Use of Performance Measurement System Data to Diagnose Freeway Bottleneck Locations Empirically in Orange County, California

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To improve freeway modeling and operations, it is important to understand how traffic conditions evolve in both time and space. The widespread availability of freeway sensor data makes detailed operational analysis possible in ways that were not available in the past. This study, inspired by several other studies of a 6-mi segment of Interstate 405 in Orange County, California, describes the evolution of traffic conditions over one morning peak period by using inductive loop detector data, including vehicle count and lane occupancy measured at 30-s intervals. With cumulative curves of vehicle count and occupancy, transformed in ways that enhanced their resolution, 10 bottleneck activations were identified in time and space over one morning peak period. At bottleneck activation, queue propagation was observed in generally predictable ways. Bottleneck outflows were carefully measured only while the bottlenecks were active, that is, while queued conditions persisted upstream and unqueued (freely flowing) conditions prevailed downstream. When bottlenecks were activated immediately following freely flowing conditions, outflow reductions were observed at queue formation. These reductions were consistent with those in previous studies. The study was limited in that only one day’s data were analyzed and ramp data were not available on the day analyzed. Future research will include further analysis of the same site by using more recent data now that ramp counts are available in the California Performance Measurement System database. Understanding the mechanisms that lead to bottleneck activation is a critical step toward improving the understanding of how freeways function and is necessary for addressing operational issues. This clear understanding provides a foundation for determining ramp metering rates and addressing the freeway characteristics that cause bottlenecks to form.

The objective of this study is to describe the evolution of traffic conditions from freely flowing to congested conditions over one morning peak period along a 6-mi segment of northbound Interstate 405 in Orange County, California (see site map in Figure 1). Inspired by two previous studies, this study identified the activation and deactivation of 10 bottlenecks. Bottleneck outflows were measured only while bottlenecks were active, and outflow reductions were observed upon queue formation. The study relied on inductive loop detector data (vehicle counts and lane occupancies) recorded at 30-s intervals along the freeway mainline on Monday, June 1, 1998, between 7:00 and 9:30 a.m. On- and off-ramp data were not available for this day. By examining the available data with a graphical technique that revealed details of changes in cumulative count and cumulative occupancy, this study identified several active bottlenecks within the study area. In addition to describing the activation of freeway bottlenecks and measuring their outflows, this study illustrates that it is advantageous to retain freeway data in its most raw form for analysis. In addition, the study confirmed that it is possible to identify freeway bottleneck activations without prespecifying speed thresholds. Finally, the study takes advantage of the rich resource in the California Performance Measurement System (PeMS) database (1). Developed by the California Department of Transportation and the University of California at Berkeley, PeMS collects historical and real-time freeway data from California freeways in order to compute freeway performance measures.

During the 2½-h period examined, 10 separate queues were observed, activating bottlenecks at six locations through the morning peak period. Once a bottleneck was activated, its outflow characteristics were examined. For example, the transition from freely flowing to queued conditions was typically accompanied by a reduction in outflow ranging between 3% and 15%. The analysis tools used in this research were cumulative curves of vehicle counts and lane occupancy constructed such that their details were amplified. A systematic analysis (illustrated here for one day at one site) is important for improving the understanding of freeway traffic dynamics and is a key first step before any kind of traffic management or control strategy such as ramp metering is suggested, modified, or evaluated.

BACKGROUND

Understanding traffic behavior at a freeway bottleneck provides a foundation for understanding how a freeway system operates. An active bottleneck is a point upstream of which there is a queue and downstream of which there is freely flowing traffic. This definition is consistent with that described by Daganzo (2), such that a bottleneck would be serving vehicles at a maximum rate, and discharge outflows measured downstream of a queue would not be affected by traffic conditions further downstream. Bottlenecks can be static (e.g., a tunnel entrance) or dynamic (e.g., an incident or a slow-moving vehicle) (3). A bottleneck is considered active when it meets the foregoing conditions and is deactivated when there is a decrease in demand or when there is a spillover from a downstream bottleneck (2, 3).
Bottlenecks are important components of freeway systems since the queues that develop upon bottleneck activation may propagate for several miles, causing delay and potentially blocking off-ramps and access to other facilities (3). Loop detectors are a good source of data for the analysis of queue locations. The data are typically readily available, simple to use, and provide basic traffic parameters such as flow, occupancy, and speed. In the future it is possible that closed-circuit television camera, cellular phone, or other location technologies will provide better surveillance data for freeways. However, currently the loop detector infrastructure provides a rich and widely available data source that can be tapped for analyzing freeway performance.

