

Exploring Traffic Phenomena with Modified Asymmetric Simple Exclusion Process Approach

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Abstract. This study proposes a modified asymmetric simple exclusion process (ASEP) approach to simulating low-to-high traffic densities, from which the three-phase traffic phenomena are explored. The chronologically-ordered flow, speed and occupancy data extracted from Taiwan freeway's dual-loop detectors are analyzed and tested. The observed traffic features do exhibit free-flow phase, synchronized-flow phase, and breakdown phenomenon, which can also be elucidated by the simulated results with the proposed approach. Paired traffic parameters are displayed by their relations and by their chronological order so that more insightful traffic features are explored.

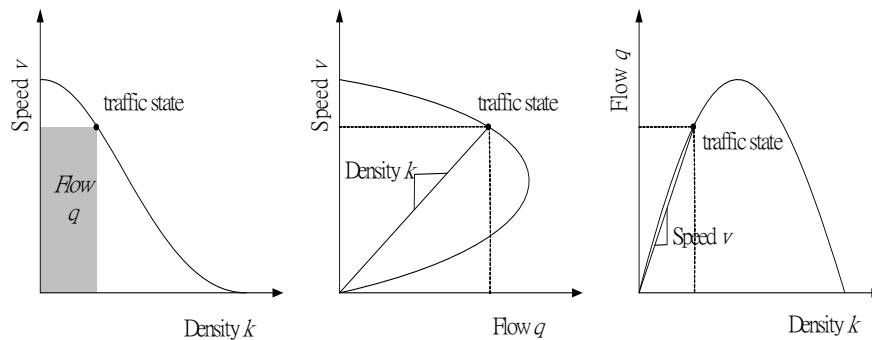
Key words: *asymmetric simple exclusion process; traffic phases; chronological order*

1. INTRODUCTION

Traffic features or traffic phenomena represent either the temporal characteristics of vehicles passing through a specific location within a time span, or the spatial characteristics of vehicles exhibited at a specific time instant over a roadway section, or the combined spatiotemporal characteristics of both. Traditionally, researchers have developed a wide range of different traffic flow models to elucidate the complex traffic features and phenomena (see, for example, the classical studies by Lighthill and Whitham, 1955; Richards, 1956; Herman *et al.*, 1959; Gazis *et al.*, 1961; Kometani and Sasaki, 1958, 1959, 1961; Newell, 1961; Prigogine, 1961; Payne, 1971, Gipps, 1981; the books by Leutzbach, 1988; May, 1990; Daganzo, 1997; Wiedemann, 1974; Whitham, 1974; Cremer, 1979; Newell, 1982; the reviews by Chowdhury *et al.*, 2000; Helbing, 2001; Nagatani, 2002; Nagel *et al.*, 2003). Most of these traffic stream models, however, were developed by curve fitting on the basis of field observations or formulated with idealized mathematical traffic stream relations. In these traffic stream models, congested and non-congested (free) flow states are normally identified, thus is regarded as the two-phase traffic theory, depicted in Figure 1. The diagrams only display the relations between paired traffic parameters without tracing their detailed evolution. Thus, one can hardly capture the exact time instants when traffic breakdowns or abnormal traffic flows emerge.

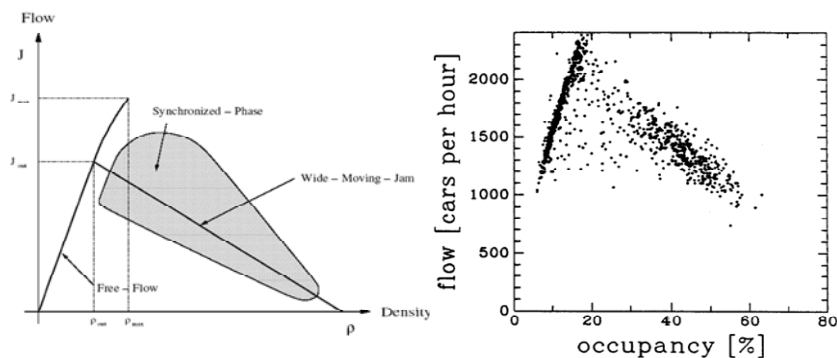
Some recent researchers have endeavored to exploring more traffic phases and their transitions (for instance, Schreckenberg and Wolf, 1998; Chowdhury *et al.*, 2000; Helbing, 2001; Helbing *et al.*, 2002). A three-phase traffic theory was proposed to track the trajectories of vehicles in the spatiotemporal domain, as depicted in Figure 2, wherein free-flow, synchronized-flow, and wide-moving-jam phases have been identified through field

observations (Kerner, 1998, 1999, 2002a, 2002b, 2004). These researchers argued that three-phase theory is more powerful than conventional two-phase theory in describing the spatiotemporal evolution of traffic features and in capturing the transitions of traffic phenomena. Subsequently, such traffic models as forecasting of traffic objects (FOTO) and automatic tracking of moving traffic jams (ASDA) were proposed to identify and trace the traffic breakdowns and spatiotemporal congested patterns (Kerner and Klenov, 2002; Kerner *et al.*, 2002, 2004).



Source: May (1990)

Figure 1 Two-phase traffic theory



Source: Kerner (2004)

Figure 2 Three-phase traffic theory

More recently, a one-dimensional asymmetric simple exclusion process (ASEP) was proposed and widely used not only as the default stochastic models for transport phenomena but also for the understanding of nonlinear physics in various areas (Katsuhiro *et al.*, 2004; Harris and Stinchcombe, 2005; Pronina and Kolomeisky, 2006; Tracy and Widom, 2008). In fact, ASEP has played a critical role on understanding the multiple non-equilibrium phenomena in systems like chemistry, physics and biology (Derrida, 1998; Schutz, 2000). This approach has also been extensively applied to describe kinetics of biopolymerization (MacDonald and Gibbs, 1968), protein synthesis (Shaw *et al.*, 2003; Chou and Lakatos, 2004), transport of motor proteins in biological cells (Klumpp *et al.*, 2003), polymer dynamics in dense medium (Evans *et al.*, 1994), car traffic processes (Nagel, 1996) and modeling of ant trails (Chowdhury *et al.*, 2004). The realistic description of many processes, such as car traffic and the biological transport of motor proteins (Nagel, 1996; Klumpp *et al.*, 2003), suggested that it is potentially useful to study multi-lane ASEP.

