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FREEWAY TRAFFIC OSCILLATIONS AND VEHICLE LANE-CHANGE MANEUVERS

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ABSTRACT

This work unveils the influence of vehicular lane-change maneuvers on oscillations in real freeway traffic. Measurements made upstream of bottlenecks reveal that oscillations formed in individual lanes when drivers squeezed their way in from neighboring lanes. Once oscillations had formed, moreover, lane changing caused the oscillations to at times grow in amplitude as they propagated upstream through queues.

The findings show that on (multi-lane) freeways where lane changing abounds, these maneuvers seemingly exert greater influence on the formation and growth of oscillations than do driver interactions that spontaneously arise in single-lane traffic. This is notable in light of the many attempts to explain oscillations as strictly a car-following phenomenon; and the findings motivate the need for theories of multi-lane traffic that describe lane changing in conjunction with car following.

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[1] Work by the first author was performed at the University of California, Berkeley and at Portland State University.

INTRODUCTION

The present work solves some long-standing puzzles on the nature of oscillatory or "stop-and-go" driving conditions in real freeway traffic. Oscillations were observed to form in freeway queues due to vehicular lane-change maneuvers. Lane changes made into small vehicle spacings were especially prone to be the triggering events. Most formations occurred short distances in advance of bottlenecks. Once oscillations had formed, moreover, lane changing similarly caused the oscillations to grow in amplitude as they propagated upstream through queued traffic.

No evidence was found that oscillations formed or grew due to driver interactions that arose spontaneously in single-lane traffic, independent of vehicles in adjacent traffic streams.[2] The finding is incompatible with previous attempts to explain oscillations as strictly a car-following phenomenon. Theories formulated and used in some of these past attempts are reviewed in the following section of the paper. Observations from some additional studies are used here as well to tease-out clues that support our present findings.

Data for the present work were collected from two extended portions of queued freeway. Measurements came both from inductive loop detectors and from video images, as described in the third section.

Macro-level analyses of the loop data are provided in the fourth section. These analyses not only confirm some previously observed features of oscillatory traffic, they further imply that oscillations formed and grew due to events in individual lanes.

The nature of these events is unveiled in the fifth section by means of more detailed, micro-level analyses of the data taken from videos. We present the systematic method used to mine these data so as to pinpoint when and where oscillations formed or grew. We then furnish vehicle trajectories (measured from videos) to show that lane-change maneuvers were the triggering events.

Final remarks are offered in the sixth section. These include discussion on certain details of oscillatory traffic in need of further study. Implications of the present findings on traffic theory are discussed as well.

[2] Much like lane changing, vehicle merging and diverging maneuvers near ramps were observed to affect oscillation growth. Description of these merging and diverging effects is saved for a future paper.

BACKGROUND

Traffic theorists have long sought to describe oscillations using models of how a driver responds to the motion of the vehicle immediately in front. Some of the earliest of these car-following models have each driver responding to her spacing (Kometani and Sasaki, 1958) or to changes in her leader's speed (Chandler et al., 1958). Responses occur following a reaction time and the magnitude of a response depends upon the driver's "sensitivity," a parameter calibrated to data. These early models have undergone various modifications: New parameters have been introduced and model forms have been altered in attempts to match model predictions with real observations (e.g. Gazis et al., 1959; 1961; Edie, 1960).

The above-cited models exhibit instabilities: For certain values of the sensitivity parameter and the reaction time, the magnitude of driver responses successively amplify as each driver passes through a disturbance (Herman and Montroll, 1959). Other classes of car-following models display instabilities as well. Models that assume drivers continuously choose their speeds so as to eliminate the possibility of collision (e.g. Kometani and Sasaki, 1959) generate instabilities when drivers over-estimate the decelerations of their leaders (Gipps, 1981). Instabilities also arise in yet another model class whereby each driver presumably seeks to maintain both a speed equal to that of her leader and her desired spacing for that speed (Michaels, 1963). Within this latter theoretical framework, a driver's inability to promptly perceive speeds and spacings can cause her to enter into a perpetual cycle of accelerating and decelerating without ever reaching a steady state (Wiedeman, 1974).

These instabilities are commonly taken as descriptions of oscillatory traffic. However, model predictions of the former do not always match real measurements of the latter. For example, previous observations of real freeway traffic indicate that oscillations exhibit acceleration and deceleration periods that are several minutes in duration (Kerner and Rehborn, 1996; Mauch and Cassidy, 2002), and this is confirmed in the present work. Car-following models, on the other hand, reportedly produce instabilities with periods on the order of a driver reaction time (only several seconds; see again Herman and Montroll, 1959).

The earlier freeway studies just cited further report that oscillation amplitudes grew in the vicinity of busy ramps. This finding suggests that vehicle merging and diverging maneuvers play a role here (and we have unveiled additional details on this matter; see footnote 2).

Further clues concerning the nature of oscillations are evident in data presented in Treiterer and Myers (1974). In this latter work, the motions of platooned vehicles in a single freeway lane were traced from aerial photographs. Drivers reportedly exhibited little change in their spacings (densities within the platoons remained high) as they underwent accelerations. These measurements have been used to support various car-following models that assume drivers behave differently while accelerating than while decelerating (e.g. Aron, 1988; Ozaki, 1993). As it turns out, however, lane changing may have been the greatest influence here; Daganzo (2002) offers the following alternative interpretation of the Treiterer and Myers data.

During acceleration cycles, densities in the single-lane platoons stayed high because (i) drivers from the neighboring lane inserted themselves into the platoons (an observable detail in the data); and (ii) drivers in the platoons may have chosen to follow vehicles at tight spacings in attempts to ward-off these insertions. It further seems that a large disturbance in one of the platoons – formerly regarded as a puzzle – can be traced back to vehicle lane changing into and out of the platoon; this becomes evident by scrutinizing Figure 1 of Treiterer and Myers.