As noted earlier, several previous studies have considered data from the same site on the same day (1, 4). A comprehensive study of congestion, excess demand, and effective capacity on California freeways (1) included an analysis of more than 4,000 freeway links in Los Angeles plus a more detailed study of the I-405 site using count, occupancy, and speed data from June 1, 1998, aggregated over 5-min intervals. The authors drew a number of conclusions, only some of which are related to the analysis in this paper. One conclusion stated that maximum 5-min freeway flows occurred at speeds of 60 mph. Because speed data were not available for this analysis, it was not possible to assess this finding. The authors also found that the maximum 5-min throughput of a link (defined in their paper as effective capacity) was dependent on link characteristics. It should be noted that 5-min data points might include data measured during more than one traffic state, so this method can sometimes be misleading, particularly if flow data measured at one point are influenced by the capacity of a downstream bottleneck. The authors also concluded that congestion delay can be decomposed into recurrent and nonrecurrent delay, which is also not addressed here. Jia et al. (1) did suggest that bottleneck throughput increased between 2% and 5% just before queue formation and that effective capacity was apparently stable. These conclusions are consistent with previous findings (5–8). However, the authors did not identify specific bottleneck locations or specify their activation or deactivation times.

As a follow-up study, graphical treatments of loop detector data aggregated at 5-min intervals by Jia et al. (1) were used by Cassidy (4) as the basis for developing several conclusions relating to freeway control. In that study, without the advantage of access to the raw 30-s data, Cassidy concluded that the freeway site used by Jia et al. (1) contained a diverge bottleneck between Stations 110 and 120 that was activated on June 1, 1998. Also, the analysis by Cassidy (4) traced queue propagation beyond Station 20, and the queue or queues present at this site had dissipated by about 9:00 a.m. Further, the analysis by Jia et al. (1) noted that measured flows at Station 120 diminished between 7:30 and 9:15 a.m. and that flows and speeds measured at Station 20 fell between about 7:40 and 8:30 a.m. A number of these findings will be addressed in the current analysis.

**METHODOLOGY**

Previous studies used cumulative curves of vehicle count and occupancy constructed from data measured at neighboring freeway loop detectors (5–11), identifying time-dependent features by using transformations of these curves. The same technique was used here to observe transitions between unqueued and queued conditions.
To illustrate this concept, Figure 2a shows a plot of cumulative vehicle count, \( N(x,t) \), for 1 h across four lanes at Station 50 on northbound I-405 on June 1, 1998. The slope of \( N(x,t) \) at time \( t \) is the flow past Station 50 at that time. During this period, nearly 9,000 vehicles were counted, and \( N(x,t) \) appears as a nearly straight line. An oblique \( N(x,t) \) was plotted in Figure 2b (9, 10), where just the vertical difference between \( N(x,t) \) and a line \( q_0 t \) was plotted at each time \( t \). The slope \( q_0 \) is an oblique rescaling rate (chosen to provide the best graphical resolution) and \( t \) is the elapsed time from the curve’s beginning. With a new \( y \)-axis, Figure 2b shows that the oblique \( N(x,t) \) amplifies the changes in flow. Figure 2c and d show a curve of cumulative occupancy (the percentage of time a detector was occupied in a measurement interval), \( T(x,t) \), measured at Station 50 for 1 h on June 1, 1998, and an oblique \( T(x,t) \), respectively (\( b_0 \) is the oblique scaling factor).

Oblique \( N(x,t) \) and \( T(x,t) \) were used to study the onset and dissipation of queued conditions at each station. These conditions are shown in Figure 2e, a flow-occupancy scatter plot (with data recorded at Station 50 between 7:00 and 8:00 a.m.). Following the arrows in Regime U (unqueued), an increase in flow is accompanied by an increase in occupancy, and a flow decrease is accompanied by an occupancy decrease. From Figure 2b and d, if conditions were unqueued, the slope changes of \( N(x,t) \) would follow the slope changes in \( T(x,t) \). Following the arrows in Regime Q (queued), an increase in flow would be accompanied by a decrease in occupancy, and similarly a flow decrease would be paired with an occupancy increase. Under queued conditions, a sudden decrease in slope of \( N(x,t) \) would be accompanied by a sudden increase in the slope of \( T(x,t) \). Vehicles confronted with the sudden onset of queueing are traveling much more slowly.

