LANE-CHANGE FREQUENCIES IN FREEWAY TRAFFIC FLOW

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Lane-change frequencies of exiting vehicles close to their intended off-ramp and of through vehicles were determined empirically for an 8-, a 6-, and a 4-lane freeway site. The results were obtained for various flow levels and as a function of upstream distance from the off-ramp. The data base used in this study was acquired by a methodology that involved aerial photographic techniques and that resulted in digitized space-time trajectories of all vehicles traversing the study sites. For each studied flow level at the various sites, lane-change frequencies are presented for each lane pair as well as for both exiting and through vehicles independent of lanes. The results show clearly that the greatest frequency of exiting-vehicle lane changes is toward the right lane and that a corresponding increased frequency of through-vehicle lane changes is toward the left lane. At the off-ramp, where the exiting vehicles leave the freeway, through vehicles have been shown to move back toward the right lane and to have high lane-change frequencies.

•WHEN a driver on a freeway far from his intended exit catches up to a slower driver in front of him in the same lane, he will usually attempt to change lanes in order to maintain his speed. However, if the driver intends to exit at a nearby downstream off-ramp, his behavior will be different because his primary concern will be to move toward the right lane. Such differences in lane-change characteristics of exiting-vehicle drivers in the vicinity of their intended exit from those of through-vehicle drivers may result in special operational and safety problems in the vicinity of off-ramps.

Some limited research results on lane-change behavior in freeway traffic flow are available (1, 2, 3, 4); but there is currently a strong need for more detailed research results to improve the understanding of how the lane-change characteristics affect the operational and safety features of freeway traffic flow. In response to this need, this paper presents data that detail the lane-change frequencies for exiting vehicles upstream of their intended off-ramp as well as for through vehicles as a function of flow level and distance from the off-ramp. The necessary data base for this study was acquired by the use of a recently developed aerial photographic technique (5).

AVAILABLE DATA

The 3 freeway sites selected each contained an off-ramp and an upstream section of the freeway. The sites were situated in the Los Angeles area and consisted of an 8-lane freeway (Ventura Freeway, westbound, at White Oak Avenue off-ramp), a 6-lane freeway (Santa Ana Freeway, southbound, at Washington Boulevard off-ramp), and a 4-lane freeway (Newport Freeway, northbound, at Katella Avenue off-ramp). More details as to the location and geometric design features of these freeway sites are presented in another report (5).

The data were collected with a 70-mm Maurer camera operated from a helicopter that hovered over the studied freeway site. The camera took pictures at time intervals of 1 sec, and the length of the photographed freeway section was of the order of 1 mile. The pictures were scanned in successive order so as to obtain digitized positions of vehicles. A specialized software system deduced individual trajectories from the digitized vehicle coordinates. The resulting trajectories yield the space-time history of each vehicle within the studied freeway site. They include longitudinal and lateral position and speed for each car in time intervals of 1 sec.

The acquired data were subjected to a statistical analysis to isolate those time periods in which the average flow level remained constant. The length of the obtained time periods ranged from 1.5 to 15 min. The data were aggregated into groups where the average flow levels of the selected time periods differ only within a small range in order to improve the statistical significance of the derived analysis results. Table 1 gives the resulting data groups that were used for this study (more details are given in another report, 5).

On the 8-lane freeway for medium and high flow, data in the range from 5,250 to 9,450 ft were obtained from basically the same data sample that was used to obtain the data in the range from 0 to 4,800 ft. For this purpose, the license numbers of the cars traversing the freeway site were photographed by a ground camera system and later assigned to the corresponding car trajectories. License numbers were also recorded at the first off-ramp downstream from the study site, and thus lane-change frequencies could be obtained from the data taken at the study site for cars that were between 1 and 2 miles from their intended off-ramps. In this case, through vehicles were redefined as all vehicles that did not exit at the downstream off-ramp. Therefore, the results obtained for through vehicles between 1 and 2 miles are based on partially the same vehicle sample as the results between 0 and 1 mile—a fact to be considered very carefully in the interpretation of the results.

