INVESTIGATION OF LANE DROPS

Browne C. Goodwin and Robert L. Lawrence, System Development Corporation, Santa Monica, California

Objectives of the study were to evaluate the effectiveness of safety and traffic operations of lane-drop configurations on several freeways. Aerial photographs were taken of traffic volumes at 3 lane-drop sites in the Los Angeles area, time-history trajectories of all vehicles were computed, and measures of traffic operations (speeds and concentrations) and safety (potential collisions) were determined. No significant differences in safety effectiveness among the 3 configurations were identified, but 1 site at which the pavement markings caused the 2 heavily traveled left lanes to merge had significantly lower speeds and higher concentrations than either of the other sites. The aerial photographic data reduction system developed during the study allows objective analysis of the complex interaction of traffic at lane drops or at other freeway configurations. However, the system needs further development before it can be an economical tool for the traffic engineer.

•IN 1971, the System Development Corporation completed an 18-month study to evaluate the effectiveness of several lane-drop design configurations with respect to safety and traffic operations. This paper summarizes that project and reviews the study findings.

PURPOSE AND TECHNICAL APPROACH

It is sometimes necessary to reduce the number of lanes on a freeway because of funding limitations or because the expected traffic demand is decreased outside of metropolitan areas. Because many variables affect the operating conditions and safety of the various lane-drop configurations, sound criteria for the selection of the proper lane-drop design for various traffic and freeway geometric conditions are needed. The objectives of this study were to

1. Determine from field data the effectiveness of existing main-line lane drops from the standpoint of safety and traffic operations;
2. Determine the effects of the significant parameters associated with various levels of safety and traffic services; and
3. Recommend configurations for lane drops based on the findings of objectives 1 and 2.

The technical approach to the study consisted of the following tasks:

1. Obtain information about the locations, configurations, traffic conditions, and accident experience at all lane-drop sites on the California freeway system and select several sites for detailed study;
2. Modify an aerial data reduction system to produce trajectories (time histories) of the distance, lane position, and velocity of all vehicles traveling through the freeway segment containing a lane drop during observation periods up to 15 min long;
3. Design and program measures of traffic operations and safety effectiveness that could be used in the analysis of trajectories produced by the data reduction system;
4. Conduct a pilot study by collecting, reducing, and analyzing aerial film from 1 or 2 sites to check out the measures and the data reduction system;

Sponsored by Committee on Freeway Operations.

5. Film and analyze additional sites with various configurations to evaluate traffic service and to determine the effects of variations in significant parameters on service; and
6. Develop design recommendations for lane-drop configurations and locations.

Because only 3 sites were filmed and analyzed, it was not possible to complete extensive parametric evaluation or to develop more than preliminary design recommendations. Additional studies are planned to complete attainment of the project objectives.

DATA ACQUISITION AND REDUCTION

Site Selection

It was initially assumed that 7 sites would be studied, encompassing at least 5 different lane-drop configurations. It was planned to collect data at 3 different traffic volume levels: fewer than 1,000 vehicles/lane/hour; 1,000 to 1,500 vehicles/lane/hour; and more than 1,500 vehicles/lane/hour. The sites were to be selected from a list of nearly 200 lane-drop locations compiled by the California Division of Highways.

An examination of aerial photographs and traffic counts of many locations showed that fewer than half of the lane drops were of the 5 configurations desired and that few had peak traffic counts of more than 1,000 vehicles/lane/hour. Sites selected for the pilot tests were where the right lane dropped at an off-ramp and counts during afternoon peaks were more than 2,000, where the right lane tapered off and Sunday afternoon peaks were about 1,000, and where the right lane dropped and striping merged the 2 left lanes. A fourth site that had a trapped lane off-ramp and high afternoon counts was filmed, but the analysis was not completed.

Data Collection

Before aerial filming could begin, it was necessary to survey the sites and install reference markings. Traffic counts were conducted at each site on several days so that a reasonably accurate estimate of flow levels during different time periods could be made.

The camera used for data collection was the Maurer 220 pulse-sequence camera, designed for aerial reconnaissance. The camera was mounted on a helicopter. A 38-mm Zeiss Biogon wide-angle lens with a relative aperture of f/4.5 was used, allowing filming about 1 mile of freeway from the helicopter hovering at 4,000 ft. Each film magazine held somewhat more than 100 ft of 70-mm Kodak Ektachrome MS aerographic color film, allowing filming about 8 min of traffic when a 1-sec frame interval was used (a 2-sec interval was also used during relatively light traffic flows). Each site was filmed for at least 3 different intervals; because of some camera jamming, 1 site was filmed for 6 shorter intervals, one of which was discarded because of extensive traffic-flow breakdown.

Data Reduction

The film was read on a Bensen-Lehner model 29E telereader. Each frame was projected on a 28- by 28-in. matte reading surface, and the operator located cross-hairs over each reference point and vehicle position. The film-reader coordinates and reference information such as film number, dates, and locations were punched on cards. After the cards were edited and stored on tape, they were processed through a program that corrects the photographic image points for the optical distortion produced by the combined effect of the camera lens and film magazine, determines the position and orientation of the aerial camera in ground coordinates, and computes the corrected car positions in the chosen ground coordinates. [The space resectioning methods follow Keller and Tewinkel's work (1).]

The resection outputs were processed by a trajectory program in which the geometric characteristics of the site are described, all vehicles are located relative to the boundaries of the freeway test section, and a given vehicle's positions from frame to frame are matched to produce a trajectory of the lane location, distance along the test section, and velocity.

The film-reading and data reduction procedures are described in detail in another report (2).

ANALYSIS OF TRAFFIC OPERATIONS

Analytical Techniques

The traffic-operations measure most commonly used is average travel time (or alternatively average overall speed). Although this type of measure gives a good indication of the general nature of the flow of traffic through a test section, it was not found to be an adequate measure for comparison of lane-drop configurations. Differences in desired speeds and in the geometry of the sites (other than those attributable to different lane-drop configurations) made the comparison of average overall speeds or travel time for different sites of little value. Those differences tended to obscure the effects of the lane drop itself on speeds and travel times.

To compare the effects of different lane-drop configurations on traffic required the development of an analytical description of the changes in speeds and in flow patterns throughout the lane-drop area. A photographed site was partitioned into short subsections, and local estimates of flow and space mean speed for each lane were calculated at the boundary points of each subsection. The flow at a boundary point was given by the number of vehicles passing the point during the filmed period, adjusted to yield cars per hour. The space mean speed at the boundary point for each lane was calculated as the harmonic mean of the speeds of vehicles observed passing the boundary point.

The values of speed and flow for each lane at each boundary point were then plotted against the distance upstream from the end of each site.

This procedure gives a very promising analytic tool for tracing the effects of lane-drop geometry on traffic operations. The graphs of speed and flows as functions of distance upstream from the exit point of each site are given in the following section. Looking at the speed graphs in particular, we can trace the effects of the lane drop at various volumes. Also, we can distinguish which disturbances were due to the lane drop and which were due to other nearby geometric features.

Furthermore, a statistical analysis indicates that, even for the short time periods of data that we have, the estimates of space mean speed have very small errors. The order of magnitude of the errors relative to the speed itself is about ±1 percent. Therefore, the random deviation of the estimated speed curve from the true mean speed curve is small. This assures us that the analysis of the mean speed curves will lead to statistically reliable results.

