An Empirical Analysis of Lane Changing on Multilane Highways

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The paper describes a macroscopic analysis of lane-changing behavior on multilane highways. It includes descriptions of the pattern and frequency of lane-changing maneuvers observed under varying road and traffic conditions, the distribution of maneuver lengths and times, and the acceptance and rejection of gaps by lane-changing vehicles. Data for the study were collected at a sample of 30 freeway-locations in Chicago.

LANE-CHANGING BEHAVIOR may be described in terms of 2 measures: (a) frequency, the number of lane changes occurring among all lanes along a given length of road, L, and over a given time span, t; and (b) pattern, the distribution of lane changes between specific lane-lane pairs along a given road length, L, and over a given time span, t.

More formally, if \( N_{ij}(t_m) \) lane changes occur between lanes i and j and within a length L of an n-lane roadway during the m th time interval of length t, then the average frequency of lane changing per unit length per unit time, \( \lambda \), over a series of M such time intervals may be defined as

\[
\lambda = \sum_{m=1}^{M} \sum_{i=1}^{n} \sum_{j=1}^{n} \left( \frac{N_{ij}(t_m)}{L \cdot M \cdot t} \right) ; \quad N_{ij} \geq 0 \text{ if } i \neq j \quad \text{ and } \quad N_{ij} = 0 \text{ if } i = j
\]

In this paper the frequency of lane changing is expressed generally as an average maneuver rate per 500 ft of roadway per minute.

Similarly, the pattern of lane changing may be expressed as an n x n transition matrix \{P_{ij}\}, such that

\[
P_{ij} = \left[ \frac{\sum_{m=1}^{M} N_{ij}(t_m)}{\sum_{m=1}^{M} V_i(t_m)} \right]
\]

where

\( V_i(t_m) = \frac{\text{volume in lane } i \text{ during } m \text{ th period } t}{} \text{ and } \quad P_{ij} = 0 \text{ for } i = j. \)

If the constraint \( P_{ij} = 0 \text{ for } i = j \) is relaxed (i.e., the values on the main diagonal may take on nonzero values) and the value of \( \sum_{j} P_{ij} \) is in turn constrained equal to unity, then the matrix \{P_{ij}\} represents a stochastic matrix, the elements of which represent the probability that a vehicle entering section L in lane i leaves that section in lane j (i.e., the vehicle changes lanes from lane i to lane j over length L).

Data on the frequency of lane changing were collected at 30 locations by means of time-lapse ground photography. The study sample included sections of 2-, 3-, and 4-lane, 1-directional roadways, situated at varying distances from entrance and exit.
ramp terminals. Mainstream volumes during the study period varied from approximately 1,000 to 5,000 vehicles per hour. Figure 1 shows the location of study sites in the Chicago area.

**FREQUENCY OF LANE CHANGING**

Figure 2 shows a set of typical time-series plots of lane-changing frequency for sections of 2-, 3-, and 4-lane roadway. Equivalent frequency plots for the same locations are shown in Figure 3. In each case, the pattern is essentially a random, apparently stationary variation about a stable mean value. This value—denoted as the average lane-changing frequency $\lambda$ for the section—varies both with location and with flow rate.

For 2-lane roadways, the mean lane-changing frequency varies from 0.7 to 1.4 lane changes per 500 ft per minute. For 3- and 4-lane roadways, the equivalent figures are 1.2 to 3.0 and 2.9 to 3.4 lane changes per 500 ft per minute. These figures are based on data collected at points at least 500 ft from a ramp terminal. The equivalent 1-minute variances follow a similar pattern: 0.6 to 0.9 for 2-lane roadways, 1.8 to 2.9 for 3-lane roadways, and 2.9 to 3.8 for 4-lane roadways.

Figure 4 shows a simple plot of the value of $\lambda$ versus total volume. In this case, the value of $\lambda$ is expressed as the average number of lane changes per 200 ft per minute. The plot suggests that the intensity of lane changing tends to peak at medium-high volume levels and to fall off at both higher
and lower flow rates. However, to talk of fitting a formal function to the data is clearly inappropriate.

