

**PARAMICS SIMULATION OF PERIODIC OSCILLATIONS CAUSED BY
NETWORK GEOMETRY**

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ABSTRACT

Traffic oscillations such as stop-and-go waves in a traffic system can be caused by reasons such as instabilities. In this paper, we intend to study a type of periodic oscillations caused by network geometry with a microscopic simulation model, Paramics. With careful tuning in Paramics, we successfully simulate such periodic oscillations, in which traffic states change periodically between a diverging junction and merging junction, and the formation process is discussed in details. This study also suggests that, given appropriate network structure and traffic conditions, local oscillations caused by randomness in car-following and lane-changing models in Paramics can maintain and become periodical and global. Finally, consistencies between a macroscopic kinematic wave model and Paramics are discussed, and future research topics and implications of the study presented.

1 INTRODUCTION

In a road network, traffic oscillations or stop-and-go waves are common phenomena, annoying to drivers, who have to decelerate and accelerate frequently. Observations and analysis of such phenomena have suggested that they can be caused by many reasons. For examples, oscillations in traffic density were analyzed and observed as caused by imbalance between lanes in [1; 2]; oscillations caused by signals and instabilities were observed in queues upstream of a bottleneck in [3]; and spontaneous oscillations caused by traffic instabilities were simulated with the Payne-Whitham model in [4].

In Section 7.3 of [5], it was demonstrated that periodic oscillations can be caused by network geometry. In a simple network, as shown in Figure 1, with empty initial conditions and constant traffic demand at the origin, periodic oscillations arise on links 2, 3, and 4 when 45% vehicles choose the shorter link 3. Studied with a commodity-based kinematic wave model, the mechanism of such oscillations is revealed as follows: (i) When two traffic streams from links 3 and 4 reach the merging junction 2 (simply, the merge), a backward shock wave, which has a downstream zone of highly congested traffic, forms on the shorter link 3 and travels backward. (ii) When the shock wave reaches the diverging junction 1 (simply, the diverge), congested traffic on link 3 blocks the releasing of vehicles from link 2 to both links 3 and 4. (iii) As a result of the blockage of the diverge, a zone of low density and flow-rate forms on link 4 and travels forward. (iv) When the zone of sparse traffic reaches the merge, link 3 is distributed more share of the capacity of link 5. Therefore, vehicles from link 3 are released faster, and a clearing rarefaction wave, which has a downstream zone of lower density and higher flow-rate, forms on link 3. (v) When the rarefaction wave reaches the diverge junction 1, more vehicles will be released from link 2 to link 4. (vi) When more vehicles from link 4 reach the merge, a shock wave forms on link 3 again. Then traffic states return to the same as in step (i) again, and periodic oscillations form and persist in the network. From the process, we can see that such oscillations are mainly caused by traffic states bouncing back and forth between the diverge and the merge, and it suggests that periodic oscillations is caused by such a network structure, given proper proportion of vehicles using each route.

In the simulation model used in [5], merging and diverging flows are explicitly calculated, and traffic instabilities are not counted. Then one may wonder if such periodic oscillations are actually the results of the specific macroscopic merging and diverging models. Although the best approach to addressing this concern is to make observations in the field, it is quite costly to capture detailed evolving dynamics of traffic even in a real network as simple as the one in Figure 1, since one has to implement a sufficient number of detectors on each link. Also, such oscillations could be quite conditional, since oscillations can be caused by many factors in a real traffic system and their interactions may prevent a clear view of possible periodic ones. Therefore, as an intermediate and helpful step toward practical observations, possible periodic oscillations are studied with Paramics [6,7] in this paper. As we know, Paramics is a microscopic simulation model, in which vehicle movement is based on models of car-following, lane-changing, and other driving behaviors. In particular, at a diverge or a merge, vehicles determine their movements based on acceptable gaps. In this sense, Paramics can introduce randomness in traveler behaviors, but we can also control the level of randomness by tuning the

simulated network carefully, so that periodic oscillations would not be significantly affected by other oscillations caused by traffic instabilities. Therefore, if periodic oscillations can also be simulated in Paramics, it is more suggestive that network geometry could be a reason of periodic oscillations.