The 3 sites for which film was collected and reduced were all located in the greater Los Angeles area. Figures 1, 2, and 3 show diagrams of the 3 sites. Project personnel drove through all of the sites many times and observed traffic operations from nearby overpasses.

Site 1 Description

Site 1 is on the Ventura Freeway inbound between the Calabasas Parkway and Mulholland Highway overcrossings. Both the pavement and the lane markings are such that the right lane is dropped. The lane drop occurred as a result of stage construction and is a transition from a newer stretch of 4-lane concrete (opened in 1967) to an older section of 3-lane asphalt. The 3-lane section continues for only about 2 miles before increasing to 4 lanes. The lane-drop taper starts at milepost 27.76, continues through a 2-deg right curve in the freeway, and ends at milepost 27.57. The lane drop is preceded by a low-volume on-ramp from Calabasas at milepost 27.90 and is followed by a low-volume off-ramp to Mulholland Highway at milepost 27.36. The only sign indicating the lane drop is placed between the on-ramp and the start of the lane-drop taper, but the sign and striping are clearly visible at least a mile upstream to drivers approaching on a long 1.5 percent downgrade. About 5 miles upstream of the lane drop the freeway has only 2 lanes, and there is only 1 on-ramp between the end of the 2-lane section and the ramp immediately preceding the lane drop, so that traffic flow is somewhat limited. The freeway climbs a hill for about 3 miles, and then gradually descends until it levels off about at the lane drop. Most of the automobile traffic appears to move to the left 2 lanes to avoid trucks slowed by the hill, and only about 10 percent of the vehicles remain in the right lane at the start of the test section ½ mile upstream of the lane-drop taper.

Figure 1. Plan and elevation view of site 1 on Ventura Freeway at Calabasas.

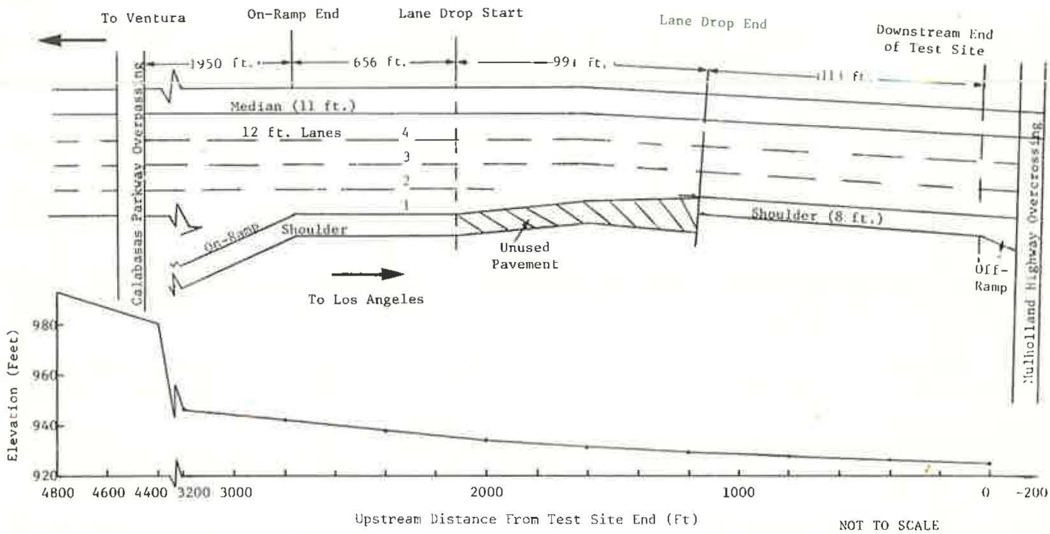


Figure 2. Plan and elevation view of site 2 on San Bernardino Freeway at Holt Avenue.

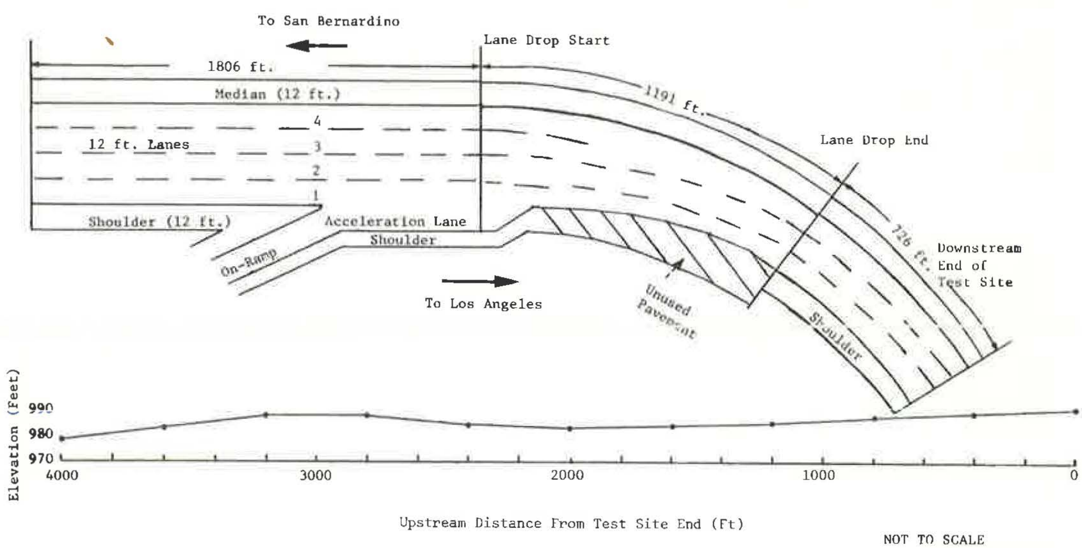
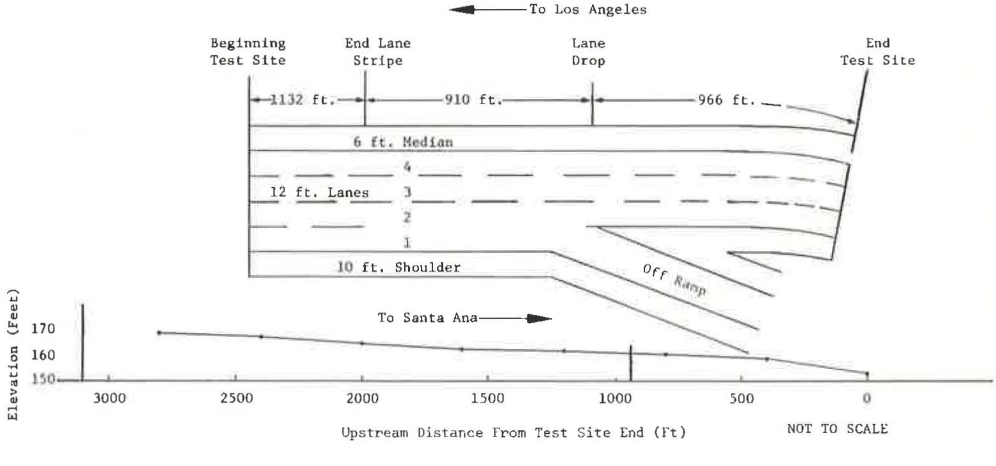


Figure 3. Plan and elevation view of site 3 on Santa Ana Freeway at Triggs Street.