An essentially similar relationship may be discerned between lane-changing intensity and average mainline speed. This is shown in Figure 5. The speed data are average minute speeds, analogous to the volume measurements shown in Figure 4, computed for the total sample of 3-lane locations. The lane-change data are expressed as the average number of lane changes per 500 ft per minute. The relationship is approximately linear in form over the 10-to-40-mph range, and lane changing tends to decrease in intensity as speeds increase above 40 mph.

Figures 6 and 7 show the variation in lane-changing frequency between specific lane-lane pairs as a function of their average minute volume and speed differentials. In each case, \( \lambda_{ij} \) is expressed as an average maneuver frequency per 500 ft per minute. The data are again based on the composite sample of 3-lane roadways. Equations based on least squares fits to these data are given in Table 1. As might be expected, lane
TABLE 1
RELATIONSHIPS BETWEEN LANE-CHANGING FREQUENCY AND LANE-LANE VOLUME AND SPEED DIFFERENTIALS ON 3-LANE, 1-DIRECTIONAL ROADWAYS

<table>
<thead>
<tr>
<th>Lane-Lane Movement</th>
<th>Equations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center to right</td>
<td>( \lambda_{CR} = 0.278 + 0.011 V_{CR} ) (( R^2 = 0.66 ), ( SE = 0.0048 ), ( \bar{X} = 0.308 ))</td>
</tr>
<tr>
<td></td>
<td>( \lambda_{CR} = 0.074 + 0.012 S_{RC} ) (( R^2 = 0.93 ), ( SE = 0.0050 ), ( \bar{X} = 0.342 ))</td>
</tr>
<tr>
<td>Right to center</td>
<td>( \lambda_{RC} = 0.517 - 0.008 V_{CR} ) (( R^2 = 0.36 ), ( SE = 0.0043 ), ( \bar{X} = 0.355 ))</td>
</tr>
<tr>
<td></td>
<td>( \lambda_{RC} = 0.045 + 0.017 S_{CR} ) (( R^2 = 0.68 ), ( SE = 0.0051 ), ( \bar{X} = 0.347 ))</td>
</tr>
<tr>
<td>Center to left</td>
<td>( \lambda_{CL} = 0.364 - 0.007 V_{LC} ) (( R^2 = 0.24 ), ( SE = 0.0073 ), ( \bar{X} = 0.347 ))</td>
</tr>
<tr>
<td></td>
<td>( \lambda_{CL} = 0.468 - 0.011 S_{CL} ) (( R^2 = 0.77 ), ( SE = 0.0027 ), ( \bar{X} = 0.27 ))</td>
</tr>
<tr>
<td>Left to center</td>
<td>( \lambda_{LC} = -0.136 + 0.026 V_{LC} ) (( R^2 = 0.94 ), ( SE = 0.0037 ), ( \bar{X} = 0.328 ))</td>
</tr>
<tr>
<td></td>
<td>( \lambda_{LC} = 0.580 - 0.017 S_{LC} ) (( R^2 = 0.81 ), ( SE = 0.0041 ), ( \bar{X} = 0.315 ))</td>
</tr>
</tbody>
</table>

Note: \( \lambda_{CR} \) = average number lane changes per 500 ft per minute between center and right lanes; similarly for \( \lambda_{RC}, \lambda_{CL}, \) and \( \lambda_{LC} \);

\( V_{CR} \) = average minute volume differential between center and right lanes; similarly for \( V_{LC} \);

\( S_{CR} \) = average minute speed differential between center and right lanes; similarly for \( S_{RC}, S_{LC}, \) and \( S_{CL} \).

Changing tends to be to the lane carrying the lower flow and to the lane with the higher speed.

**PATTERNS OF LANE CHANGING**

The pattern of lane changing along a portion of multilane road may be represented conveniently by a transition matrix, \( P_{ij} \), the elements of which represent the probability of a single vehicle making a transition, i.e., changing lanes, from lane \( i \) to lane \( j \), within a given distance and a given time span. Figure 8 shows a set of typical transition matrices, calculated for the 6 study locations used in the discussion of lane-changing frequency.

