An Empirical Study of Transient Freeway Traffic States along Kinematic Waves

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ABSTRACT
Data from several freeway locations reveal various features of transitions in traffic states. Two types of transitions are discussed in this paper; transitions near a merge and transitions along shock waves during the onset and dissipation of a queue. The former was studied by analyzing the spatial changes in flow, density and space-mean speed along kinematic waves near a merge. It was found that the length of transition in terms of flow, density and speed are respectively around 80m, 120m and 180m, indicating that the transition in flow occurs within a short distance while the transition in speed occurs in much longer space. The analyses of transitions along shock waves reveal that the durations of transitions due to regime changes are site-specific. One of the two freeway facilities analyzed in this study exhibited durations of 10–15 minutes while the second site exhibited durations in the range of 20–24 minutes. However, within each site, the transitions during the onset and dissipation of queues displayed similar durations. Finally, it was found that the transition durations are influenced by changes in speed before and after transitions, shock wave speed and the presence of freeway ramps.

INTRODUCTION
A transition occurs when vehicles accelerate or decelerate while traffic changes from one (stationary) state to another. A transition takes place over a particular time and distance due to limited acceleration or deceleration capabilities and driving behavior. Traffic states change for various reasons; demand change, onset or dissipation of congestion, changes in bottleneck discharge rate, changes in ramp flows, etc. As these are common features of urban freeways, freeway traffic undergoes transitions frequently and rarely exhibits stationary states for a prolonged period of time. However, the temporal and spatial features of transitions are relatively unknown.

This study seeks to understand the characteristics of transitions that arise near 1) merges and diverges on freeway (e.g.) and 2) the tail-end of a queue. The first type of transition is stationary, such that it does not propagate over space as a shock wave. For this type of transition, the length of the transition zone with respect to traffic variables is analyzed using a dataset from FHWA’s Next Generation Simulation program (NGSIM, http://ngsim.fhwa.gov). The data consist of individual vehicle trajectories whose resolution is suitable for analyzing this type of transition. The results show that the transition in flow takes place in a relatively short distance (~80 m downstream of the on-ramp) while the transitions in density and space-mean speed occur over longer distances (120 m and 180 m on average, respectively).

The transition zone near the tail-end of a queue moves upstream as the queue grows and moves downstream as the queue recedes with decreasing demand. The dynamics of the transition zone is studied by analyzing the relationship between transition durations and rates (at fixed locations) and various traffic and geometric variables. Several freeway sites in the U.S. and Europe are selected for this study to verify reproducibility and compare differences across sites. In particular, data from inductive loop detectors are analyzed to study the features of transition zones near the tails of queues. These detector data are suitable for analyzing this type of transition since the propagation of a transition zone can be observed over a long distance. The results show that transition durations and rates are lane-specific for the onset of queue and are affected by the speed of a shock wave, change in speed and the presence of a merge and/or diverge.
The remaining manuscript is organized as follows. The following section describes previous research on the features of transition and motivations of the present study. Then a description of the method used to measure the length of transition zone near the on-ramp is provided along with the various features observed from the measurements. The analysis of transitions along shockwaves, delineating uncongested and congested regimes, is provided next. Finally, a discussion of the results and their implications in relation to the existing macroscopic theory is provided.

BACKGROUND

Traffic flow is often modeled with macroscopic traffic parameters such as flow, density and space-mean speed. Examples of such models are a kinematic wave model by Lighthill-Whitham (1) and Richards (2) (LWR) model and its simplified version by Newell (3). Although the LWR model was developed decades ago, it has been widely accepted and used today primarily due to its simplicity (involving few parameters) and capability to predict key traffic evolutions at the macroscopic level. The LWR model is based on an assumption that there exists a well-defined relationship between traffic flow and density. However, plots of flow and occupancy (the dimensionless measure of density) constructed using real data from freeways often displayed wide scatter and provided limited clues on their fundamental relationship.