The heaviest traffic flow at the site occurs on Sunday afternoon and consists mainly of automobiles returning to Los Angeles from recreational areas. Less than 5 percent of the vehicles are trucks. Traffic increases throughout Sunday afternoon, and the peak occurs in the early evening. Speeds on the section are generally higher than the 65-mph limit, probably because of the long, smooth downgrade and good visibility, but the end of the slope and the rougher pavement encountered after the lane drop seem to slow all vehicles.

Site 2 Description

Site 2 is comparable to site 1 in pavement configuration and traffic characteristics except that the pavement striping merges lane 3 into the left lane and steps the 2 right lanes to the left. Site 2 is on the San Bernardino Freeway inbound between the Archibald Avenue and Vineyard Avenue overcrossings. At the time the site was filmed, the pavement ended on the right; since then a fourth lane and an off-ramp on Vineyard Avenue have been added on the right. The lane-drop taper, as indicated by the striping on the freeway shoulder, starts at milepost 6.65 and continues to milepost 6.43, but the sign indicating that the left 2 lanes should merge is at milepost 6.90. The sign indicates that lane 4 should merge right, but actually lane 4 continues to follow the arc of a 6,500-ft radius, right curve in the freeway, and the third lane is merged left into lane 4. The Holt Avenue on-ramp enters the right lane at milepost 6.80 but carries very little traffic.

Heaviest traffic at this site is also on Sunday afternoon and evening and consists of vehicles returning from weekend recreation. Traffic flow occasionally breaks down in the early evening hours because of reduced capacity downstream. Between 5 and 10 percent of all vehicles are trucks. Traffic was observed to flow in marked platoons, more so than at site 1, but the effects of the lane-drop merger on heavy platoons of traffic in the 2 left lanes slowed many vehicles considerably. This phenomenon will be discussed below in greater detail.

Site 3 Description

Site 3 has the right lane trapped onto an off-ramp. It is located on the outbound Santa Ana Freeway at the Triggs Street off-ramp, milepost 13.17. The 4-lane section starts at the Long Beach Freeway interchange, about 1 mile upstream of the lane drop, but traffic from the Long Beach Freeway enters the Santa Ana Freeway from a left ramp. Immediately downstream of the lane drop, the freeway curves to the right and descends to pass under 3 overcrossings; the fourth lane reappears briefly as an auxiliary lane between the Atlantic Boulevard South on-ramp (near milepost 12.95) and the Atlantic Boulevard North off-ramp (milepost 12.75). There is also an on-ramp from Triggs Street at milepost 13.04 and an off-ramp to Atlantic Boulevard South at milepost 13.00.

Traffic at this site is very heavy every weekday afternoon and usually reaches breakdown conditions between 3 and 4 o'clock. The breakdown appears to be caused by a backup into the lane-drop area from downstream rather than by the lane drop. More than 20 percent of the traffic consists of trucks (although film was collected and reduced for 1 period during the Teamster Union strike when less than 5 percent of traffic was trucks; the lane drop is located in an industrial and commercial area. The late afternoon traffic is mostly commuter traffic from downtown Los Angeles to the residential areas southeast of the city.

Site 1 Traffic Operations

The results for site 1 show a uniformity of behavior at all flow levels (Figs. 4 and 5). The speeds in each lane remain approximately constant until two-thirds of the way through the lane-drop taper. At this point speeds in all lanes decrease linearly until the end of the test section. The rate of decrease in all lanes is approximately the same. The uniformity in speed decrease in all lanes suggests that the cause of decrease is not the lane drop itself but rather some other geometric feature. In fact, the site description shows that at the point where speeds begin to decrease a long downgrade (which extends upstream of the beginning of the test section) flattens out and driver sight distance

Figure 4. Traffic flow rate at site 1 on June 7, 1970.