It is true, on the other hand, that oscillations have been observed on single-lane roads and test tracks (Smilowitz et al., 1999; Sugiyama et al., 2003) and in tunnels where lane changing was prohibited (Edie and Baverez, 1958). On these and perhaps other facilities, oscillations might be explained by the driver interactions described by car-following models (or something at least akin to these descriptions). What we provide in the present paper, however, is evidence of an important role played by lane-changing maneuvers on (multi-lane) freeways where these maneuvers abound. To our knowledge, it is the most compelling evidence of its kind offered to date.

DATA

Traffic data were collected in both travel directions of the freeway site shown in Fig. 1, a 6-km-long stretch of Interstate 80 in California’s San Francisco Bay Area. During afternoon rush periods, vehicles in both directions encountered downstream bottlenecks, as labeled in the figure. The resulting queues filled the regular-use freeway lanes for much of the rush.[3] Freeway flows within these queues varied with location (from about 7,000 to 8,000 vph) due to inflows and outflows from the ramps.

[3] The high-occupancy vehicle lanes (labeled with diamond-shaped icons in Fig. 1) remained freely flowing during much of the rush and were therefore excluded from analyses.

Measurements came from two sources, the first being inductive loop detectors. These are located in every travel lane at (slightly irregular) intervals of about 0.5 km. Detector stations are numbered 1 – 8 in the figure. Vehicle counts, occupancies and time-mean speeds were collected over 30-sec sampling intervals and were used for the macro-level assessments presented in the following section.[4]

Additionally, a video surveillance system provided unobstructed views of traffic over the western-most freeway portions, as demarcated with dashed lines in Fig. 1. Traffic data extracted from these videos were used for the micro-level assessments in a later section.

MACRO-LEVEL ANALYSES

Next presented are features of oscillatory traffic observed in the loop detector data. We found that oscillations tended to form just upstream of bottlenecks. As in earlier studies, the oscillations exhibited periods of rather extended duration; they propagated upstream through queued traffic at a (nearly) constant wave speed; and they often grew in amplitude while doing so. Beyond confirming the above, we found that oscillations displayed certain patterns that were distinct across lanes.

These distinctions are clues to the lane-specific events (lane changing) that triggered formations and growths. The following macro-level analyses confirm the general features of oscillatory traffic described above and unveil the clues concerning the triggering mechanism.

Fig. 2(a) presents time series curves of vehicle speeds in the westbound travel direction. These were measured in each lane and at each detector station during a 50-minute period (on Aug. 19, 2002) when queues had filled the regular-use lanes. The freeway geometry for westbound travel is schematically shown left of the figure as a convenience for the reader. The numbering scheme used for the detectors is re-presented there as well.

The speed data in Fig. 2(a) were filtered to eliminate noise caused by driver differences and to retain longer-run trends. This was achieved in a simple way by plotting the vertical deviations between cumulative values of (time-mean) vehicle speeds at time, t,

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[4] Due to detector malfunctions, these data were not available for eastbound and westbound traffic in the shoulder lane at station 3 and for eastbound traffic in one of the center lanes at station 1.

s(t), and the quantity $\bar{s}(t)\times(t-t_0)$ at all t, where $\bar{s}(t)$ is a longer-run average of the 30-sec time-mean speeds and t_0 is the start time of this 50-minute observation period.[5]
The resulting wiggles in each "speed deviation" curve are oscillations; they mark periods when vehicle speeds were higher (positive slopes) and lower (negative slopes) than the longer-run average. These wiggles confirm that oscillatory periods can persist for several minutes, and not just for short durations comparable to a driver reaction time.

Dotted arrows in the figure trace some kinematic waves. These appear straight and parallel, consistent with past reports that wave speed is independent of flow in queued traffic (e.g., Windover and Cassidy, 2001; Mauch and Cassidy, 2002).

Marked differences in oscillation amplitudes are evident when comparing wiggles at downstream-most detector 8 with those, for example, at detector 1. This indicates that oscillations generally grew as they propagated upstream. The trend is confirmed in Fig. 2(b). It shows for each detector station the Root Mean Squared Error (RMSE) of speed deviations measured for the 50-minute period.[6] Two curves display RMSEs in each of the center lanes; a third curve, shown in bold, is the average of all four regular-use lanes.

Inspection of the latter (bold) curve shows that the upward trend in (average) growth was interrupted only at detector 3. We attribute this interruption to high vehicular merging activity at the nearby on-ramp (see footnote 2). All three curves in Fig. 2(b) show relatively small RMSEs at downstream detector 8, suggesting that this location is about where most oscillations formed.

The reader will further note the distinctions in each of these RMSE curves. These distinctions are clues that oscillation growth was triggered by events in individual lanes.

Clues that lane-specific events also triggered oscillation formations are evident in the data as well. Referring again to Fig. 2(a), we see that speed deviation curves at downstream detector 8 reveal asynchronous oscillatory patterns across lanes; i.e., the emerging wiggles at this downstream location are not aligned across curves. Oscillations became more synchronized only after propagating to upstream detectors.

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[5] The $\bar{s}(t)$ was computed as a moving average over a 5-minute period spanning each t; (t – 2.5 mins, t+2.5 mins). By using a moving average, we present shorter-run deviations from averages that gradually, but systematically, changed over time.

[6] Each RMSE was computed using 30-second samples as $\left[\frac{1}{T}\sum_{t=0}^{T}\left(s(t)-\bar{s}(t)\right)^2\right]^{1/2}$, where here T = 100 since the 50-min period shown in Fig. 2(a) is composed of 100 thirty-second intervals and $s(t)$ and $\bar{s}(t)$ are as previously defined.

This synchronization pattern is also visible in Fig. 2(c). The figure displays correlation coefficients of speed deviations for all pairs of neighboring (regular-use) lanes; the values shown are averages of the pair-wise correlations over the 50-minute observation period. The relatively low correlation at detector 8 (where oscillations formed) implies that oscillations separately emerged in each lane, such that emergence was a result of the conditions in individual lanes. (A slight reduction in correlation near station 3 can again be attributed to large inflows from the on-ramp.)

Oscillations in the opposing (eastbound) travel direction display features that are qualitatively like those just described. Visual inspection of Figs. 3(a) – (c) attests to these similarities; each of these figures was constructed from detector data taken over a 1-hour period of queued traffic (on June 25, 2003).