In each case, the individual values in the cells of the matrix represent average transition probabilities computed from a sequence of successive, 15-minute observations of lane-changing behavior at each location. The variance of these successive 15-minute observations is given in parentheses in each cell.

Similar transition matrices were developed for each of the other 26 study locations included in the sample of ground photography. The total set was classified according to study locations and to the average rates of flow during the observation periods and then subjected to a statistical grouping analysis. The results of this analysis are shown for one study location in Figure 9. Similar analyses, with similar results, were performed for each of the other sections of 2-, 3-, and 4-lane roadways studied.

![Figure 8. Typical lane-changing transition matrices.](image-url)
Figure 9. Results of grouping analysis.

Though the data sample is small (and hence some caution is suggested), results suggest that there is little systematic difference between the lane-changing patterns observed at different flow levels for a given location or geometric configuration.

In the 3-lane example in Figure 9, for instance, medium-volume and very high-volume observations or patterns tend to occur at similar flow levels. The differences that do exist appear to be in terms of the intensity rather than the pattern of maneuvers and to be within rather than between volume groupings. This is particularly noticeable if the values of $P_{ij}$ are readjusted to remove the effects of volume and yield simple estimates of the conditional probability of a lane change occurring between lanes $i$ and $j$, given that a lane change of some sort occurs. Similar results were obtained at each of the other locations studied. In no case did the pattern of lane changing appear to vary systematically with variation in total traffic flow.

TIME AND DISTANCE REQUIRED TO CHANGE LANES

The discussion so far has focused on a simple, macroscopic description of lane-changing behavior. Attention is directed here, and in the next section, to a more
detailed examination of the actual mechanics of lane changing, expressed, first, in terms of the time and distance required to complete the lane-changing maneuver and, second, in terms of gap acceptance behavior.

Data Collection

Data for the study were derived from 70-mm aerial photography taken at the points shown in Figure 10. A lane change was considered to commence (Fig. 11) when a vehicle first encroached on the lane line separating the lane in which it was currently traveling from that into which the lane-change maneuver was to be made. The maneuver was considered to be completed once the vehicle had completely crossed that line. The remaining head and tail portions of the maneuver were then analyzed separately. The head portion of the maneuver is the time and distance required for a vehicle to move from a straight-ahead path in its origin lane to first intercept the dividing lane line, and the tail portion of the maneuver is the equivalent time and distance required for a vehicle to return to a straight-ahead path after crossing that line.

Numerical Results

Figure 12 shows the relationships between volume, speed, and maneuver time; Figure 13 shows the relationships between volume, speed, and maneuver distance.
The functions $T = h(q, v)$ and $L = g(q, v)$ (where $T =$ maneuver time, $L =$ maneuver length, $q =$ volume, and $v =$ speed) are represented on the figures by families of parabolic curves, each solid "contour line" representing the locus of points of either constant maneuver time or maneuver distance. The range of the data set, i.e., the range of traffic conditions studied, precluded development of a complete contour map for either maneuver length or maneuver time for all traffic conditions. The existence of a parabolic relationship between maneuver length and time and between traffic volume and speed is, however, strongly suggested by the data shown in Figures 12 and 13.

Figure 14 shows the results of an analysis of the head and tail portions of the lane-changing maneuver. The average time required for the head of the maneuver was 1.25 seconds with a standard deviation of 0.4 second and for the tail, 1.95 seconds with a standard deviation of 0.5 second. Figure 15 shows the equivalent distances. The mean distance for the head was 110 ft and for the tail, 160 ft.

The distribution of lateral placement for the changing vehicle prior to and after the lane-changing maneuver is shown in Figure 16. Vehicle placements are relatively widely distributed with respect to the centerline both before and after the maneuver. The average vehicle moved laterally 27 ft before encountering the lane line and 30 ft after crossing the line before regaining a straight travel path. The average lateral speed of the changing vehicle during the head of the maneuver was thus 2.2 ft per sec, and during the tail, 1.5 ft per sec. For the total maneuver, including the head and the tail, the average lateral speed of the changing vehicle was 3.1 ft per sec, reflecting the higher average lateral speed achieved during the core of the maneuver as the vehicle was actually crossing the lane line.

