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Evolution of Oscillations in Congested Traffic: Improved Estimation Method and Additional Empirical Evidences

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ABSTRACT

This paper provides additional empirical evidence confirming a recently proposed theory on the evolution of oscillations in congested traffic. It also proposes an improved method for computing the variation in oscillation amplitude, consisting in evaluating the oscillation amplitude along characteristic lines that travel at a constant wave speed. It is also shown that the theory is robust in that approximate input parameters can be used with little loss in accuracy.

The paper also provides an interesting finding regarding the evolution of oscillations within freeway segments with no entrances or exits. While previous studies found an increase in oscillation amplitude in such segments, our data indicates that this is not the case in general. This finding can have important implications for understanding driver behavior in homogeneous freeway segments.

INTRODUCTION AND BACKGROUND

The stop-and-go motion of vehicles and congested traffic is still a puzzling phenomenon. To this date, there is no traffic flow model that is able to replicate the oscillations in flow, speed or density revealed by freeway sensing devices. More importantly, our understanding of the phenomenon is still partial although there are several important findings and research contributions in this area in recent years.

A systematic study of stop-and-go oscillations started with Mauch and Cassidy (1), who unveiled for the first time important features of their propagation. They showed that (i) oscillations propagate upstream at a nearly constant speed independent of the flow, (ii) the period of oscillations does not change as it propagates, but (iii) its amplitude changes considerably. Findings (i) and (ii) are easily explained by the kinematic wave model (2,3) with triangular fundamental diagram (4). However, finding (iii) came as a surprise.

Upon closer examination, (5) found that merging traffic from a queued and un-metered on-ramp causes oscillations to diminish in amplitude as they propagate past the ramp, and that diverging maneuvers near off-ramp increase oscillation amplitude. Additionally, they proposed a simple theory that explains these phenomena and concluded that the amplitude of freeway oscillations:

- diminishes by a factor of $\frac{\alpha}{1+\alpha}$ as it propagates backward through a congested merge, and
- increases by a factor of $\frac{\beta}{1-\beta}$ as it propagates past an off-ramp,

where α and β are, respectively, the merge ratio, i.e., the ratio of flow entering the merge from the on-ramp and from the freeway (6,7), and the fraction of flow that takes the off-ramp. This theory was validated by (5) with remarkable accuracy in two different on-ramps on Interstate 80 near San Francisco, California and one off-ramp on Queen Elizabeth Way near Toronto, Canada.

The objective of this paper is twofold: providing additional empirical evidence to further validate the theory in (5), and to improve upon the estimation of the oscillation amplitude and growth. The new estimation method recognizes that oscillations travel at the speed of traffic characteristics, and therefore changes in oscillation amplitude are measured along these characteristic lines. Additionally, oscillations are analyzed individually, as opposed to the more aggregated framework (5).

This paper is organized as follows. In the next section, we will describe the sites and data utilized in this paper, which correspond to the Atlanta freeway network. After that we present the proposed methodology, followed by the results of our research work. Finally, we present a discussion and outlook.

DATA DESCRIPTION

The data used in this analysis were obtained from Georgia NaviGator, Georgia's Advanced Transportation Management System (ATMS), and covered the 8-month period between October 2007 and May 2008. During this period 59% of the mainline detection stations in the network were generating continuous data streams with an 89% availability ratio. Data were selected from a corridor that covers a stretch of about 15 miles of the I-285 freeway, extending between N Decatur Road at the South end and Riverside Drive NW at the North end (Site A in Figure 1).

From the south end to the I-285 / I-85 interchange there are four lanes while in the rest of the segment there are five lanes. Traffic volume and speed data are available lane-by-lane aggregated over 20 sec intervals at detection stations spaced approximately 1/3rd mile apart. While the data on the mainline lanes were very detailed, the sparse availability of data on the ramps limited the analysis to some extent.

In the following analysis, the 20 sec data are aggregated up to 5 min and 20 sec aggregates (320-sec) for a clearer representation of the results.

METHODOLOGY

The methodology proposed in this paper seeks to analyze the evolution of the amplitude of oscillations as they propagate upstream against congested traffic. The main difference with previous studies is that the changes in amplitude are computed along the path of the oscillation, which travels upstream with a speed of w (which is to be estimated as well). This wave speed in congestion corresponds to the speed of the characteristics and congested traffic. Interestingly, empirical evidence from around the world suggest that this speed usually varies in the range of $12 < w < 16$ mph. In our case, the wave speed for the segments analyzed in this study turns out to be 14.71 mph as shown in (8). To formalize the methodology, let $N(t,x)$ be the cumulative number of vehicles that have crossed freeway location x by time t . These curves are discrete in x and t since detection takes place at n discrete locations $x_i, i=1..n$, along the freeway and the data at each location is aggregated in intervals of 20 sec. For convenience, however, we consider here the time-continuous version of these curves by incorporating a piecewise linear interpolation between consecutive time intervals.

As in previous studies, oscillations are analyzed using the function

$$r(t,x) = N(t) - \bar{N}(t),$$

which represents the vertical deviations between the cumulative vehicle count by time t and the 320-sec moving average of the counts spanning that t , $\bar{N}(t) = [N(t + \tau, x) + N(t - \tau, x)]/2$, with $\tau = 160$ sec. These $r(t,x)$ curves are drawn as piecewise linear interpolations between consecutive vehicle arrivals, such that a curve's slope at any t is the flow difference at that t from a longer-run 320-sec average. Thus, the wiggles clearly evident in these deviation curves are oscillations, with positive (or negative) slopes revealing periods of positive (or negative) flow perturbations.

A collection of these curves is shown in Figure 2 overlaid on top of a time-space speed map (each band on the time-space map or each curve on the oscillation image represents a detector). The difference between oscillations in free-flow (lighter colors in the time-space speed plot) and oscillations in congestion (darker colors) become apparent in the figure. The former travel downstream at the speed of traffic, and tend to have smaller amplitude whose variations are fully explained by changes in traffic demand. The figure also shows that oscillations in congestion tend to change in amplitude as they propagate upstream. As in previous studies (1,5), the curves in Figure 2 show that the period, δ , of an oscillation is in the order of several minutes.