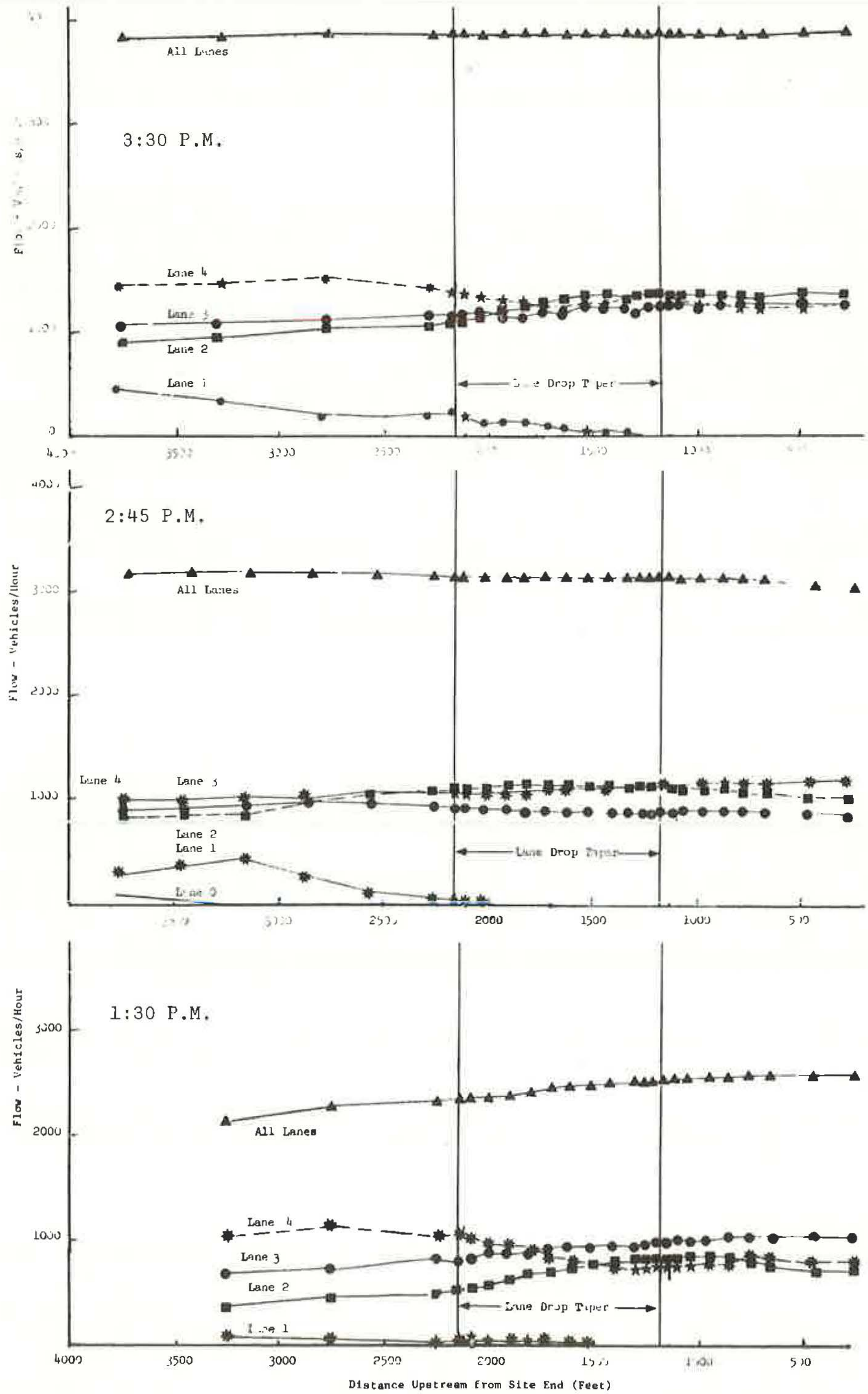
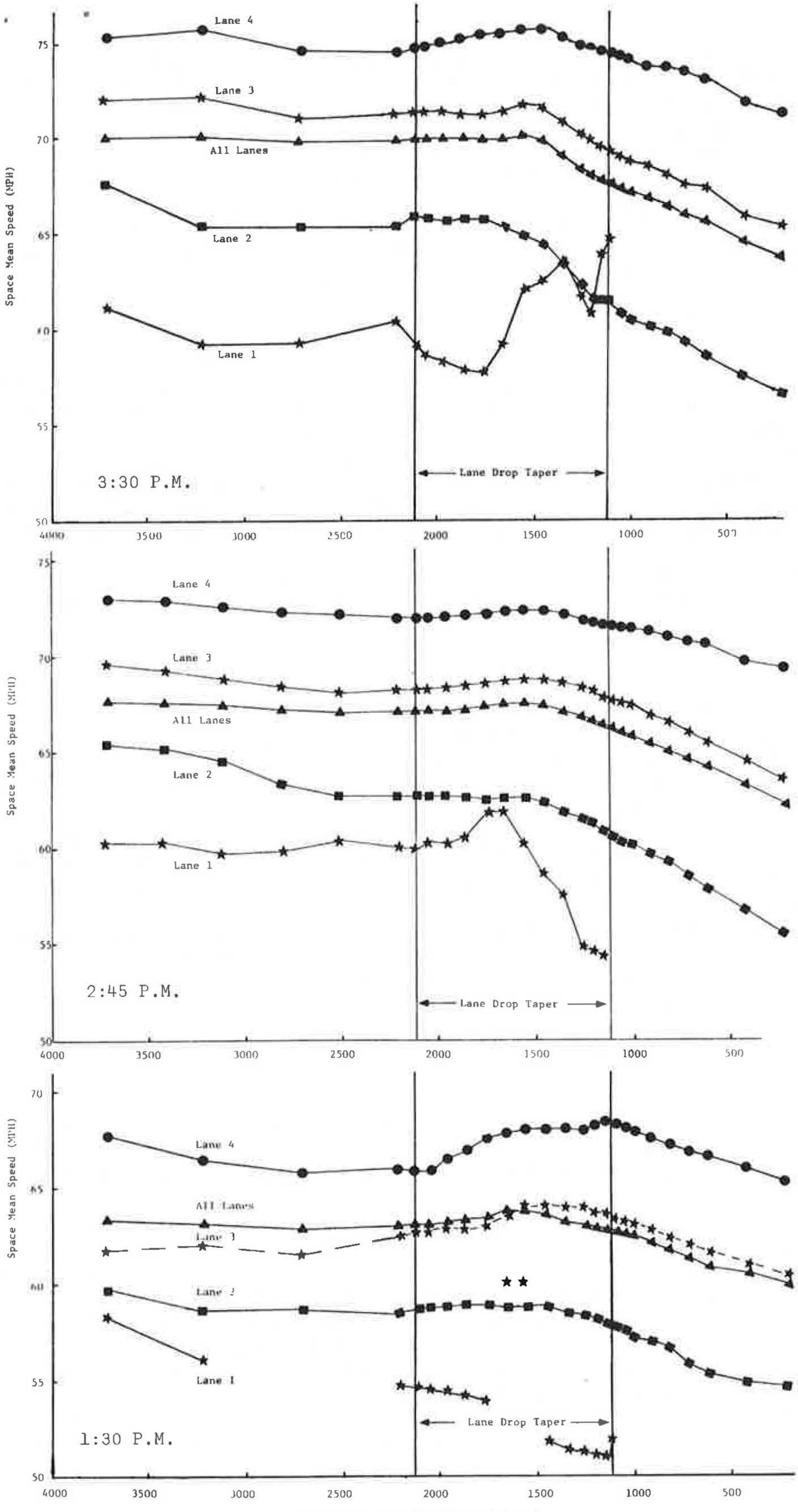


Figure 5. Space mean speed at site 1 on June 7, 1970.



is decreased; also, there is a transition from smooth concrete to rougher asphalt. These features probably account for much of the change in speeds. The high speeds observed at the beginning of this site are partially due to the long downgrade but are not atypical for California freeways. Similar speeds at the same site have been confirmed by many observers on several Sunday afternoons.

Figure 4 shows that the flow in lane 1 at the beginning of the test section is already less than 10 percent of the total flow. Light flows in the right lane are characteristic of all sites studied. The movement of vehicles from lane 1 to lane 2 is smooth and gradual, and almost no cars are in lane 1 near the end of the taper; the fluctuations of the speed curve in that region are not considered significant.

Site 2 Traffic Operations

The results for site 2, in which lane 3 is merged into lane 4, also show a uniformity of behavior at all flow levels (Figs. 6 and 7). The 2 lanes that merge at the lane drop show a severe decrease in speeds; however, lane 1 has almost no speed drop and lane 2 has only a slight drop. The disturbances in speed in all lanes increase as the flow increases. The traffic flow rate curves indicate the vehicles in lane 4 follow the signing and start to merge right upstream of the lane drop, then are forced back to the left by the pavement markings in the lane-drop taper area. Flows in lanes 1 and 2 remain relatively undisturbed except for the influx of a few vehicles from the on-ramp upstream of the lane drop.

The slight speed increase in lanes 1 and 2 at the upstream end of the lane-drop taper was observed during all 3 film periods, but no explanation of its cause has been found.

Site 3 Traffic Operations

The speeds at site 3 show a gradually changing pattern of speed decreases as flow increases (Figs. 8 and 9). At the moderate flow levels (the lightest flows filmed at this site were commensurate with the highest flows filmed at sites 1 and 2), speeds in lanes 2 and 3 slightly decreased in the lane-drop area and recovered in the downstream area. At this flow level there was no disturbance of speeds in lane 4.

As flow increased, the decrease in speeds in lane 2 became intensified, and the recovery in lanes 2 and 3 was delayed. Only at the highest flow level analyzed was there even a slight decrease in the speeds in lane 4. At this flow level no recovery of speed was seen in lanes 2 and 3.

Figure 8 shows that only about 10 percent of the flow was carried by lane 1 at the beginning of the test section. Most of those vehicles accomplished their merge into lane 2 well before the end of lane 1, but a small proportion of cars made their lane changes in the last 50 ft before the off-ramp.

ANALYSIS OF TRAFFIC SAFETY

Accident Analysis

It was originally proposed that the traffic safety of different lane-drop site configurations be evaluated by using accident data collected at various sites. Because it was expected that the sensitivity of inferences drawn from accident data would be limited by the necessity of using long time averages in order to obtain stable accident statistics and by the grossness of the traffic volume data available, this approach was to be augmeted by the analysis of aerial data.

The results obtained by Tye (3) confirmed our expectations about the limited usefulness of accident data. In this study the relative safety of 147 lane-drop sites on California freeways was explored through the use of 1965 and 1966 accident report records. In the study, no definitive results were obtained indicating any differences in the accident experience at the different lane-drop configurations considered in the present study. The variation of observed accident rates was greater within each configuration than among configurations. Tye indicates that the failure to discover significant differences among configurations may result from factors such as inaccurate

Figure 6. Traffic flow rate at site 2 on July 26, 1970.

