}{2a}(v_1^2 - v_3^2) > 0 \qquad (22)$$

where a is taken to be 10 ft/sec^2 and T to be 1 sec. The hazard region for the vehicle pair 1 and 4 can be similarly carried out.

Risk Criterion 3

The third criterion is commonly known as the California safe-driving rule, which requires that the following vehicle maintain a distance of at least one car length for every 10 mph of speed. In other words, the hazard region is defined as

$$v_1 > \frac{15}{L}(x_3 - L) \qquad (23)$$

for the pair 1 and 3, and

$$v_4 > \frac{15}{L}(x_4 - L) \qquad (24)$$

for the pair 1 and 4.

The percentage of vehicles that fall in the hazard regions by using the three criteria is summarized in Table 11.

As we note from Table 11, the values of a and b are very small in both service levels for criterion 1. This criterion may not provide an effective risk measure. The risks under criteria 2 and 3 are all significantly higher than the risk of all vehicles that form pairs of leader and follower. Approximately 37 percent and 42 percent of the drivers violated the California safe-driving rule at service levels B and C respectively as compared to 33 percent at service level C when all pairs of leader-followers are included. We can thus say that, based on the California rule, the lane changer is likely to take more risk to perform a lane change as compared to the usual following process. This is conceivable because lane changing accounts for only a brief moment in the entire travel period of a vehicle, and the driver can afford such a high risk. Furthermore, the 33 percent figure for drivers violating the California rule for service level C indicates that this rule is too conservative, and many drivers pay little attention to it.

SUMMARY AND APPLICATIONS

Aerial photographic traffic data of three different sites have been analyzed in detail. Probability density distributions of some important traffic parameters and their sum-

Table 9. Speed statistics (in feet per second).

Service Level	Variable	Lane 1 Mean	Lane 1 Standard Deviation	Lane 2 Mean	Lane 2 Standard Deviation	Lane 3 Mean	Lane 3 Standard Deviation
B	v_1	82.6	11.3	89.3	9.1	93.5	6.9
	v_2	73.0	11.1	84.5	7.6	90.5	6.0
	v_3	87.0	7.8	88.7	8.5	91.0	7.5
	v_4	84.8	8.3	85.1	10.9	85.3	6.7
	v_5			85.4	11.2		
	v_6			84.0	9.1		
Mean speed		78.3	9.5	85.5	6.7	89.5	5.1
C	v_1	79.9	11.9	82.3	10.1	82.8	8.8
	v_2	71.9	10.1	79.4	7.8	81.4	7.2
	v_3	81.4	7.9	81.5	9.6	82.4	8.1
	v_4	79.7	6.6	76.9	9.6	80.0	7.9
	v_5			80.2	9.1		
	v_6			80.5	9.0		
Mean speed		74.4	10.7	80.9	7.5	82.5	6.4

Note: Lanes 1, 2, and 3 are the original lanes of the lane changer except in the case of the mean speed of all vehicles.

Table 10. Relative speed statistics (in feet per second, service level C only).

Variable	Lane 1 Mean	Lane 1 Standard Deviation	Lane 2 Mean	Lane 2 Standard Deviation	Lane 3 Mean	Lane 3 Standard Deviation
v_{21}	-7.9	7.2	-3.0	7.8	-1.36	6.2
v_{31}	1.6	9.8	-0.9	9.8	-0.67	6.0
v_{32}	9.5	9.0	2.1	9.4	0.75	6.7
v_{41}	-0.13	10.1	-5.4	11.4	-3.04	8.0
v_{51}			-2.7	9.1		
v_{52}			0.7	7.4		
v_{61}			-2.4	10.2		

Table 11. Proportion of vehicles in hazard region.

Service Level	Criterion 1 a[a]	Criterion 1 b[b]	Criterion 2 a	Criterion 2 b	Criterion 3 a	Criterion 3 b
B	0	0.006	0.1536	0.1867	0.3253	0.4217
C	0.0125	0	0.3053	0.2741	0.3956	0.4486

[a]Risk of the vehicle pair 1 and 3. [b]Risk of the vehicle pair 1 and 4.

mary tables are presented for some selected films.

The time and space headways have approximately the same type of probability density functions with decreasing mean and standard deviation when traffic volume increases or when the lane number increases (outer lane is lane 1). The successive headways are independent (with very few exceptions).

The speeds (time and space) are approximately normally distributed with increasing mean and decreasing standard deviation according to increasing lane number. When traffic volume increases, the mean and standard deviation both decrease (for the same lane). Successive speeds are heavily correlated.

The relative speeds (space measurements) are normally distributed with close-to-zero mean and standard deviation decreasing with increasing lane number and increasing volume.

Space speeds and relative speeds do not appear to bear any correlation with space headways. However, it does appear that more cars are violating the California safe-driving rule in the inner lane than in the outer lane.

Analysis of relevant parameters (speeds and space headways of the lane changer and its neighboring vehicles) at the moment a lane change was performed were made, employing the Long Island Expressway aerial photographic data of service levels B and C. The mean and standard deviations of the relevant parameters were tabulated. Discussions were made in terms of the relations among the parameters and the risk measure when a lane change is made.

Some of the materials we found in this study may be helpful in terms of traffic operation and control. Knowing the time and space headway distributions of vehicles in each service level enables us to have a better estimate of the available gap between successive vehicles. This will result in upgrading on-ramp control performance. That is, we could estimate the available number of gaps per hour for a given level of service and efficiently control the on-ramp flow.

The lane-changing analysis could be similarly carried out in the vicinity of a freeway on- or off-ramp, and the gap statistics can be compared with the current no-ramp freeway section. With the help of risk analysis and accident records, we would be able to identify the most hazardous region for operational movement.

The microscopic gap characteristics are also very useful in the digital simulation of freeway traffic. One of the most important elements in a digital simulation model is lane changing. The stochastic character of the lane changing can be easily taken into account by incorporating the probability distribution functions of all relevant parameters in the simulation model. In the long run, the lane-changing behavior in the simulation model will be statistically equivalent to the real traffic at corresponding service levels.

Moreover, the exact forms of speed and headway distributions are more useful and realistic than their mean values in characterizing vehicle speeds and headways. These distributions could be incorporated into a freeway traffic simulation model to produce more meaningful results.

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