AN ANALYSIS OF MINIMUM ACCEPTABLE GAPS FOR LANE CHANGING

The following 3 definitions are used in this analysis:

1. Accepted Gap—the time (or distance) headway between the leading and lagging vehicles that defines the gap accepted by the maneuvering vehicle and is measured at the start of the maneuver;
2. Accepted Lead—the time (or distance) headway between the maneuvering vehicle and the leading vehicle in the destination lane measured at the start of the maneuver; and
3. Accepted Lag—the time (or distance) headway between the maneuvering vehicle and the lagging vehicle in the destination lane measured at the start of the maneuver.
Table 2 gives the values of the 95 percentile minimum gap, lead, and lag values observed in the field. The data are based on a total of 1,706 lane changes observed under varying traffic conditions and are stratified by lane density for the destination lane and relative maneuver speed measured between the maneuvering vehicle and the leading-lagging vehicles defining the destination gap. The 95 percentile value was selected somewhat arbitrarily as representative of the average minimum value for a given traffic condition. The observed values of minimum accepted time gap, lead, and lag vary respectively from 1.1 to 2.9 sec, 0.2 to 0.7 sec, and 0.3 to 0.6 sec. The equivalent distance gap, lead, and lag headway measures are respectively 86 to 341 ft, 13 to 80 ft, and 14 to 76 ft.

No stable relationship is discernible between the observed minimum accepted gap, lead, or lag values and the traffic density in the destination lane. Minimum accepted gap, lead, and lag values in both time and space, however, tend to increase as the relative maneuver speed increases. This increase is most marked in lead rather than lag values. As might be expected, the minimum accepted gap size is greater for a given traffic condition than the sum of the equivalent minimum accepted lead and lag values, suggesting that either the lead or the lag value may be critical in any given maneuver but probably not both.

FORMULATION OF AN ACCEPTANCE FUNCTION FOR LANE CHANGING

Unlike most other gap acceptance and rejection situations, it is not possible in the case of a lane change to identify a rejected gap directly. Some mild computational gymnastics must be resorted to, therefore, in order to generate an empirical acceptance function.

Assume that the size of the gap immediately available to a driver in an adjacent lane in no way influences his initial desire to change lanes, and that the probability of his wishing to change lanes remains constant for a given set of environmental conditions. These conditions might include roadway geometrics, overall volume of traffic, or the relative speeds between given lanes of traffic. Assume also that gap acceptance behavior as observed in the field is an unbiased sample of the behavior of all drivers under a given set of environmental conditions, and that an unbiased estimate may be made of the frequency distribution of available gaps in each adjacent lane.

Table 2

<table>
<thead>
<tr>
<th>Traffic Density in Destination Lane (vpm)</th>
<th>Relative Maneuver Speed (fps)</th>
<th>Distance (ft)</th>
<th>Time (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Lag</td>
<td>Lead</td>
</tr>
<tr>
<td>0 to 3 &lt;10</td>
<td>35 -a</td>
<td>126</td>
<td>-a</td>
</tr>
<tr>
<td>4 to 7 &lt;10</td>
<td>48 27 300</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8 to 11 &lt;10</td>
<td>30 42 341</td>
<td></td>
<td></td>
</tr>
<tr>
<td>17 to 22 &lt;10</td>
<td>20 18 110</td>
<td></td>
<td></td>
</tr>
<tr>
<td>23 to 28 &lt;10</td>
<td>17 18 92</td>
<td></td>
<td></td>
</tr>
<tr>
<td>29 to 34 &lt;10</td>
<td>17 13 86</td>
<td></td>
<td></td>
</tr>
<tr>
<td>35 to 40 &lt;10</td>
<td>28 18 89</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 to 3 &gt;10</td>
<td>76 18 166</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 to 7 &gt;10</td>
<td>20 80 296</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8 to 11 &gt;10</td>
<td>61 _b _b</td>
<td>_b</td>
<td>_b</td>
</tr>
<tr>
<td>17 to 22 &gt;10</td>
<td>15 54 215</td>
<td></td>
<td></td>
</tr>
<tr>
<td>23 to 28 &gt;10</td>
<td>27 _b _b</td>
<td>_b</td>
<td>_b</td>
</tr>
<tr>
<td>29 to 34 &gt;10</td>
<td>14 _a _a</td>
<td>_a</td>
<td>_a</td>
</tr>
<tr>
<td>35 to 40 &gt;10</td>
<td>_a _a _a</td>
<td>_a</td>
<td>_a</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