The acquired data were also analyzed to obtain traffic flow characteristics, such as lane distributions of vehicles, overall speed distributions, speed distributions for each lane, and gap acceptance, as a function of upstream distance of through and exiting vehicles from the exit ramp.

DATA ANALYSIS

For the data analysis, each of the study sites was divided into zones 600 ft in length starting at the nose of the off-ramp and progressing upstream. In each zone all lane changes of exiting and through vehicles were determined and classified by lane-change type; i.e., the number of changes from lane 1 to lane 2, from lane 2 to lane 1, from lane 2 to lane 3, and so on was obtained for the various data groups. Trajectories that entered the sites but terminated before reaching the off-ramp were excluded from this analysis because they could not reveal whether they were exiting- or through-vehicle trajectories (such trajectories can be generated at the end of a data collection period).

If the number of changes by through vehicles from lane i to lane j in the zone at distance d from the off-ramp is denoted by $n_{i,j}(d)$, the frequencies of through-vehicle lane changes

$$L_{T,i,j}(d) = n_{i,j}(d)/[N(d) \times 0.1135 \text{ mile}] \quad (1)$$

were formed in each zone. N(d) is the total number of through-vehicle trajectories that were available in the zone, whereby a trajectory that did not extend all the way through the zone was only counted as that fraction of one that equaled the available trajectory length in the zone divided by the length of the zone. The division by 0.1135

Table 1. Average flow levels of study sites.

Number of Freeway Lanes	Flow	Avg Number of Vehicles/Hour		Time Period (sec)
		Through	Exiting	
8	Low	4,450	437	1,040
	Medium	5,520	595	1,120
	High	7,320	771	2,525
6	Medium	4,440	484	400
	High	5,680	560	180
4	Medium	2,520	427	1,405

mile, the length of a zone, in Eq. 1 yields results in terms of number of through-vehicle lane changes per through-vehicle-mile in each zone.

Correspondingly, the frequencies of exiting-vehicle lane changes,

$$L_{E,i,j}(d) = e_{i,j}(d)/[E(d) \times 0.1135 \text{ mile}] \qquad (2)$$

were formed in each zone, where $e_{i,j}(d)$ is the number of exiting-vehicle lane changes from lane i to lane j in the zone at distance d from the off-ramp, and E(d) is the total number of exiting-vehicle trajectories [analogous to N(d)] that were available in the zone. The results from Eq. 2 yield the number of exiting-vehicle lane changes per exiting-vehicle-mile in each zone.

Furthermore, the frequency of any lane change of a through vehicle per mile was computed by forming the sum $\sum_{i,j} L_{T,i,j}(d)$. Correspondingly, the frequency of any exiting-vehicle lane change per mile was computed by forming the sum $\sum_{i,j} L_{E,i,j}(d)$.

RESULTS

The obtained lane-change frequencies per vehicle-mile are shown in Figures 1 through 6. For the sake of simplicity, all data points are plotted at the midpoints of the zones for which they were obtained, although they actually present an average value over the entire zone.

The sample sizes represented in these figures range from a few to about a hundred lane changes, depending on the data group (the actual results are presented in an earlier report, 5, Appendix F). This means that many of the variations of the plotted data points are statistically insignificant. Therefore, smooth curves have been hand-fitted through the data points with an attempt to indicate only statistically significant features of the data. In the figures showing lane-change frequencies classified by lane-change types, data points for very small sample sizes were omitted.