These figures indicate that wiggles in the eastbound travel direction were more developed and more synchronized across lanes, even at downstream detectors (stations 1 and 2 for eastbound travel), than were their counterparts in westbound traffic. This difference was to be expected. The bottleneck for eastbound traffic resides relatively far downstream of the detectors (see Fig. 1). Thus upon their arrivals to these detectors, the oscillations in eastbound traffic had already become more fully formed and better synchronized.

The distance between detectors and bottleneck notwithstanding, the RMSEs (Fig. 3(b)) increase just upstream of detector 1 and display differences across lanes. And although the (average) pair-wise correlations (Fig. 3(c)) were already high at downstream detectors 1 and 2, these correlations increase at upstream locations. The features suggest that, once again, formations and growths were triggered by lane-specific events. The nature of these events is presented next.

MICRO-LEVEL ANALYSES

An oscillation's formation is revealed when a vehicle's speed begins to vary while its leader's speed does not. Oscillation growth is revealed when a kinematic wave carries speed variations that increase at upstream locations.

To pinpoint when and where the above indicators of interest occurred, vehicle speeds were individually measured (from video) over short, contiguous freeway segments and were then compared across segments in ways that would detect all but perhaps the most subtle systematic variations. Lastly, vehicle trajectories were constructed for each time-space region that contained the indicators of formation or growth. These trajectories showed that lane changes were always the triggering events. Illustrations are provided below.

Formation

Fig. 4(a) illustrates a portion of westbound freeway near the downstream bottleneck; this is a location where oscillations often formed. Vehicles involved in formations were identified by measuring their speeds (trip times divided by distance) over contiguous 100-meter-long segments. Two such segments (labeled “upstream” and “downstream”) are shown in the figure.

As an illustration, Fig. 4(b) displays speeds for 46 vehicles that were separately measured on the upstream segment (shown with circles) and on the downstream one (squares). These were measured in lane 2 (see Fig. 4(a)) and the vehicles represented in Fig. 4(b) are numbered 0 – 45 in the order of their entries into the upstream segment. (Only vehicles that traversed the upstream and downstream segments without changing lanes are represented in this figure so as to simplify the numbering scheme.) The dark line in the figure displays moving averages of speeds on the upstream segment; the lighter line shows moving averages on the downstream segment; and the moving average for each vehicle n was computed from the speeds in the vehicle set numbered (n–2, n+2).

The figure reveals the formation of an oscillation. Speeds on the upstream segment fell and then rose back to their initial values, as is characteristic of an oscillation. Visual inspection of the figure shows that this cycle began with a marked reduction in the speed of vehicle 11. Notably, no such cycle is evident on the downstream segment, indicating that the oscillation emerged on the upstream one.

Vehicle trajectories not only confirm this formation, but unveil its cause. Fig. 4(c) displays the trajectories for the vehicles numbered 2 – 26 and for an additional vehicle that triggered the formation by changing lanes.[7] The latter, drawn in bold, inserted itself directly in front of vehicle 11. From the trajectory of vehicle 11, we see that its driver decelerated soon after the insertion and then accelerated once she had recovered (approx) her earlier spacing.

One further sees in Fig. 4(c) that decelerations were amplified among higher numbered vehicles. These amplifications indicate that driver car-following behavior can contribute

[7] Each trajectory was constructed by measuring the vehicle’s arrival times at a series of fixed reference points spaced at 15 m increments.

to oscillations. The point we make is that *the formation was triggered by a lane change* (the insertion in front of vehicle 11) and did not arise spontaneously.

The amplifications noted above caused speeds on the upstream segment to diminish from one vehicle to the next. This state gradually propagated backward and was eventually no longer felt on the upstream segment. The trajectories also show that the oscillation imparted little or no speed variations to vehicles on the downstream segment.

The reader will note that these effects so clearly evident in the trajectories are conveyed in Fig. 4(b) as well. Moving average speeds, like those in the latter-cited figure, were therefore used to search the data for instances of formations. In all, more than 1470 vehicle speeds were measured. These measurements were made in lanes 2 and 3 (see again Fig. 4(a)) and were taken over three contiguous 100-m-long segments. We judged that a formation occurred when the following two criteria were satisfied.

(i). The greatest difference in the moving average vehicle speeds on some segment (measured from the zenith to the nadir of a cycle like the one shown with the dark line in Fig. 4(b)) had to exceed 7 km/hr. Cycles marked by smaller differences showed no signs of propagating to upstream segments, leading us to conclude that these were merely statistical fluctuations.

A second criterion was established to ensure that instances of (i) actually emanated within the segment from which the measurements came, and had not instead formed downstream and propagated back to the subject section.

(ii). Where (i) was satisfied and the greatest speed variation was displayed by the moving average for vehicle n (e.g. n = 23 in Fig. 4(b)), we verified that (i) was not measured on the downstream segment among vehicles in the set numbered (n–20, n).

Limiting our check for (ii) to 20 vehicles seemed appropriate. Given the kinematic wave velocity estimated from our data, one would expect that a wave would, on average, propagate through less than 15 vehicles per 100 m (see Newell, 1993). The data further indicated that extending the check for (ii) beyond 20 vehicles ran a risk of inadvertently measuring the effects of a kinematic wave that carried some other oscillation.

Ten instances of formation were detected in the above fashion.[8] The trajectories then constructed for each time-space region containing a formation showed that lane changes

[8] Our search was limited by the time and cost of extracting data from videos.

were *always* the triggering events. There were no exceptions. (Trajectory plots for many of these formations are provided in Ahn, 2005.)