This paper uses the Root Mean Squared Errors (RMSE), s , as a measure of oscillation amplitude at the detector i in the time interval $(t, t + \delta)$; i.e.:

$$s(t, x_i) = \left[\sum_{t=0}^n (N(t) - \bar{N}(t))^2 / n \right]^{1/2}.$$

With all, the evolution of s along a wave traveling at a speed of $-w$ is given by the sequence

$$S(t, x_i) = s(t + (x_i - x_1)/w, x_i), \quad i=1..n,$$

where t is measured at x_1 , which represents the most downstream detector location under analysis. Using this convention, a wave emanated at (t, x_1) will reach detector i by time $t + (x_i - x_1)/w$, as sought.

In the next, we analyze several sequences of $S(t, x_i)$ using the data from the I-285 freeway segments shown in Figure 2, and for several waves emanated at different times t .

EXPERIMENTAL RESULTS

In this section we provide experimental evidence corroborating the theory in (5). This evidence is both qualitative and quantitative, depending on the availability of the ramp data. More precisely, there are many instances where it is observed that the variation in $S(t, x_i)$ between neighboring detectors is qualitatively consistent with the theory (i.e., positive variation if there is an off-ramp, and negative if there is a congested on-ramp between detectors), but the ramp data is not available to quantify this variation and compare it with the predictions of the theory.

Table 1 shows the freeway segments and dates selected for both qualitative and quantitative analysis; while Table 2 shows the weather conditions for these dates. Although the dates selected are all severely congested, the weather varies. At this point, it is unknown if weather conditions have an effect on the propagation of oscillations. Further research is ongoing.

Qualitative results

An extensive analysis of the data revealed a high degree of agreement with the theory. In this section, we show two examples: one in a broad spatial scale and one at a more detailed scale.

Figure 3 presents the evolution of $S(t, x_i)$ for a 15-mile segment on I-285 (Site A) with three different waves, labeled W1, W2 and W3. On the charts to the right, vertical solid line (green) and dashed line (purple) represent the location of on-ramps and off-ramps, respectively. In this case waves travel in the direction of decreasing x (as shown by the arrow). It can be observed that in most cases S decreases when passing through an on-ramp, and increases when passing through an off-ramp, as expected. In cases where there is an off-ramp immediately followed by an on-ramp with no detector in between, the change in amplitude could be positive or negative depending on the relative ramp flows. There are a few cases in the figure where oscillation amplitude increases when passing through an on-ramp. A possible explanation is that these on-ramps may be uncongested, which violates the main assumption of the theory.

It is worth noting that in segments without ramps and with several detectors (e.g. between milepost 29.3 and 30.7, and 34.5 and 36.2), one cannot observe a consistent trend; see ovals in Figure 3. This contrasts the results of (5) which reported an increase in oscillation amplitude in such segments.

Figure 4 shows the result of $S(t, x_i)$ for traffic in the counter clockwise direction on I-285. The segment shown in this figure is much shorter in order to provide a more detailed view. Specifically we look at two on-ramps (MilePost=33.36, and MilePost=32.74) and one off-ramp (MilePost=32.47), which are respectively labeled with red solid lines and green dashed line on the time-space diagram. It can be observed that the trend of $S(t, x_i)$ when passing through the on/off-ramps matches the prediction of the theory.

Quantitative results

In this section we have selected a collection of ramps where a detection device is installed and works properly. In order for the theory to hold, the freeway has to be congested and ramps need to fulfill the following criterion. The criterion for on-ramps is that both the freeway and the ramps should be congested. For the off-ramps the freeway should be congested. The theory doesn't require the merge ratio α (or diverge ratio β) to be always constant. Instead it requires the ratio to be constant during the passage of the oscillation. For prediction purpose, we select periods when the merge/diverge ratio is a constant to simplify the process. Information about the location of the ramps and the dates selected for analysis is shown in Table 1.

Merges

The on-ramp we selected is the southbound on-ramp at the Lavista Rd. junction with I-285. As mentioned above, to test the theory in the case of merges one has to select time periods where the on-ramp is congested and where the merge ratio is constant. To accomplish the former, Figure 5 shows the time series of the speed of vehicles in the on-ramp. As shown in the figure, we assumed that the on-ramp is congested whenever the speed drops below 30 mph. Once these congested periods were identified we estimated the merge ratio as in (5); i.e., as the slope of the linear regression line between on-ramp flow and freeway flow upstream of the ramp. One linear regression was estimated at approximately every 20 minutes using 20 sec flow data.

Figure 6 (a) shows a typical result of the merge ratio estimation. As can be seen, the merge ratio is approximately constant within well-defined time intervals, but not during the whole congested period. This variation in merge ratio may be partially explained by the geometry of this merge, which has a rather long insertion area of approximately 0.3 miles. In such a situation drivers have multiple choices for insertion and the insertion segments where drivers are actually changing lanes into the freeway may vary in time. This variation in the actual insertion segments is directly related to variations in the merge ratio.

The prediction error was computed as follows. Suppose that the wave travels in the direction of increasing x and that there are two detectors at locations x_1 and x_2 with an on-ramp in between at location x_0 , with $x_1 < x_0 < x_2$. According to the theory, $S(t, x_2) = S(t, x_1)/(1 + \alpha)$ so that the prediction error, $E(t)$, can be expressed as

$$E(t) = (S(t, x_2) / S(t, x_1) - 1 / (1 + \alpha)) * 100\%$$

Figure 7 presents the prediction errors $E(t)$ for the different dates and time periods selected for this analysis. Each chart in the figure was constructed assuming a constant merge ratio (shown in each chart) consistent with the ones estimated above. It can be observed that the prediction error falls well below 10% for extended periods of time. This can be considered as an

extremely good result since it represents the error at the most disaggregate level — individual wave path. A more aggregate error measure is also of interest and allows us to compare the results in this paper with the (5). Table 3 shows the average error during the entire time periods analyzed each day. As expected, the aggregate errors (between -2% and 5%) are smaller than the disaggregate errors and in the same range as reported in (5).