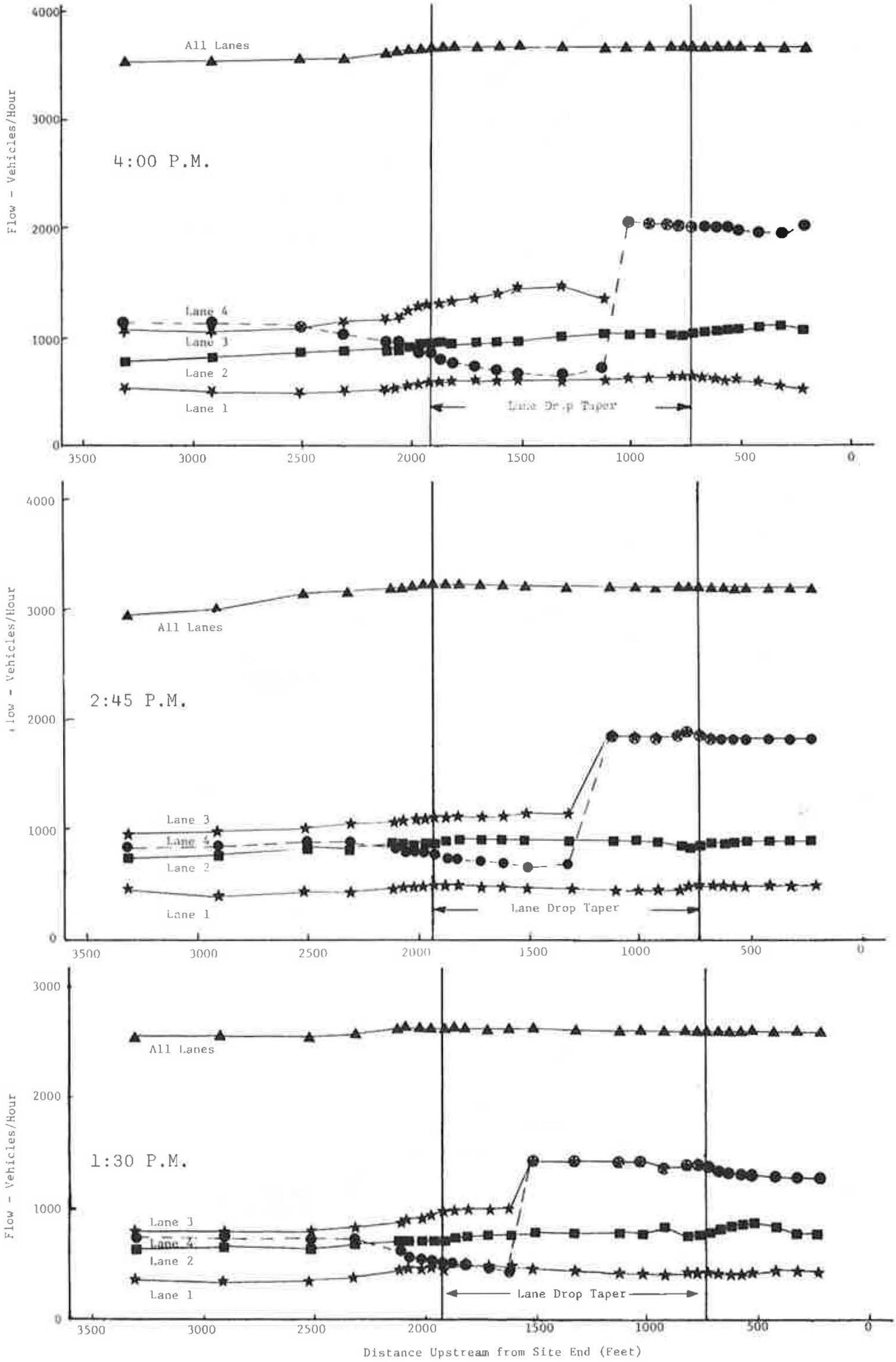


Figure 7. Space mean speed at site 2 on July 26, 1970.

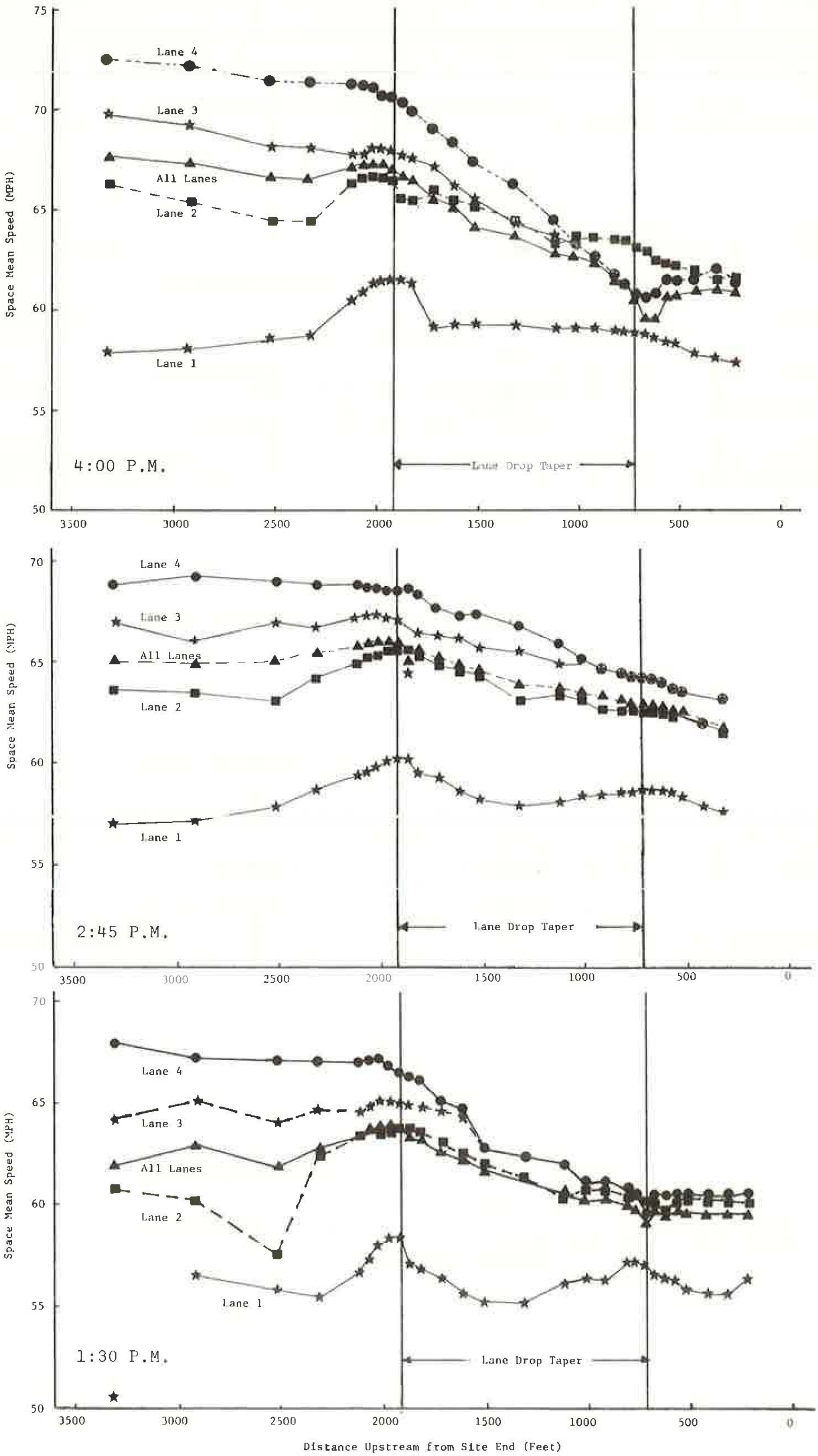


Figure 8. Traffic flow rate at site 3 on May 6 and June 3, 1970.