Finally, the lane changes that triggered formations tended to be those made into vehicle spacings that were small. As evidence, Fig. 5 shows the distributions of spacings filled by lane-change vehicles during a 10-minute period when video images were surveyed for lanes 2 and 3 of the freeway portion previously shown in Fig. 4(a). The darkened bars in Fig. 5 correspond to spacings that, when filled by a lane-change vehicle, triggered formations (9 observations in this period). The unshaded bars display all (other) spacings that were filled during the period without triggering formations or growths (18 observations). The median of the former is 27 m, while the median of the latter is 40 m. (The means are 32 m and 43 m.) The difference in these medians is statistically significant, as determined by the Wilcoxon two sample test at the 95% confidence level; see Rice, 1994[9]. This difference indicates that oscillations tended to emerge when drivers "squeezed their way" into neighboring lanes.

Growth

Details of oscillation growth were unveiled by studying eastbound traffic on the freeway portion shown in Fig. 6(a). Queued traffic at this location was commonly marked by well-formed oscillations that sometimes grew in amplitude as they propagated upstream. Vehicle speeds were once again measured over short, contiguous segments, including the two labeled "upstream" and "downstream" in the figure.

Fig. 6(b) displays the speeds of 51 vehicles in lane 2 on these two segments. The solid lines are, once again, moving averages taken over 5 vehicles.

Speeds on the downstream segment (squares) chart the fall-and-rise cycle that characterizes an oscillation. The speeds on the upstream segment (circles) do so as well. The reader can verify how speed changes downstream tend to be passed upstream to vehicles of higher arrival number, indicating that the oscillation propagated backward through traffic.

Notably, speeds on the upstream segment drop to lower values than do their downstream counterparts. This pattern indicates that the oscillation's amplitude increased (i.e., the oscillation "grew") as it propagated from one segment to the next. Further visual inspection of Fig. 6(b) shows that vehicle 29 was the first to display a speed on the upstream segment that was lower than any observed on the downstream segment.

[9] The Wilcoxon test was used in light of the small sample sizes.

The trajectories in Fig. 6(c) unveil the cause of this growth.[10] Two consecutive vehicles, shown with bold trajectories and labeled A and B, were inserted in front of vehicle 29. The (lightly drawn) trajectories of lower arrival number confirm that vehicles were already undergoing oscillatory motions prior to these insertions; e.g. the trajectory of vehicle 28 clearly displays a deceleration-acceleration pattern, though it was not affected by the insertions of A and B. What these insertions did was to amplify temporarily the (pre-exiting) decelerated state; the driver of vehicle 29 temporarily adopted a lower speed in response to the insertions and the resulting state propagated upstream through vehicles of higher arrival number.

The eventual insertion of a third vehicle (labeled C in the figure) took place within a relatively large spacing and did not induce the drivers of upstream vehicles, such as vehicle 35, to adopt an even lower speed. The insertion did, however, prolong the period over which vehicles traveled at a lower speed; i.e., it displaced the acceleration wave in time, as shown with dotted lines in Fig. 6(c). It seems that lane changing may explain the relatively long oscillatory periods observed in real traffic, though the evidence of this is limited at present.

Our search for instances of growth consisted of measuring more than 1500 speeds. Measurements were taken from four contiguous segments and in four lanes (lanes 2 through 5). Oscillation growth was judged to have occurred when the moving average speeds satisfied the following.

(i). The greatest differences in the vehicle speeds on each segment (again measured from the zenith to the nadir of a cycle) exceeded 7 km/hr.

(ii). To ensure that instances of (i) grew systematically in amplitude as the oscillation propagated, we compared the lowest speed measured on a given segment with the lowest speed on the upstream neighboring one. Where the former was displayed by the moving average of vehicle n (n = 26 in Fig. 6(b)), we surveyed speeds on the upstream segment for vehicles in the set numbered (n, n+20). The difference between the two minimum speeds across the two segments had to be at least 1 km/hr.

With this threshold of 1 km/hr adopted in (ii), the lowest speed in an oscillatory cycle would diminish by less than 8.5 km/hr with every kilometer traveled by the kinematic wave. This constitutes very subtle growth; e.g. when emerging in lightly queued traffic where vehicle speeds approach free flow rates, an oscillation growing in this fashion

[10] These trajectories were constructed from video images, as described in Hranac et al. (2004).

would propagate at least 10 kilometers before devolving to a jammed state. Hence our threshold would fail to detect only the smallest and most subtle oscillatory growth.

Eleven separate instances of growth were thus detected. Trajectory plots showed that *every* instance was triggered by lane changing; Ahn (2005) presents plots for most of these instances.

The data indicate that growth was more likely to be spurred by lane changes made into spacings that were small. Fig. 7 presents distributions of spacings filled by lane-changing vehicles during a 10-minute period. These were measured in lane 2 of the freeway portion previously shown in Fig. 6(a). The darkened bars in Fig. 7 correspond to spacings that, when filled by a lane changer, triggered growth (8 observations). The unshaded bars are all the other spacings filled by lane changes in the period (41 observations). The median of the former is 30 m, while the median of the latter is 45 m. (The means are 34 m and 54 m.) As in the case of formation, these two medians were statistically different at the 95% confidence level (see footnote 9).

CONCLUSIONS

The findings unveil a causal relation between vehicle lane-changing maneuvers and oscillatory traffic. Rational criteria were established to detect oscillation formations and even subtle instances of growth; and lane changing triggered every formation and growth thus observed (10 and 11 observations, respectively). Data illustrate how car following behavior also contributes to oscillation formation and growth. The point is that lane changing maneuvers always initiated these phenomena. We observed no instances of spontaneous formation or growth.

In retrospect, the findings may seem unsurprising; i.e., that stop-and-go conditions can be triggered by exogenous events like lane changing may even be what much of the driving public intuitively suspects. We argue, however, that the findings are notable in light of the large (scientific) literature that ignores any role of lane changing and instead views oscillations solely in terms of car-following. By having shown the need for theory that considers lane changing in conjunction with car following, we hope the present work will re-direct this line of thinking reflected in the literature. We believe that this, in itself, would constitute a meaningful advancement in traffic flow theory.

