Extended Abstract Submitted for Presentation at the 1st LATSIS Symposium 2012

Traffic Hysteresis and the Evolution of Stop-And-Go Oscillations

By
Danjue Chen[1], Soyoung Ahn[2], Zuduo Zheng[3], Jorge Laval[1]
[1]School of Civil and Environmental Engineering, Georgia Institute of Technology
[2]School of Sustainable Engineering and the Built Environment, Arizona State University
[3]Civil Engineering and Built Environment School, Queensland University of Technology

The present study unveils the mechanism of stop-and-go oscillations development in relation to traffic hysteresis. We (i) establish the causal relationship between hysteresis and the evolution of oscillations, (ii) quantify this relationship (at macro and micro levels) by linking the amplitude of oscillations to the magnitude of hysteresis, and (iii) examine the changes in discharge rate after experiencing oscillations.

We report three major findings:

(i) Distinct orientation and magnitude of hysteresis are closely linked to different stages of oscillations development. Ordinary traffic hysteresis, representing a retarded recovery of spacing (or flow), is prevalent in the pre-cursor and growth stages, whereas nominal or even reverse hysteresis characterizes the stabilization stages.
(ii) The amplitude of an oscillation is strongly correlated with the magnitude of hysteresis.
(iii) The discharge rates from an oscillation in the pre-cursor and growth stages often diminish because some vehicles do not fully recover their pre-oscillation spacing. This implies that oscillations forming close to an active bottleneck can contribute to a significant reduction in bottleneck discharge rate.

Characterization of traffic hysteresis

Newell's car-following (CF) model assumes that a driver in car-following mode behaves the same as her leader with displacements in time τ and space d (Newell 2002). The model does not exhibit hysteresis in speed-spacing relations and growth or decay in disturbance.

Figure 1 illustrates examples of nominal, ordinary, and reverse hysteresis. The *nominal* hysteresis is characterized by the evolution of speed-spacing relations in the same (linear) path during deceleration and acceleration (Figure 1a); i.e., a vehicle trajectory is nearly superimposed with the theoretical trajectory constructed based on the lead vehicle assuming Newell's model (Figure 1b). In the presence of *ordinary* (*reverse*) hysteresis, speed-spacing relations evolve clockwise (counterclockwise), which translates into rightward (leftward) deviations of a trajectory from the Newell trajectory; see Figure 1c-1d (Figure 1e-1f). These examples illustrate that the hysteresis orientation may be closely related to the development of oscillations.

Traffic hysteresis is measured at the micro and macro levels. Microscopic measurements are taken from the speed-spacing (Ahn et al. 2012) or speed-η evolutions (Chen et al. 2012) of individual vehicles, where η is the ratio of actual spacing to steady-state spacing given by Newell 's CF model (Laval and Leclercq 2010). The magnitude is measured in terms of average steady-state spacing deviation Δs and average η deviation ($\Delta\eta$) with respect to speed; see Figure 2a-b.

At the macro level, we measure the flow and density along the movement of a vehicle platoon according to Edie's generalized definitions (Edie 1961, Laval 2011) (see Figure 3a). The magnitude of macroscopic hysteresis is then measured as the average flow difference with respect to density (see Figure 3b). Note that a measurement region is shaped a parallelogram with the incline of the average wave speed in the platoon to ensure a near steady-state inside the region.

Characterization of oscillations development stages

We analyzed five instances of oscillations observed in the NGSIM data for US101. Figure 4 shows an example of an oscillation that propagates in space as a set of deceleration and acceleration waves. These waves are identified by tracing the points of significant speed changes using continuous wavelet transform (Zheng et al. 2011a, 2011b, Zheng and Washington 2012) for the method.) In the figure, oscillations undergo different development stages as they propagate in space. Four distinct stages are characterized below:

(i) ***Pre-cursor***: The speeds of the deceleration and acceleration waves are close to zero, indicating localized slow-and-go driving motions.
(ii) ***Growth***: The waves propagate backward in space at the speed of 10-15 mph and the amplitude (defined as the minimum speed between the waves) increases significantly as the waves propagate.
(iii) ***Stabilization***: The amplitude remains relatively constant as waves propagate backward in space.
(iv) ***Decay***: The amplitude diminishes as waves propagate. This stage was rarely observed in our sample.

