Application of the Three-Phase Theory in Greek Freeways

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Abstract
This study involves a first step for the application of Kerner's "three-phase theory" in greek freeways. Three cross-sections which could be regarded as effectual bottlenecks were chosen to identify the three traffic phases of Kerner's theory and their transition in cases of spontaneous and non-spontaneous flow breakdown phenomena. Results revealed that there is a foundation for further analysis of the theory to account for the simulation of traffic movement in freeways.

Key-words: Three-phase traffic theory, Free flow, Synchronised flow, Wide Moving Jam, Bottleneck

1. INTRODUCTION

A wide range of mathematical traffic flow models and traffic flow theories have been developed to explain and model the behavior of traffic (Herman et al, 1958; Gazis et al, 1961). Especially in the cases of freeways a huge number of publications have been devoted to empirical investigations of spatiotemporal traffic features (Kontaratos, 2006; Tilch et al, 2000). According to all those theories traffic could either be "free" or "congested". Traffic becomes congested when the "bottleneck" phenomenon takes place due to several reasons such as change of geometrical characteristics, roadworks, on- and off- ramps and most commonly due to expected or unexpected incidents (accidents, broken-down vehicles, etc). This congestion results in a decrease in average vehicle speed, which is called "breakdown phenomenon" (Banks, 2001).

In the case of the so called "homogeneous" or "stationary" states (Kerner et al, 1996), the best way to show "free" and "congested" traffic is by using the fundamental flow-speed diagram. According to this diagram, there are two different areas. "Free" traffic is defined as the upper part of the curve, which has a positive slope. The point at which the "free" flow ends is at a limit point of speed. The lower part of the diagram is defined as the "congested" traffic with a negative slope.

[1] (1957-2007)

Researchers working mainly on the US road system (where very few long segments exist) support most of their traffic flow research in the effects of turbulences produced by "bottlenecks" at on- and off- ramps. Contrary in Europe, due to long segments and high speed limits, homogenous traffic appears along long distances. This led theorists to study the phase transitions of traffic as induced phenomena spontaneously appearing. The most striking point about which an international debate is in progress is whether there appears spontaneous phase transition in traffic or not. Kerner (2004) established a theory – called three phase traffic theory – which explains the metastability of the non-congested traffic at the domain that an induced traffic breakdown may appear and the possibility of "free flow" to change to "synchronized flow" only. The aim of this research was to test the existence of the three-phase traffic theory in a long segment of the National Freeway Athens – Lamia in locations of effectual bottlenecks.

2. THREE-PHASE TRAFFIC THEORY

A traffic phase is a traffic state considered in space and time that possesses specific empirical spatiotemporal features. Traffic states are characterised by a certain set of statistical properties of traffic variables such as traffic flow, vehicle speed, vehicle gap and density. The three-phase theory is a qualitative theory and involves the existence of three traffic phases, namely "free flow" [F], "synchronized flow" [S] and "wide moving jam" [J]. Both "synchronized flow" and "wide moving jam" are considered as congested flow. "Synchronized flow" traffic phase takes place when the downstream front does not maintain the mean speed as the jam propagates. The downstream front of "synchronized flow" separates "synchronized flow" upstream from "free flow" downstream. The "wide moving jam" traffic phase takes place when the mean speed of the downstream front of the jam remains the same as the jam propagates.

"Synchronized flow" is a continuous traffic flow with no significant stoppage, as often occurs inside a "wide moving jam". Therefore, the word "flow" reflects this feature. There is a tendency towards synchronization of vehicle speeds across different lanes and this is due to a relative low probability of overtaking and passing. On the other hand, the term "wide moving jam" is used to reflect the characteristic feature of the jam to propagate through any state of traffic flow and through any bottleneck while maintaining the speed of the downstream front.

The phase transition from "free low" to "synchronized flow" is the well-known breakdown phenomenon and it is symbolized as F ->S. This phenomenon is mostly observed at freeway bottlenecks. The F -> S transition is fundamentally associated with intrinsic traffic features of the dynamic characteristics of traffic and thus, it can occur spontaneously without any bottlenecks. The probability of a F -> S transition at a bottleneck is much higher than further away from the bottleneck because the bottleneck causes a deterministic perturbation in free flow that is localized at the bottleneck. This bottleneck could be an on- or off-ramp. The higher the flow at an on- or off- ramp, the greater the amplitude of this deterministic local perturbation caused by the bottleneck to the main road. Moreover, the merging and weaving of vehicle movements in the vicinity of an on- and off- ramp also cause a random perturbation which is responsible for a random component of the overall local perturbation on the main road.