SUMMARY AND CONCLUSIONS

The largest sample sizes occur in the 3 data groups for the 8-lane freeway. For each of these data groups, Figures 4, 5, and 6 show a pronounced maximum of through-vehicle lane changes from the left lanes toward the right lanes in the zone right at the off-ramp, i.e., from 0 to 600 ft upstream of the off-ramp nose. In this zone, the lane-change frequencies from lanes 2 to 1 are consistently higher than the corresponding frequencies of lane changes from lanes 3 to 2 and lanes 4 to 3. Another set of maxima appears in the zones from 3,600 to 4,800 ft but for the opposite types of lane changes, namely, lane changes from lanes 1 to 2, lanes 2 to 3, and lanes 3 to 4.

These features can be explained if seen in relation to the corresponding behavior of exiting vehicles shown also in Figures 4, 5, and 6. Pronounced maxima of exiting-vehicle lane changes from lanes 2 to 1 occur in the zone from 1,800 to 2,400 ft for low and medium flow and in the zone from 2,400 to 3,600 ft for high flow of the 8-lane freeway site. Maxima for lane changes from lanes 3 to 2 and lanes 4 to 3 are less pronounced and appear at larger distances from the off-ramp than the maxima for the exiting-vehicle lane changes from lanes 2 to 1.

Combining these features for through and exiting vehicles reveals that through vehicles change lanes toward the left as exiting vehicles change lanes toward the right upstream of the off-ramp. As the exiting vehicles exit in the zone from 0 to 600 ft, through vehicles move back into the right lane with a high lane-change frequency; this also causes increased lane-change frequencies of through vehicles from lanes 3 to 2 and lanes 4 to 3.

Analogous behavior, although less pronounced, is found for the 6-lane freeway site for medium flow. For high flow on the 6-lane freeway site, exiting-vehicle lane changes were too sparse to be shown on a meaningful graph. But data shown in Figure 2 suggest that the frequencies of through-vehicle lane changes from lanes 2 to 1 and lanes 3 to 2 do not have maxima in the zone from 0 to 600 ft from the off-ramp nose.

Figure 1. Four-lane site, medium flow.