Figure 5 shows the trajectories in each development stage that are shifted to the most upstream vehicle in the group along the wave path. In the figure, each trajectory deviates rightward from the preceding one in the pre-cursor and growth stages, evidently as a result of strong presence of ordinary hysteresis among vehicles. Moreover, the deviations never recover for many vehicles, suggesting a reduction in discharge rate. (This will be discussed shortly.) In contrast, no obvious deviations are observed in the stabilization stage, indicating presence of nominal or yet reverse hysteresis.

The above observation is quantified in Table 1. The pre-cursor and growth stages show larger decreases in minimum speed, Δv_{min}, indicating larger increases in oscillation amplitude. These two stages also show larger magnitudes of hysteresis, as measured by Δs and $\Delta\eta$, indicating a strong correlation to the amplitude. Figure 6 further confirms this observation: the relationships between Δv_{min} and ΔS and between Δv_{min} and $\Delta\eta$ reveal negative trends that are statistically significant.

Table 1 summary of measured amplitudes of oscillations and hysteresis

Oscillation Stage	Sample Size (vehs)	Average Δv_{min} (ft/s)	Average Δs (ft)	Average $\Delta\eta$
Pre-cursor	28	-2.07	20.04	0.23
Growth	44	-1.46	17.35	0.31
Stabilization	58	-0.19	7.59	0.15

Reduction in discharge rate from oscillations

Here we further examine the reduction in discharge rate from oscillations in different development stages. Particularly, in the pre-cursor and growth stages (Figure 7a-b), we observe strong clock-wise (macroscopic) hysteresis with open loops, leading to significant discharge rate reductions (as large as 25%; see Figure 7d-e). In contrast, the stabilization stage (Figure 7c) is characterized by mild hysteresis with full recovery of discharge rate (see Figure 7f). The result indicates that oscillations forming near an active bottleneck can lead to a significant reduction in bottleneck discharge rate and that the amount of reduction should depend on the period of oscillations and duration of pre-cursor and growth stages. We further infer that a reduction in bottleneck discharge rate is attributed not only to voids created by lane-changes with finite acceleration (Cassidy and Rudjanakanoknod 2005; Laval and Daganzo 2006; Laval and Leclercq 2008), but also to growth of oscillations triggered by these lane-changes.

References

Ahn, S., Vadlamani, S., Laval, J., 2012. A method to account for non-steady state conditions in measuring traffic hysteresis. In Press. Transportation Research Part C.

Cassidy, M.J., Rudjanakanoknad, J., 2005. Increasing capacity of an isolated merge by metering its on-ramp. Transportation Research B, 39(10), 896-913.

Laval, J.A., Daganzo C.F., 2006. Lane-changing in traffic streams. Transportation Research B, 40(3), 251-264.

Chen, D., Laval, J., Zheng, Z., Ahn, S., 2012. Traffic oscillations: A behavioral car-following model. In Press. Transportation Research Part B.

Laval, J.A., 2011. Hysteresis in traffic flow revisited: an improved measurement method. Transportation Research Part B, 45, 385–391.

Laval, J.A., Leclercq, L., 2008. Microscopic modeling of the relaxation phenomenon using a macroscopic lane-changing model. Transportation Research part B, 42(6), 511-522.

Laval, J.A. and Leclercq, L., 2010. Mechanism to describe stop-and-go waves: A mechanism to describe the formation and propagation of stop-and-go waves in congested freeway traffic. Philosophical Transactions of the Royal Society A.

Edie, L. C., 1961. Car following and steady-state theory for non-congested traffic. Operations Research 9, 66-77.

Newell, G. F., 2002. A Simplified CF Theory: A Lower Order Model. Transportation Research Part B, 36(3), 195-205.

Zheng, Z., Ahn, S., Chen, D., Laval, J., 2011a. Applications of wavelet transform for analysis of freeway traffic: bottlenecks, transient traffic, and traffic oscillations. Transportation Research Part B, 45(2), 372-384.

Zheng, Z., Ahn, S., Chen, D., Laval, J., 2011b. Freeway traffic oscillations: microscopic analysis of formations and propagations using wavelet transform. Transportation Research Part B, 45(9), 1378-1388.

Zheng, Z., Washington, S., 2012. On selecting an optimal wavelet for detecting singularities in traffic and vehicular data. Transportation Research Part C. In press.