Another group of researchers treated traffic streams in a temporal domain as nonlinear systems wherein complex traffic patterns and characteristics have been identified. Dendrinos (1994), Zhang and Jarrett (1998), Lan *et al.* (2003a) and Shang *et al.* (2005) found chaotic

traffic features under certain circumstances. Lan *et al.* (2003b) performed cellular automaton (CA) simulations and found that self-organization phenomena exist when the traffic phase transits from free-flow to congested states. More recently, Lan *et al.* (2008) analyzed the field traffic data and found that different nonlinear traffic patterns, including chaotic, periodic, stochastic, and fixed point equilibrium, might emerge depending on the observed time interval, history data, and times of day. The aforementioned studies have indicated that various traffic phases could exist in traffic stream diagrams, and different phases could transform from one to another as time evolves. These works, however, merely aimed at investigating the temporal traffic patterns without considering the chronological order of traffic series, hence some inherent traffic characteristics may not be utterly disclosed, or at least, the in-depth information about traffic evolutionary dynamics may not be fully understood.

In view of the discrepancy of traffic features exploration in temporal and spatiotemporal domains and the lack of considering chronological order in most previous traffic stream modeling, the present study aims to propose a modified ASEP approach to simulating the traffic phenomena. Paired traffic parameters were displayed in our empirical study both by their relations and by their chronological order to gain more insights into traffic features. This would facilitate the development of advanced real-time traffic management/control strategies. The remaining parts of this paper are organized as follows. Section 2 introduces the rationales for our modified ASEP approach. In section 3, the field traffic data directly extracted from Taiwan's freeway is analyzed and a demonstration of the modified ASEP simulations is performed. The discussions and direction of future studies are addressed in the final section.

2. METHODOLOGIES

This section introduces the rationales for asymmetric simple exclusion process (ASEP) approach and performs a simulation with low and high traffic densities, from which the two-phase traffic phenomena are identified. A modified ASEP approach is further proposed and used to simulate various traffic densities from low to high, from which the three-phase traffic phenomena are identified.

2.1 The ASEP approach

Consider a system of two parallel one-dimensional lattices where identical particles can move along the channels (lanes) and between them (see Figure 3). Each lattice has L sites, and every site can be occupied by at most one particle or it is empty. At every time step a site is randomly chosen either from lane 1 or lane 2. In the bulk of the system the particle dynamics is described by the following rules. A particle can change the lane with the rate w_1 or w_2 from the channel 1 or 2, correspondingly, if the vertical neighboring site is available (see Figure 3(a)). The particle at site $1 \leq i < L$ can also move from left to right along the same channel to site $i+1$, if this site is empty. The rates for horizontal moves from site i depend on the occupancy state of site i on another lane. The particle on lane 1 moves to the right with the rate $1-w_1$ if the vertical neighboring site is not occupied, otherwise it jumps with the rate 1. Similarly, for the particle on lane 2 the horizontal transition rates are equal to $1-w_2$ (the vertical neighbor is empty) or 1. These rules satisfy the condition that the total probability per unit time of leaving the site i (in any direction) is always equal to 1 (Pronina and Kolomeisky, 2004).

Note that in this ASEP approach the particle first tries to change the lanes, and if it fails it moves horizontally. In addition, there are special entrance and exit dynamic rules at the

boundaries. Particles can enter the system with the rate α if any of the first sites at each lane is not occupied. When a particle reaches the exit site L it can leave the system with the rate β if the exit site on another lane is occupied. Otherwise, the exit rates are $\beta(1-w_1)$ and $\beta(1-w_2)$ for the channels 1 and 2, correspondingly.

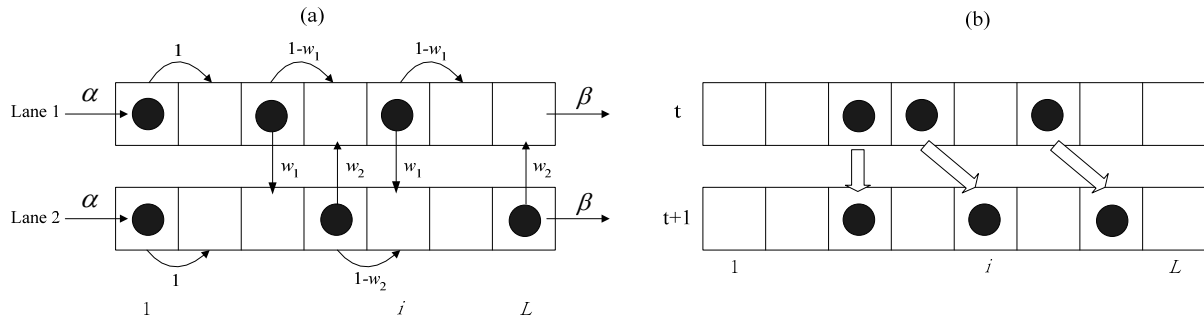


Figure 3 A schematic representation of two-lane particles movement with ASEP approach

For simplicity, in the present work we consider only the case of full asymmetry in the vertical transition rates with $w_1=1$ and $w_2=0$. In other words, a particle at site i time step t will move to site $i+1$ at time-step $t+1$, unless the front site $i+1$ is occupied by another particle. According to the simple rule, without considering multiple lanes and the changing rate, the ASEP for traffic model can be demonstrated as Figure 3(b). After the ASEP for traffic model was formulated, we started to simulate several types of traffic state from low density to high density to observe the results. In the beginning, we assumed that the vehicles were randomly scattered on a circular road and started to move ahead in accordance with the ASEP. Figure 4(a) was the simulated result for low density with four time-steps. From Figure 4(a), we have found that the scattered vehicles can move freely (i.e., each vehicle is separated) after several time steps. In other words, traffic congestion will not occur as long as the density is low. In contrast, Figure 4(b) was the simulated result for high density with four time-steps. From which, we have found that there is a queue in the middle and the queue moves backward with time-step evolution (see the frame marked in red). In other words, traffic congestion will emerge when the density is high. Such simulated results with ASEP have properly display some traffic phenomena also found in real word.