The rest of the paper is organized as follows. In Section 2, network tuning in Paramics is documented and explained in details so that simulation results can be replicated by any interested parties. In Section 3, the formation of periodic traffic oscillations is demonstrated and analyzed. Finally, in Section 4, discussions of the findings in this paper are presented.

2 NETWORK TUNING

In our study, we consider the same network structure as that in Figure 1, but tune it specifically for Paramics simulation. The simulated network is shown in Figure 2(a), where traffic moves from left to right. This network has one origin zone and one destination zone, and traffic demand is set to be the capacity of link 2 at the origin. In this network, link 2 is very long so that the generation of vehicles at the origin does not significantly affect traffic dynamics at the diverge. The lengths of links 3 and 4 are $L_3=5282.3$ ft = 1.004 miles/1610 m (ft=feet, m=meter hereafter) and $L_4 = 10711$ ft = 2.0286 miles/3265 m, respectively, and the longer link 4 has two lanes, but link 3 just one. Note that link 4 is actually divided to four links in Paramics to obtain reasonable diverging and merging angles. For the purpose of simplicity, straight links instead of curved links were used to form a triangle network between the merge and the diverge, and this simplification does not cause any speed reduction at the top point of link 4 in Figure 2, according to our observation. In the network, all links are set to be major highway links, with speed limit at 65 mph/104.6 kmph (mph=mile per hour, kmph=kilometer per hour hereafter). We also find that choices of next lanes at the diverge and the merge significantly affect how vehicles make use of left lanes on links 4 and 5, and choices in Figures 2(b) and 2(c) yield the best balance between right and left lanes on these links, although the less-used left lanes are still observed.

Since randomness in travelers' behaviors can cause local traffic oscillations in Paramics, which may adversely affect the formation of periodic ones, we will tune the traffic system to be as deterministic as possible. In our study, we only consider one car type, and cars are released at the origin deterministically and evenly so that traffic on link 2 is as homogeneous as possible. Further, all vehicles have predefined choices of routes when they are generated, and the proportion of vehicles taking the shorter link 3 is 45% as in [5].

In our simulations, we use Paramics Modeller of version 4.2 for network tuning and traffic simulation and set the seed of random number generator to be 100 so that simulation results are repeatable. Furthermore, the time step detail is set to be 4 (i.e. vehicle movement is computed every 0.25 s). Two Paramics API plug-ins have been developed: one for deterministic, even releasing of cars at the origin, and the other for forcing a car to follow its predefined route. Note that, even after tuning of the road network, car-following and lane-changing logic in Paramics has not been touched. That is,

there is still randomness in vehicles' behavior. This can be observed from Paramics simulations and verified by the existence of local oscillations at merges as shown in Section 3.

In our study, we start with an initially empty network and simulate traffic dynamics from $t=0$ to 1 hour. Since, as predicted in [5], periodic oscillations are caused by traffic dynamics on links 3 and 4, we place 101 detectors on link 3 and 213 on link 4, to best capture the details of traffic dynamics², and the distance between two adjacent detectors is mostly 47 ft/14.3 m. Note that, in Paramics, 1 detector = multiple loops in different lanes. We also place one detector on link 2 at 100.2 ft/30.5 m upstream of the diverge and one detector on link 5 at 108.5 ft/33.1 m downstream of the merge. Vehicle counts (flows), occupancies, and velocities are collected at each detector and aggregated over all lanes and a period of 0.5 min, using a detector data aggregator API developed at UCI [8].