In an attempt to better make sense of the scatter, Cassidy (4) first identified periods of stationary traffic states from the data and then plotted the congested flow-occupancy relationship using the aggregated data over the stationary periods. The resulting scatter-plots showed well-defined relationships between queued flow and occupancy, supporting the validity of the LWR model. However, data during non-stationary traffic states still appeared below the underlying relationship. Muñoz and Daganzo (5) studied “transition zones” that emerge when a queue forms at a bottleneck and propagates as a “shock” upstream and then dissipates with decreasing demand. This study was conducted on a California freeway over two loop detector locations on a weekday. Using the data from the loop detectors, they found that the transition occurred as predicted by the LWR model: data points on the flow-occupancy curve moved from the uncongested to congested branches (and vice versa), and the transition zone propagated upstream at the speed predicted by the kinematic wave model. Moreover, they estimated the error by assuming instantaneous transition based on the estimated transition duration (several minutes) and the speed of a shock wave. The resulting error was within five-vehicle spacing, indicating that the accuracy of the LWR model suffers little from assuming instantaneous transitions. However, the shocks and transition zones were traced over a short distance (two loop detector locations) only on a single day. Thus, factors that influence the transition process could not be studied.

The LWR theory describes traffic states and their dynamics within a homogeneous section where flow is conserved. Thus, applying this theory becomes cumbersome when traffic flow is not conserved due to merging and diverging flows at freeway interchanges. This shortcoming was addressed in Newell (3). He treated the merges and diverges as points, where discontinuities in traffic state occur (instantaneously). Then, a traffic state downstream of the merge exhibits a flow that is larger by the inflow than the state upstream of the merge. This implies that in a queued state, vehicles accelerate instantaneously at the merge and display trajectories that are piece-wise linear. A similar logic applies to a diverging case, such that a diverging point defines the boundary between downstream and upstream states, with a larger flow upstream of the merge. In reality, merging and diverging take place over some time and
distance due to systematic lane-changing (to reach destination or exit lanes), finite acceleration and deceleration capabilities. The present study investigates the features of transitions that occur by merging flow as well as regime changes at the onset and recovery of queues. The aim is to study transition zones at the tails of queues over long segments over multiple days in order to obtain statistically significant results. Other variables that affect the characteristics of transition zones are also analyzed.

TRANSPORT DUE TO MERGING FLOW
This section is concerned with the spatial characteristics of transitions near a merge during congestion. This is analyzed using the trajectory data extracted from eastbound Interstate 80, (I-80) near San Francisco, CA. A schematic of the site is provided in Figure 1. The length of the study section is approximately 500 m, with an on-ramp at Powell Street. There are six freeway lanes including a high occupancy vehicle lane. The on-ramp is located at about 120 m downstream of the upstream boundary of the study area shown in Figure 1.

The trajectory data and supporting loop detector data for this site are publicly available through the Next Generation Simulation (NGSIM, http://ngsim.fhwa.gov/) program funded by the Federal Highway Administration. The details of the data collection method and some preliminary analyses are provided in Hranac et al. (6). In short, the trajectory data are available at the resolution of 1/10th of a second; i.e., the positions of each vehicle were recorded at 0.1 second intervals over 500 m (on I-80). More than 5,000 vehicles were recorded during congestion over a 45-minute period (4:00–4:15 PM and 5:00–5:30 PM) on April 13, 2005.

Methodology
Spatial characteristics of transitions due to merging were analyzed by tracing how macroscopic traffic variables, such as flow, density and space-mean speed, evolve over space along kinematic waves. Since it is difficult to measure these variables directly from the trajectories, more aggregated measures were extracted from the data. Specifically, the study section was divided into 30-m-long contiguous sub-sections as illustrated in Figure 2. Thus, the study section is divided into fourteen segments; the first one from 30 m to 60 m and the last section from 420 m to 450 m (see Figure 1). For each sub-section, headway and spacing were measured every 0.1 seconds. Then, averages over 10 seconds were computed to form discrete measurements at every 30 m × 10 sec time-space region. Finally, flow and density in each time-space region were

![FIGURE 1 Freeway site, eastbound Interstate 80.](image-url)
estimated by taking the reciprocals of average headway and spacing, respectively. The space-mean space is then the ratio of flow to density by definition.

Using these processed data, speed contours were constructed to assess general conditions on the study section. The speed contours from 4:00 to 4:15 PM are presented in Figure 2 as an example. As noted in the legend of the figure, speed in each time-space segment is shaded in grey scale according to the space-mean space estimated (in km/h). It shows that the average speed ranged from near 0 to 35 km/hr, indicating heavy congestion for this facility. The figure illustrates several kinematic waves (dotted lines in the figure) signaling a series of decelerated and accelerated states that characterize stop-and-go traffic. The average speed of kinematic waves was around −20 km/hr (this was computed by tracing the arrival times of each wave at the downstream and upstream ends). To reduce noise in the observations, near-stationary states were identified as the time-space regions bounded by neighboring kinematic waves. Ten such regions were identified in the time periods 4:00–4:15 PM and 5:00–5:30 PM. The 10-second flows, densities and space-mean speeds were then averaged for each segment during the periods of the identified stationary states.

