A Study on the Wave Development and Evolution Characteristics of Stop-and-Go Traffic

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Abstract: This paper investigates characteristics of the stop-and-go traffic wave that occurs frequently in congested traffic, and describes its development and evolution in time and space. Using NGSIM trajectory dataset, we investigated the relationship between the development of stop-and-go waves and lane changing events which causes deceleration of vehicles and subsequent wave growth and dissipation. Asymmetric traffic theory assuming the separation between acceleration and deceleration behavior was used as a framework for interpretation and explanation of the observed results. And, reciprocal interactions between consecutive stop-and-go waves were studied. Finally, we concluded that the characteristics of stop-and-go waves are closely related to asymmetric driving behavior.

Key Words: Stop-and-Go wave, Traffic oscillation, Asymmetric driving behavior.

1. INTRODUCTION

In traffic congestion, where the neighboring vehicles restrict the subject vehicle’s behavior, and lane changing events cause slow-down of following vehicles, stop-and-go traffic, which is characterized by deceleration wave followed by acceleration wave, frequently develops. Not only does it induce a waste of petroleum and emission of deleterious gas, but it also causes unnecessary increase of driver’s travel time. Among traffic phenomena, stop-and-go traffic is one of the major issues in traffic modeling. Numerous researches have studied to reveal the properties of stop-and-go wave, which it is often called as traffic oscillation. Nevertheless, the stop-and-go traffic’s detailed mechanisms, explaining the full life cycle of it has not been thoroughly investigated and understood, yet. Still, it remains as unrevealed area in traffic theory. For better understanding on traffic flow in congestion traffic, we have to know characteristics of stop-and-go traffic first.

Recently, significant researches on driving behavior under car-following and traffic oscillation have been studied. Car-following behavior is closely related with the development and evolution characteristics of stop-and-go traffic since drivers not only always look around other vehicles but also are influenced by their action under congestion period. Newell (2002) proposed simplified car-following theory. This model, based on the triangular shape fundamental diagram, used to represent the car-following behavior with an assumption that a driver has symmetric driving behavior, and cannot explain traffic oscillation. It gives a solution of the kinematic equation, introduced by Lighthill, Whitham (1955) and Richards (1956). The assumption, however, is inadequate for real traffic, and this model cannot fully explain the wave characteristics of stop-and-go traffic. Ahn and Ma (2008) compared speed-
spacing relationship under general car-following conditions with regard to lane changes. They investigated trajectories of I-80 and US-101 NGSIM datasets, and argued that in lane changing situation, drivers have different speed-spacing relationship from the general car-following model.

Del Castillo (2001) announced a model to explain how traffic oscillation occurs frequently and described the life cycle mechanism. In his model, he assumed that vehicle’s trajectories do not require being parallel. He adopted density term only to explain the process of traffic oscillation. On the whole, stop-and-go wave grows in dense traffic, whereas it decays if otherwise. Density, of course, has a great influence upon traffic oscillation, but it is not enough to explain development and evolution of stop-and-go waves. Similarly, Kim and Zhang (2004) explained stop-and-go waves using probabilistic wave propagation model. Under their work, traffic oscillation develops according to relative differences of reaction time and gap time values. They treated birth and death of traffic perturbation as a stochastic phenomenon. Yeo and Skabardonis (2009) proposed the asymmetric driving behavior theory. They defined 5 traffic phases: acceleration, deceleration, stationary, free-flow and coasting. In their theory, a driver has two different curves: A-curve and D-curve. In other words, drivers possess distinct sensitivities for gap acceptance in acceleration and deceleration situations. In coasting phase, driver adjusts the gap while keeping his speed. So, stop-and-go waves are frequently generated near D-curve. Laval and Leclercq (2010) described the formation and propagation of stop-and-go waves in congested freeway traffic. According to their results, drivers have distinct behaviors when they accelerate or decelerate as if having an asymmetric personality to drive. Nevertheless, they introduce timid and aggressive driving modes to explain the congested traffic situation. Characteristics of stop-and-go waves cannot be fully clarified by only driver’s tendencies. Zheng et al. (2010) investigated the impact of lane changing maneuvers (LCM) to trigger traffic oscillations. Then, they compared LCM effect with car-following behavior to investigate oscillation. Still, they do not consider driver’s behavior and then ascribed the formation and propagation characteristics of traffic oscillation to driver’s aggressiveness.