FIGURE 2 Methodology illustrations: (a) raw \( N(x,t) \), Station 50; (b) oblique \( N(x,t) \), Station 50; (c) raw \( T(x,t) \), Station 50; (d) oblique \( T(x,t) \), Station 50; and (e) occupancy versus flow, Station 50.
across the detector, which is reflected in the increase in measured occupancy. This method was relied on in this study when changes in slope of oblique $N(x,t)$ were compared with $T(x,t)$ constructed from data recorded at the same measurement location. By using flows and occupancies measured during stationary periods determined from the oblique plot, values were charted on a scatter plot to confirm the results.

DATA

As shown in Figure 1, the freeway study site is located on northbound I-405 between Post Miles 0.60 and 6.21 in Orange County, California. Along the study site, there are four northbound mainline lanes and a left-hand high-occupancy-vehicle (HOV) lane separated by a striped buffer. Auxiliary lanes are also present at Stations 30, 50, 130, and 140. Five interchanges are located within the study area. There are 14 loop detector stations that are numbered 10 to 140 from south to north. Freeway ramps are located between each pair of stations with the exception of Stations 100 and 110.

Data were collected from the mainline lanes on Monday, June 1, 1998, for a 24-h period. Single inductive loop detectors recorded vehicle counts and occupancy aggregated in 30-s intervals for each lane. With figures not shown here, it was determined that the HOV lane remained unqueued throughout the day. Therefore data from the HOV lane are not included here. While the data for this project were being processed, it was determined that figures were not available for all on-ramps and off-ramps; Lanes 1, 2, and the HOV lane at Station 20; the auxiliary lane at Station 30; and the auxiliary lane at Station 50. Finally, the data for Loop 4 at Station 20 were found to be underreporting both occupancy and count and were not used in this analysis.

ANALYSIS

The steps taken in the analysis of the data measured in the study corridor are described next. As an initial step in the analysis, scatter plots (not shown here) of the raw 30-s occupancy data versus time were prepared for each loop for the entire day. The results for all loops were similar, indicating a noticeable peak in the data between 6:00 a.m. and 9:30 a.m. Next, as shown in Figure 1, raw occupancies were averaged across all mainline lanes and interpolated between detector stations for each 30-s interval and plotted using time as the $x$-axis, distance as the $y$-axis, and variation in occupancy on a scale from dark gray to white. The change in shade from dark grey to white indicates an increase in the percentage occupancy recorded. It is clear from Figure 1 that higher occupancies were measured beginning just before 7:30 a.m. until shortly after 9:00 a.m.

Next, oblique $N(x,t)$ and oblique $T(x,t)$ were constructed for each loop detector and for each station. Figure 3 shows the result for Station 50. Using the left axis, the oblique $N(x,t)$ was plotted using total counts measured in all four mainline lanes, and an oblique scaling rate of 9,000 vph was chosen to amplify the changes in flow throughout the morning peak period (the period between 7:00 a.m. and 9:30 a.m. is shown). Figure 3 also shows oblique $T(x,t)$ for Station 50 using the right axis, and the plot includes the total lane occupancy measured by all four mainline detectors. An oblique scaling rate of 3,000 s/h was chosen for this plot. Next, stationary periods were identified as piecewise linear segments shown superimposed over $N(x,t)$ and $T(x,t)$.

**FIGURE 3** Station 50, Loops 1 to 4, oblique $N(x,t)$ and $T(x,t)$. 

![](image.png)
A straightedge can be used to verify these delineations. These periods are further delineated by vertical lines. The average flow measured in vehicles per hour (in bold) and average occupancy (measured in seconds per hour) were then added to the plot. Each stationary period represents a traffic state (flow-occupancy pair) that can be plotted on a flow-occupancy plane. It should be noted that numerical flow or occupancy thresholds were not used here; rather the relative changes in flow and occupancy were considered.