Already a few theories of driver lane-changing behavior have been developed for multi-lane traffic (e.g. Gipps, 1986; Kerner, 2005). One such theory with notably few parameters (Laval and Daganzo, 2006) shows that lane changes in dense traffic can create voids between vehicles and that these voids can propagate forward through bottlenecks. The theory can thus explain the reductions in discharge flows that are commonly measured when certain types of freeway bottlenecks become active. In fact, the theory has been shown to match discharge rates and other traffic details at an active merge bottleneck (Laval *et al*., 2005). Faithful descriptions of the oscillatory conditions that arise upstream of bottlenecks might come from a model of this kind, once it has been suitably refined for this purpose.

Identifying the needed model refinements might, however, require further observation and experiment. After all, certain details of oscillatory traffic remain puzzling. We have, for example, only very limited evidence that lane changing causes the relatively long oscillatory periods observed in this and other studies. Further, we do not yet know the mechanism by which propagating oscillations gradually synchronize across lanes, though here again lane changing could play an important role. Studies on these matters are ongoing.

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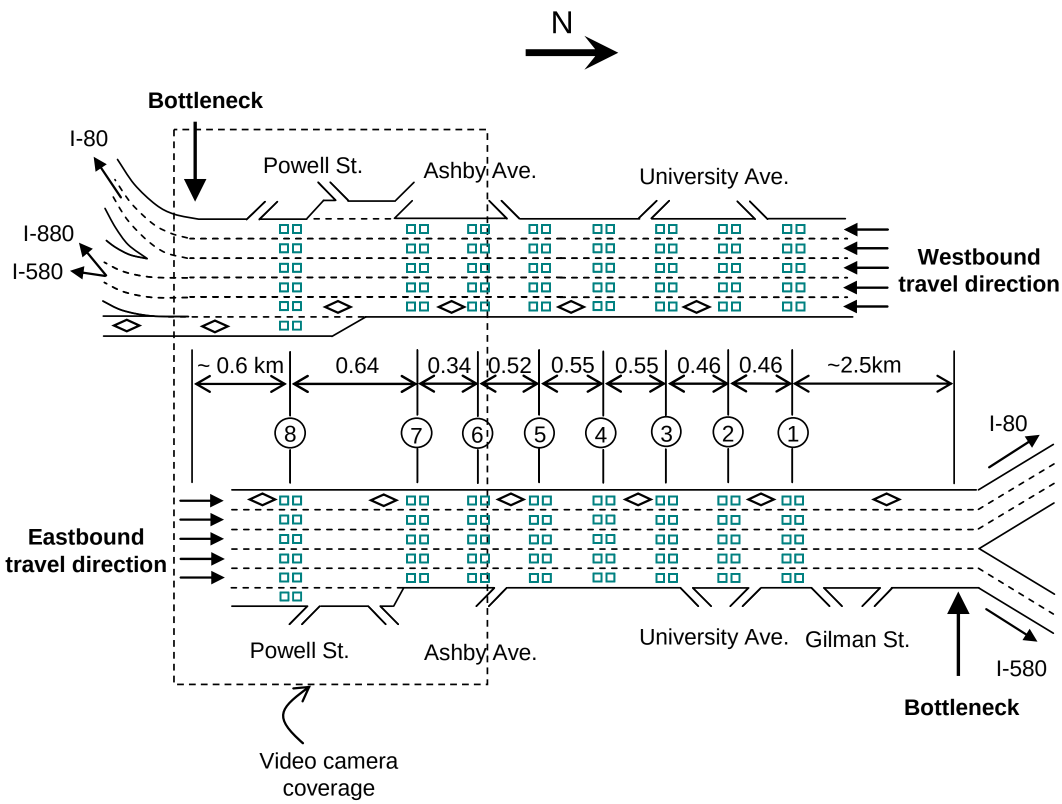
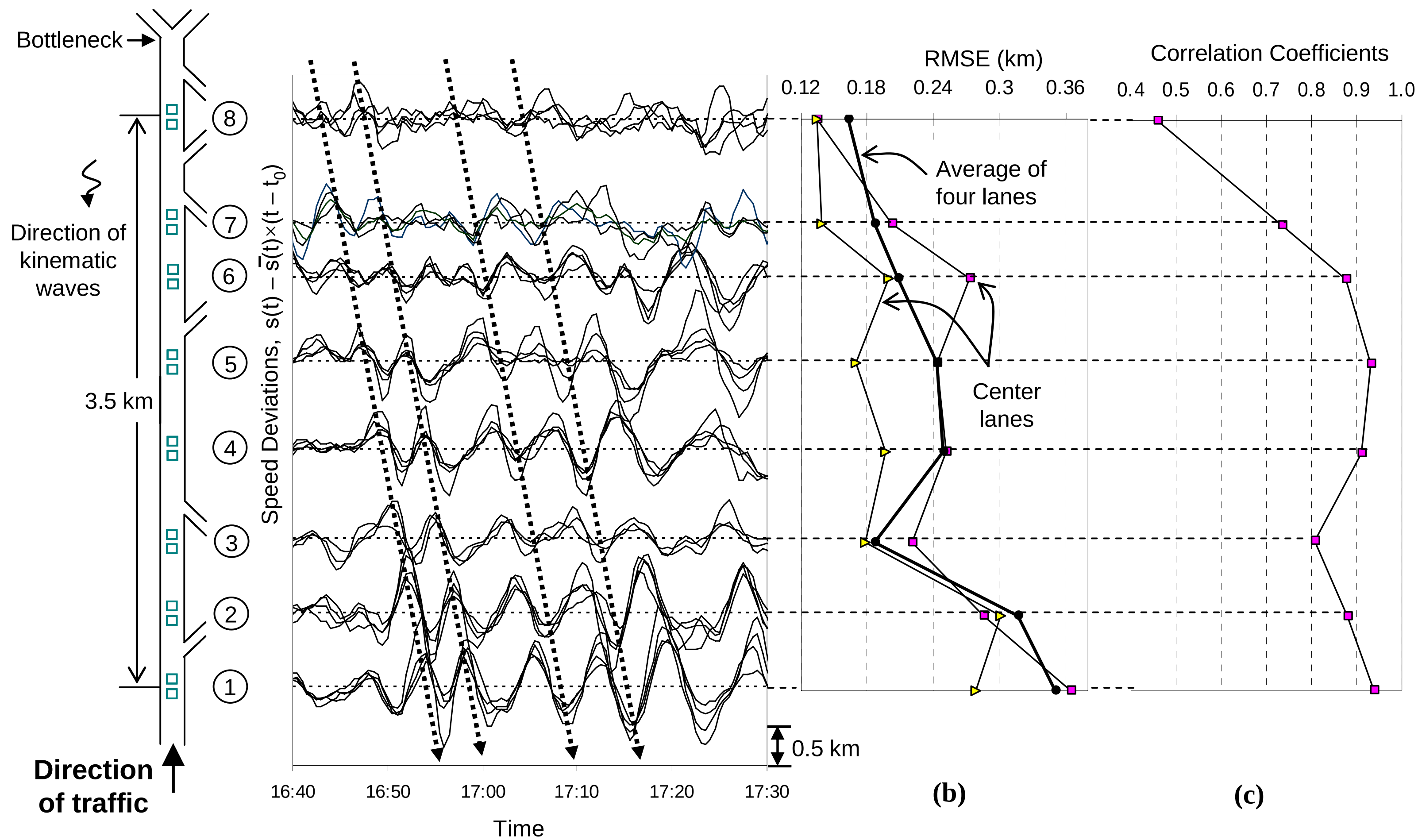