Diverges

In this case, the relevant parameter is the proportion of flow exiting the freeway at the off-ramp, β . This proportion was estimated as the ratio between the difference in detector counts upstream and downstream of the ramp, and counts at the upstream detector. The site selected is the exit ramp from I-285 to US 78/Stone Mountain Parkway. One linear regression was estimated at every 40 minutes using 20 sec flow data. We then plotted $\beta(t)$ curves and identified the periods where the constant assumption seems reasonable. Figure 6 (b) presents one such curve, or it can be seen to have between $t=15.8$ and $t=16.8$ the outflow ratio is rather constant (between 0.07 and 0.08).

An analogous lead to the previous section, the prediction error in the case of a diverge is the difference between the observed variation amplitude, $S(t, x_2)/S(t, x_1)$, and the theory prediction $1/(1-\beta)$. These prediction errors are shown in Table 4 and Figure 8. Again, for most of the time the errors are within the 10% band, while larger errors can be explained by a change in the exit proportion. As before, aggregate errors during the time periods analyzed are smaller and fall within $\pm 5\%$.

DISCUSSION

This paper provided additional empirical evidence confirming the theory in (5). It also proposed an improved method for computing the variation in oscillation amplitude, which involves the evaluation of the oscillation amplitude along characteristic lines that travel at a constant speed in the upstream direction. It was also shown that the theory is robust in that approximate input parameters α and β can be used with little loss in accuracy.

We also found a result contradicting the observations in (5) for segments without ramps. While (5) found a consistent increase in oscillation amplitude in such segments; our data indicates that this may not necessarily be the case in general. In fact, roughly 50% of the cases analyzed in this paper pertain to a decrease in oscillation. This is an interesting finding because, prior to this study, the explanation to the finding (5) was the effect of lane changes. According to our finding, however, there must be other factors that influence whether or not oscillation amplitude increases. An understanding of the latter may have important implications in the improvement of traffic simulation models. The authors are currently investigating this realm.

ACKNOWLEDGEMENTS

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TABLE 1 Ramps Selected for Analysis

Research	Ramp types	Location	Traffic Direction	Length	Time	Date
Qualitative	Both	I-285 between N. Decatur Road and Riverside Drive NW	clockwise	15 miles	PM	10/24/2007
	Both	I-285 between I-85 North C/D and exist to Buford Hwy	counter clockwise	2 miles	AM	10/29/2007
Quantitative	On-ramp	Lavista Rd. merges into I-285	clockwise	0.68 miles	PM	10/24/2007 05/02/2008 05/08/2008 05/23/2008
	Off-ramp	I-285 exit to US 78/Stone Mountain Highway	clockwise	0.26 miles	PM	10/24/2007 05/08/2008 05/15/2008 05/23/2008

TABLE 2 Weather Conditions on Selected Dates

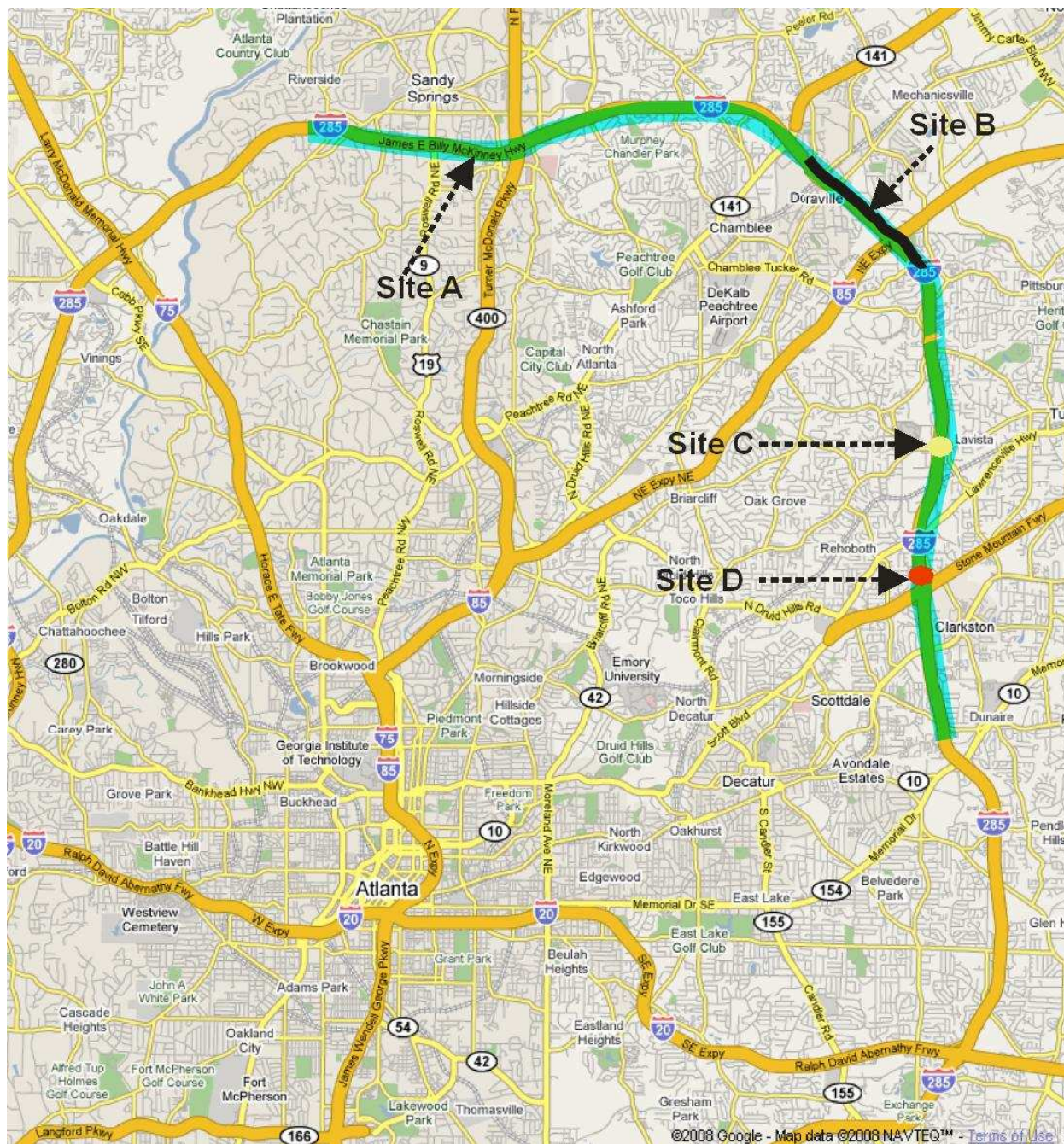
Date	Weather
10/24/2007	Rainy
10/29/2007	Clear
10/30/2007	Clear
05/02/2008	Clear
05/08/2008	Clear
05/15/2008	Lightly rainy
05/23/2008	Lightly rainy