On the lower portion of Figure 3, each nearly stationary period (referred to as a numbered segment at the bottom of the figure) was identified as either queued or unqueued. For example, Figure 3 shows (referred to as a numbered segment at the bottom of the figure) was in flow and occupancy were considered. Occupancy thresholds were not used here; rather the relative changes in flow-occupancy plane. It should be noted that numerical flow or occupancy values are plotted on the inset as Point 3, which falls in Regime Q. This procedure continued for the remainder of the morning peak for all detector stations.

The onset of queued conditions recorded at 7:22 was followed by a sequence of nearly stationary queued periods until 8:36. During this period each reduction in \(N(x,t)\) was accompanied by an increase in \(T(x,t)\), the signal of queued conditions. The flow-occupancy values for each stationary period identified (Segments 3, 4, 5, and 6) were also plotted on the inset in Figure 3, confirming that conditions continued to remain in the queued regime.

At 8:36 a reduction in \(T(x,t)\) was visible accompanied by a slight increase in flow. When the values were plotted on the flow-occupancy plane, Segment 7 returned to the unqueued regime. At 8:44 and at 9:00 there were decreases in both flow and occupancy—signals of unqueued conditions at Station 50 (see Figure 2e), confirmed by the locations of Points 8 and 9 on the flow-occupancy plane. Therefore, at Station 50, the beginning and ending of the queued sequence occurred at 7:22 and 8:36, respectively.

Although not critical to confirm the analysis just described, it may be noted that the slope of a line connecting the origin to a point on the flow-occupancy plane is related to the speed prevailing during that state. As shown, States 1, 2, 7, 8, and 9, which fall into the unqueued regime, would sustain higher velocities than States 3 to 6, which lie in the queued regime with lower velocities. However, it is not necessary to apply any sort of speed threshold at this point.

The same procedure was followed for Stations 60, 70, 80, 90, 100, and 120 (see Figures 4 through 9) and Stations 10 to 40 and 130 to 140 (not shown here) by using data measured across all mainline lanes as well as for each individual detector (12). By identifying stationary unqueued and queued states at each station, confirming them using a flow-occupancy scatter plot, and mapping the points on Figure 1, the result was a visual description of queue propagation and dissipation, resulting in the identification of 10 distinct bottleneck activations at six distinct locations. Figure 1 uses points (diamonds) to map the

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**FIGURE 4** Station 60, Loops 1 to 4, oblique \(N(x,t)\) and \(T(x,t)\).
FIGURE 5  Station 70, Loops 1 to 4, oblique $N(x,t)$ and $T(x,t)$.

FIGURE 6  Station 80, Loops 1 to 4, oblique $N(x,t)$ and $T(x,t)$. 
FIGURE 7  Station 90, Loops 1 to 4, oblique $N(x,t)$ and $T(x,t)$.  

FIGURE 8  Station 100, Loops 1 to 4, oblique $N(x,t)$ and $T(x,t)$.  

$N(90,t) - q_0 t', q_0 = 8750$ vph

$T(90,t) - b_0 t', b_0 = 2800$ seconds per hour

$N(100,t) - q_0(100)t', q_0 = 8500$ vph

$T(100,t) - b_0(100)t', b_0 = 2000$ seconds per hour
position of the backward-moving shock (with higher occupancy) that passes upstream after bottleneck activation, with solid lines connecting those points. The result is a map of the tail of each queue upon activation as far as can be determined from the loop detector locations. Also shown are points (squares) representing the times marked by the passage of recovery waves (with lower occupancy). These squares are also connected by solid lines to demark the transition from queued to unqueued conditions. Dashed lines were added by interpolation to approximate conditions between measurement locations.

It should be noted that Queue 7 resulted from a bottleneck located somewhere downstream of Station 140, outside of the study area, and that queues spilled back upstream of Station 10 (outside of the study area) for three time periods between 7:45 and 8:25. Finally, when one is dealing with loop detector data measured at discrete points along the freeway, it is only possible to identify the location of an active bottleneck as being between two detector stations.