![Speed contours](image)

**FIGURE 2 Speed contours (km/h) of I-80 from 4:00 – 4:15PM, April 13, 2003.**

**Results**

Figures 3(a)–(c) present an example of flow, density and space-mean speed over the 14 segments during a stationary period of 5:18–5:23 PM (at segment 14). Each plot shows the evolution of flow, density and speed marked by the passage of two neighboring kinematic waves. As noted on the plots, traffic moves from segments 1 to 14, and the waves propagate against traffic flow in congestion. The Powell St. on-ramp is located in section 4, where a discontinuity in state is expected to occur. It is also expected that the sections upstream of the on-ramp exhibit higher density and lower flow and speed as compared to the sections downstream. The length of transition is measured in two parts; upstream and downstream of an on-ramp. The study site was
not long enough to measure the length of transition upstream. Thus, this manuscript focuses on the length of transition observed downstream of the on-ramp. In Figure 3(a), a marked increase in flow is observed starting at section 4, which persists until section 8. After the substantial increase (nearly 1500 vph), the flow stabilized and remained nearly constant over the rest of the freeway sections. The length of transition zone in this case is thus measured as 90 m. It is notable that the sections upstream of the on-ramp (sections 1–3) display relatively stable flow, indicating that flow transition occurs mostly downstream of the ramp. A similar pattern of substantial increase followed by stabilization is observed for the other nine periods. The transition length with respect to flow varied between 60 m and 120 m with an average change in flow of about 1,000 vph. It is, however, observed that the transition in density is gradual and persists over a longer stretch of the freeway as shown in Figure 3(b). Note that the density continues to increase until section 4 and then gradually decreases until section 10. Hence, the length of transition upstream is 90 m or longer as the starting point of transition upstream is not captured. The transition length downstream of the ramp is about 180 m with a decrease of about 50 vehs/km. Another notable feature is that density remains high until section 7 and then starts to decrease. A similar pattern is observed for the other ten stationary periods, such that the average change in density is about 40 vehs/km with the transition length of 90 to 180 m. Transition in space-mean speed displays a similar pattern as the density. As illustrated in Figure 3(c), the speed transition has already begun in section 1, and the speed continues to decrease until section 4. Then it gradually increases back until section 12. Thus, the length upstream is at least 90 m, and the length downstream is about 240 m with an increase of about 7 km/hr. The length of the transition (downstream of the ramp) in speed is the largest compared to flow and density and ranges between 120 m and 240 m with an average speed increase of 5 km/hr.
FIGURE 3 Evolutions of traffic variables over freeway sections; (a) flow vs. freeway section (b) density vs. freeway section; (c) space-mean speed vs. freeway section.

It appears that the transition length varies over different stationary periods. To find the origin of these variations, the length of transition vs. each traffic variable is plotted as presented in Figure 4(a)–(c). The plots reveal that the length of transition depends on the change in speed (see Figure 4(c)) while the effects of change in flow and density appear negligible. However, this preliminary observation could not be tested statistically since the sample is small. Thus, a more systematic evaluation is left for future investigation.
Finally, the spatial evolution of flow and density is traced on a flow-density plane, shown in Figure 5. The circular data points correspond to the 10-second flow-density relationship measured over the fourteen segments. The scatter displays a linear trend, and the equation of a linear model (i.e. the equilibrium relationship) is presented in the figure. The parameter of the linear term, $-19.89$ km/hr, represents the speed of backward-moving kinematic waves. The estimated value is consistent with the values reported in numerous empirical studies (e.g. 7). Moreover, the $x$-intercept of the equation yields a jam density of about 120 veh/km, which is close to other reported values as well (e.g. 8). The data points of dark triangles in Figure 5 represent the flow-density relations from segments 4 to 14. These are averages over all ten stationary periods. The plot illustrates that the increase in flow due to on-ramp inflow is considerable from sections 4 to 7 while the density is nearly constant. The opposite feature is observed downstream of section 4, such that the flow remains nearly constant while the density gradually decreases and converges to the equilibrium line. This is consistent with the observation made from Figure 3.
TRANSITION ALONG SHOCK WAVES
The tail of a queue (a shock wave) separates a queued state from a freely flowing state in space. In this study, we analyzed the characteristics of traffic transitions that arise as the queue grows (i.e. propagates against traffic flow) and recedes with decreasing demand. In particular, transition durations and rates were measured along the freeway in the direction of the queues’ movements to observe any changes in relation to various geometric and traffic features. The transition rate is defined as the rate of speed change during transition and can be calculated as the ratio of speed reduction to the transition duration.