TABLE 3 Prediction for on-ramp

Date	Time period (hr)	Merge Ratio (α)	Duration (min)	Average Error (%)
10/24/2007	15.8 ~ 16.3	0.34	30	2.05
10/24/2007	16.7 ~ 17.2	0.60	30	5.01
05/02/2008	16.3 ~ 17.8	0.34	90	-0.26
05/08/2008	16 ~ 16.35	0.2	21	2.04
05/08/2008	16.6 ~ 17.15	0.2	33	-2.09
05/23/2008	17.05 ~ 17.9	0.32	51	-0.96

TABLE 4 Prediction for off-ramp

Date	Time period (hr)	Outflow Ratio (β)	Duration (min)	Average Error (%)
10/24/2007	16 ~ 18.6	0.08	156	1.23
05/08/2008	15.7 ~ 16.7	0.072	180	4.96
05/08/2008	17.9 ~ 19	0.072	66	2.0
05/15/2008	15.4 ~ 16.6	0.115	69	-5.06
05/23/2008	14.5 ~ 16.1	0.075	96	2.24
05/23/2008	17.7 ~ 19.1	0.09	84	1.21



Note: Site A: Green Band; Site B: Black Band; Site C: Yellow Ellipse; Site D: Red Ellipse

FIGURE 1 Study area.

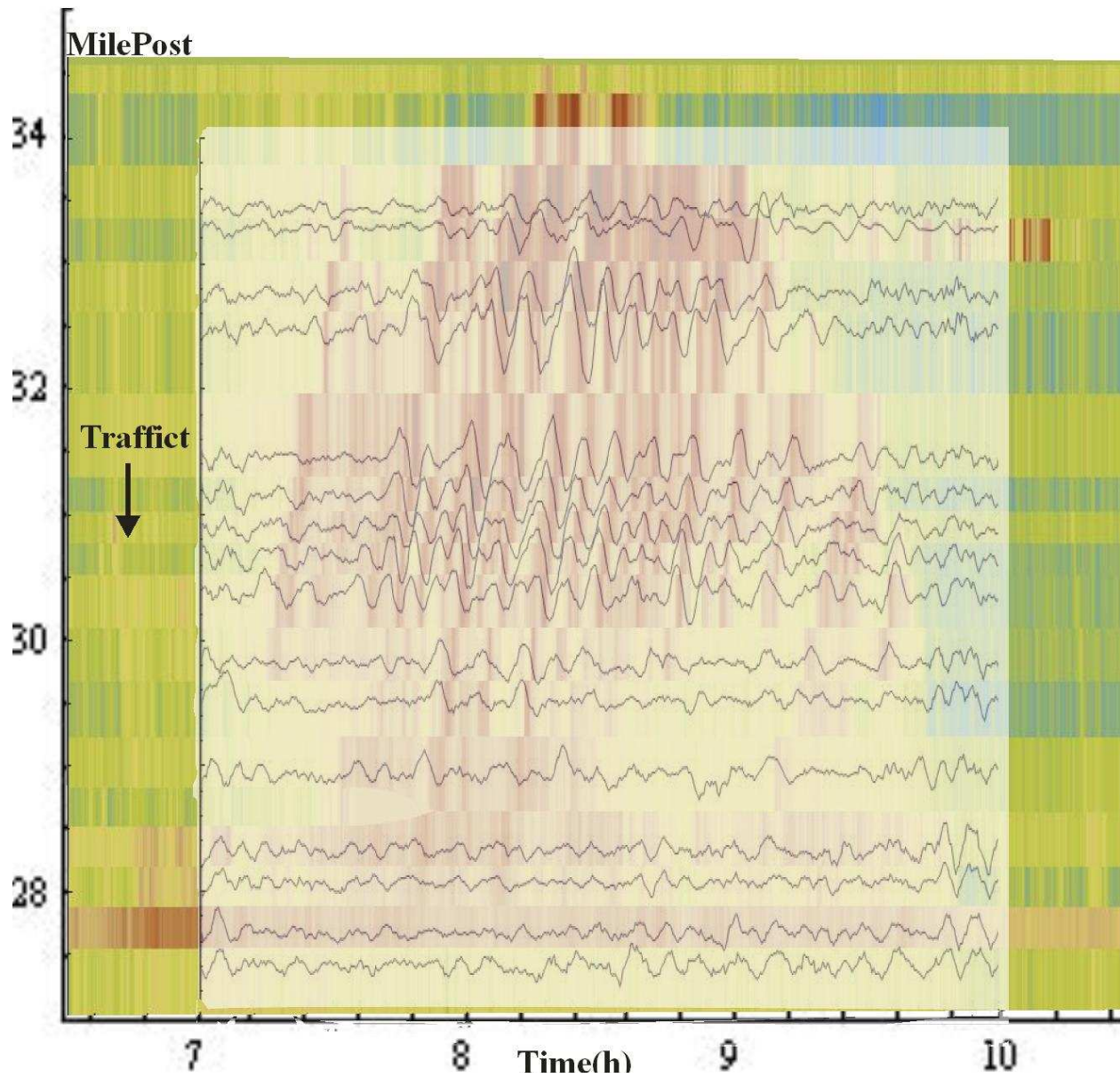


FIGURE 2 Time-space speed vs. oscillation on I-285 for counter-clockwise traffic (AM, Oct.29th, 2007).