From the above simulations, we have recognized free-flow state, congested-flow state and critical density of transition from free-flow state to congested-flow state via proposed ASEP. Even though these simulated results have depicted the traffic phenomena taking place in real world, to precisely formulate traffic stream diagrams we need to further elaborate on how many time-steps are adequate and to calculate the stable values of traffic parameters as one manipulates the ASEP simulation. In reality, the number of vehicles that can move ahead at one time-step may not be exactly the same as that at another time-step, but it will come to a stable value after several time-steps evolution. The stable value can be qualified as a symbol of stable state, and the speed of stable state also reaches a fixed value, called stable speed. For instance, the numbers of vehicle at various time-steps which can move ahead in Figure 4(a) are different. At time-step t , the value for moving vehicles is six; while at $t+1$, the value is seven; at $t+2$, the value is eight, and at both $t+3$ and $t+4$, the values are nine. Namely, the traffic state at time-step $t+4$ have come to a stable state. In this case, a stable traffic state does not emerge until four time-steps evolution. Meanwhile, the moving distance of nine vehicles for one time-step will sum up to nine sites, i.e., the average speed of each vehicle is 1 (unit: site/time-step). Likewise, the numbers of vehicle which can move ahead in Figure 4(b) are different, too. Instead of average speed equal to 1 for low density, the average speed of high

density at stable state (i.e., time-step $t+4$) is equal to 0.6. Obviously, the average speed has slowed down due to the high density. It is noted that traffic flow at stable state in Figure 4(a) is 9 (unit: vehicles/time-step) while that in Figure 4(b) is also 9, rather than 15, because traffic flows are counted by the number of movable vehicles instead of total vehicles.

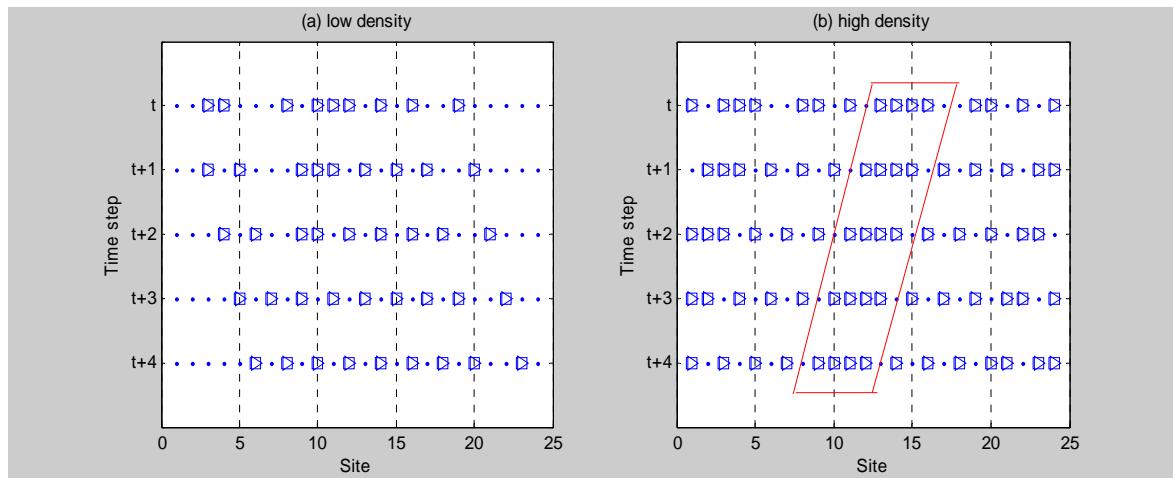


Figure 4 Simulated results for low and high traffic densities with ASEP approach
(Note: symbol \square represents vehicles move ahead)

Even though having known that traffic state with high density can emerge congestion, we are curious about the critical point—a point transferring from non-congested phase to congested one—when will emerge as we simulate traffic states from low density to high density. Accordingly, we still adopted the ASEP to simulate traffic states by adding vehicles one by one from low density to high density. Two simulated results with critical difference were presented in Figure 5. In Figure 5(a), five vehicles were randomly scattered on a road with ten sites length, i.e., density equals 0.5 (unit: vehicle/site); while in Figure 5(b), just one vehicle was added on the same road. However, five vehicles can move ahead freely after four time-steps evolution in the left panel, while traffic congestion caused by three vehicles emerged in the right panel instead. It indicates that traffic congestion will occur when the density is over 0.5 and thus the value 0.5 can probably be regarded as a critical density for traffic phase transferring from free-flow state to congested state.

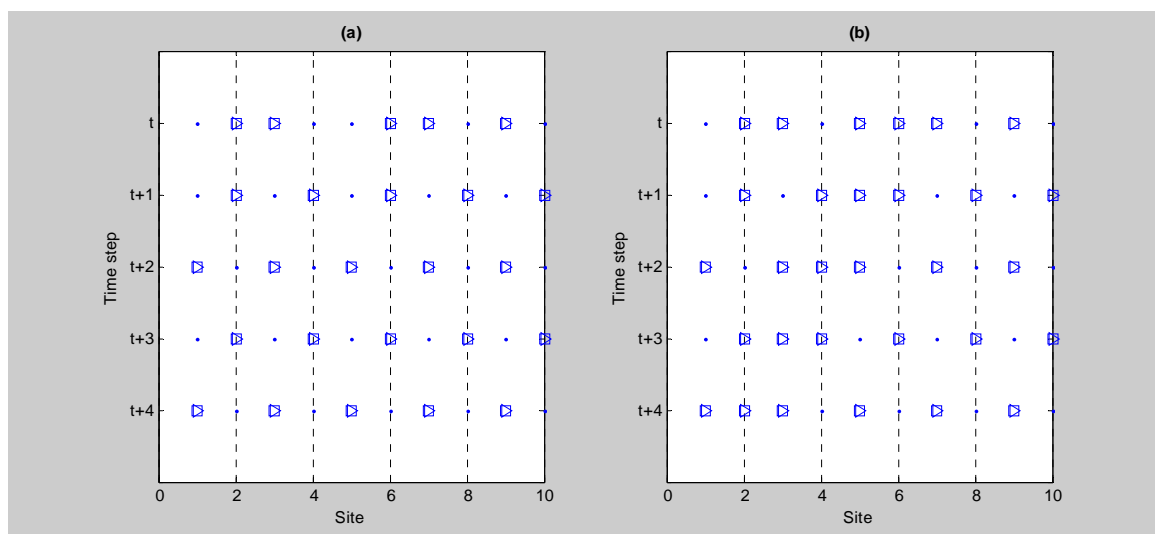


Figure 5 Simulated results at critical density (0.5 vehicle/site) with ASEP approach

2.2 The Modified ASEP Approach

In fact, the processes of vehicles moving ahead in real world are not as simple as the above-mentioned rules of ASEP shown in Figure 6(a); thus, we need to modify the rules. Figure 6(b) demonstrates the modified rules of ASEP for traffic evolution. Consider the starting delay exists when vehicles at the back normally possess a time lag if they wish to follow the leading vehicles to move again from a static position. In this study, the vehicle (at site i and time-step t) has to hold one time-step rather than start immediately at the next time-step if the front site is occupied by another vehicle. Thus, the last vehicle remains in the same site at $t+2$ even if the site ahead was empty at $t+1$ as shown in Figure 6(b).