Figure 1: Interstate 80 near San Francisco, California



(a) **(b)** **(c)**

Figure 2: Westbound I-80 (August 19, 2002)
(a) Speed Deviation Curves
(b) Root Mean Squared Errors of Speeds
(c) Average Correlations Among Speed Deviations in Neighboring Lanes

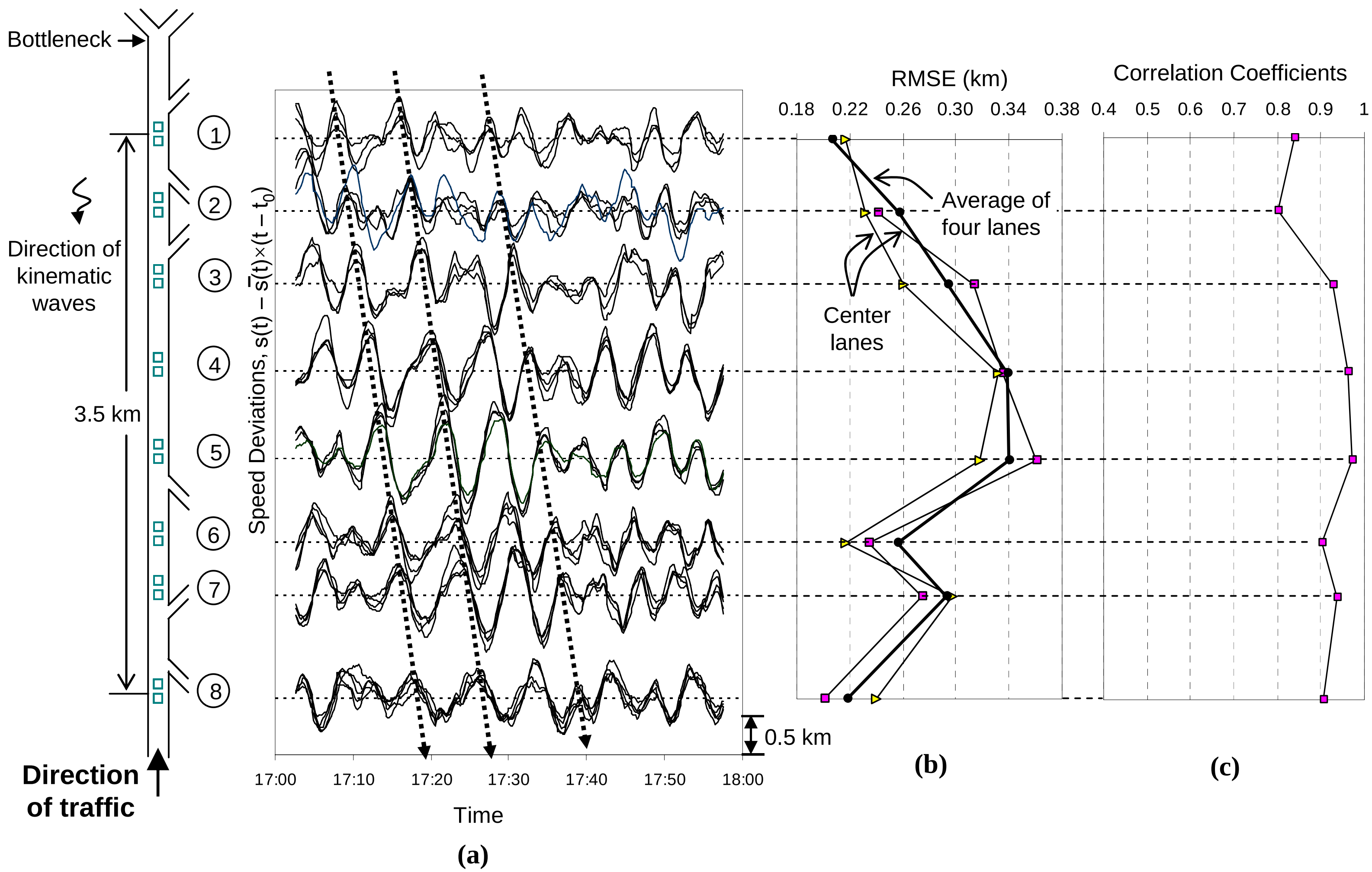


Figure 3: Eastbound I-80 (June 25, 2003)
(a) Speed Deviation Curves
(b) Root Mean Squared Errors of Speeds
(c) Average Correlations Among Speed Deviations in Neighboring Lanes