Sites and Data
Two freeway sites in the U.S. and Europe were selected to analyze transitions along shock waves. Each study site and the data obtained are described below.

M4, U.K.
Figure 6(a) shows a schematic of a 4-km stretch of M4 located in the outskirts of London, U.K. as it was configured in 1998. A recurrent bottleneck at the lane-reduction, and the resulting queue persisted for several hours. The queues typically spilled over beyond station 7, which corresponded to a queue length of about 2 km. This site is interesting in that there is no on- or off-ramps, such that flow is conserved throughout the site. Thus, it was ideal to study how the structure of a transition changes over space in the absence of exogenous factors. On this stretch, eight loop detector stations (squares in the figure) are located at every 500 m. Data from each detector consist of event-based speed. These data were aggregated at 30-second sampling intervals for more efficient handling of the data. Data from twenty three weekdays in November and December, 1998 were used in the analysis.

Interstate 80, California, U.S.A.
Traffic data from the second site, shown in Figure 6(b), were collected from 6-km stretch of eastbound Interstate 80 near San Francisco, California. A major recurrent bottleneck (as labeled in the figure) activates during afternoon rush periods, and the resulting queues fill the general-purpose lanes for several hours. As shown in the figure, the 6-lane facility becomes 5-lane facility immediately downstream of the Ashby off-ramp. The left farthest lane is designated for...
high occupancy vehicles during rush hours. There are eight loop detector stations throughout the stretch as shown in the figure. The detectors are located in each travel lane at intervals of about 0.5 km. Time-mean speeds with 30-sec sampling intervals were used to measure conditions during transition. Transitions were analyzed from stations 5 to 8 as a queue often starts near the merge at Ashby Ave. before a downstream queue arrives. This site is suitable to study the effect of merges and diverges on transition durations. Twenty nine queues from July–September, 2002 were analyzed.

Findings
Transition durations and rates were measured using time mean speed data. To reduce noise and estimate the start and end times of transitions more accurately, 5-minute moving average speeds were used. An example of the moving-average speeds is presented in Figure 7. The figure was constructed for lane 1 at stations 3–6 on M4 on November 13, 1998. The start and end points of transitions for the onset and recovery of a queue are also marked in the figure. It is notable that a transition during the onset of a queue is marked by a continual decrease from freely-flowing to congested speeds. Similarly, a transition during the recovery (clearance) of queue is marked by continual increase from congested to free-flow speeds. Free-flow and congested speeds were determined for individual lanes and locations based on their typical speed curves. At the three sites, free-flow speeds ranged from 90 km/hr to 120 km/hr, and speeds during congestion ranged from 10 to 70 km/hr.
Once the start and end times of transitions were identified, various explanatory variables were measured to identify factors that influence the durations of transitions along shock waves. The dependent variables and explanatory variables considered in this study are as follows.

- **Dependent variables**: transition duration or transition rate
- **Explanatory variables**:
  - *Loop*: loop detector stations are correlated with distance from bottlenecks and are used as a proxy.
  - *Lane*
  - Initial speed, $v_i$: 5-minute moving average speed at the start of transition (km/hr)
  - Ending speed, $v_e$: 5-minute moving average speed at the end of transition (km/hr)
  - Change in speed, $\Delta v$: $v_e - v_i$
  - Speed of shock wave, $w$: computed based on start times of transition at the most upstream and downstream stations.

As part of a preliminary analysis, a bivariate relationship between transition duration and each variable was studied. Testing for statistical significance was done in the framework of multivariate statistical analysis, incorporating all measured variables simultaneously. A description of this work is provided later in the manuscript.

Figures 8(a) – (d) show plots of lane-wise average transition durations (dark circles) vs. stations located upstream of the bottleneck. Figure 8(d) corresponds to durations for all three lanes, which are computed based on average speed curves across lanes. Stations 3 through 7 are analyzed and shown in the plots, as queues rarely propagated to stations 8 through 10. The
vertical lines crossing each circle represent the bounds of standard error. The average durations were 11–15 minutes for the three lanes with their standard errors less than 2 minutes. It appears that the average durations do not change significantly longitudinally over space, and the changes are even less pronounced for all lanes combined. To the contrary, a close inspection of Figure 8 suggests that the average durations are different across lanes. Figure 9 confirms this observation. In this figure, the average durations and their standard error bounds are presented by lane (with data from the five stations combined). The figure clearly shows that the average duration tends to increase toward right lanes, such that the average duration in lane 3 is about 15 minutes as opposed to 11 minutes and 12 minutes in lanes 1 and 2, respectively. During the dissipations of queues on M4, the lane-wise transition durations were slightly larger and ranged from 14 to 17 minutes. For I-80, the durations were larger such that the lane-wise durations ranged from 20 to 24 minutes during the onset and from 22 to 23 minutes during the dissipations.