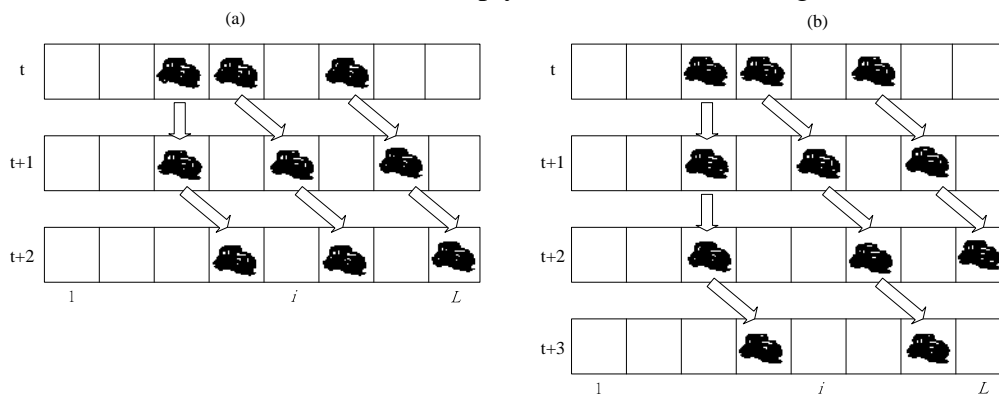


Figure 6 Comparison of traffic evolution with (a) ASEP rules and (b) modified ASEP rules

We adopt the modified ASEP approach to simulate the various traffic densities from low to high values and the corresponding traffic stream diagrams are presented in Figure 7. It shows that the simulated traffic stream diagrams depicting the relationships between paired-traffic variables are different from the conventional two-phase traffic phenomena. Instead, the paired relationship, in terms of flow-density, is similar to that proposed by three-phase traffic theory.

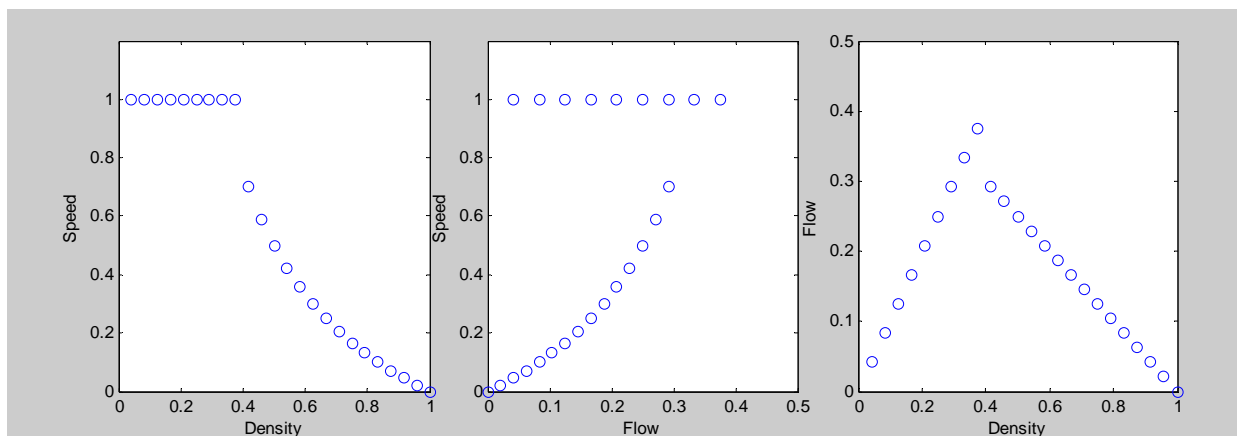


Figure 7 The traffic stream diagrams produced by modified ASEP simulations
(flow: vehicles/time-step; speed: site/time-step; density: vehicle/site)

It is noted that in this diagram vehicles can move ahead freely over time when density is less than (or equals) 0.375, i.e., traffic congestion will emerge once the density is larger than the critical value 0.375. Compared with the critical value 0.5 derived from the ASEP approach, the critical density 0.375 derived from the modified ASEP approach is much more reasonable. In addition, there were delicate changes existing in the formulated traffic stream diagrams. For instance, an erupted and large decrease of flow took place in the flow-density diagram (see right plot in Figure 7) when density was slightly higher than the critical value (0.375). In

contrast to the distinct decrease of flow, the amount of augmentation for density was small, i.e., from 0.375 to 0.416. Similar circumstance occurred in speed-density diagram (see left plot in Figure 7). Such delicate transformation between states indicates the fact that a phase transition from free-flow state to congested state is occurring at the point and the transition state is transient and unstable.

3. SIMULATIONS WITH MODIFIED ASEP APPROACH

In this section, we graphically demonstrate our modified ASEP simulations. Different manifolds of traffic phases generated from temporal traffic data extracted from the field are compared with the traffic stream diagrams generated from the above modified ASEP simulations.

3.1 Data

Our data was directly extracted from dual-loop detectors installed at a 3- to 4-lane mainline stretch of the Freeway No. 1 in Taiwan, located in the northern area of Taipei County. In order to disclose the diversity of traffic phases in different situations, we collected successive ten-day's raw data, containing flow, time-mean-speed, and percent occupancy per lane per 20-second, recorded in the median lane at station 421 inbound to Taipei City. The ten days (2004.02.01 to 2004.02.10) covered seven weekdays and three weekend days.