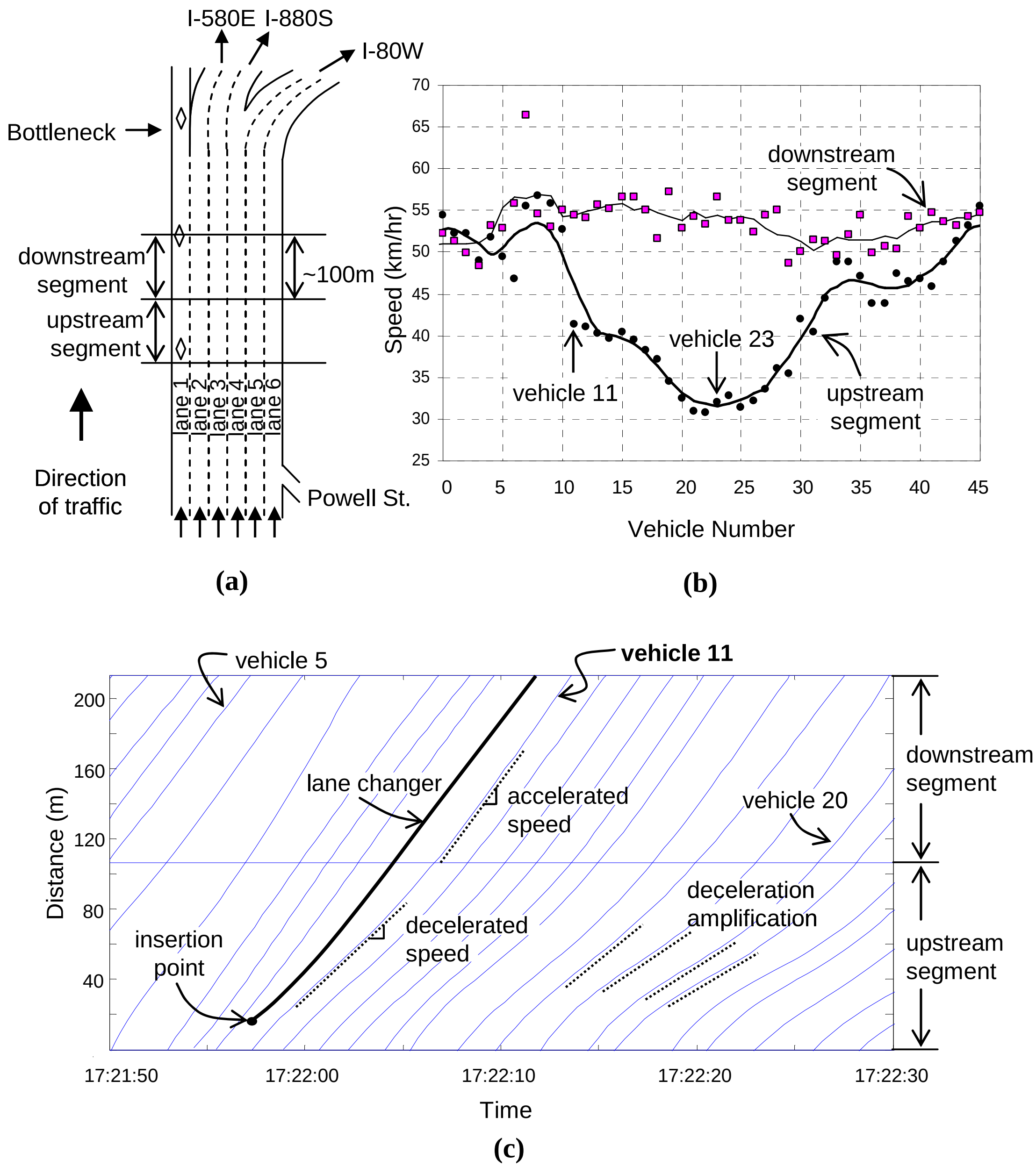


Figure 4: Formation of an Oscillation
(a) Westbound I-80
(b) Vehicle Speeds
(c) Vehicle Trajectories

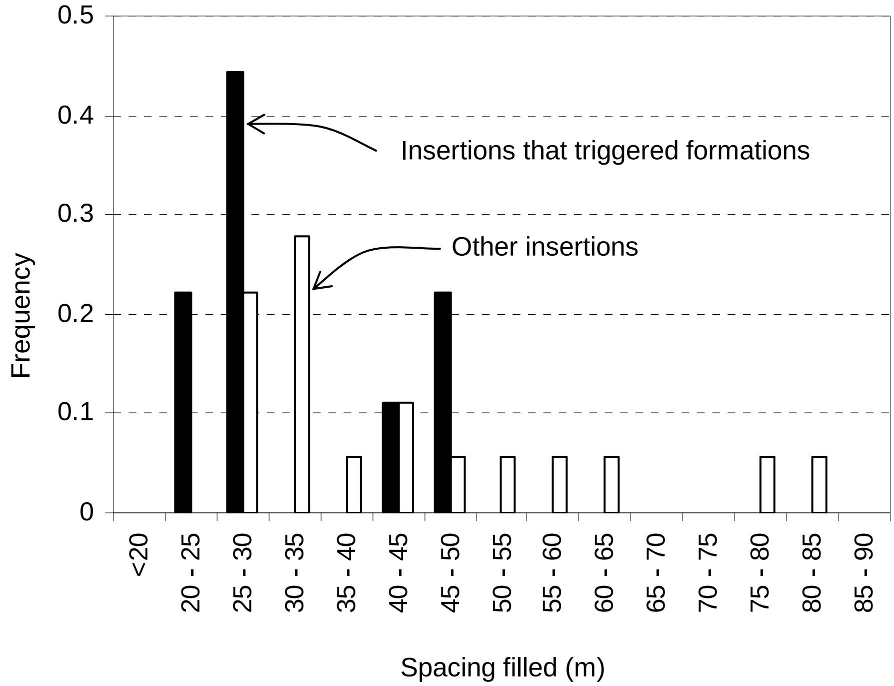


Figure 5: Distributions of Spacings Filled (Westbound I-80)