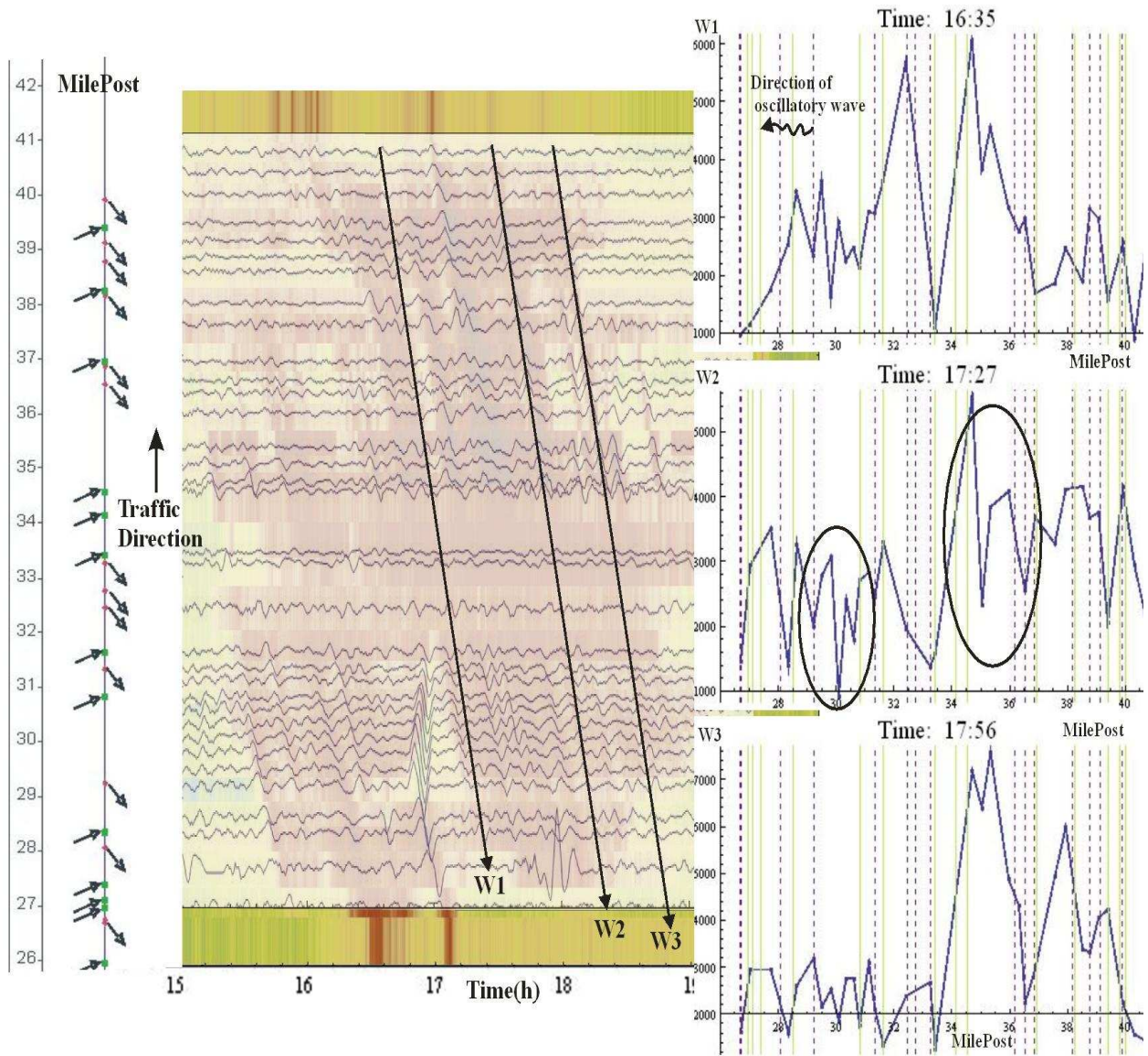


FIGURE 3 Qualitative results for Site A on I -285 (PM, Oct.24th, 2007).