RESULTS

As described above and mapped on Figure 1, a total of 10 active bottlenecks were identified on this section of northbound I-405 on June 1, 1998. As shown in Figure 1, Queue 1 formed between Stations 50 and 60 and Queue 2 formed between Stations 70 and 80. Queue 2 extended beyond Station 10 and deactivated Queue 1. Queue 3 formed between Stations 90 and 100 and merged with Queue 2, thus deactivating Queue 2. Queue 3 was deactiavated at 7:42:00, and Queue 10 formed between Stations 80 and 90. Queue 10 was deactivated, and Queue 4 formed between Stations 50 and 60. No queuing was observed at Station 60 in the period 7:54 to 8:01. Queue 5 formed between Stations 110 and 120 and merged with Queue 4, deactivating the upstream bottleneck. Queue 5 quickly dissipated, and Queue 9 became activated between Stations 90 and 100. Queue 9 dissipated and Queue 6 became active between Stations 70 and 80. At 8:39 Queue 6 dissipated. Queue 7, which spilled back from some downstream bottleneck, was observed at Station 140 at 8:34 and dissipated a few minutes later. Queue 8 briefly formed between Stations 90 and 100 and dissipated a few minutes later.

Table 1 summarizes some characteristics of each queue, including its location, and average bottleneck input flow, and bottleneck outflow measured while it was active. In addition, for the five bottleneck activations that were preceded by freely flowing conditions (Queues 1, 2, 3, 5, and 8), the values of the sustained bottleneck input and outflows before queue formation are also given. The differences between the prequeue flows and active bottleneck input flows are given as percentages and range between 3% and 15%. In previous studies of freeway bottlenecks with higher-resolution detection (and fewer interruptions from on- and off-ramps), active bottleneck discharge flows were reported in which flows were measured immediately downstream of active bottlenecks (5–8). For this study, bottleneck input flows (measured just upstream of the head of the queue) and bottleneck outflows (measured at the next station downstream of the head of the queue) are being reported since in all cases there is an on- or off-ramp entering the downstream segment.

Diagnosis of Queue 1

A bottleneck was activated between Stations 50 and 60 subsequent to freely flowing conditions. From Figure 3 (and other plots not shown here), the queue’s shock arrival was visible at Station 50 at 7:22:00, then arrived at Station 40 at 7:22:30 and at Station 30 at 7:24:30 (this is visible from flow reduction and occupancy increase). In Figure 4, a corresponding flow reduction was visible at Station 60 at approximately 7:22, and it is clear that this reduction came from upstream as shown by the consistency of $N(x,t)$ and $T(x,t)$. Queue 1 was deactivated.
Diagnosis of Queue 2

A bottleneck was activated between Stations 70 and 80 by virtue of its shock arrival, which was visible at Station 70 at 7:33 and Station 80 at 7:38:30. Between 7:00 and 7:17:30, the input flow was steady at 1,347 vph. At 7:17:30 there was a 64% surge in flow (to 2,208 vph) sustained for 2:30 min, followed by a drop in input flow (to 655 vph until 7:26:30), and 2 min later Queue 1 was activated.

Diagnosis of Queue 3

A bottleneck was activated between Stations 90 and 100 for a short time, based on the visibility of a shock arrival at Station 90 at 7:36 and Station 80 at 7:38:30, as shown in Figures 6 and 7. The sharp flow decreases and occupancy increases confirm this effect. Further, a flow reduction was visible at Station 80 at 7:36, which came from upstream as shown by the consistency of $N(x, t)$ and $T(x, t)$. Upon its activation, Queue 3 deactivated Queue 2 further upstream at approximately 7:41. Upon its dissipation, Queue 3 activated Queue 10 between Stations 80 and 90 at approximately 7:42. By plotting $[N(90, t) - N(100, t)]$ to gain an approximation of the University Drive on-ramp flow, it appears that there might have been a slight surge in flow from 993 vph to 1,080 vph at about 7:35 (9% increase), which was followed by the activation of Queue 3 for a short time at 7:36.

Diagnosis of Queue 5

Between Stations 110 and 120, Queue 5 was activated for a short time as shown in Figures 4 to 8. The queue’s shock arrival was visible at Station 110 at 7:54:00, Station 100 at 7:54:00, Station 90 at 7:56:30, Station 80 at 7:57:30, Station 70 at 8:00, and Station 60 at 8:01 (a flow decrease was accompanied by a sharp occupancy increase in all instances). Queue 5 merged with Queue 4 between Stations 50 and 60 at about 8:01. Queue 5 was deactivated a few minutes later as Queue 9 was activated between Stations 90 and 100. Plotting an oblique curve of $[N(110, t) - N(120, t)]$ revealed the approximate flow using the University Drive off-ramp. There was a large surge in flow from 553 vph between 7:30 and 7:49 to 1,428 vph until 7:54, when Queue 5 was activated (representing a 158% increase).