When the breakdown phenomenon takes place at a freeway bottleneck, the bottleneck is called an "effectual bottleneck". After a congested part due to the F -> S transition has occurred upstream of the effectual bottleneck, the downstream front of this pattern is spatially fixed at a freeway location in the vicinity of the "effectual bottleneck". This downstream front of the congested pattern separates "free flow" downstream from "synchronized flow" upstream of the "effectual bottleneck". Within this downstream front vehicles accelerate from "synchronized flow" upstream of the front to "free flow" downstream of the front. The freeway location where the downstream front of the congested pattern is spatially fixed is called an "effective location" of the "effectual bottleneck".

"Wide moving jam" only takes place after the occurrence of the F -> S transition. Following that and usually not at the same location, the phase transition from "synchronized flow" to "wide moving jam" takes place and it is symbolized as F -> S -> J transition. Hence, according to the three-phase traffic theory, a moving jam cannot emerge spontaneously after the "free flow" phase. In the "wide moving jam", this traffic phase propagates through any other traffic states of traffic flow and through any bottlenecks while maintaining the mean speed of the downstream front of the jam. The characteristic speed depends on control traffic parameters like weather and other conditions.

At any flow rate (density) in free flow where "synchronized flow" could emerge, the critical amplitude of a local perturbation required for "wide moving jam" emergence is considerably higher than the critical amplitude of a local perturbation that is required for "synchronized flow" emergence. For this reason, a local region of "synchronized flow" can occur spontaneously in free flow rather than a moving jam. This also explains why the existence of the critical (limit) density for "free flow" is related to an F -> S transition rather than to spontaneous moving jam emergence. The width of the "wide moving jam" only changes when the characteristics of flow upstream change over time. There are two main types of congested patterns that can occur spontaneously upstream of an isolated bottleneck:

a) The synchronized flow pattern SP where "synchronized flow" occurs upstream of the isolated bottleneck only with no "wide moving jam" emergence.
b) The general pattern GP, which takes place where "synchronized flow" occurs upstream of the bottleneck and "wide moving jam" emerge spontaneously in that "synchronized flow".

3. EXPERIMENTAL DESIGN

To fully comprehend the nature of traffic phenomena, traffic should be examined in both space and time, hence, in respect to spatiotemporal features. The work presented herein demonstrates measurements along a 3-lane 2 km segment of the National Highway Athens-Lamia, bounded by the grade-separated junctions of Lykovrisi and Kaliftaki.

In the site vicinity, three CCTV control cameras are installed by the Athens Traffic Management Center -ATMC (Sermpis, 2006) providing 24-hour traffic data on specific cross-sections of the roadway for both directions. The first and second cross-sections are located immediately downstream of the off-ramp junctions (Lykovrisi and Kaliftaki respectively), whereas the third one is located 200m upstream of the Kaliftaki junction on-ramp. The chosen sector was in the vicinity of effectual freeway bottlenecks, hence, in the vicinity of some inhomogeneities on the freeway. The beginning of the off-ramp lane could be considered as the location of a bottleneck due to the off- ramp. At the same time, the beginning of the merging region of the on- ramp lane with the main road could be considered as the location of a bottleneck due to the on-ramp. In Figure 1 the detector locations and the lane and ramp configurations of the cross-sections are illustrated.

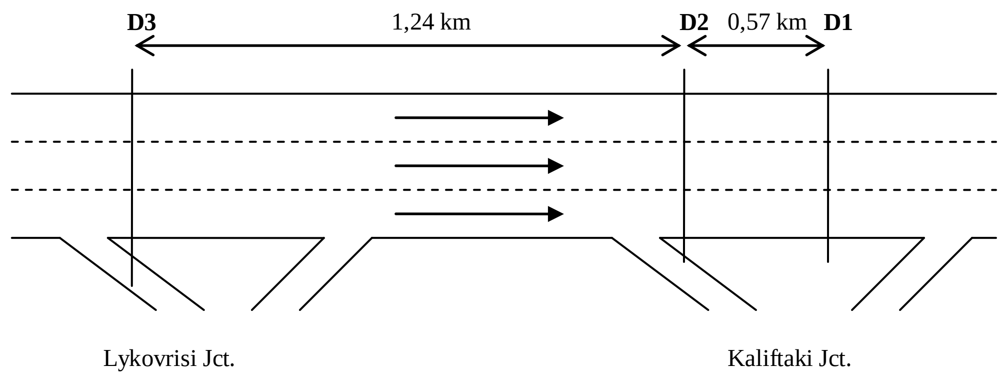

Figure 1: Design of the site location.