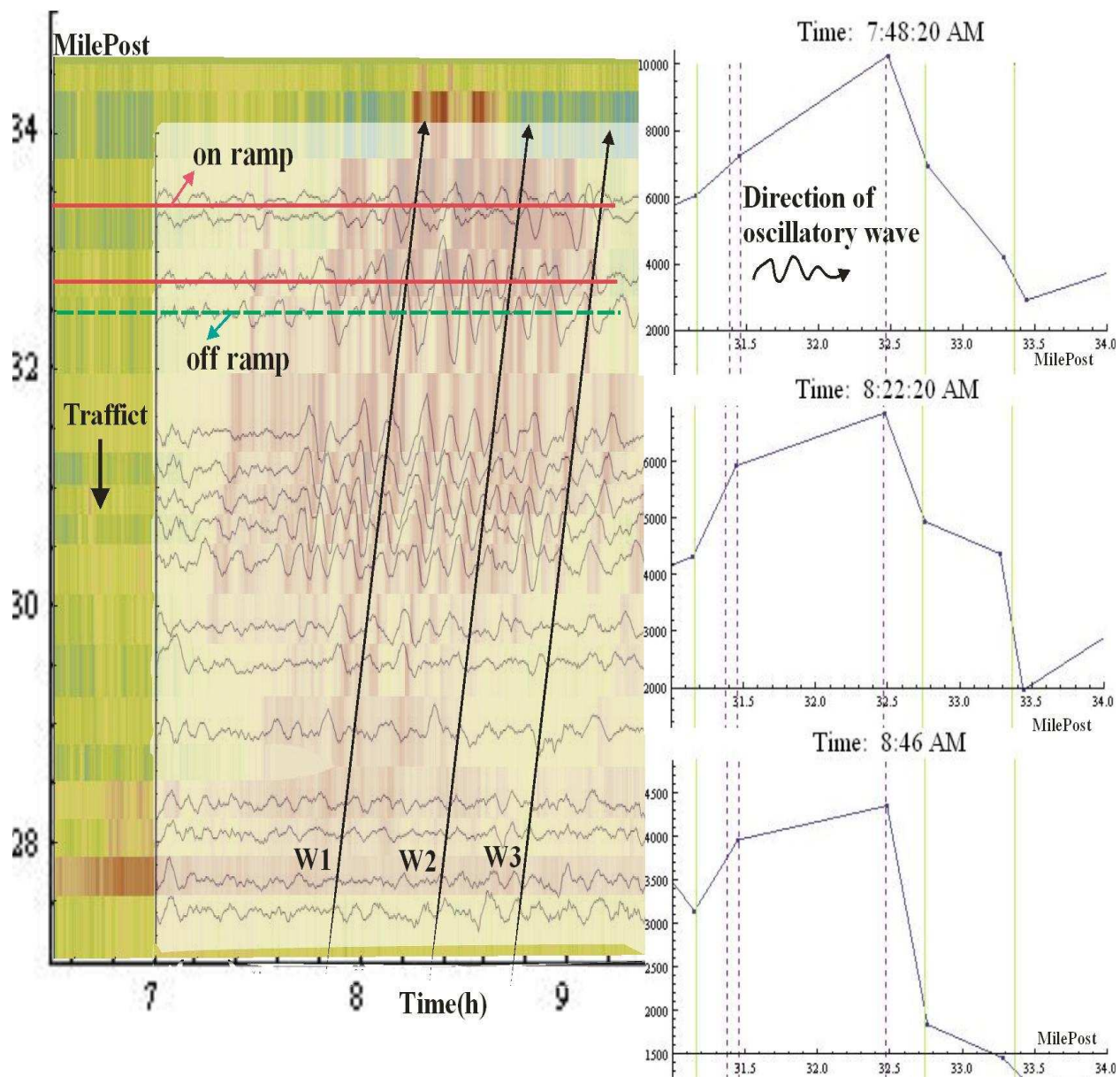


FIGURE 4 Qualitative results for Site B on I-285 (AM, Oct.29th, 2007).

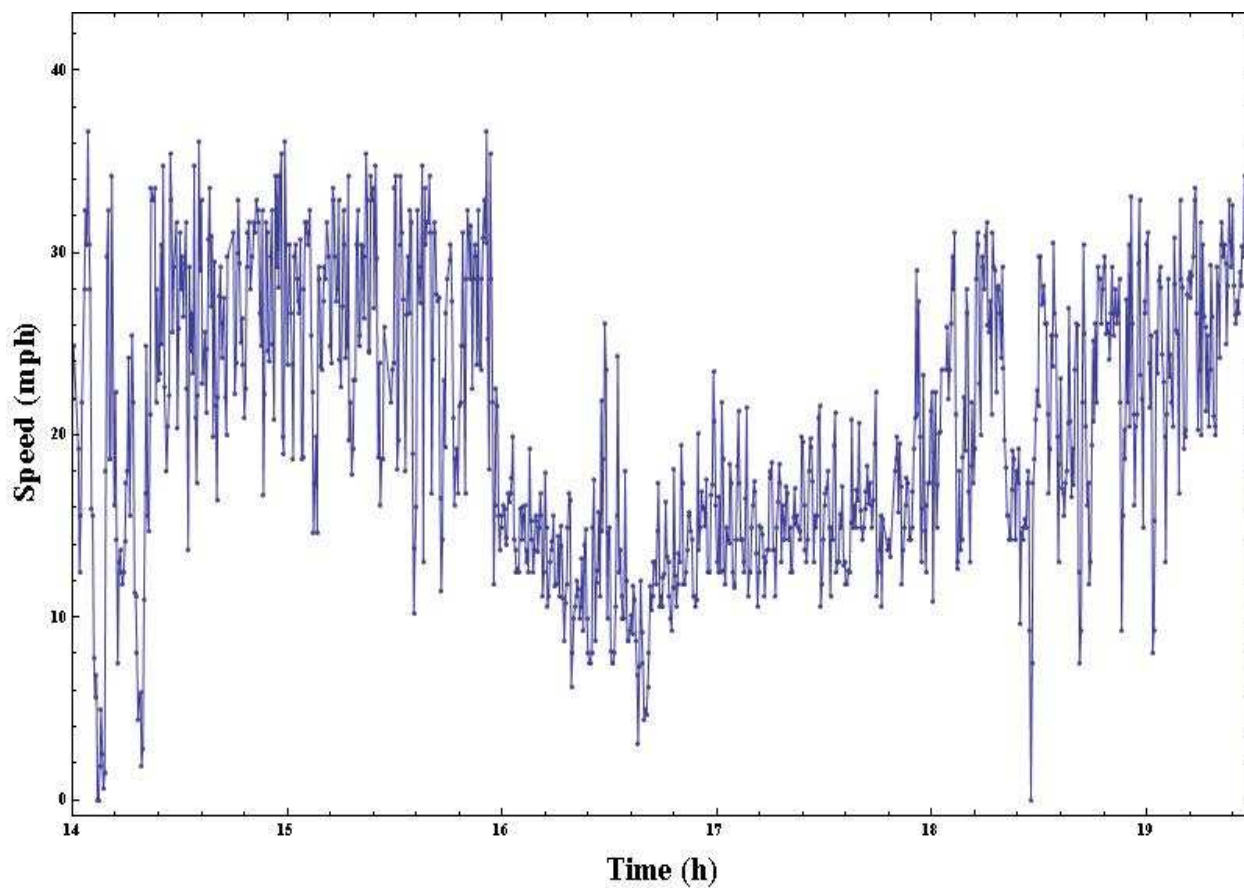


FIGURE 5 Speed in the on-ramp at Site C on I-285 (May.8th, 2008).