Feature composition technique was used to convert raw data to analyzed data as follows. The traffic raw data during the ten days was accumulated from 20-second traffic series into 3-minute series: flows were directly summed up from each 20-second flow; speeds were the weighted average of each 20-second time-mean-speed multiplied by its corresponding flow; occupancies took the arithmetic mean from the 20-second occupancies. Figure 8 shows the successive ten-day's 3-minute flow, speed, and occupancy series. Figure 9 displays the successive ten-day's paired-traffic scattergrams in upper panels and the chronologically ordered paired-traffic evolutions in lower panels.

From Figure 8, it can be seen that the successive traffic flow fluctuated from day to day, wherein the traffic volumes were lower and had no distinct peak curves on the 1st day (2004.02.01), the 7th day (2004.02.07) and the 8th day (2004.02.08) compared to the other seven weekdays, reflecting the fact that these three days were at weekend or holiday. From Figure 9, the paired-traffic relationships have approximately complied with the fundamental traffic stream diagrams. Nevertheless, we note that the majority of the paired-traffic points in the top panel did not locate in the congested phase—the areas of low-volume-low-speed, low-speed-high-occupancy, and low-volume-high-occupancy. Only a few of them are distributed in the congested phase. To explore various traffic phases, we deliberately divide the traffic time-series into six time periods according to times of day: 01:00-07:00, 07:00-09:00, 09:00-12:00, 12:00-17:00, 17:00-21:00 and 21:00-01:00. For brevity, however, only traffic phases in periods 07:00-09:00 (morning peak) and 09:00-12:00 (morning off-peak) are discussed in detail here. It is obviously noted that the traffic series extracted from an “isolated” station can only explore the temporal traffic features, without the spatiotemporal features.

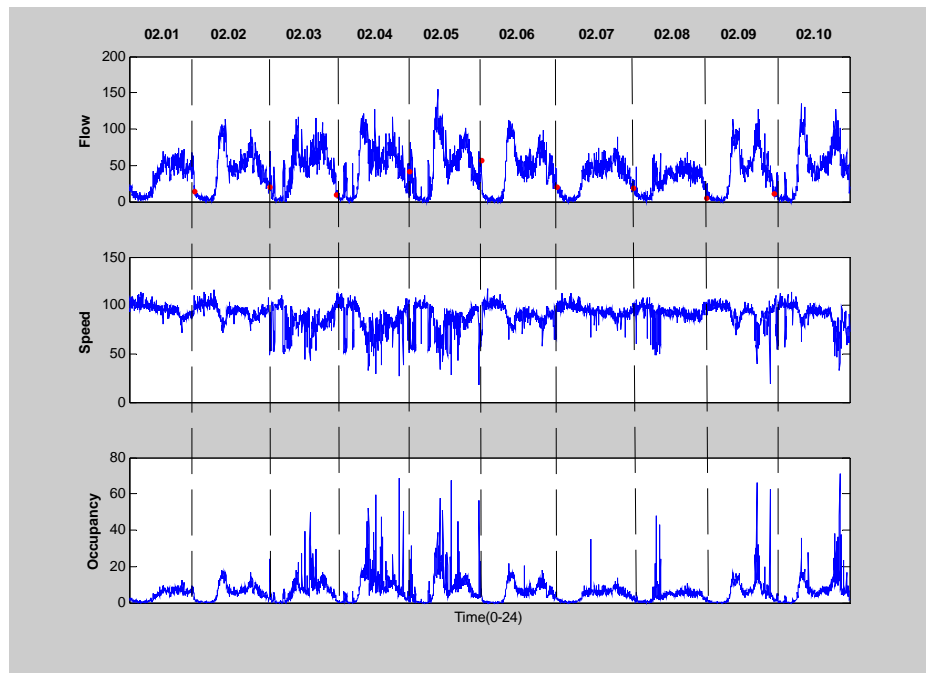


Figure 8 Successive ten-day's 3-minute traffic series
(Taiwan Freeway No. 1, station 421, northbound)

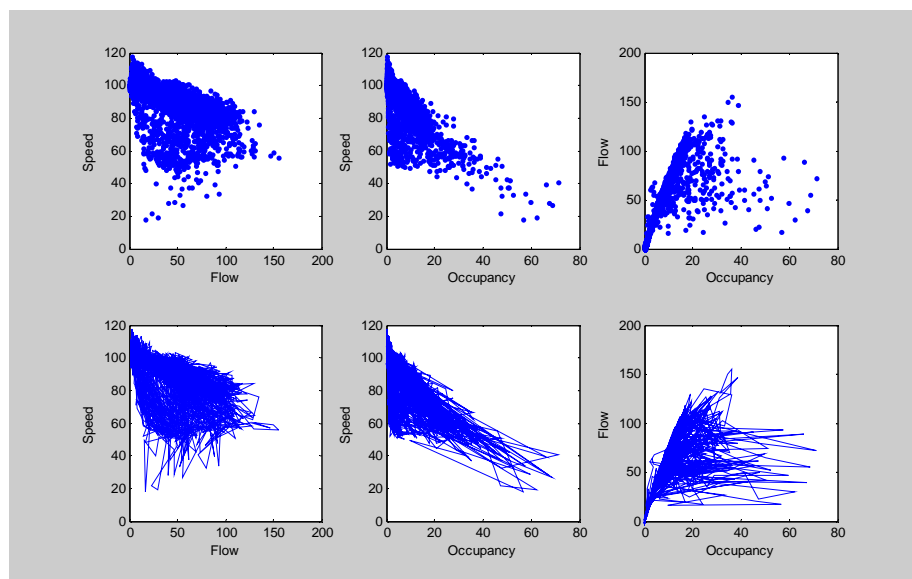


Figure 9 Successive ten-day's 3-minute paired-traffic scattergrams (upper panels)
and their chronological ordered evolutions (lower panels)
(Taiwan Freeway No. 1, station 421, northbound)

3.2 Exploration of Traffic Phases

In accordance with the above paired-traffic relationships (Figure 9), we have known that paired-traffic relationships without considering temporal order are approximately similar to conventional traffic stream diagrams; however, we hope to learn of whether the features of traffic phases in the real world are different from those depicted by fundamental traffic stream diagrams or different from those formulated by the modified ASEP approach proposed. From the right plot in the basic traffic stream diagrams of Figure 1 and Figure 7, it is simply assumed that the relationships between flow and density would either follow the shape of a parabolic curve or the inverted λ curve from left to right and evolve according to the traffic

status, for example, from a free-flow state to a jam state. However, in a real traffic series, such as Figure 10 below, the dynamical paired-traffic relationships at different times of day have displayed entirely different patterns from the basic traffic stream diagrams.