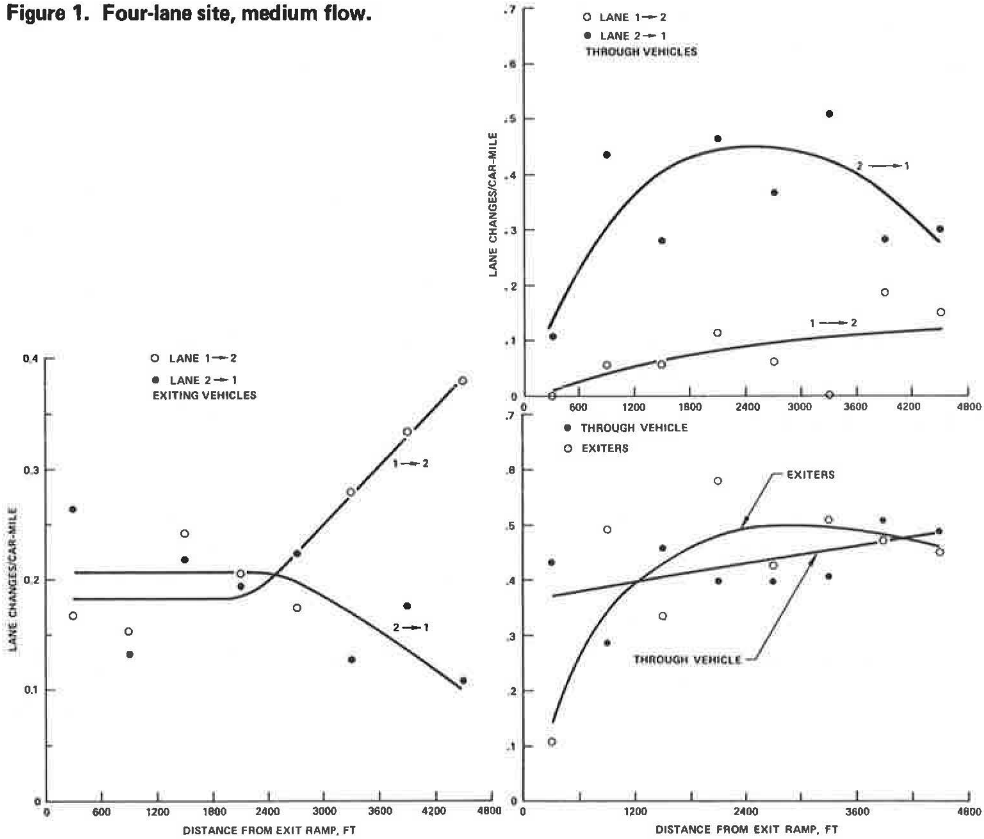


Figure 2. Six-lane site, high flow.

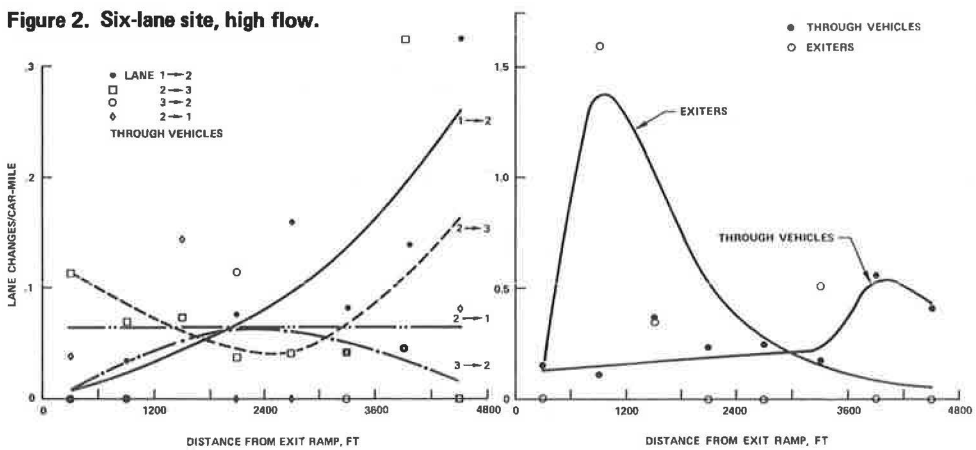


Figure 3. Six-lane site, medium flow.