3. ANALYSIS OF PERIODIC OSCILLATIONS

3.1 Static states and fundamental diagram

For links 3 and 4, relationships between flow-rates or speeds and occupancies at all detectors are shown in Figure 3. From Figures 3(a)-(b), we can see that traffic on link 3 can be under- or over-critical, but mostly over-critical. From Figures 3(c)-(d), we can see that traffic on link 4 is always under-critical, but there is a high deviation in speed, because vehicles on link 4 may travel at lower speeds when they come out of congested diverging area or have to decelerate to merge on to link 5. From these figures we can see that, in most cases, lower flow-rates correspond to lower speeds and more congested traffic on link 3, but correspond to sparser traffic on link 4. Since all cars are of the same type, and occupancy is proportional to density, these figures also represent the fundamental diagrams on links 3 and 4, which are close to the triangular one in [9,10]. However, comparing to the triangular fundamental diagram used in Section 7.3 of [5], the slope of left branch (i.e. free flow speed) is higher, while the slope of the right branch (i.e. absolute of shock wave speed) lower.

3.2 Traffic oscillations around the diverge and the merge

Flow-rates around the diverge are shown in Figure 4, where out-flow from link 2 is observed at about 100.2 ft/30.5 m upstream of the diverging point, in-flow to link 3 at about 183.7 ft/56.0 m downstream, and in-flow to link 4 at about 132 ft/40.2 m downstream. From the top figure, we can see high oscillations in flow-rates on the three links, and they have the same changing directions with each other. For example, at around 24 min, in-flow to link 3 starts a jump, then followed by in-flow to link 4 and out-flow from link 2. From observation of Paramics simulations, we found that the correlation in flow-rate jumps is caused by a backward traveling shock wave on link 3, whose downstream traffic is highly congested. When this shock wave reaches the diverge, vehicles taking link 3 cannot exit from link 2, queue up around the diverge, and thus

² In Paramics v4.2, detectors should not be placed too close to a node (e.g. less than 70 ft/21.3 meters). Otherwise, passing vehicles may not be detected.

block vehicles taking link 4, even which is always under-critical. In this sense, in Paramics, vehicles taking links 3 and 4 observe First-In-First-Out among each other on link 2. As a result of synchronization between traffic dynamics on three links and FIFO on link 2, in-flows to links 3 and 4 are almost always 0.45 and 0.55 times out-flows from link 2 respectively, which are the proportions of vehicles choosing links 3 and 4 at the origin, as shown in the bottom figure. Note that oscillations on links 2 and 3 are between stop and go traffic, but those on link 4 are not: on the former links, traffic is mostly congested, and small flow-rates correspond to slow or stop traffic; but on link 4, traffic is under-critical, vehicles always travel at free-flow speed, and low flow-rates correspond to sparse traffic.

Simulation results around the merge are shown in Figure 5, where out-flows from links 3 and 4 and in-flow to link 5 are observed respectively at locations of 100, 94, and 108.5 ft/30.5, 28.7 and 33.1 m from the merging point. From the top figures, we can also observe oscillations in flow-rates around the merge, but their changing directions are not the same. For example, at around 26 min, a big jump in out-flow of link 4 is followed by a rise in out-flow from link 3 and a jump in in-flow of link 5. In Paramics simulations, traffic dynamics at around 26 min is observed as follows: more vehicles on link 3 merge to link 2, but the overall in-flow to link 5 decreases. Opposite changing directions between two out-flows can also be seen from their cumulative flows in the bottom figure. Note that out-flow of link 3 is no longer linearly proportional to in-flow of link 5. Otherwise, we expect to obtain equilibrium states as discussed in Section 7.2 of [5].

From both figures, we can see that traffic on link 3 oscillates between congested states with higher flow-rates and those with lower flow-rates, and traffic on link 4 oscillates between free flow states with higher flow-rates and those with lower flow-rates. For the purpose of convenience, we call these states respectively as go traffic and stop traffic on link 3, and high traffic and “empty” traffic on link 4. Therefore, from both figures, we can clearly see the following pattern in the change of traffic states on links 3 and 4 around the diverge and merge: go and stop traffic on link 3 leads to high and empty traffic on link 4 at the diverge, respectively; high and empty traffic on link 4 leads to stop and go traffic at the merge, respectively. That is, traffic on link 3 serves as a switch of the diverge: go traffic clears the merge, and stop traffic blocks it; while traffic on link 4 serves as a switch of the merge: high traffic blocks the merge, and empty traffic clears it.