-a Insufficient data.
-b Only large values were observed.
Then one may write
\[ r(t) = a(t) \cdot p \cdot F(t) \]
where
\begin{align*}
  r(t) & = \text{the percentage of gaps accepted that are of size } t, \\
  a(t) & = \text{the percentage of size } t \text{ gaps available to all drivers,} \\
  p & = \text{the percentage of available gaps of all sizes into which a lane change is desired, and} \\
  F(t) & = \text{the percentage of drivers who will accept a size } t \text{ gap.}
\end{align*}

The formulation can be transposed and \( F(t) \) can be expressed as
\[ F(t) = r(t)/a(t) \cdot p \]

The parameters \( r(t) \) and \( a(t) \) can be directly measured through sampling techniques applied to actual freeway operations. The parameter \( p \), however, remains unknown. However, because we assume that \( p \) is constant, we may consider 2 gap sizes, \( t_1 \) and \( t_2 \), and compute
\[ F(t_1) = \frac{r(t_1)}{a(t_1) \cdot p} \quad \text{and} \quad F(t_2) = \frac{r(t_2)}{a(t_2) \cdot p} \]

The ratio of \( F(t_1) \) to \( F(t_2) \) can be written
\[ \frac{F(t_1)}{F(t_2)} = \frac{r(t_1) \cdot a(t_2)}{r(t_2) \cdot a(t_1)} \]

Let
\[ N(t) = \frac{r(t)}{a(t)} \]

Then
\[ \frac{F(t_1)}{F(t_2)} = \frac{N(t_1)}{N(t_2)} \]

If there exists some gap size \( t_0 \), which we can assume to be acceptable to all drivers, then at this value \((t = t_0)\) the acceptance function \( F(t_0) \) will take on the value of 1.0, i.e., \( F(t_0) \) represents the horizontal asymptote for the acceptance function. Therefore
\[ \frac{F(t)}{F(t_0)} = F(t) = \frac{N(t)}{N(t_0)} \]

Determination of the acceptance function \( F(t) \) thus requires estimation of the values of \( r(t) \) and \( a(t) \). Given these values, one may determine, at least conceptually, a functional form for the gap acceptance curves and, hence, compute its mean and variance. Comparison of these values for functions developed for different highway and traffic conditions then provides a convenient basis for evaluating gap acceptance behavior within the lane-changing process.

The time and distance measurements of headway, lag, lead, and gap sizes used in this analysis are shown in Figure 11. All distance measurements are made at the outset of the maneuver. The time measures are then calculated as follows:
Time headway for changing vehicle in origin lane
= distance headway/speed of changing vehicle
Time lag for changing vehicle in destination lane
= distance lag/speed of lagging vehicle
Time lead for changing vehicle in destination lane
= distance lead/speed of changing vehicle
Time gap for changing vehicle in destination lane
= distance gap/speed of lagging vehicle

Comparison of the speeds of the leading and lagging vehicles in the destination lane indicated that the values did not differ significantly for any of the traffic conditions studied.