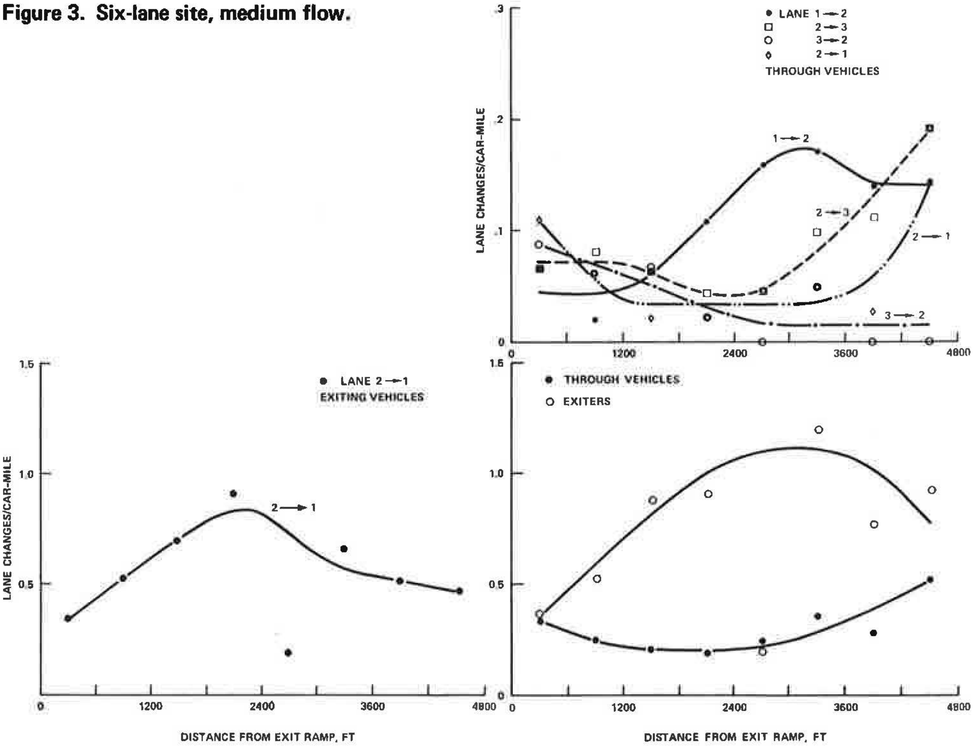


Figure 4. Eight-lane site, high flow.

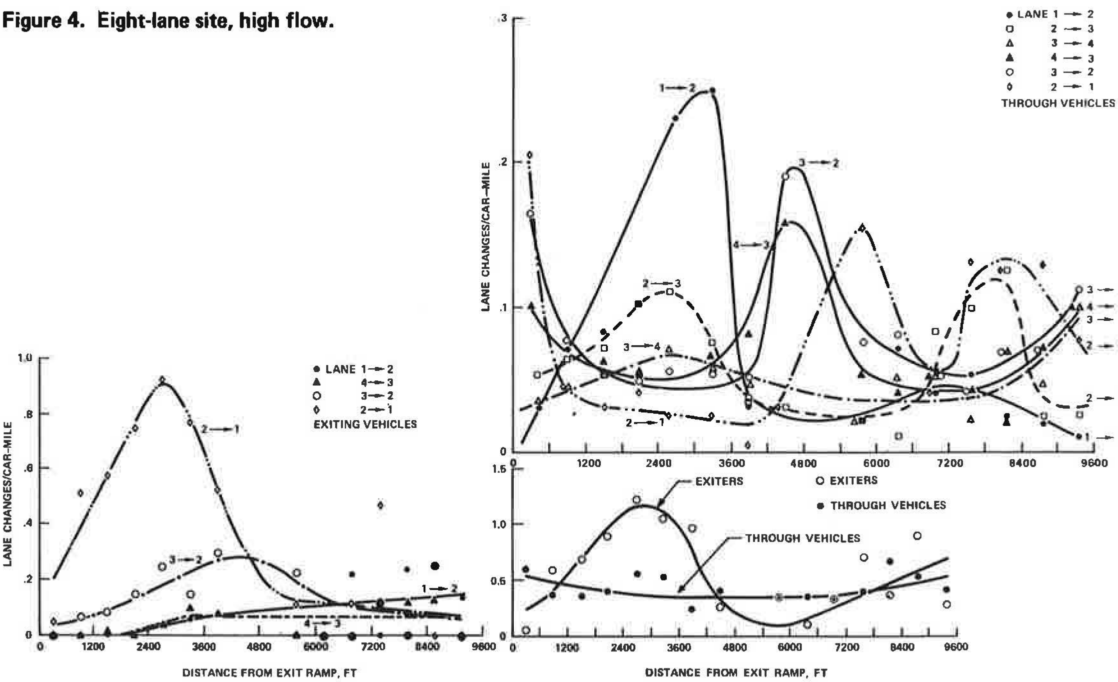


Figure 5. Eight-lane site, medium flow.