3.3 Formation of periodic oscillations

In Figure 6, we show vehicle speeds and flow-rates at nine locations on both links 3 and 4 from 8 min to 24 min. In these figures, lines with crosses are for link 3 and those with circles for link 4. As shown in Figure (i1), after vehicles on link 4 reach the merging point at 9.5 min, vehicles on link 3 have to slow down. This forms a zone of low speed and low flow-rate traffic on link 3, i.e. stop traffic. Then this zone of stop traffic moves backward on link 3 along a shock wave, which can be seen from the down-slopes in Figures (h1)-(a1), and reaches the diverging point at about 16.5 min. Thus the speed of the shock wave is -10.3 mph/ -16.6 kmph, which is a reasonable number according to [11]. Moreover, we can also see that, the region of the down-slopes, i.e., the interface between go and stop traffic, keeps increasing when it travels upstream. We hereafter

denote the stop traffic state downstream to the shock wave by S2. Note that, in an ideal case, the stop traffic state S2 should prevail on link 3 when the shock wave travels upstream. However, due to drivers' non-uniform deceleration when meeting the shock wave, a local go traffic state G3 forms and is followed by another stop traffic state S1. That is, S2, G3 and S1, whose total length is about 8 min (half the period), could have been one stop wave in the ideal case. Then in this road network, each of these states will cause a set of global oscillations, whose mechanism is explained at the end of this section. Therefore, local oscillations break one set of global oscillations into three, as illustrated in Figure 7. Further, from the left figures, vehicle speed does not change significantly on link 4 when they are not affected by merging or diverging traffic. In addition, from the right figures, we can see that speed and flow-rate on link 3 are consistent in changing directions with each other. Therefore, we hereafter only consider speed for link 3 and flow-rate for link 4, when checking traffic dynamics in the network.

In Figure 7, we show traffic dynamics on links 3 and 4 from 16 min to 60 min. In these figures, we can see the evolution of oscillations between stop and go traffic on link 3 and those between high and empty traffic on link 4. In the simulation, we can observe three sets of periodic oscillations, and we denote the associated traffic states by H2, E2, G2, and S2 for oscillation 2, for example. That we can identify consistence among states is because all states are moving in limited speeds. The pattern of periodic oscillation 2 can be seen in the figure as follows. First, as shown in Figure (a1), a zone of stop traffic, S2, occurs on link 3 at 16.5 min, caused by the first merging shock wave described in Figure 6. Since S2 has high occupancy and low speed, it blocks the diverge, and this in turn reduces out-flow to link 4. Then, a zone of empty traffic, E2, forms on link 4 at 17.5 min, as shown in Figure (a2). Note that there is a delay from S2 to E2, since the blockage of the diverge depends on how vehicles distribute on link 2 and may not be immediate. Second, E2 travels along the free flow on link 4 and reaches the merge at 19 min, as shown in Figure (i2). Since traffic demand on link 4 is very low, the merge is cleared, and higher flow-rate is allowed on link 3. That is, we have a zone of go traffic, G2, around 21 min, as shown in Figure (i1). Note that there is also a delay from E2 to G2. Third, since traffic on link 3 is congested, G2 travels upstream and reaches the diverge at around 26 min, as shown in Figure (a1). After that, the diverge is cleared, more out-flow is allowed to enter link 4, and this yields a zone of high traffic, H2, on link 4 at around 26 min, as shown in Figure (a2). Fourth, H2 travels at free flow speed and reaches the merge at around 27.5 min, as shown in Figure (i2). Since total traffic from links 3 and 4 surpasses the capacity of link 5, out-flow from link 3 is reduced and S2 forms at around 28 min, as shown in Figure (i1). Fifth, S2 travels upstream to the diverge at around 33 min, as shown in Figure (a1). This finishes a cycle of oscillation 2, whose period is about 15.5 min. From these figures, we can easily observe other cycles of oscillation 2 and cycles of oscillations of sets 1 and 3.