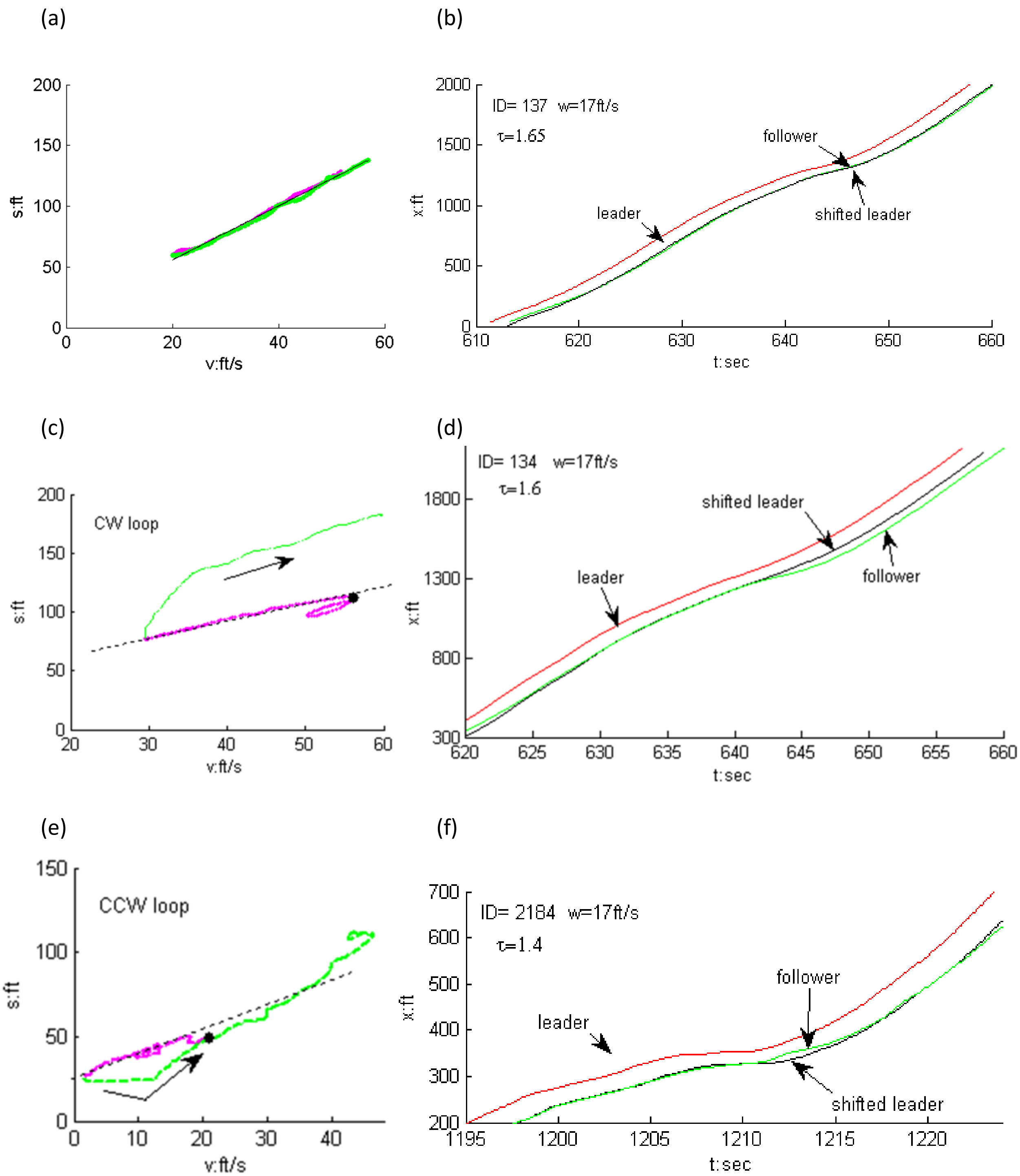

Figure 1 Examples of traffic hysteresis observed in the NGSIM data (US101): (a-b) nominal hysteresis; (c-d) ordinary hysteresis; (e-f) reverse hysteresis.