**FIGURE 8** Lane-wise average transition duration (and standard error) vs. detector station (a) lane 1 (left-most lane); (b) lane 2; (c) lane 3; (d) all lanes.
Multivariate analysis of variance (MANOVA) was used to determine statistically significant factors of transition durations and transition rate. MANOVA was used for identifying significant factors in lieu of multivariate regression as the sample sizes were relatively small (20–30 queues). One of the key assumptions of MANOVA is that the observed values for the dependent variable are normally distributed. This was not the case for the observed transition durations and rates. Thus, transition durations were transformed by taking natural logs, which yielded distributions that were approximately normal.

The explanatory variables were then transformed for the purpose of MANOVA. Lane and loop station numbers were used as different factor levels, and $v_i$, $v_e$, $\Delta v$, and $w$ were divided into four factor levels using the 25th, 50th, and 75th percentiles of the measurements as thresholds. All explanatory variables were then tested for correlation among them to identify a set of orthogonal variables. The correlation coefficients and the corresponding $p$-values for the onset of queue on M4 are exemplified in Table 1. The shaded $p$-values indicate that the correlations of the corresponding pairs are significant. It is notable that all speed related measurements, except for the wave speed, are correlated with one another and with $Lane$. Moreover, the ending speed and the change in speed are correlated with loop. Based on this observation, the MANOVA was performed on two separate sets of explanatory variables: the first set consisted of $Lane$, $Loop$, and $w$ while the second set included $\Delta v$ and $w$. Note that $\Delta v$ was omitted for transition rate as it is already accounted for in computing the transition rate.

![FIGURE 9 Average transition duration (and standard error) vs. lane number.](image)

The results from MANOVA are summarized in Table 2. It shows that for the onset of a queue on M4, $Lane$, $w$ and $\Delta v$ are significant including interactions between $Lane$ and $w$. A similar result was obtained for I-80, except that $Loop$ (a proxy for distance from a bottleneck)
was also found to be significant. This is attributable to the presence of on- and off-ramps on I-80 while the M4 site does not contain any ramps (see Figure 6). The result implies that a transition duration or rate does not change along a shock wave in the absence of exogenous factors, and that merges and diverges affect the structure of the transition. The result for the queue dissipation is consistent with the result for the queue onset in that 1) Loop is a significant factor for I-80 only, implying that merging and diverging flows affect the transition durations and rates, and 2) $\Delta v$ and $w$ are significant factors. The only exception is that Lane is not a significant factor for the recovery of a queue in general (other than the transition duration on M4).

### TABLE 2 A Summary of Results from MANOVA

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### CONCLUDING REMARKS

This study has provided empirical observations on the characteristics of state transitions. Two types of transitions were analyzed; stationary transitions near a merge and dynamic transitions along kinematic waves during the onsets and dissipations of queues. The former was analyzed by observing the spatial changes in traffic flow, density and space-mean speed over short, contiguous segments near a merge. The results showed that the transition in flow occurred within a distance of about 80m while the transitions in density and space-mean speed occurred over longer distances of about 120m and 180m, respectively. The dynamic transitions were studied on a homogenous freeway segment (in the absence of interchanges) and on a freeway segment with several interchanges. The former freeway exhibited transition durations of 10–15 minutes while the latter exhibited durations of 20–24 minutes. However, within each site, the transitions during the onset and dissipation of queues displayed similar durations. Significant factors of the transition durations and rates were identified via MANOVA. The results indicated that transition durations and rates are lane-specific during the onset of a queue while the lane effect did not seem significant when the queues dissipate. Change in speed, shock wave speed and the presence of freeway interchanges were found to be significant factors.

This study provides valuable insights as to how long (over time and space) a transition takes place and how the structure of the transition changes by various geometric and traffic features. These findings are important in understanding the errors associated with the first order kinematic wave model, which assumes instantaneous regime change. Thus, a better understanding of traffic transitions can help assess the need for more complex traffic flow models.

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