The purpose of this research is to find wave characteristics of stop-and-go traffic, which includes the wave development and evolution mechanism in congested traffic including the effect of lane change events, which frequently occur in merging area where most bottlenecks are located. This research is based on the work by Yeo and Skabardonis (2009), who provided an explanation on the development of stop-and-go waves from the asymmetric theory’s view (See Newell, 1965; Yeo, 2008). We extended it to reveal more detailed evolution of stop-and-go waves with lane-changing events, and also investigated the interaction between adjacent stop-and-go waves using NGSIM (2006) trajectories database.

![Figure 1 NGSIM data example, US101, Lane 1, 8:20-8:35 am(time x 0.1sec)](image-url)


2. WAVE DEVELOPMENT CHARACTERISTICS

Stop-and-go waves grow or dissipate in congested traffic under certain conditions. Yeo and Skabardonis (2009) showed that asymmetric behavior is closely related to stop-and-go wave’s development. Also, they mentioned that lane-changing event is the main influencing factor determining stop-and-go wave’s development. Thus, it is needed to investigate the relationship between lane-changing events and stop-and-go waves.

2.1 Methodology

To investigate a status of stop-and-go traffic, we traced groups of vehicle platoon from trajectories data. As platoon size increases, it becomes more difficult to identify precise traffic state because it denotes average value. Also, when it decreases, it shows a lot of fluctuation errors according to the individual vehicle’s behavior changes. Thus, we fixed one platoon size to 3 vehicles after comparing with 1, 5, 7 and 9-vehicle platoons. Then, we investigate the difference between two different wave phases: growth and dissipation. Specifically, in growth case, 3 vehicles in a platoon are evolved into growth phase at wave. Following those trajectories, we observe flow and density values before entering and after escaping a wave. Throughout this work, we observed that a driver behaves differently on stop-and-go traffic according to his corresponding traffic state. Figure 2 shows trajectory pairs of platoon when they cross a stop-and-go wave. Two arrow lines show stop-and-go wave’s direction of propagation.

In traffic congestion, lane changing maneuvers used to influence other drivers’ behavior. For example, a driver, who is in a target lane following the lane changing vehicle, makes slowdown to adjust gap for avoiding collision or interruption. Thus, lane changing maneuvers have impacts on stop-and-go traffic in both origin and target lane. According to this reason, we investigated how lane changing events affect the stop-and-go traffic.

We investigated the properties of lane changing maneuvers (e.g. lane changing duration, preparation time). First, Thiemann, Treiber, and Kesting (2008) announced that realistic
duration including preliminary and post-processing of a lane change might be 5~6sec. Also, Ahn and Ma (2008) studied speed-spacing relations under general car following and lane changing. They presented that anticipation periods due to lane changing maneuvers are 12sec for new followers. In this paper, we assume that lane changing affecting period is 12sec since it is more conservative.

Figure 3 36sec time window

As described in Figure 3, we need to assign affected area of lane changing vehicles. For this purpose, we introduce 36sec time window to count the number of lane changing vehicles which affected stop-and-go waves. The procedure to set up the time window is as follows:

a. Choose a target vehicle and find the point when it enters a stop-and-go wave (starting point).

b. Follow its trajectory during 12sec prior and posterior to starting point and find two end points of trajectory.

c. Draw an imaginary trajectory as 12sec before at downstream.

d. Connect two trajectories (i.e. real and imaginary) as if trajectory moves to upstream with average wave speed(16km/h) and make a closed shape as described in Figure 3-a.

e. Find the imaginary starting point and draw the line from that to starting point like red arrow line in Figure 3-a.

f. Separate the closed shape into two regions (① and ②).

g. Assign positive value to incoming lane changes, whereas outgoing lane changes are negative.