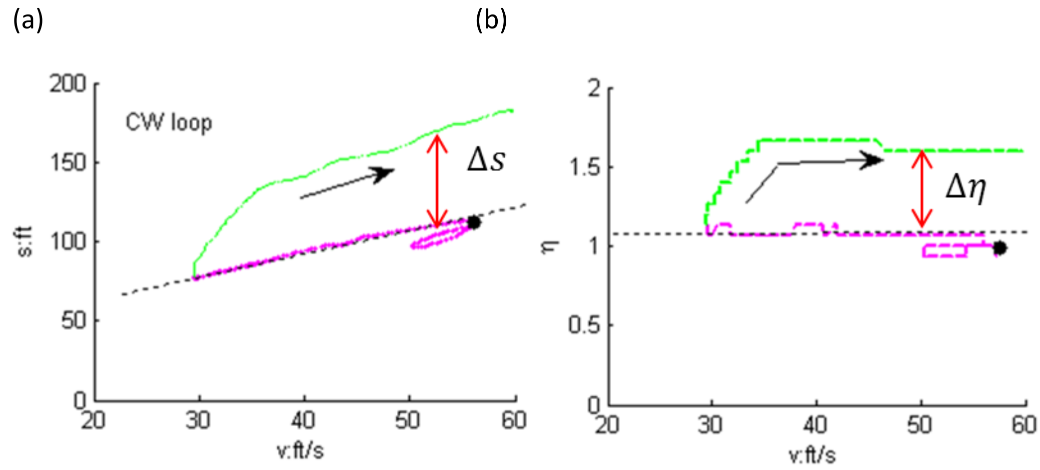

Figure 2 Microscopic measurement of magnitude of hysteresis: (a) speed vs. spacing; (b) speed vs. η.

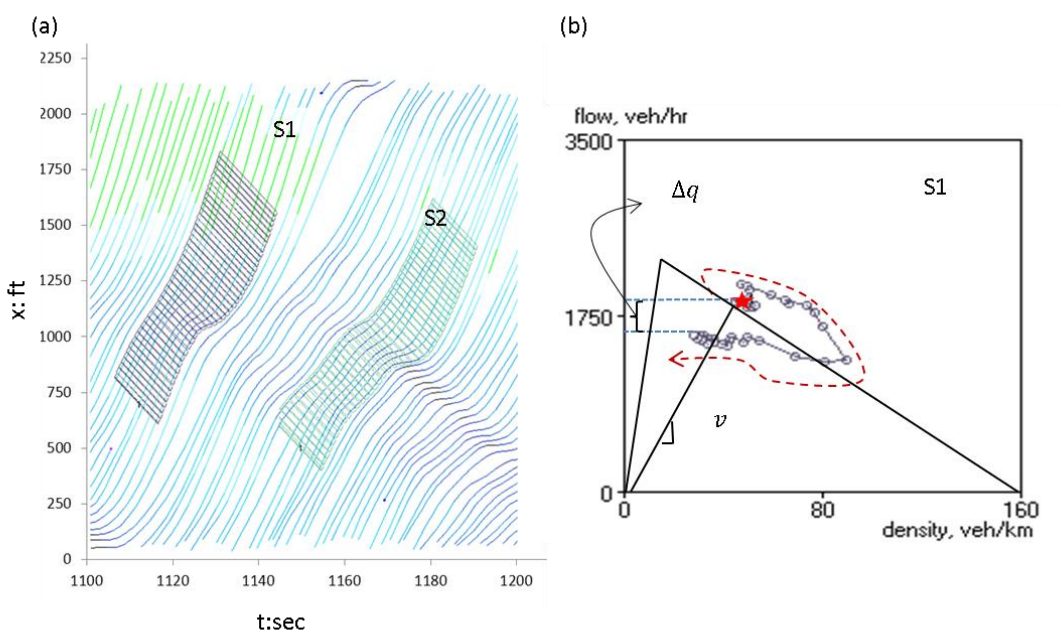

Figure 3 Macroscopic measurement of magnitude of hysteresis: (a) measurement regions along a platoon of trajectories; (b) density vs. flow.