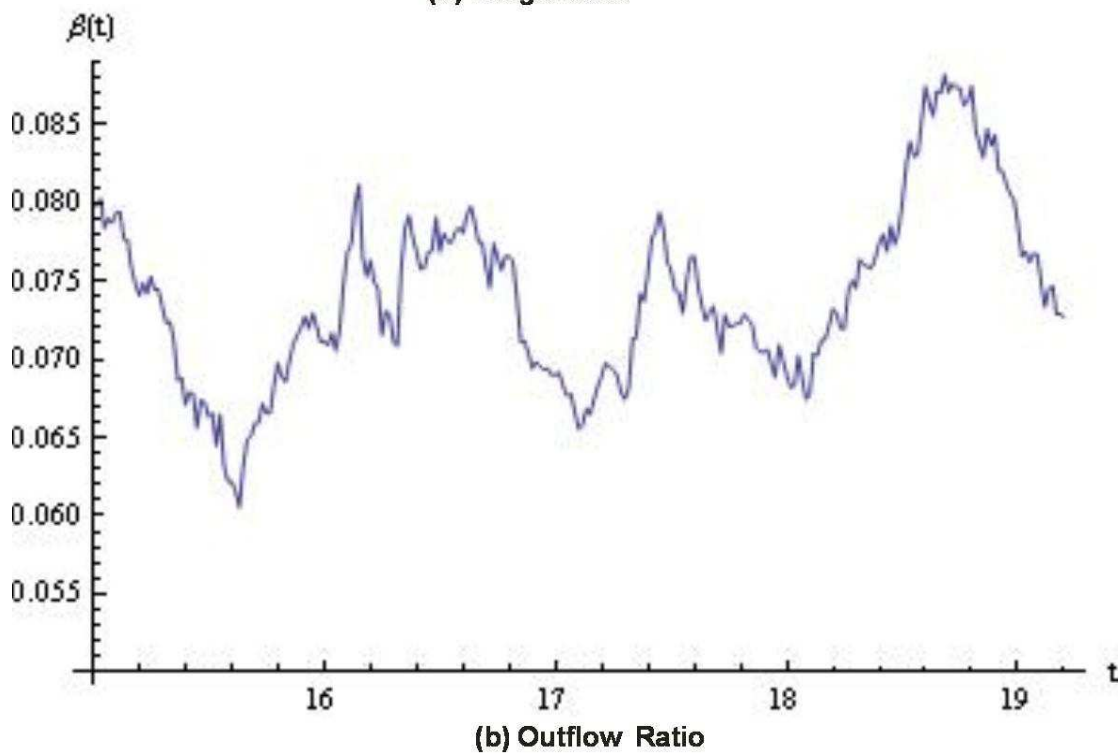
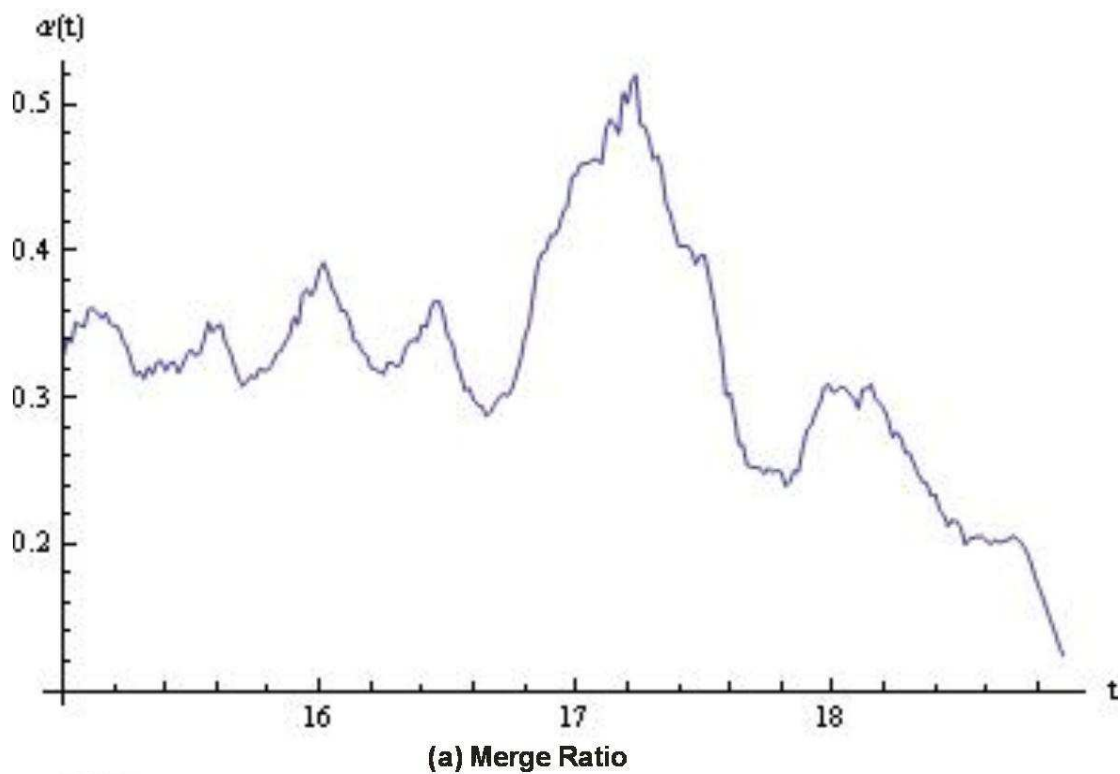


FIGURE 6

- (a) Merge ratio in the on-ramp at Site C on I-285 (Oct.24th, 2007).
 (b) Outflow ratio in the off-ramp at Site D on I-285 (May.8th, 2008).