h. Count the net lane changes

First, we regard that lane-changing maneuvers have affects on surrounding traffic for 12seconds. In other words, following drivers may anticipate a small disruption on downstream as much as 12seconds before. Therefore, we introduce 36seconds affecting time window of lane changing maneuvers. In procedure d, we adopt the average wave speed since lane changes have affects on upstream traffic as fast as wave speed. In procedure e and f, we separate the time window into two regions. Even if outgoing lane changes occur in region 2, they do not usually affect following stop-and-go waves. Thus, we do not consider the cases that outgoing lane changes took place in region 2. Finally, we count incoming lane changes as positive, and outgoing as negative, the net lane changes inside 36sec searching window is summed up. It’s based on our simple presumption that each lane change has a same amount of impact on traffic. Then, we can conclude that the same impact applies on the state of stop-and-go traffic when the sum of lane changes equal zero, as well as when there are no lane changes.
2.2 Results
2.2.1 Phase Transition by Stop-and-Go Wave
Observing the traffic state change on stop-and-go waves is a very important for understanding detailed driving behavior under congestion period. We describe the traffic phase transition of growth and dissipation case in Figure 4, respectively. Two figures show how traffic states evolve at passing stop-and-go waves. Seeing Figure 4-a(i.e. growth case), traffic states move towards a virtual A-curve, in which minimum speed of vehicle inside a wave drops, or sojourn time period inside wave increases. Because drivers tend to avoid breaking the vehicle, they make attempts to have a sufficient gap once they pass a wave. Thus, traffic state becomes stable after growth. Otherwise, in dissipation case, traffic state moves toward D-curve passing stop-and-go waves since they reduce a gap from leader vehicle rather than deceleration. Thus, after dissipation wave, traffic state moves toward upper region that traffic becomes unstable. Through this result, we observe that drivers take different actions under acceleration and deceleration in congestion and can be explained by asymmetric behavior theory by Yeo (2009).

![Figure 4 Traffic phase transition by a stop-and-go wave](image)

2.2.2 Lane Changing Maneuvers & Wave Development
According to previous researches (Yeo et al., 2009; Laval et al., 2010), lane changing maneuvers is closely related with stop-and-go wave development. We investigate impacts of lane changing maneuvers on stop-and-go traffic and observe the relationship between net lane changes and traffic state for growth and dissipation case in Figure 5, respectively. Seeing Figure 5-a, as the number of net lane changes inside time window increases, the region occupied by growth or dissipation state moves downward in fundamental diagram. More net lane changes traffic state becomes more unstable. It implies that A-state traffic can absorb more lane change impact than D-state traffic. It has to be also noted that for same net lane changes, dissipation occurs in lower region than growth state, which shows that the closer to A-curve, the more likely traffic state is to develop into dissipation.
To compare traffic states for growth and dissipation cases, we plot them respectively for same net lane changes. Figure 6 describes the difference of entering traffic state between growth and dissipation case according as net lane changes varies between -1 to 1. We omit 2 and -2 cases due to the lack of data. For same net lane changes, stop-and-go traffic can be evolved into either growth or dissipation according to entering traffic state. Specifically, it is more probable that traffic can be developed into growth state, as its entering state is upper region in flow-density diagram. In other words, it means that highly potential traffic to be developed into growth state is at upper and more outward region than dissipation case in the flow-density diagram.
3. WAVE INTERACTION CHARACTERISTICS

3.1 Methodology
Usually a vehicle in congested traffic meets multiple stop-and-go waves. Seeing that stop-and-go waves seem to have some spatial frequency, it can be thought that adjacent stop-and-go waves may interact. In other words, they can influence each other resulting in dissipation or growth by providing the downstream stop-and-go wave with A or D-state traffic from the upstream one. We investigate how the state of wave changes according to time gap of two consecutive stop-and-go waves. Using same method for the single wave characteristics study, we observed 3-vehicle platoons passing two neighboring waves for 4 different stages: Before 1st wave, After 1st wave, Before 2nd wave, and After 2nd wave. For “before wave” cases, we acquired flow and density values before the driver starts main deceleration action. In the same way, we obtain data of “after wave” cases right after a driver finishes main acceleration actions. Figure 7 (left) illustrates platoon trajectories as explained above. Then, we classify patterns of the multiple waves’ evolution into 4 combinatorial cases according to the state of each wave: Growth (1st Wave)-Growth (2nd Wave), Growth-Dissipation, Dissipation-Growth, and Dissipation-Dissipation.

Additionally, we focus on interactions of consecutive stop-and-go waves with varying time gap. Figure 7 (right) describes the method to obtain time gap value, which is the duration from escaping point of the 1st wave to next deceleration point. Usually, most of drivers pass the 1st STG wave and start to accelerate. When they meet the 2nd STG wave, they decrease vehicle’s speed. Therefore, we define influencing time gap from beginning of acceleration to main deceleration.

![Figure 7](image-url)

Still, platoon analysis is insufficient to observe individual vehicles’ properties since drivers who belong to same platoon do not have same driving personality. Thus, for more microscopic view of driving behavior, we investigated all of individual vehicles which pass 2
consecutive waves. But, as you can see in single wave characteristics, state of stop-and-go traffic is affected by lane changing vehicles. For this reason, individual vehicles which are influenced by lane changes are excluded.