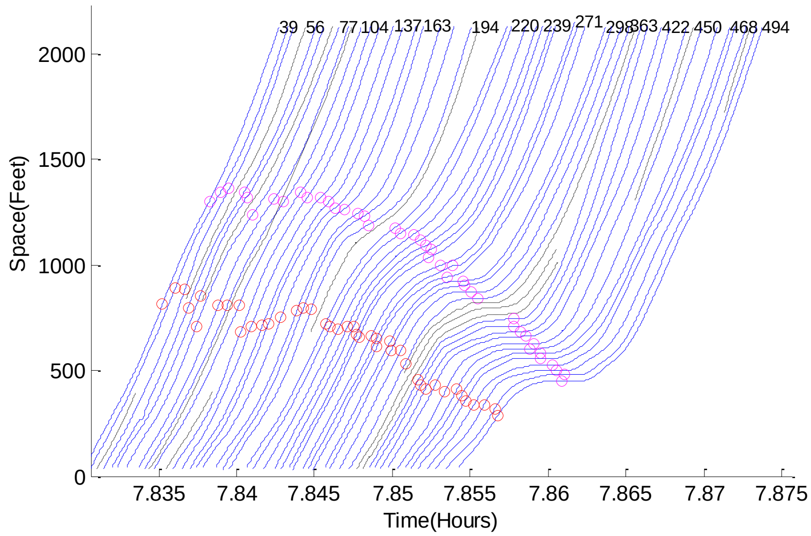

Figure 4 Propagation of an oscillation; red (purple) circles mark the deceleration (acceleration) wave.

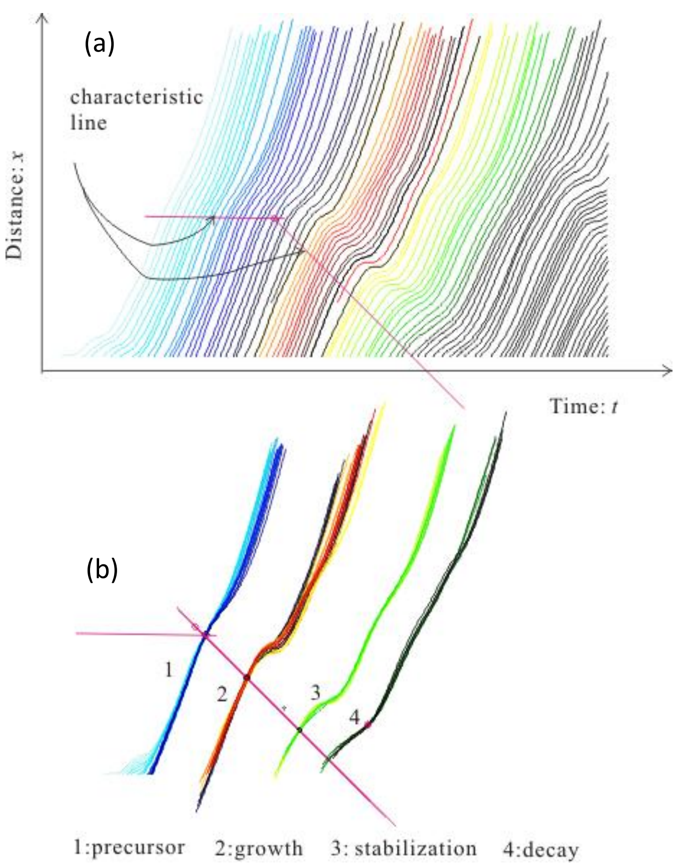

Figure 5 Four stages of oscillation development: (a) an example oscillation with characteristic lines (deceleration waves); (b) shifted trajectories for each stage.