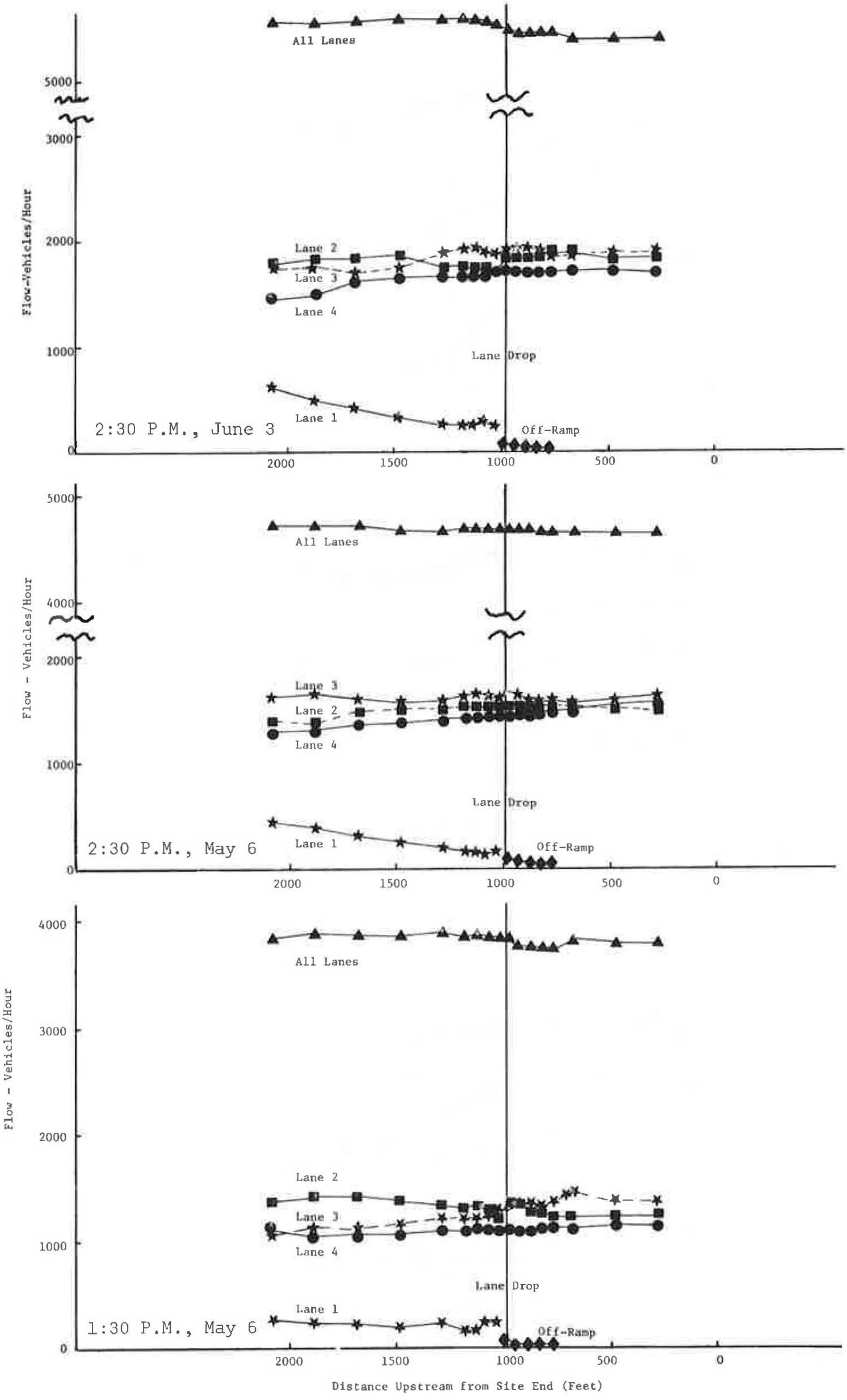
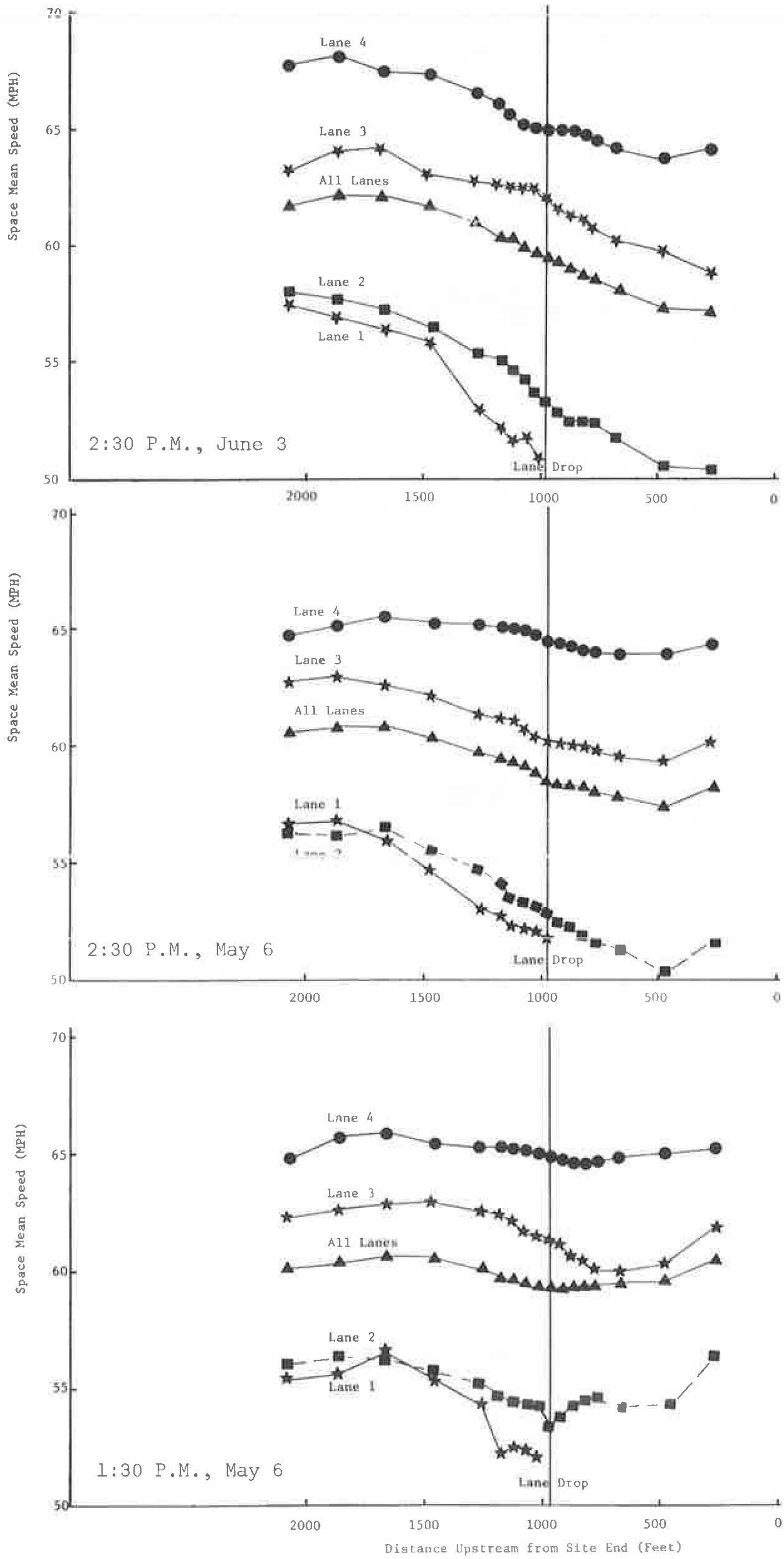


Figure 9. Space mean speed at site 3 on May 6 and June 3, 1970.



traffic volume information, masking of the effect of a lane drop by the presence of some other conflict-producing geometric feature, or variation in accident-reporting procedures from location to location or agency to agency.