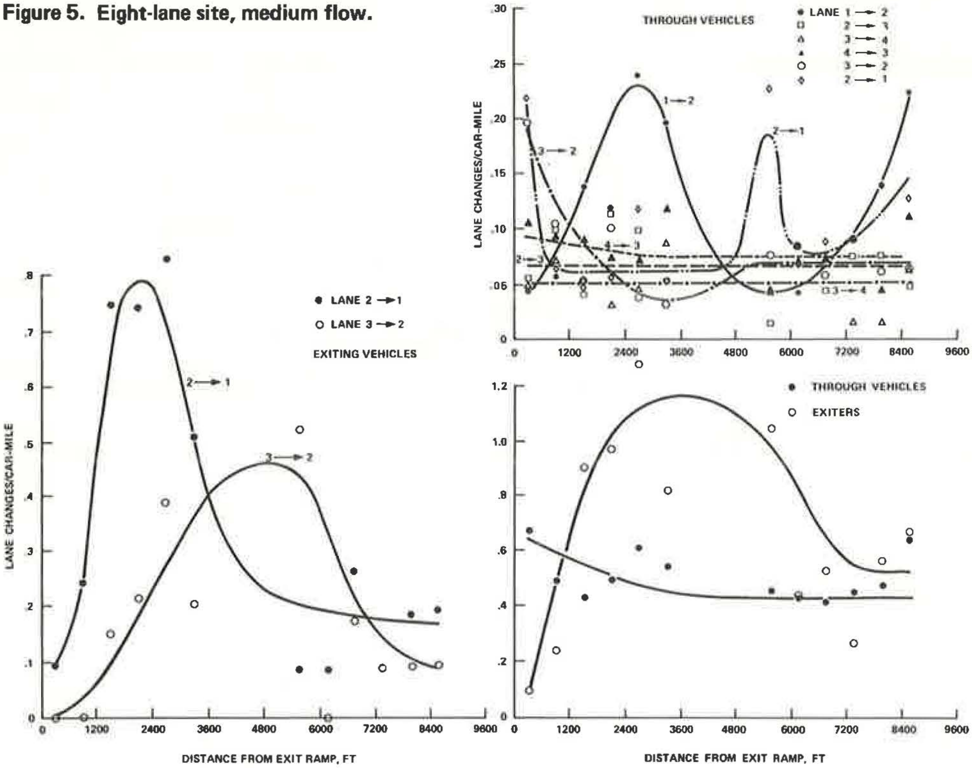
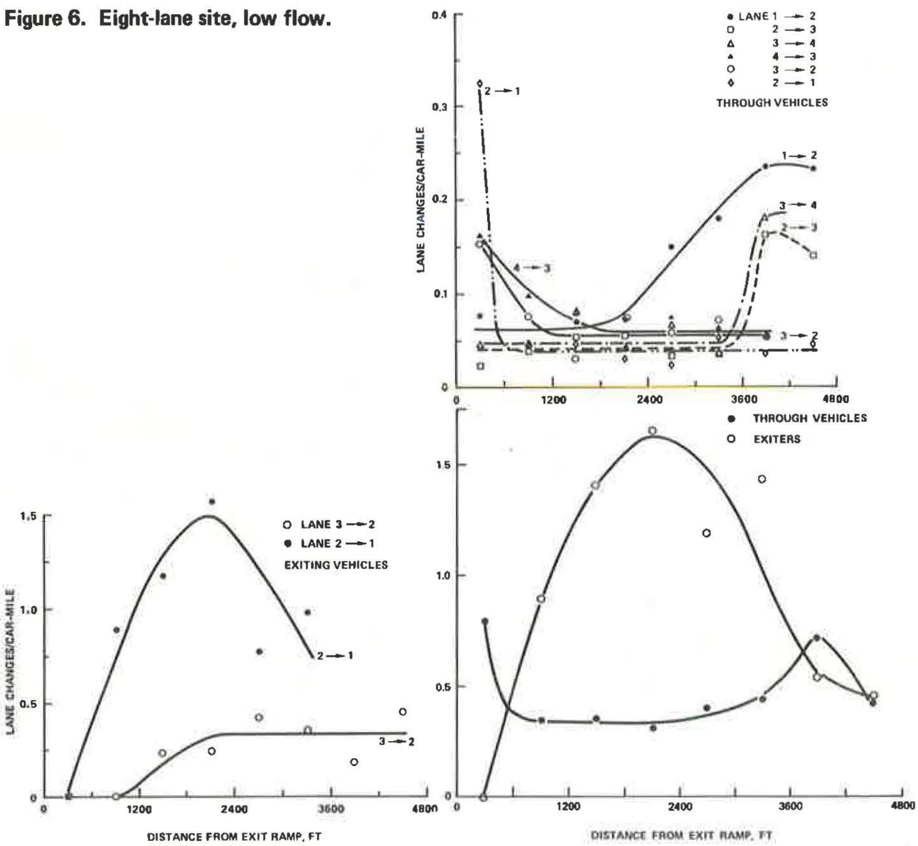


Figure 6. Eight-lane site, low flow.