In Figure 8, we draw a contour plot of traffic states on links 3 and 4. From the figure, we can observe the pattern of oscillations as described above. In addition, we can also observe traffic dynamics in terms of wave propagation. The interface between two adjacent high and empty traffic states on link 4 can be considered as a traveling wave in the speed of 80 mph/128.7 kmph, which is the free flow speed on link 4. On link 3, the interface from a go traffic state to a stop traffic state is a shock wave, and the reverse a

rarefaction wave. From Figure (a), we can see that both shock and rarefaction waves travel backward in a similar speed at around -10.3 mph/ -16.6 kmph. However, there is a slight difference in their speeds, which causes the width of a traffic state to increase or decrease with time. Also, there is a difference in the width of corresponding states on links 3 and 4, and this difference is caused by merging or diverging effect. Further, the period of an oscillation equals to the time taken by a shock wave and a rarefaction wave on link 3 and two traveling waves on link 4, and is about 15 min. Actually, from Figure 7(a2), we can see that oscillation 1 experiences three whole periods from 15 min to 60 min.

We know that the initial states of oscillations 1 and 2, G1 (or H1) and G2, are caused by the first merging shock wave on link 3. In the simulation, we have an additional oscillation 3, which is initially caused by local oscillations. That is, in oscillation 3, local oscillations persist and then turn into global periodic oscillations. Existence of oscillation 3 further confirms that such special network geometry as in Figure 1 or 2 is able to turn local oscillations into periodic, global ones. On the other hand, this feature also proves the necessity of reducing randomness in a road network as much as possible, since, otherwise, too many oscillations can interact with each other and the pattern of periodic oscillations may not be clearly observed.

4 CONCLUSION

In this paper, we successfully demonstrated periodic oscillations in a simple road network with Paramics simulations. This study enhanced the suggestion that network geometry can cause stop-and-go waves, which was initially proposed in [5] with a macroscopic, commodity-based kinematic wave model of network traffic. This study shows, given similar conditions, microscopic and macroscopic models can match each other's results in the following aspects. First, at a diverge, out-flow to each branch is determined by the proportion of vehicles diverging to this branch. Second, at the merge, an upstream link can be distributed more space when the other carries empty traffic. Third, at the system-wide level, periodic oscillations can be simulated in both models, and the period obtained from Paramics simulations is about 15 min, which is consistent with 11 min^3 in [5]. However, two types of models have discrepancy between each other due to the difference in the level of details they concern about. For example, in [5], only two oscillations 1 and 2 associated with the first merging shock waves are predicted, but local instabilities cause another oscillation in Paramics simulations.

In our simulations, if using different time step details, we can still observe periodic oscillations with the pattern described in Section 3, but only small differences can exist in the number of periodic oscillations, shock wave speeds, and periods. We also tried another random seed number of 1000 and only obtained slightly different results. These experiments further suggest that the network geometry and proper proportions are the main reasons why periodic oscillations can exist, and we are quite confident that such periodic oscillations can be simulated in other well-developed traffic models.

³ The difference in periods is caused by that in shock wave speed and that in the fundamental diagram. In [5], shock wave speed is higher at -16.25 mph / -26 kmph. That is, if we use similar fundamental diagram, we can expect closer period.

In the follow-up studies, more properties of such oscillations can be analyzed, especially the formation conditions on routing proportions and network structure. Here we set the proportion of vehicles taking link 3 as 45%, and then what is the range for this proportion in order to generate such oscillations? In an extreme case, for example, when all vehicles take only one route, we do not expect to see these oscillations. Also, the length of link 4 is twice that of link 3, and do we expect such oscillations for different lengths? How about the number of lanes for two links? Further, what are the relationships between the period of such oscillations and lengths, number of lanes, or proportions?