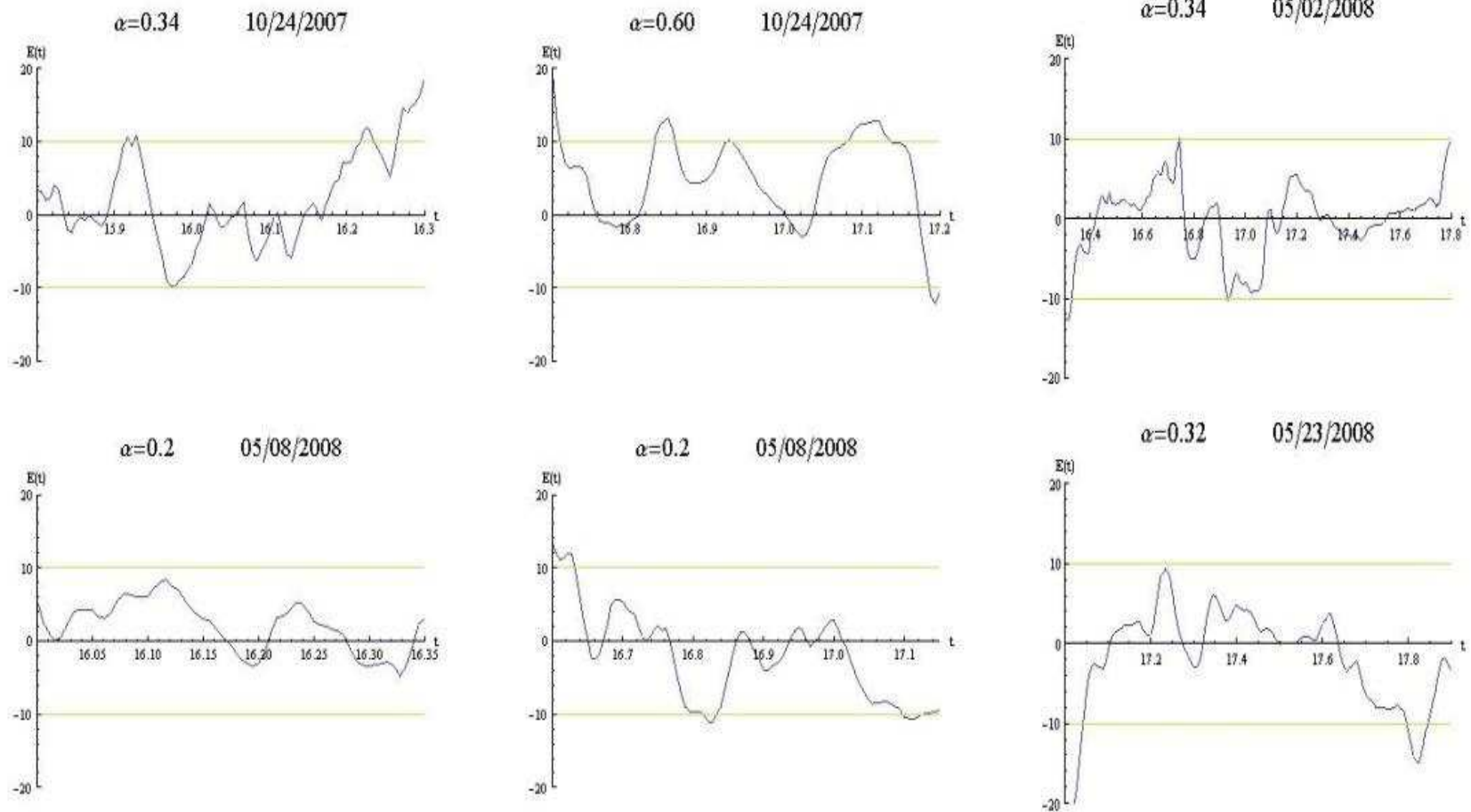


FIGURE 7 Prediction errors for on-ramp at Site C on I-285 (Errors are shown in percentage).

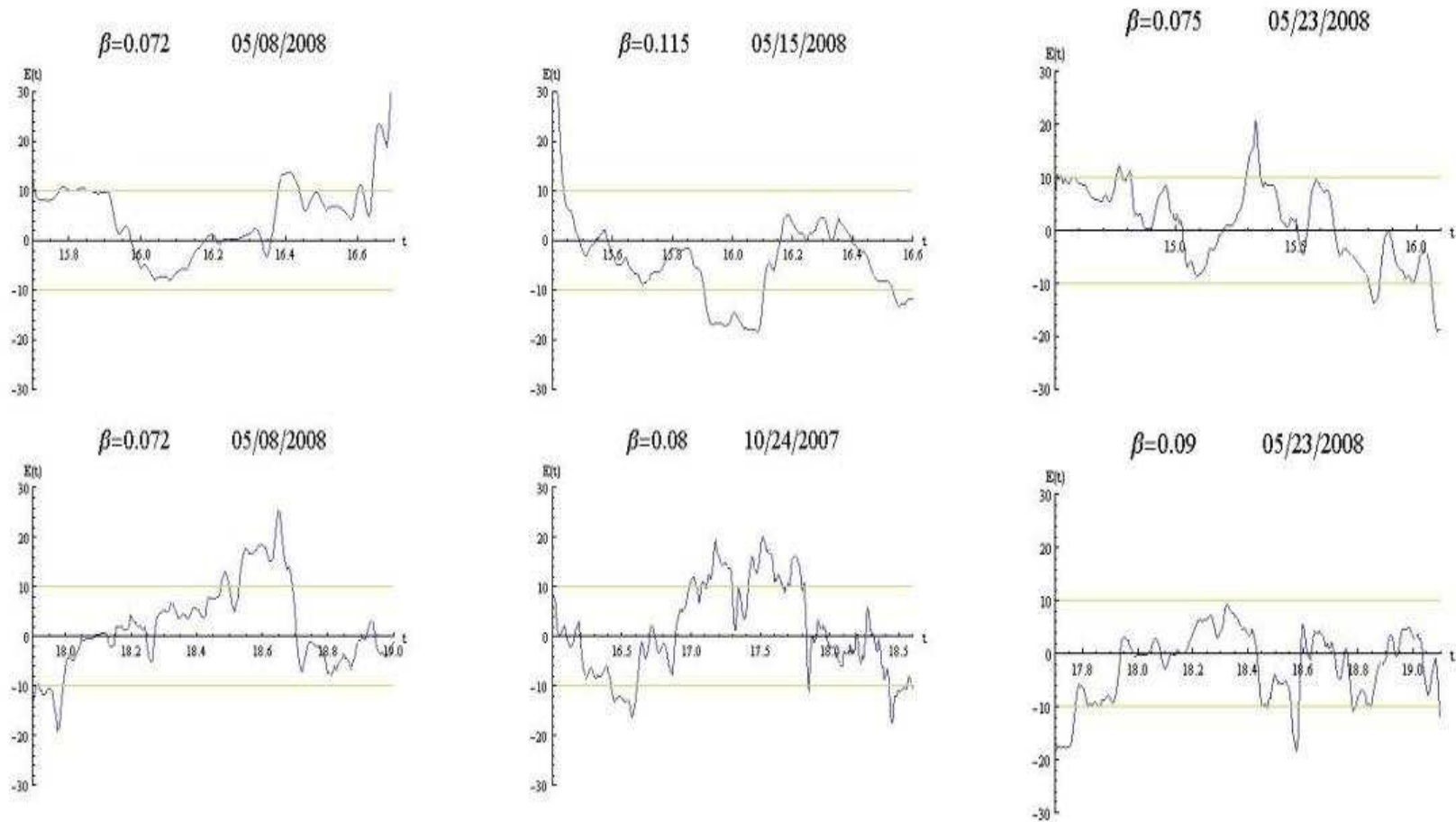


FIGURE 8 Prediction errors for off-ramp at Site D on I-285(Errors are shown in percentage).