Despite the problems in developing conclusive results encountered by Tye in his study, accident report summaries for the sites under study were obtained from the California Division of Highways, and a brief analysis was conducted.

At site 1, only 1 of the 7 accidents reported in the 2-year period seems lane-drop related. Most accidents appear to result from vehicles traveling too fast down the hill preceding the lane drop and running off the road into the median fence. At site 2, 4 of 19 accidents reported seem lane-drop related, and several others occurred during the heavy congestion on Sunday evening. The accident rate (for similar annual travel volumes) was significantly higher at site 2.

At site 3, there were at least 11 of 40 accidents reported of a type that might be lane-drop related. There were many more accidents reported at this site, in a somewhat shorter section than either of the other two, but the annual traffic volume at the site was about 3 times that at the others. Most of the accidents at site 3 involved vehicles stopping during the afternoon congestion.

However, the number of accidents reported in the immediate vicinity of the lane drops is no greater than the number reported in adjoining areas. Figure 10 shows the number of accidents reported in ⅕-mile intervals near the lane-drop sites. These graphs indicate that the lane drops investigated do not have higher accident rates than the nearby sections of 3- and 4-lane freeways.

Analytic Techniques

The traffic-safety measures of a lane-drop site are defined for the field experimental program in terms of "hazardous conditions." If one observes a set of trajectories (determined by aerial photography techniques) along a lane-drop site where vehicle 1 has speed v_1 and vehicle 2 has speed v_2 and both vehicles are in the same lane, then the hazard associated with the 2 vehicles will depend on the separation distance, $\Delta x = x_1 - x_2$, and on the speeds of the 2 vehicles, v_1, v_2. It is hypothesized that there is a region defined by a function of v_1, v_2, and Δx, such that when (v_1, v_2, Δx) is in this region the probability of a collision is substantially greater for the corresponding pair of vehicles.

The formulations described below for determining the occurrence of hazardous conditions were applied to data collected by using the aerial photography system. After trajectories have been produced, at each of the intervals $i\Delta t$ ($i = 1, 2, \ldots, N$) all pairs of car-following vehicles that fall within the lane-drop test section are determined. Each car-following pair is then tested to determine whether it falls in the hazardous region. For each $i\Delta t$, there result an h_i, which is the total number of car-following pairs that fall within the hazardous region, and an N_i, which is the total number of car-following pairs at $i\Delta t$. The response, or safety-effectiveness measure corresponding to a lane-drop site configuration, is then given by

$$R = \sum_{i=1}^{N} h_i \Big/ \sum_{i=1}^{N} N_i$$

where N is the total number of observation instants. R is termed the "hazard ratio" and represents the average percentage of time each car spends in a hazardous condition.

Hazard Region 1

The first hazard region considered was based on the measurement of the closing speed between a pair of car-following vehicles and the separation distance between them. The pair would fall within the hazardous region if the separation distance between them was so small that the following vehicle would have to decelerate at a rate greater than 5 ft/sec/sec to avoid hitting the lead vehicle. It was expected that this region would give a measure of those vehicles that made a lane change by cutting in too close to a following vehicle. However, almost no pairs fell within this region so that the hazard ratios computed by using this measure were extremely low. The values computed for this

Figure 10. Number of accidents in ⅕-mile intervals.

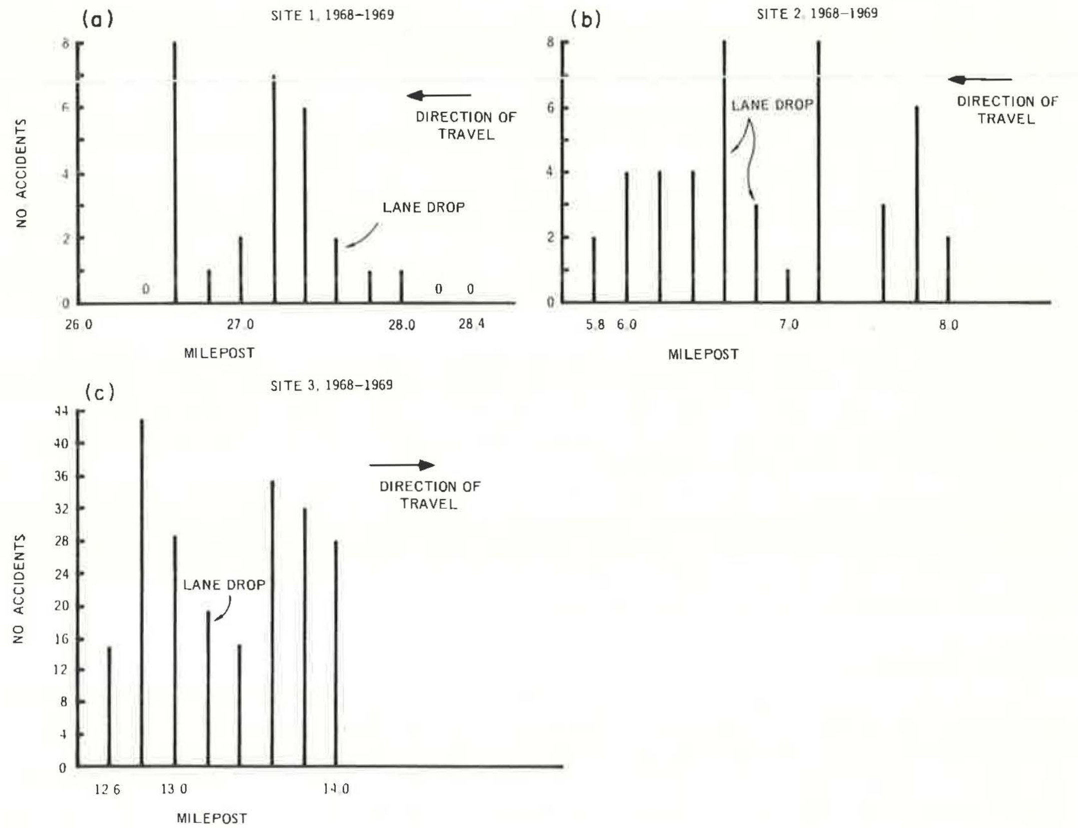
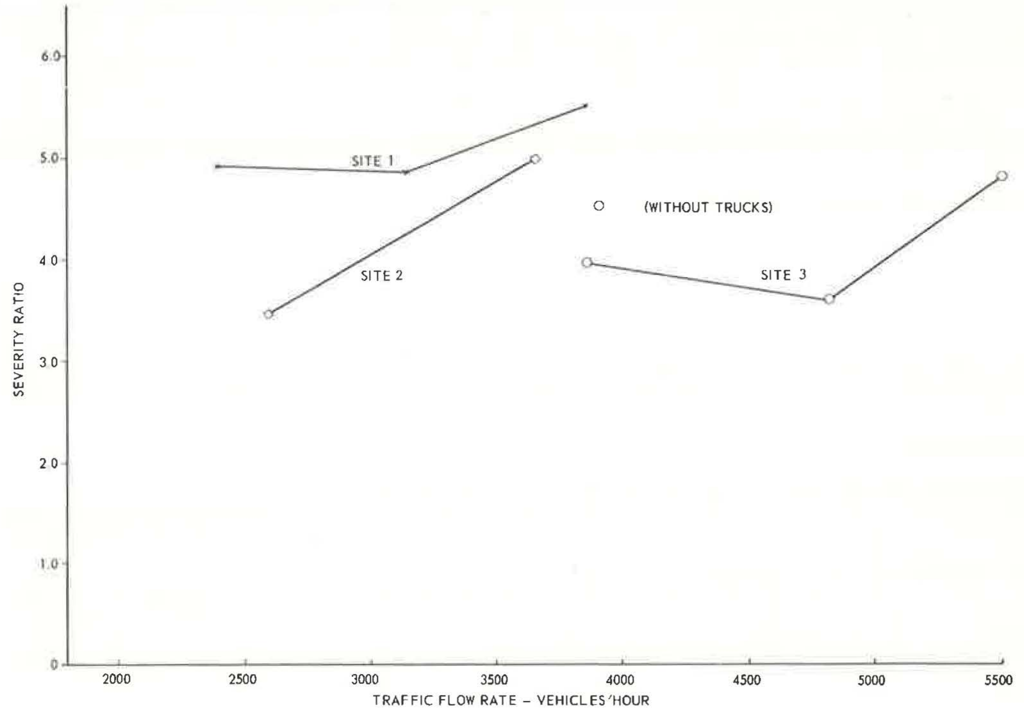