The data set was first stratified according to the traffic density in the destination lane and the direction of the maneuver; i.e., lane changes to the left or to the right were separated. The availability of gaps in the adjacent lane was initially estimated on the assumption that the positioning of vehicles in adjacent lanes was independent (i.e., that it was equally likely for a vehicle in the lane adjacent to the maneuvering vehicle to be positioned at any point within the available gap). The availability function was calculated as

$$P(\text{gap} \leq T_K) = \frac{\sum_{i=1}^{K} t_i n_i}{\sum_{all \, j} t_j n_j}$$

and

$$P(\text{lag or lead} \leq T_K) = \frac{\sum_{i=1}^{K} t_i n_i}{\sum_{all \, j} t_j n_j} + \frac{t_K \text{(number of gaps} > t_K)}{\sum_{all \, j} t_j n_j}$$

where

- $t_i$ = gap of size $t_i$ and
- $n_i$ = number of times $t_i$ is observed.

The assumption of independence between lanes, however, is only weakly supported by empirical analysis. In view of this, a second method was developed to estimate the availability distribution, $a(t)$, based on the simplistic stratification of the data set according to the distance headways and relative speeds of the vehicles involved in the lane-changing maneuver.

The asymptote to the presumed acceptance function $t_0$ was estimated by first discounting all but the lower 95 percent of the 2 distributions $r(t)$ and $a(t)$. The values of $r(t)$ and $a(t)$ were then aggregated successively for each interval in the distribution from $n$ to $n - K$ until the following inequality was satisfied:

$$\frac{\sum_{j} r(t_j)}{\sum_{j} a(t_j)} \geq \frac{r(t_j)}{a(t_j)} \text{ for all } j \leq (n - K)$$
where
\[ t_{95} = t_n \text{ and} \]
\[ n = \text{the interval corresponding to the} \]
\[ 95 \text{ percentile gap.} \]

Let
\[ \frac{\sum r(t_j)}{n-K} = \frac{N(t_i)}{n-K} \]

and
\[ r(t_j)/a(t_j) = N(t_j) \text{ for all } j \leq (n-K) \]

\( F(t_j) \) can now be written as the ratio
\[ F(t_j) = \frac{N(t_j)}{N(t_0)} \]

A set of gap acceptance functions based on the entire data set considered as a whole
is shown in Figure 17. Figure 18 shows an equivalent set of acceptance functions based
on a 5-level density stratification. The results of a probit analysis applied to the en­
tire data set are shown in Figure 19. The estimated equation is
\[ Y = 1.523 + 1.513 X \]

where
\[ X = \log_e \text{[gap size]} \text{ and} \]
\[ Y = \text{probit of } F(t). \]

The mean accepted gap size derived from this analysis is 1.985 seconds. The
equivalent lead and lag values are 0.527 second and 0.676 second.
In an attempt to assess the influence of ramp terminals on lane-changing behavior, we made estimates of the average lane-changing rate, $\lambda$, at varying distances from a sample of exit and entrance ramp terminals. Separate data were collected for 2-, 3-, and 4-lane, 1-directional roadways and for varying volume levels. For each location, the data were tested for any systematic bias or nonrandom characteristic or both that could be related to the design of the highway or its environs. Similar analyses were also performed systematically for lane-changing patterns by the use of the transition matrix notation described earlier. Figures 20, 21, and 22 show the results of these analyses respectively for 2-lane, 3-lane, 4-lane roadways.

The sparseness of the data for a given location and geometric configuration and the absence of any significant experimental control over potentially confounding influences makes it difficult, if not impossible, to draw very meaningful conclusions from these figures. In each case there is a tendency, albeit weak and nonsystematic, for the intensity of lane changing to increase in the vicinity of the ramp terminal. This is most marked on 3-lane roadway sections and much less marked on 2- and 4-lane sections. The variation about this trend, however, is extremely high. In no case are there grounds for developing a formal relationship between average lane-changing frequency and distance to and from ramp terminals. Variations in mainstream volume do not appear to exert any systematic effect on the spatial distribution of maneuver intensity.