The study in this paper and further studies on periodic oscillations caused by network geometry will provide us important clues on where to observe such oscillations in field and what to expect from field observations. First, a network has to be in a proper structure, e.g., similar to the one in Figure 1, and on-ramp or off-ramp flows cannot have too much influence. Second, one may want to find the situations where proportions of choosing two links are in the proper range, e.g., close to the theoretical range in [5]. For examples, one may want to check a network with a toll road, which can still have free flow when other routes are heavily congested with stop and go traffic; one may also check cases when a significant portion of travelers are not familiar to a longer, wider link with sparse traffic and prefer to take a shorter, narrower link with stop and go traffic; or one may check a location with a relatively long collector/distributor road, where a proportion of vehicles could be tempted to use the “bypass”. Third, since local oscillations will prevent us from having a clear view of the pattern of global, periodic ones, it is helpful to have sufficient homogeneity in traveler’s behaviors. Fourth, a sufficient number of detectors have to be set up in order to observe the detailed dynamics of periodic oscillations.

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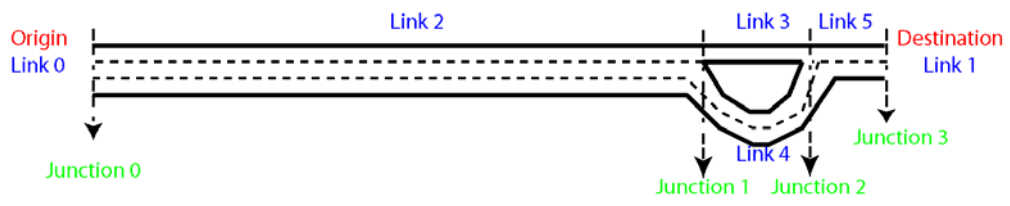
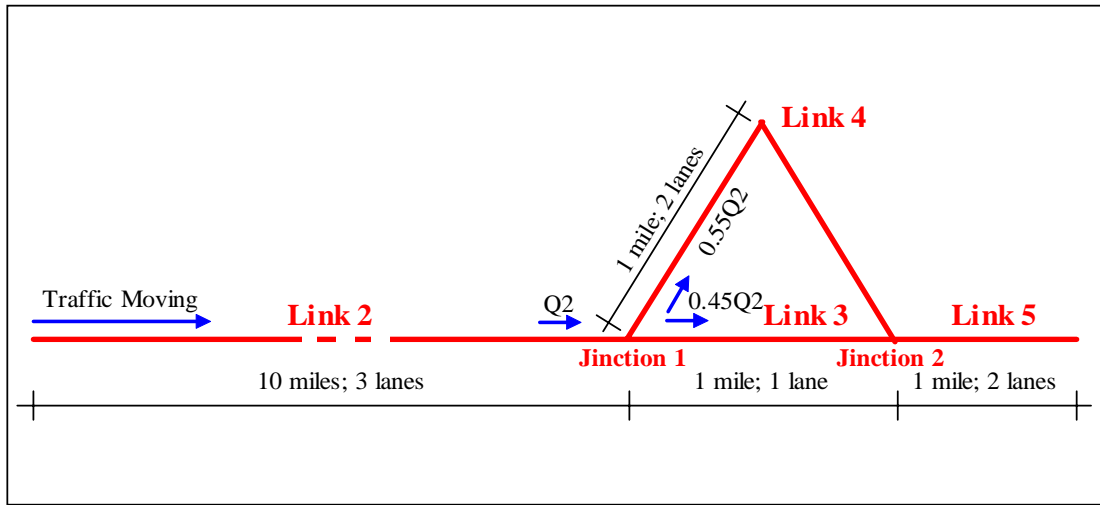
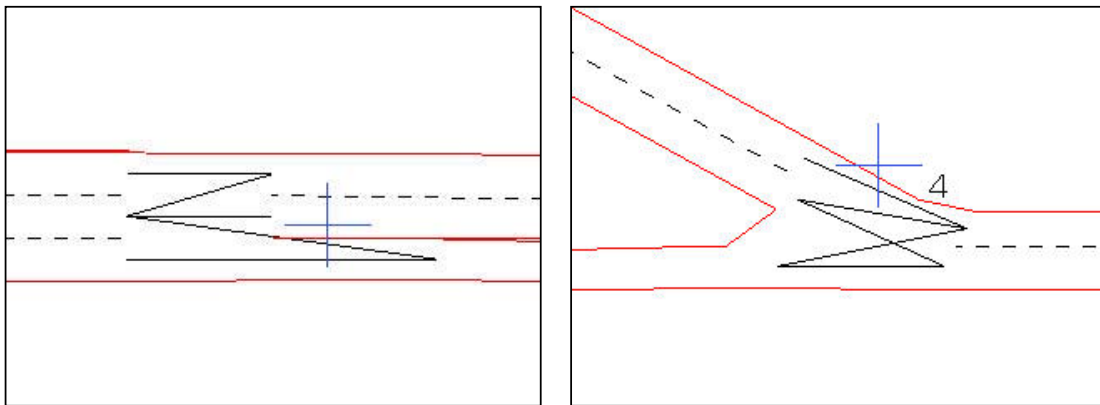