In Figure 10, the collective dynamics of flow-occupancy start in the early hours (01:00-07:00), and the dynamics mainly advance along a direction at an approximately 60° angle from low volume to high volume (about 150 vehicles/3-minute/lane). After that, some of the dynamics spread out and move towards high-occupancy cluster as indicated in the morning peak-hours (07:00-09:00). The phenomena become more copious in the subsequent times of day (09:00-12:00), i.e., the dynamics of flow-occupancy behave like molecular diffusion which continually spreads out from collective points along a direction at an approximately 60° angle to high-occupancy direction and return back.

The collective points (09:00-12:00) along the direction at an approximately 60° angle (the bold line in the right top panel in Figure 10) is regarded as the free-flow phase; while the area scattering with dots (encompassed by the bold triangle in the same panel in Figure 10) is considered as the synchronized-flow phase, which is categorized as congested traffic. We also note that traffic flows at other times of day (e.g., 09:00-12:00, 12:00-17:00, and 17:00-21:00) no longer retain the same high volumes as in the morning peak hours (07:00-09:00), but rather, they evolve with slightly lower maximum volumes. Such a “breakdown” phenomenon (maximum traffic flows drop slightly) oftentimes occurs at the phase transition from the free-flow phase to the synchronized-flow phase. Likewise, the transitive phase has been found in the traffic stream diagrams generated by our modified ASEP simulations in Figure 7.

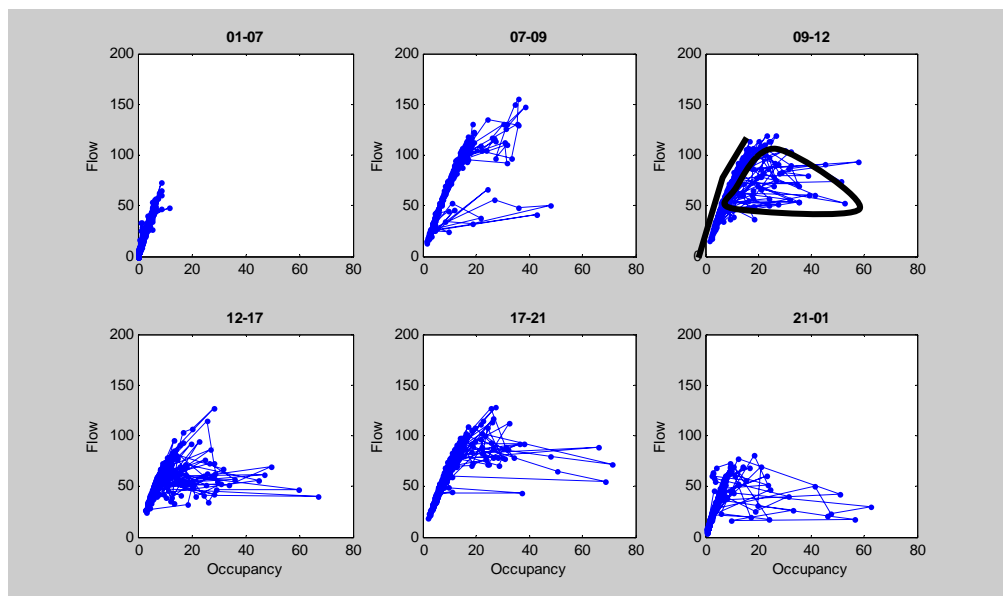


Figure 10 Flow-occupancy relationships at different times of day
(Taiwan Freeway No. 1, station 421, northbound)

The flow-occupancy relationships of successive ten-day's field traffic series have revealed at least three kinds of traffic phases: free-flow phase, synchronized-flow phase, and a breakdown phenomenon at different times of day. To further exploit the characteristics of various traffic phases, we divided the successive ten-day's traffic series into ten individual one-day's traffic series, and selected nine out of ten to reexamine their flow-occupancy relationships in the morning peak hours (07:00-09:00) and off-peak hours (09:00-12:00), see Figures 11 and 12 below.

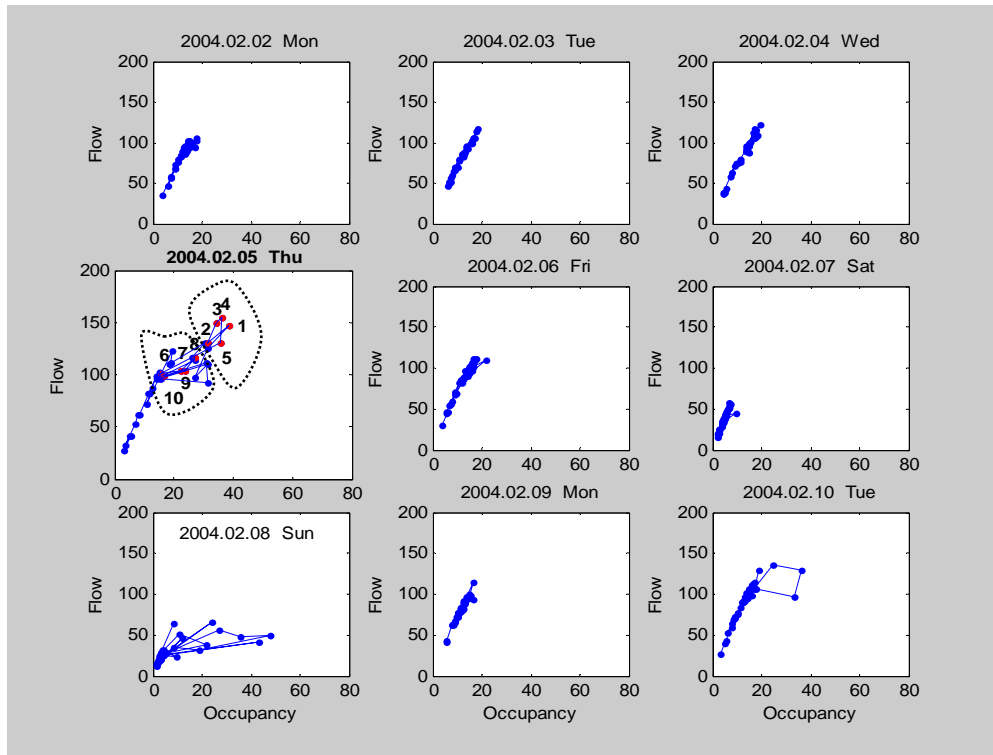


Figure 11 Flow-occupancy relationships for nine days in morning peak hours (Taiwan Freeway No. 1, station 421, northbound, 07:00 ~ 09:00)