Examination of the distribution of minute-by-minute maneuver counts at each location confirms the general results reported earlier. The distribution of maneuvers was again essentially random at all except 3 locations. These 3 were each immediately downstream from an entrance ramp. Examination of the distributions for these locations indicated that the major discrepancy between the observed and the theoretical random distributions could in each case be attributed to the effect of intermittent platoons of vehicles entering the freeway via the upstream on-ramp.

The general, if not very conclusive, finding is confirmed by the variation in $\lambda$ along a section of approximately 1,500 ft of the Edens Expressway in Chicago (Fig. 23). The figure shows the profile of a gradual increase in the lane-change rate on the approach to the interchange, a decrease within the interchange area, and a sudden increase immediately downstream of the entrance ramp.

Examination of the equivalent patterns of lane changing, expressed as transition matrices $P_{ij}$, yielded equally inconclusive results. Again, the pattern of maneuver tended to reflect the proximity of the ramp terminals.
terminal—indicated in this case by an increase in the values of $P_{ij}$ associated with movements into and out of the lane adjacent to the ramp terminal. Again, however, this trend was not sufficiently marked to enable formal distinction to be drawn among the patterns observed at varying distances from entrance and exit terminals.

In interpreting these results, one should recognize that lane-changing maneuvers are generated for a wide variety of reasons and that their patterns and intensity are influenced by many different factors. Ramp location is only one such factor, albeit an important one. Of at least equal importance are the quality and location of directional signing, the location of adjacent ramp terminals, the volume of truck traffic, the relative speeds in the adjacent traffic lanes, and the aggressiveness of individual drivers. All these and more contribute significantly to the pattern and intensity of maneuvers observed at any one point in either time or space. Given the systemic, and rather crude, viewpoint adopted here and the absence of any significant degree of experimental control, it is not surprising that the results obtained were relatively bland and inconclusive.

Equally important, however, is the fact that no generally dominant influence of ramp terminals on lane-changing behavior was detected at the level of analysis pursued here. Given that most, if not all, of the locations studied represented good rather than bad examples of geometric design, this suggests that lane-changing behavior is not seriously influenced by the proximity of ramp terminals, and particularly that the intensity of maneuvers is not increased by ramps spaced at the intervals (roughly $1/2$ to $1^{1/2}$ miles) observed in the field.

### SUMMARY AND CONCLUSIONS

This paper has presented a selection of elementary empirical results concerning lane-changing behavior on 1-directional, multilane roadways. The discussion has ranged from considerations of the frequency and pattern of lane changing to an analysis of the mechanics of the actual lane-changing maneuver and the effects of ramp location on lane-changing behavior. All of the analyses have been based on field data collected in the Chicago area.

Lane changing is shown to be essentially a random event in the traffic stream, subject to considerable variation at any point in either time or space. Average frequencies and patterns of maneuver exhibit a weak, but systematic, relationship to traffic and roadway conditions. Maneuver times and lengths similarly tend to vary as a function of the volume and speed of traffic. Gap acceptance behavior displays only a very weak, and as yet largely undefined, relationship to traffic flow. Although the average rate of lane changing varied considerably across the set of traffic conditions and field locations included in the study, the distribution of maneuvers over time remained random in virtually every case. The major exceptions to this finding were study locations situated immediately downstream from high-volume entrance ramps. There was no indication that the overall pattern or intensity of lane changing changed from random to nonrandom at a given distance from an entrance or exit terminal.
A final word of caution is in order. Although these findings are based on the analysis of a relatively large and well-defined data base, the amount of substantive information underlying some of the conclusions and the range of traffic and design conditions for which these conclusions are valid without extrapolation are relatively small. A truly definitive analysis here should be based on a much larger sample of study locations. In all cases, it should be borne in mind that only a very crude experimental control could be exercised over the collection and analysis of the data and that all of the results pertain to data collected in the Chicago area; no information was obtained, for example, on lane changing on grades where the results may be very different from those obtained here for level terrain. Equally, no attempt was made to explain why lane-change maneuvers occurred but only to describe some of their characteristics. Clearly, this analytical perspective is reflected in and may partially bias the results discussed here.

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REFERENCES