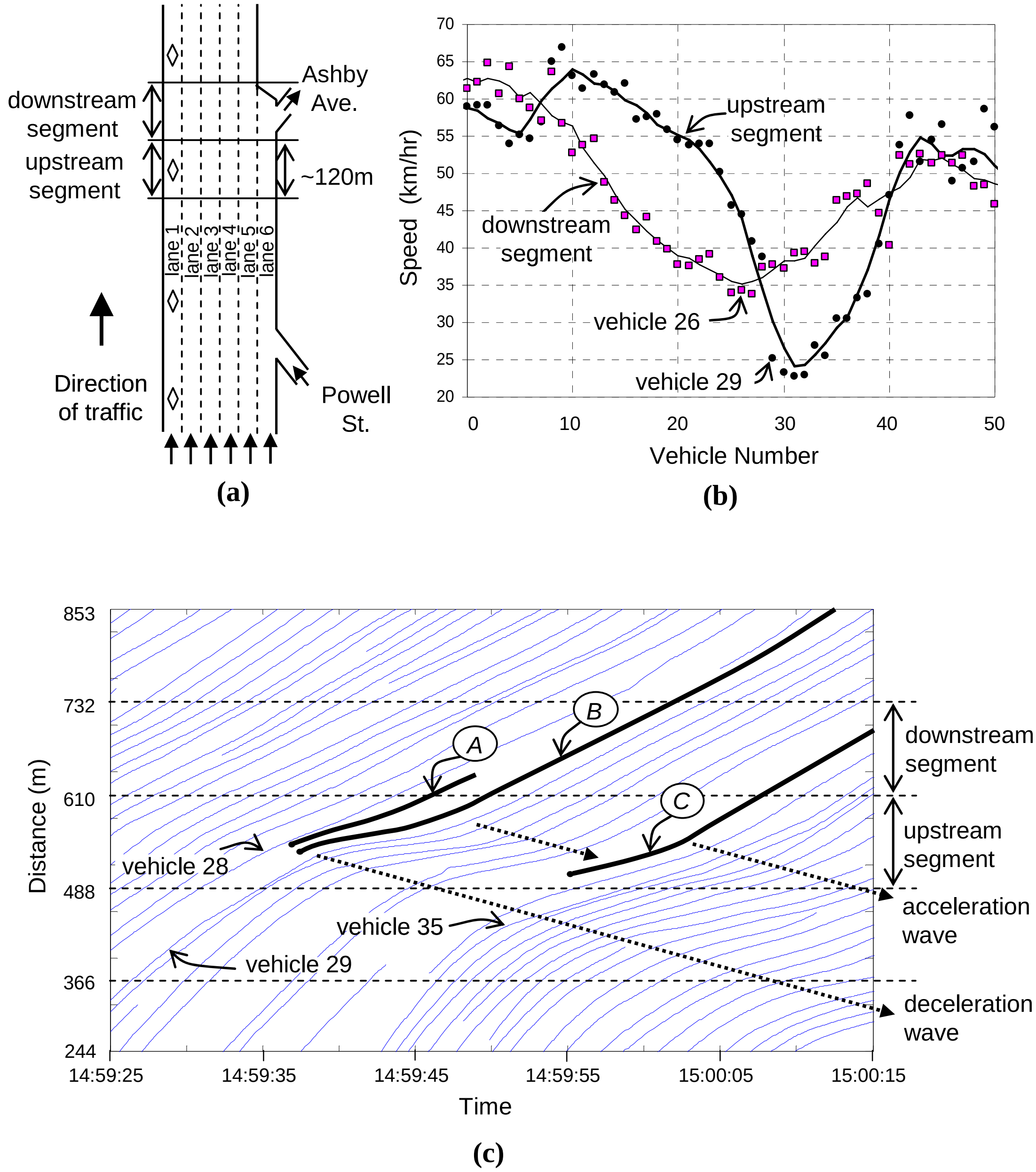


Figure 6: Growth of an Oscillation
(a) Eastbound I-80
(b) Vehicle Speeds
(c) Vehicle Trajectories

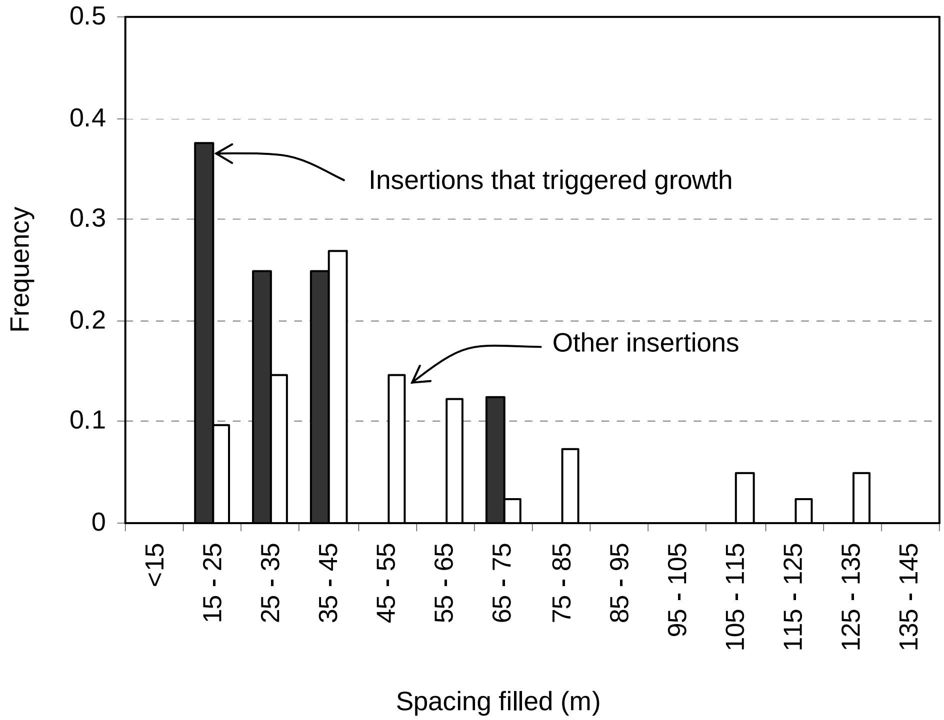


Figure 7: Distributions of Spacings Filled (Eastbound I-80)