The experiment took place throughout different time periods covering a wide range of traffic conditions, while vehicles in all lanes (including the on- and off- ramps) were recorded. The first period was from 21/8/2007 to 22/8/2007 (Tuesday to Wednesday), the second one from 14/9/2007 to 16/9/2007 (Friday to Sunday), while the third one was from 14/11/2007 to 17/11/2007 (Wednesday to Saturday).

The traffic data collected by the ATMC, based on automated image processing techniques, provided detailed data for each passing vehicle: time entering and exiting the imaginary loop, speed, and occupied lane. Speed and flow counts were averaged over 60s sampling intervals and then processed with 15-element moving average algorithm to remove noisy data.

4. DATA ANALYSIS

Three days were chosen from the collected data to demonstrate the findings of this research. For each day one figure was produced in which the speed and flow profiles for each lane for the three cross-sections D1, D2 and D3 are illustrated (Figures 2, 3 and 4).

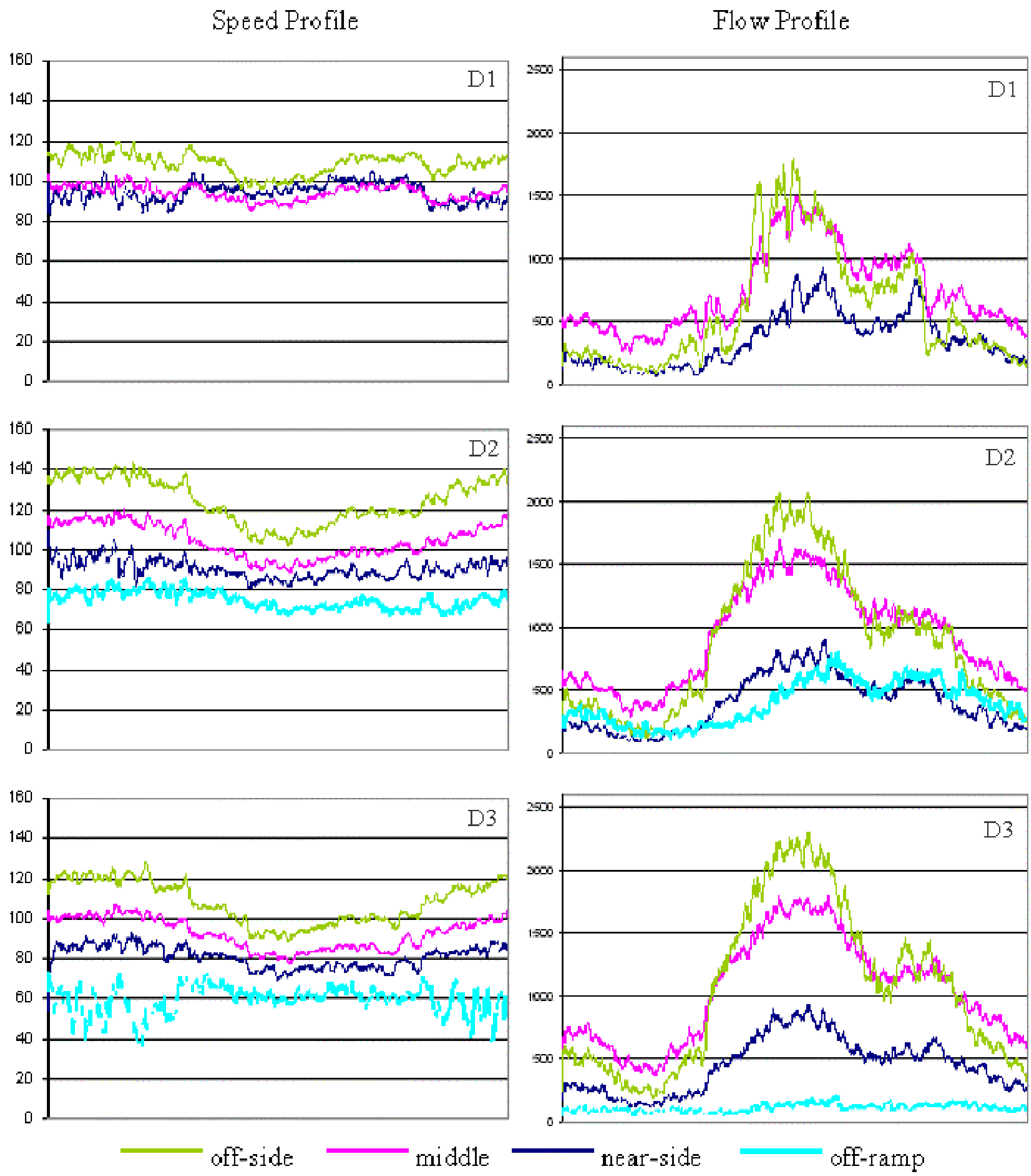

Figure 2: Cross-sections' speed and flow profiles (Sunday 16/9/2007)

Traffic capacity on each lane is estimated to be about 2100 veh/h. Results revealed that due to the special characteristics of that day (Sunday) the examined highway segment operated at free flow traffic conditions. Hence, for cross-section D1 it is not clear whether there exists any phase transition. Cross-sections D2 and D3 seem to involve a phase transition from free flow to synchronized flow (F -> S) at the time at which traffic flow takes higher values (roughly estimated above 1000 veh/h for the off-side and the middle lanes).