For the 4-lane freeway site, Figure 1 shows that the maximum of the frequency of exiting-vehicle lane changes from lanes 2 to 1 occurs in the zone from about 1,200 to 3,600 ft from the off-ramp nose. Through vehicles exhibit a corresponding increase in lane changes from lanes 1 to 2 in the same zone. No maximum occurs for through-vehicle lane changes from lanes 2 to 1 in the zone from 0 to 600 ft from the off-ramp nose.

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DISCUSSION

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The author presents the results of an extensive, empirical analysis of lane changing on freeways, based on a set of photographic data collected at a series of 4-, 6- and 8-lane freeway locations in California. The data set on which his analysis is based represents an extremely rich data source for the analyst of freeway traffic flow; it is perhaps the richest source of its type that has been developed to date.

Attention is focused primarily on variations in lane-changing frequencies, expressed as a function of distance from the downstream off-ramp. Separate graphical analyses are presented both for through- and for exiting-vehicle behavior, and also for varying levels of total traffic flow. The results indicate a clear pattern of compensatory behavior on the part of through vehicles in response to the lane-changing maneuvers of exiting vehicles. They show that through vehicles tend, in the main, to move away from the lane adjacent to the off-ramp at a considerable distance upstream from the ramp nose and to return to that lane as soon as the exiting traffic has departed from the through pavement.

In commenting on Pahl's paper, I would like to focus my remarks on 2 topics: The first of these deals with a collection of essentially methodological issues; the second is concerned with the potential implications of research of this type for the design or traffic-control engineer.

Previous empirical research on lane changing (1, though, as the author notes, it is somewhat sparse in its content) has tended to suggest strongly that lane changing is best treated as a stochastic phenomenon, subject only to relatively limited systematic influences. One such influence is clearly the presence of an exit ramp. In this context, the somewhat "noisy" statistical pattern that emerges from the present data set is perhaps not surprising. It would, however, be extremely interesting if the simple, graphical analyses presented here could be supplemented by a more rigorous statistical examination of the data. The writer appreciates that this is by no means a trivial undertaking, and he fully recognizes the author's rationale for presenting simple, "hand-fitted" curves in his paper. It may, however, be argued with some validity that such a simple portrayal may in fact lead to deceptive, simple, and potentially erroneous conclusions.

One might, for example, find it useful to examine the variability in average lane-changing frequencies over a succession of short time periods for each given location and each flow level. The result of this analysis may then be compared in turn with the aggregate pattern of behavior presented here as a function of distance upstream from an exit ramp. Previous research conducted by the writer (1) suggests that such location-specific variance in lane-changing behavior may in fact be higher than that observed between different locations.

In a similar vein, the same research indicated only a relatively weak tendency for overall minute-by-minute lane-changing intensities to vary systematically with respect to ramp location and design. The distribution of maneuvers at each location was essentially random and the major impact of adjacent ramp terminals was reflected in the presence of intermittent platoons of vehicles entering the freeway from an on-ramp. It is also interesting to note here that analysis (1) of lane-changing behavior in the vicinity of one cloverleaf interchange in Chicago yielded a profile as shown in Figure 7. The lane-change rate gradually increased on the approach to the interchange, decreased within the interchange area, and suddenly increased immediately downstream of the entrance ramp.