Diagnosis of Queue 8

Finally, Queue 8 was activated between Stations 90 and 100, as shown in Figures 5 to 7, where the shock arrival was visible at Station 90 at 8:51, Station 80 at 8:54, and Station 70 at 8:57. The recovery wave followed just before 9:01. Traffic conditions returned to free flow after this time. In order to assess the flows from the University Drive on-ramp and the Culver Drive off-ramp, oblique curves of $[N(100, t) - N(90, t)]$ and $[N(100, t) - N(120, t)]$ were plotted, respectively. At
8:45:30 and at 8:50 it appeared that there were surges in flow at both locations followed by the activation of Queue 8.

CONCLUSIONS

This study focused on the analysis of freeway traffic conditions along a 6-mile segment of northbound I-405 in Orange County, California. Using PeMS data collected on one day (June 1, 1998), it was shown that a total of 10 queues formed and dissipated on this day. The analysis tools used were curves of cumulative vehicle count and occupancy, based on data collected at 30-s intervals. By transforming these curves it was possible to visually identify stationary periods of queued and unqueued traffic. It was not necessary to aggregate the data over longer time periods, nor was it necessary to establish arbitrary speed thresholds to identify bottleneck activations. It was also shown that when bottlenecks were activated immediately following freely flowing conditions, flow reductions ranging between 3% and 15% were observed upon queue formation. Because of limitations in detector locations, it is difficult to draw major conclusions regarding bottleneck capacity. This study also found that there were no queued conditions in the adjacent, buffer-separated HOV lane. In most cases, bottlenecks were activated in the vicinity of on- or off-ramps. In some cases it was possible to link changes in ramp flow to the onset of queueing. Further research in this regard is ongoing.

It was mentioned earlier that previous studies (1, 4) analyzed data measured on the same day (June 1, 1998) at the same site at a 5-min aggregation level. The analysis by Jia et al. (1) noted that link (bottleneck) outflow depends on its temporal and spatial characteristics. This study can be seen to confirm that finding when and if the outflow is measured at an active bottleneck. The research by Jia et al. (1) also found evidence reductions in outflow upon queue formation (on the order of 2% to 5%) and relatively stable bottleneck outflow; these findings seem reasonable based on the results of this analysis. The findings by Cassidy (4) included the diagnosis of a diverge bottleneck between Stations 110 and 120. Although this occurrence appeared to hold for a short period (Queue 5), there were also bottleneck activations at other locations, apparently caused by the impacts of flows to and from other ramps. Queues emanating from locations within this site did propagate upstream past the study limits, and the site was affected by a bottleneck downstream of Station 140. These findings are consistent with those of Cassidy (4). One difference is that it appeared that queued conditions began at approximately 7:38, which was later than noted by Cassidy (4). Most important, the results of this analysis indicate the need for a comprehensive understanding of where, when, and how bottlenecks are activated before conclusions are made about freeway capacities, specific control measures, or both. It would also be helpful to analyze accident logs from the day in question.

This study was focused on one particular day at one particular site, in part because of previous studies at the same site and on the same day. However, the study was limited by the absence of ramp counts and higher detector resolution. Because of the rich resource of the PeMS database, future research will include further analysis of the same site with more-recent data now that ramp counts are available for periods since 2002. Given the unlimited possibilities to examine this site over multiple days (again thanks to the richness of PeMS data), future research should concentrate on replicating this study and on ways to partially automate or simplify the analysis across multiple days. The results of a larger-scale analysis could be used to calibrate or validate freeway simulation models. It has been shown that it is highly advantageous to retain freeway data in its most raw form for analysis. In addition, the study confirmed that it is possible to identify freeway bottleneck activations without prespecifying any arbitrary speed thresholds. It is hoped that this procedure could be first replicated in a manual fashion and perhaps then be semiautomated by using a large database of traffic conditions such as PeMS.

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