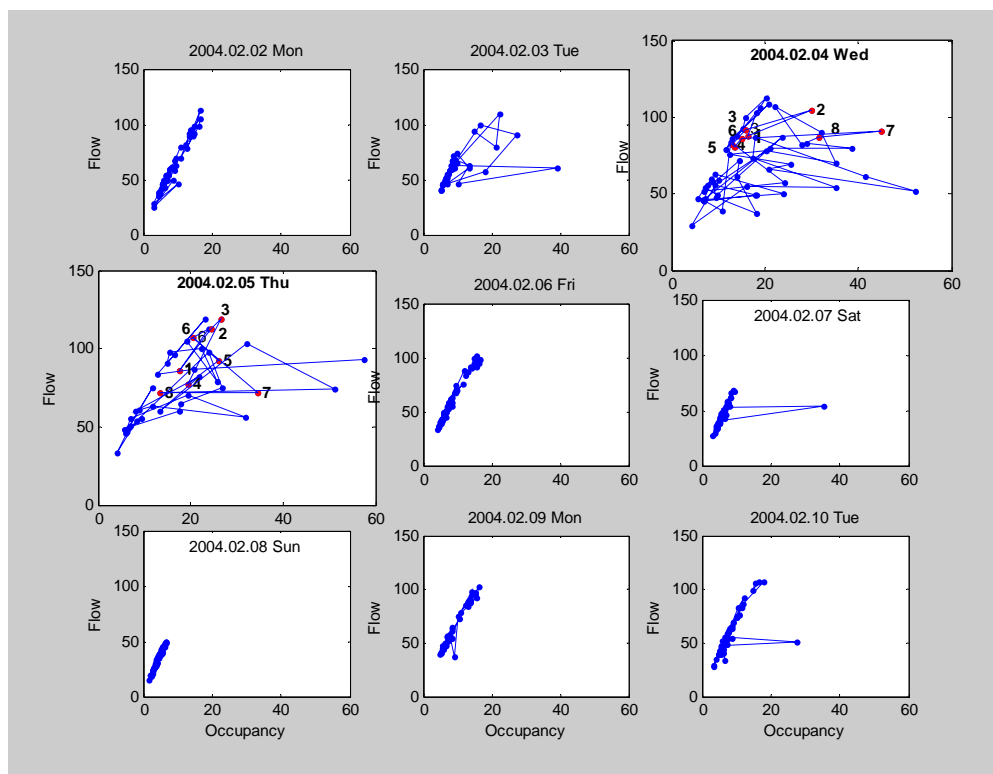


Figure 12 Flow-occupancy relationships for nine days in morning off-peak hours (Taiwan Freeway No. 1, station 421, northbound, 09:00 ~ 12:00)

From Figures 11 and 12, we found that the patterns associated with congested traffic phases appearing on two days, 2004.02.04 and 2004.02.05. The matter we are really interested in is

the congested traffic phases which could contain breakdown phenomenon and synchronized flow. Hence, we attempted to trace ten selected points to elucidate the evolution of breakdown phenomenon by observing the chronological order of flow-occupancy in morning peak hours on 2004.02.05. The ten points are enlarged and displayed in the left middle panel of Figure 11, and their values (flow vs. occupancy: vehicles/3-minute vs. %) were chronologically recorded as follows: No.1 (147, 38.6, 08:23), No.2 (131, 31.6, 08:26), No. 3 (150, 34.4, 08:29), No. 4 (155, 36.0, 08:32), No. 5 (130, 35.6, 08:35), No. 6 (101, 15.8, 08:38), No. 7 (104, 22.1, 08:41), No. 8 (116, 27.0, 08:44), No. 9 (104, 23.7, 08:47), and No. 10 (99, 16.3, 8:50).

According to the above sequential order values, we can approximately classify the ten points into two groups encompassed by two dotted circles in the panel of Figure 11. The first group consists of five points (No. 1 through No. 5), while the second group contains the other five points (No. 6 through No. 10). It was interesting to find that the average velocity of five points in the first group did not rapidly decrease compared with the neighboring points located at pre- and post-time periods, despite high volumes and high occupancies of these five points. However, the phenomenon only lasted for a short period of time. In other words, the so-called “breakdown phenomenon” is an unstable phase which only plays a transitive role between free-flow phase and synchronized-flow phase. This unstable phase can easily vanish through a few slight internal disturbances, and there is no guarantee to appear every time even though congested traffic exists. For instance, there was also a synchronized flow phase on 2004.02.04, but the breakdown phenomenon was absent. Regarding the second group, it can be considered as an onset of the synchronized flow phase because the consequent traffic phase is the synchronized flow phase. According to Figure 11, it can be assessed that the traffic will transit from free-flow phase to congested traffic phases if the occupancy is approximately over 20%.

We further traced the synchronized-flow phase shown on 2004.02.04 and 2004.02.05. As depicted in Figure 12, we observed that the enlarged flow-occupancy diagram on 2004.02.04 no longer retains free-flow phase, but has already become a diffusive area where dots in the area randomly spread out, i.e., go toward the right direction and return back later. Similarly, the enlarged flow-occupancy diagram on 2004.02.05 shows a breakdown phenomenon transformed into a synchronized-flow phase. The fact associated with synchronized-flow phase that we attempt to further explore is the temporal order of flow-occupancy relationship, that is, what we want to probe is the intrinsic information behind the trajectories of synchronized flow phases. Again, we chose eight points and traced them with numbering 1 through 8. The flow-occupancy data (vehicles/3-minute vs. %) for the eight points on 2004.02.04 were chronologically recorded as follows: No. 1 (88, 16.4, 09:32), No. 2 (105, 30.0, 09:35), No. 3 (92, 15.8, 09:38), No. 4 (82, 13.0, 09:41), No. 5 (81, 13.4, 09:44), No. 6 (86, 15.0, 09:47), No. 7 (91, 45.0, 09:50), and No. 8 (87, 31.6, 09:53). Other flow-occupancy data of eight points on 2004.02.05 were No. 1 (86, 17.7, 09:32), No. 2 (113, 24.4, 09:35), No. 3 (119, 26.6, 09:38), No. 4 (77, 19.4, 09:41), No. 5 (92, 26.0, 09:44), No. 6 (107, 20.6, 09:47), No. 7 (72, 34.6, 09:50), and No. 8 (72, 13.3, 09:53).