Also, we can determine the platoon level state of stop-and-go waves into two stages (growth and dissipation) based on the results of single wave characteristics. In growth case, minimum speed of vehicle inside a wave drops, or the influenced time period increases. Accordingly, we apply two parameters to decide an individual vehicle’s state in waves. One is an amount of vehicle’s speed drop and the other is the sojourn time in a wave. In growth case, the speed drop increases, while in dissipation case, it decreases as the shockwave propagates upstream. Similarly, the influenced time period increases compared with the previous vehicle’s influence time. As described in Figure 8, in growth case, both speed-drop ratio and sojourn time ratio will be greater than 1. While they are less than 1 in dissipation case. Thus, we can use product of two dimensionless ratios to determine wave phase. Then, we tried to find the relationship between gap time and wave phase transition in two consecutive waves.

![Wave phase decision criteria](image)

3.2 Results
3.2.1 Phase Transition between Multiple Stop-and-Go Waves
Under congested traffic, numerous stop-and-go waves are generated, developed and finish its life time. Finding the spatiotemporal relationship among those waves are required for better understanding on characteristics of stop-and-go traffic. Investigating vehicles’ trajectories passing two stop-and-go waves successively, we describe wave phase transition of 3-vehicle platoons in flow-density plane with arbitrary fundamental diagram in Figure 9 and 10, which illustrate ‘Growth-Growth’ case and ‘Growth-Dissipation’ case respectively.

First, in ‘Growth-Growth’ case, traffic states start from near D-curve location and move towards A-curve location before they meets 2nd waves as in Figure 9-a. Then, moving to D-curve state when they meet the second wave, their traffic state will result in growth state as shown in Figure 9-b because D-state traffic is more vulnerable to a small perturbation. Meanwhile, traffic states move along A-curve after 1st wave and stays near A-curve when they meet the second wave in ‘Growth-Dissipation’ case, which is shown in Figure 10. Because the traffic state near A-curve is more stable, stop-and-go traffic will be evolved into dissipation phase. These results shows good agreement with asymmetric theory (Yeo, 2008)
3.2.2 Influencing Time Gap and Stop-and-Go Wave

We observed many platoon trajectory pairs to investigate interactions of stop-and-go waves. But, platoon analysis is not enough to explain reciprocal features of stop-and-go waves in more detail. For this reason, to identify interactions of two consecutive stop-and-go waves, we investigated influencing time gap. Also, we determined traffic phase of waves based on wave phase decision criteria as described in Figure 8. Then, we look into traffic phase transition of two waves with varying influencing time gap. Figure 11 illustrates diagrams of phase transition of two waves according to influencing time gap. Figure 11-a shows distribution of growth case at the 1st wave, whereas Figure 11-b shows dissipation case.

Seeing Figure 11-a, it is more probable to dissipate at the 2nd wave in relatively short time gap. In other words, dissipation case at the 2nd wave is a little more positive skewed than the growth case. After escaping from stop-and-go wave with growth phase, vehicle moves to A-curve from D-curve. Then, it has a sufficient gap to absorb impact of traffic perturbation. Therefore, the wave phase at 2nd wave may be growth in the short influencing time gap, which is little possible to be affected by other external factor- lane changing maneuvers.

Table 1 shows the proportion of wave phase transition of two stop-and-go waves. When traffic crosses the 1st wave as growth phase, it will develop into dissipation phase at the 2nd wave than growth. But, since dissipating traffic may become dense after the 1st wave, it will be going growth phase at next wave.
4. CONCLUSION

The main purpose of this research is to investigate characteristics of the stop-and-go traffic. First, we observe the wave development characteristics and investigate the impact of lane changes on stop-and-go traffic based on the NGSIM US-101 dataset. The result shows the detailed relationship between lane changes and stop-and-go wave evolution (growth and dissipation) and it is empirical evidences of Yeo (2008)’s research using trajectories data. Hence, the results provide backgrounds to control stop-and-go wave’s development in congestion period. Furthermore, interactions of two consecutive stop-and-go waves are studied. We measure influencing time gap of two waves and reveal how stop-and-go waves spatiotemporally evolve according to the influencing time gap. Finally, we show that phases of two adjacent stop-and-go waves are mutually correlated.

REFERENCES