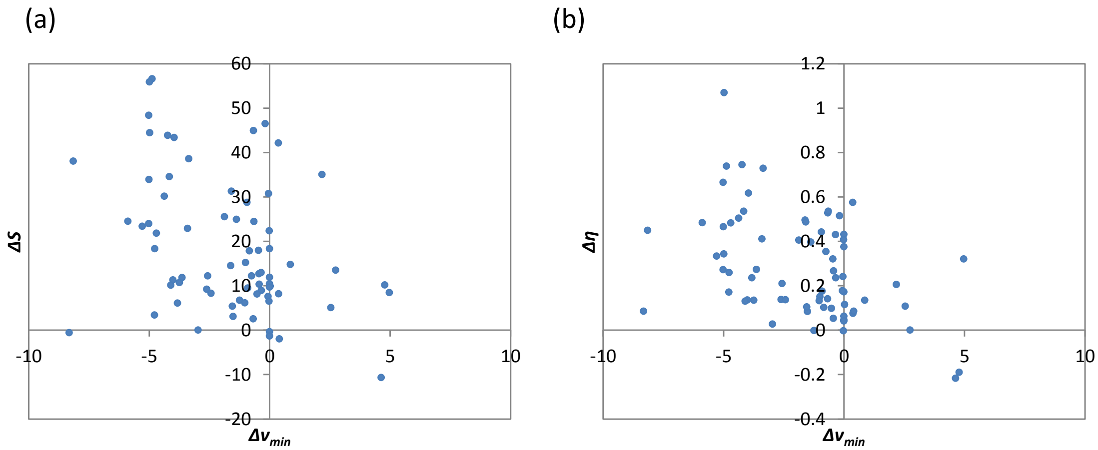

Figure 6 Relationships between the magnitude of hysteresis and the amplitude of oscillations

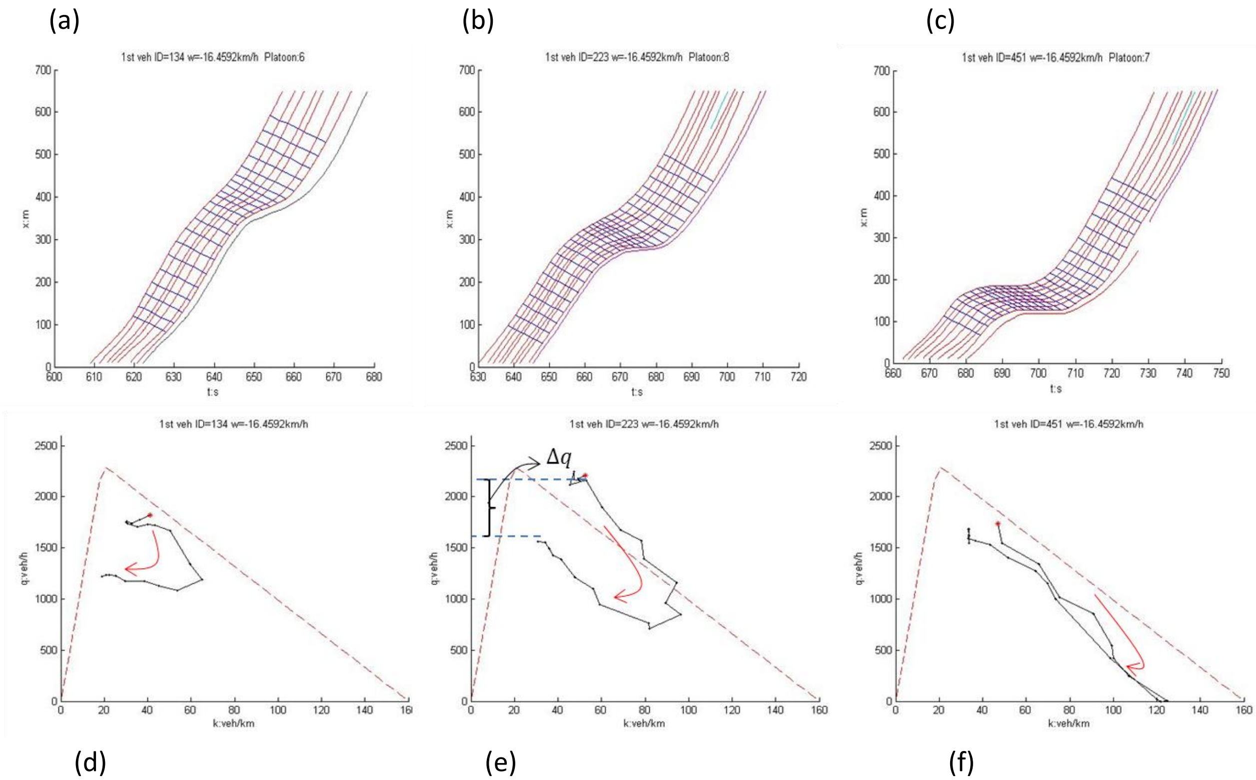

Figure 7 Discharge rate from a traffic oscillation: (a-c) platoons for precursor, growth, and stabilization stages; (d-f) hysteresis loops for precursor, growth, and stabilization stages (a red dot denotes starting point).