Similar statistical comparisons may also be made of the observed patterns of behavior in a variety of different ways. One possible mechanism is to describe the overall pattern of lane-changing behavior at a given location and a given flow level in terms of a simple "lane-change transition matrix." Figure 8 shows 6 such matrices, based on data developed at Northwestern University (6). Estimation of a set of compatible matrices of this type, for each of a series of different locations or different flow levels or both, can provide the analyst with a simple base for the statistical comparison of varying patterns of lane-changing behavior both at a given location and across several locations or flow levels or both. A variety of other alternative descriptors may equally well be suggested, each of which might perhaps provide a useful statistical supplement to the graphical analysis presented here.

Of perhaps more important practical concern than the preceding, somewhat academic comment on methodology is the question of the manner in which the results of the present study may be put to use by the freeway designer or traffic operations engineer. I would like to address my final remarks to this point.

Clearly, the analytical results presented here, and particularly the level of detail incorporated within the underlying data set, represent a significant resource for the traffic flow-theoretician. They also, however, have no less significant implications for the highway designer or traffic engineer.

The sympathetic relation, for example, observed between the behavior of through vehicles and that of exiting vehicles upstream of an off-ramp has clear implications both for the development of freeway control logic and also, particularly, for the identification of optimum detection and control locations for a given section of highway. Equally, the patterns of lateral turbulence observed on the approaches to an exit ramp suggest both potential constraints on throughput capacity and possible limitations on the spacing and configuration of adjacent ramp terminals. Similar implications may also, at least potentially, be drawn from the results in terms of the location and design of directional signing, the details of ramp geometrics, and the vertical and horizontal alignment of the through pavement.

Figure 7. Typical lane-changing transition matrices.

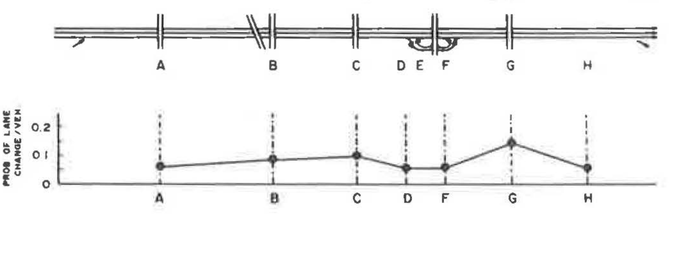
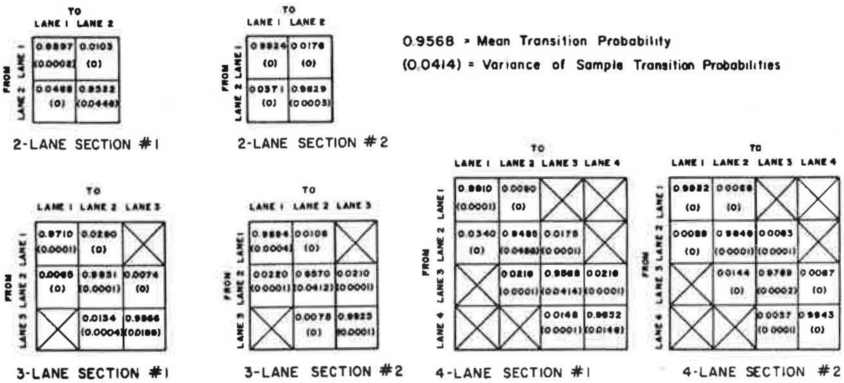


Figure 8. Variation in lane-changing frequency with distance from cloverleaf interchange on 3-lane roadway.



Clearly, examination of such questions in the context of highway design and operational control lies outside the scope of the present study. To answer them, one would need to structure at least a psuedo-experimental design that would examine the variation in lane-changing behavior at a broader mix of locations. The behavior would be expressed explicitly as a function of varying ramp configuration, sign layout, or the vertical-horizontal alignment of the freeway. The present study, though it does not address such questions, provides a valuable and substantive foundation for their analysis.

References

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