The above chronological values (Figure 12) indicate that the synchronized-flow phase wanders randomly within a triangle of the flow-occupancy diagram. Every pace between any two moves is different. Such circumstance is like a driver following another one—if the front driver moves faster (slower) then the follower accordingly moves faster (slower). Namely, a “stop-and-go” manner is suitable to portray such a synchronized-flow phase traffic behavior. In addition, it is interesting to note that some flow-occupancy data values in the synchronized-flow phase (approximate 60° angle) are equivalent to those in the free-flow

phase or the breakdown phenomenon. However, their time-mean-speeds (not shown in this paper) are on average lower than those in the free-flow phase and in the breakdown phenomenon. The main reason is due to the starting delay of vehicles in the synchronized-flow phase which are less fluent than the free-flow phase, as presented in the modified ASEP approach. Therefore, one should simultaneously inspect the three variables with care when identifying the complicated traffic phases.

4. DISCUSSIONS

The simulated results using our proposed modified ASEP approach have satisfactorily displayed the real-world traffic phenomena. The associated fundamental traffic stream diagrams with the simulated results have not only concurred with the three-phase traffic theory but also consistent with the field observed traffic series, from which various traffic phases including free-flow phase, synchronized traffic phase, and breakdown phenomenon were disclosed. The chronological order of field observed traffic series was further put to highlight on tracing the features of various traffic phases. According to the above explorations, some theoretical implications and practical applications are discussed below.

Obviously, the variety of traffic phases deriving from real traffic dynamics with consideration of chronological order is much abundant than both conventional traffic stream diagrams and those formulated by the modified ASEP approach. Although the “one time-step” was a trial value adopted by the modified ASEP approach to depict the starting delay of vehicles, yet the simulated results, compared with the field observed traffic patterns, have indicated that “one-step” time lag is an acceptable parameter to interpret traffic phenomena taking place in real world. Undoubtedly, keep exploring more traffic phases by adjusting the parameters of ASEP or adding some rules into it to be more in line with the actual drivers’ behavior deserve further explorations. In addition, in accordance with our exploration on the freeway ten-day’s data, the flow-occupancy relationship did not follow the conventional parabolic curves, but rather the inverted λ curves in three-phase traffic theory, which were the same as the paired-relationship formulated by our modified ASEP simulations. The left part of the inverted λ curves represents a free-flow phase, while the right part depicts a synchronized-flow phase. The projecting portion at the upper part exists a “breakdown phenomenon,” which can be regarded as a transitive phase transforming the free-flow phase into the synchronized-flow phase.

More specifically, the dynamical paired-traffic relationships at different times of day have displayed entirely different patterns from the traffic stream diagrams. The field data show that the collective dynamics of flow-occupancy start in the early hours (01:00-07:00), and the dynamics mainly advance along a direction at an approximate 60° angle as the flow increases. During the morning peak-hours (07:00-09:00), some of the dynamics have spun off from the 60° angle cluster to form another high-occupancy clusters. Apparently, in line with the above explorations, an instantaneous control is deemed necessary before such a spin-off takes place because the basic rationale for managing the recurrent congestion is to enforce any control mechanism so as to retain the flows in the stable free-flow phase without abruptly jumping into the unstable congested ones. The core logic for managing the non-recurrent congestion, on the other hand, is to select sensitive instantaneous parameters to quickly diagnose the abnormal flow such that the delays incurred by the incidents can be cut down. In other words, with consideration of the chronological order of paired-traffic data, more plenty of instantaneous traffic information than the conventional traffic stream diagrams has been

disclosed. With the advantages of our proposed modified ASEP, abundant traffic phases and their transitions can be explored to facilitate the development of real-time traffic management and control strategies.

It should be mentioned that the traffic series extracted from an isolated station can only explore the temporal traffic features, not the spatiotemporal features, thus the traffic stream diagrams at a fixed station could not become hologram on behalf of all of the traffic phases in a section of road. Developing a simulated model which can reasonably interpret the traffic phenomena in real word seems to be a viable alternative to make up the shortage. Nevertheless, in terms of the developing a simulated model to augment the exploration of traffic phases, several aspects regarding the prerequisites and restrictions between the spatiotemporal model and temporal characteristics of dynamical traffic are worth to be discussed further in order to completely capture the fundamentals of traffic operations. First, in the processes of formulating traffic model, traffic density from low to high was manipulated gradually to form traffic stream diagrams, whereas traffic density in reality varied inconstantly over time rather than increasing gradually. The dynamical traffic, particularly short-term, varied quickly and traffic stream diagrams are in reality not straight lines, but instead a diffusive area in which the paired-variable dots (such as flow vs. occupancy) randomly spread out and repetitively go toward the right direction and return back later. Future study should take the diffusive effects into account while refining the simulation models.

Eventually, different methods of exploring traffic phases remain individual advantages and restrictions, regardless temporal phases or spatiotemporal phases. The temporal traffic phases with sequential order extracted from detector stations may shed light on the variety of traffic phases in providing proofs of field study; however, lacking of tracking trajectories of vehicles on the road is the insufficiency of this investigation. In contrast, a spatiotemporal model may successfully trace the trajectories of vehicles together with time evolution, nevertheless, the calibration using a real data still remain rather spaces to make up with. In this study, the traffic stream diagrams formulated by our modified ASEP and a critical point, which is transient and unstable, were demonstrated. Corresponding to the various traffic phases derived from the field traffic data, the breakdown phenomenon was also found, suggesting that the modified ASEP should be effective to depict the traffic phenomena in spatiotemporal domain, although yet validated. Future study can consider validating our modified ASEP approach with the field spatiotemporal traffic phenomena.

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