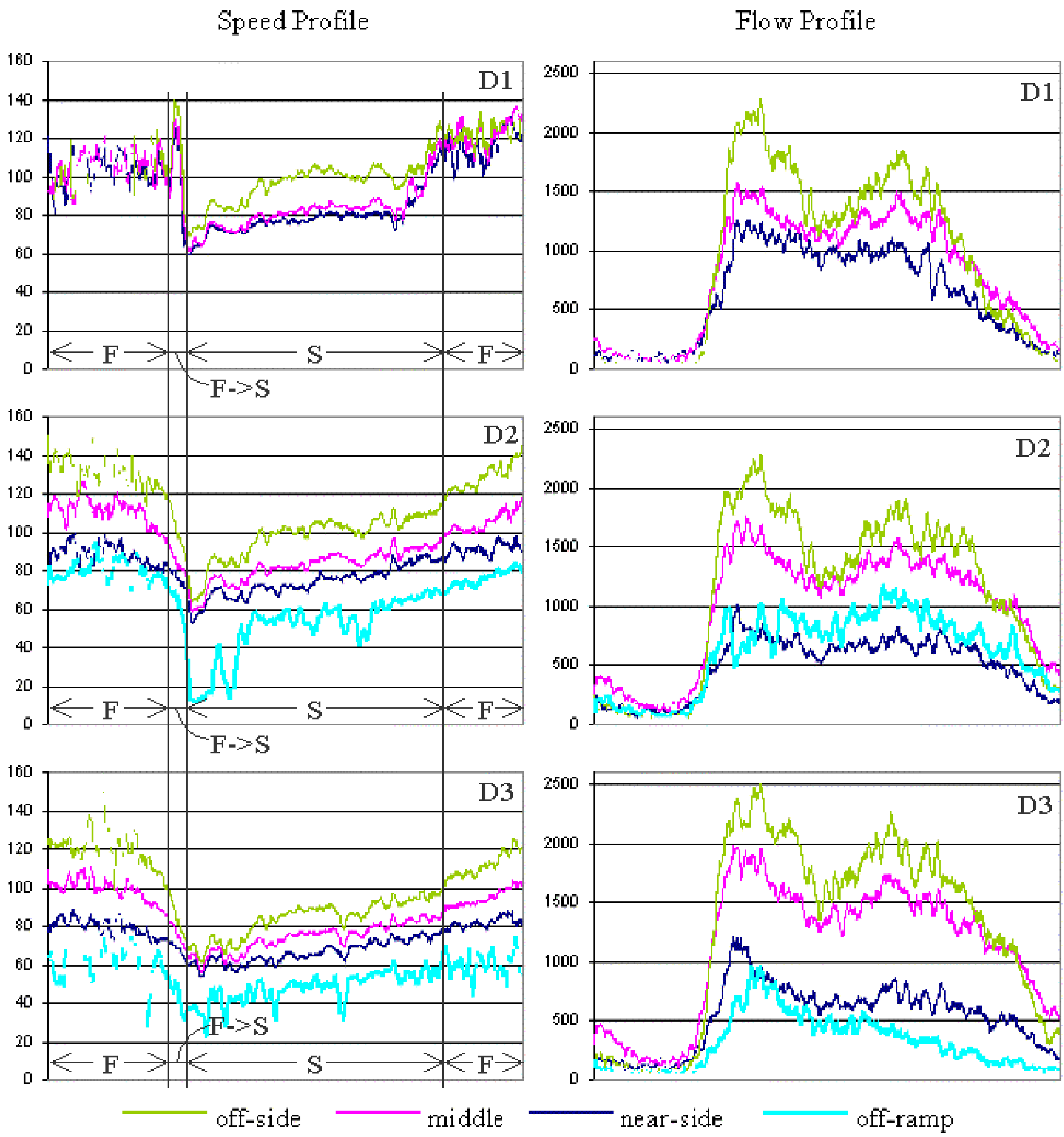

Figure 3: Cross-sections' speed and flow profiles (Wednesday 14/11/2007)

The phase transition from "free flow" to "synchronized flow" (F -> S) is clearly shown in Figure 4. For cross-section D1 there is a clear F -> S phase transition which takes place when the incoming traffic flow starts to increase. For cross-section D2 this phase transition takes place once again when the traffic flow starts to increase. This coincides with the time when the off-ramp lane traffic flow increases and exceeds the near-side lane traffic flow, meaning that at that cross-section vehicles move in such a way as to reach the near-side lane close to the off-ramp to exit the freeway. Hence, cross-section D2 behaves as an effectual bottleneck. At the beginning this phase transition has a greater effect on the off-side lane, because on that lane vehicles move with higher speeds and hence, the merging of the vehicles from the near-by lanes has a greater effect. Therefore, this phase transition evolves as follows: at some point the free flow traffic phase ends and the transition to the synchronized flow begins. The transition duration depends on the special spatiotemporal characteristics of the effectual bottleneck. The synchronized traffic flow phase begins with its lowest speed value and then reaches a more or less floating average speed value, when the effect of the effectual bottleneck impedes traffic movement upstream. When the traffic flow (towards the end of the day) starts to decrease, a transition from "synchronized flow" to "free flow" takes place (S -> F) with a rather short duration. In cross-section D3, the same phenomenon as in cross-section D2 takes place for two reasons. The first one involves the off-ramp effectual bottleneck and the second one the effect of cross-section D2 breakdown phenomenon upstream.