Figure 11. Severity ratio.



measure also fluctuated greatly at different sites and at different traffic flow rates within the same site, so it was decided to discard the measure as a means of evaluating safety effectiveness.

Hazard Region 2

The second hazardous region was defined by considering a driver's response to a rapid braking maneuver of a vehicle in front of his, including an allowance for a lag in his response time. The predicted positions of the 2 vehicles are given by

$$x_1 = x_1 + v_1 t + (1/2)\,at^2$$

$$x_2 = x_2 + v_2 t + (1/2)\,a(t - T)^2$$

where a is the deceleration rate of both vehicles and T is the response time lag. The hazard region is given by

$$v_2 T - (x_1 - x_2 - L) + (1/2a)\,(v_2^2 - v_1^2) > 0$$

where L is the average vehicle length, 17.6 ft. For the current study, a was taken to be 10 ft/sec/sec and T to be 1 sec. Hazard ratio 2 parallels the time criteria discussed by St. John and Glauz (4, 5, 6).

Hazard Region 3

A third region was defined by using the California safe-driving rule, which states that there be at least 1 car-length separation between vehicles for every 10-mph average speed. This can be expressed as

$$v_2/15 = (\Delta x - L)/L$$

which gives the boundary described by the equation

$$v_2 = (15/L)\,(\Delta x - L)$$

The hazardous region corresponding to this safe-driving rule is given by

$$v_2 > (15/L)\,(\Delta x - L)$$

Severity Ratio

The measures discussed above all have what we felt was a common deficiency: They assign equal weights to all potential collisions and do not discriminate between those that have higher probability of occurring or greater potential impact and those that are only marginally hazardous. We, therefore, developed an additional measure known as the "severity ratio," which assigns to each hazardous condition a weighting factor equal to the square of the predicted impact velocities. This weight,

$$w = v_c^2$$

where

w = weighting, and
v_c = projected relative velocity at time of collision,

is a measure of the kinetic energy of the impact. This weighting was implemented for the second hazardous region described above, producing the severity ratio. This ratio is proportionate to the average kinetic energy of the impact of all car-following pairs.

$$s_r = \sum v_c^2 \Big/ \sum_{i=1}^{N} N_i$$

where

$\sum v_c^o$ = all car-following pairs in a hazardous region,
N_i = the number of car-following pairs at time $i\Delta t$, and
N = number of observation instants.

Safety Effectiveness Results

Figure 11 shows the results of the computation of the severity ratio. Hazard ratios 2 and 3 exhibit similar behavior. The approximate standard deviation for the hazard ratios was 0.01 and for the severity ratios was 0.5. When these measures of dispersion were used, the differences between the ratios for the two comparable sites, 1 and 2, were not significant.

INTERPRETATION AND APPLICATIONS

A comparison of the changes in speeds at site 1, where both the pavement and lane striping are dropped on the right, and at site 2, where the pavement is dropped on the right but the stripting merges lane 3 left into lane 4, indicates that traffic in the merging lanes is more unstable at site 2. At site 1, the few vehicles entering the lane-drop area in lane 1 were able to merge smoothly into large gaps in lane 2; but at site 2, because lane 3 and lane 4 traffic was quite dense, the merging movements resulted in reduced headways and subsequently slower speeds. It is likely that restriping site 2 to a configuration similar to that at site 1 would have resulted in an improvement in traffic flow stability through the lane-drop area; however, subsequent addition of a fourth lane and an off-ramp at the downstream end of the lane drop prevented experimental validation of this hypothesis.

Observations of traffic in lanes 3 and 4 at the upstream end of site 2 indicated a problem with lane-drop signing. Although the pavement markings merged lane 3 left into lane 4, the signs informed lane 4 drivers that they should merge right. Although this signing had the effect of distributing merging operations over a longer segment of the freeway than might otherwise have occurred, it also had the effect of requiring more lane changes than were really necessary. The problem of signing for a center lane merged either to the left or right has not yet been satisfactorily resolved, although the California Division of Highways has implemented several ingenious combinations of curves and grades to give the driver the illusion that an outside lane rather than a center lane is being dropped.

Although very few sites at which the pavement was dropped on the left were found in California, and none was found that had high traffic volumes and was also suitable for the aerial photographic techniques used in this study, it would be expected that lane drops resulting from stage construction would frequently be located on the left. Because ramps are usually located on the right and overpasses are usually constructed to span the maximum anticipated width of the roadway, it is easier to add a lane near the median than on the right shoulder. If the traffic flow rates at the left-lane drops are heaviest in the left lanes, it is likely that pavement striping similar to configuration D, merging lane 2 right into lane 1, would provide better traffic service than configuration B, merging the left lane to the right.

The hazard and severity ratios computed for all 3 sites in this study gave no indication of significant differences in the safety effectiveness of the different configurations, and accident analysis of California lane-drop sites corroborated these findings. Although it is premature to state that there are no differences in safety for different lane-drop configurations, it appears that differences in traffic operations are more significant.

ACKNOWLEDGMENT

This study was conducted as a National Cooperative Highway Research Program project and was sponsored by the American Association of State Highway Officials in cooperation with the Federal Highway Administration. The opinions and findings expressed or implied in this paper are those of the authors and not necessarily those of the sponsoring agencies.

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