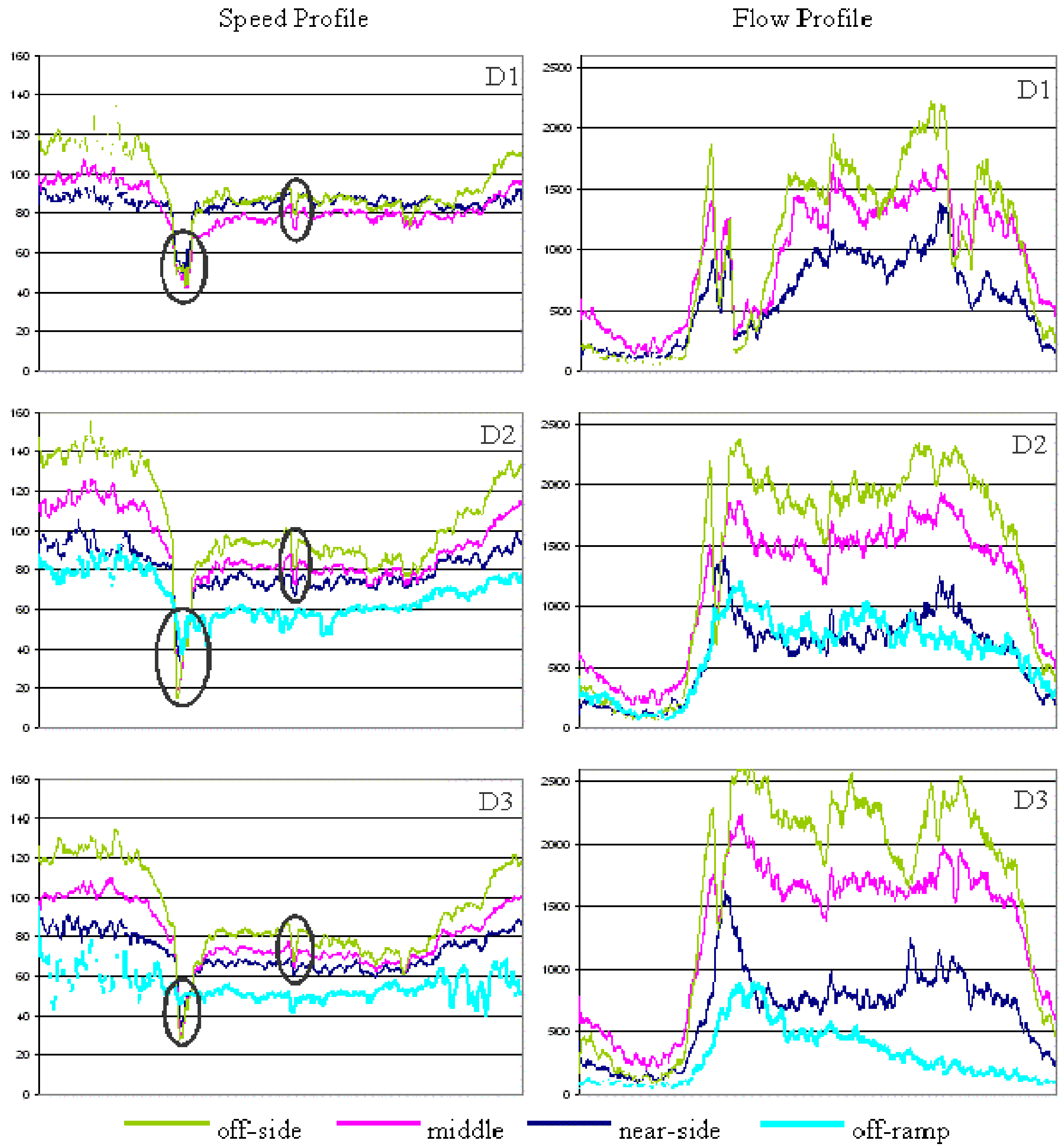

Figure 4: Cross-sections' speed and flow profiles (Friday 14/09/2007)

On this day, two phenomena took place. The first one took place in the morning when the incoming traffic flow started to increase. An incident downstream (which could be regarded as a non-spontaneous breakdown phenomenon) of cross-section D1 resulted in the sudden decrease of traffic flow. The effect of the incident started around the time of the phase transition from "free flow" to "synchronized flow". From Figure 4 it becomes apparent that there was a transition from "free flow" to "synchronized flow" and then a transition from "synchronized flow" to "wide moving jam" (F -> S ->J). The second phenomenon was due to another incident around noon, which once again led to a transition from “synchronized flow” to “wide moving jam” (S -> W). The duration of the incident was relatively small and hence, the “wide moving jam” traffic phase did not have a long duration.

DISCUSSION

Several traffic models have been developed through the years to account for the simulation of traffic movement. Especially earlier traffic flow theories behind these models do not explain and hence, predict many spatiotemporal traffic pattern features. Kerner introduced a concept that is currently referred to as “synchronized flow” and the related “three-phase traffic theory” to account for the special characteristics of traffic movement.

The aim of this research was to test Kerner’s “three-phase traffic theory” in the National Freeway Athens – Lamia of Greece. The first step towards the scope of the research was to test the basic concepts of the theory before moving on to its more analytical spatiotemporal characteristics analysis. Hence, a segment was selected in which effectual bottlenecks could result in spontaneous breakdown phenomena.

Analysis indicated that indeed at least two distinct traffic phases and the transitions between them could be identified. The F -> S transition took place spontaneously when the incoming traffic flow resulted in congested traffic conditions. Moreover in the case of non-spontaneous incident, a transition F -> S -> J evolved. Therefore, it could be concluded that Kerner’s “three-phase theory” should be further tested in cross-sections with heavier traffic flow in on- or off- ramps to identify both macroscopically and microscopically its detailed features.

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