Figure 1. A simple network causing periodic oscillations



(a) The simulated network in Paramics



(b) Choice of next lanes at Junction 1

(c) Choice of next lanes at Junction 2

Figure 2. Studied network in Paramics

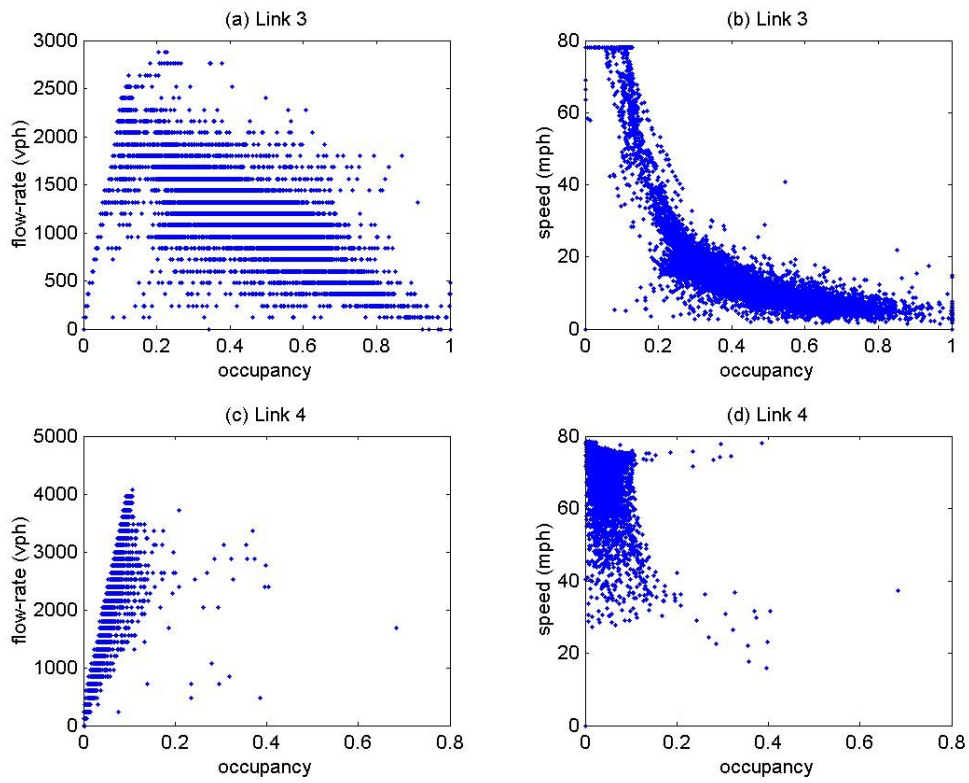


Figure 3. Occupancy-flow and occupancy-speed relationships on links 3 and 4

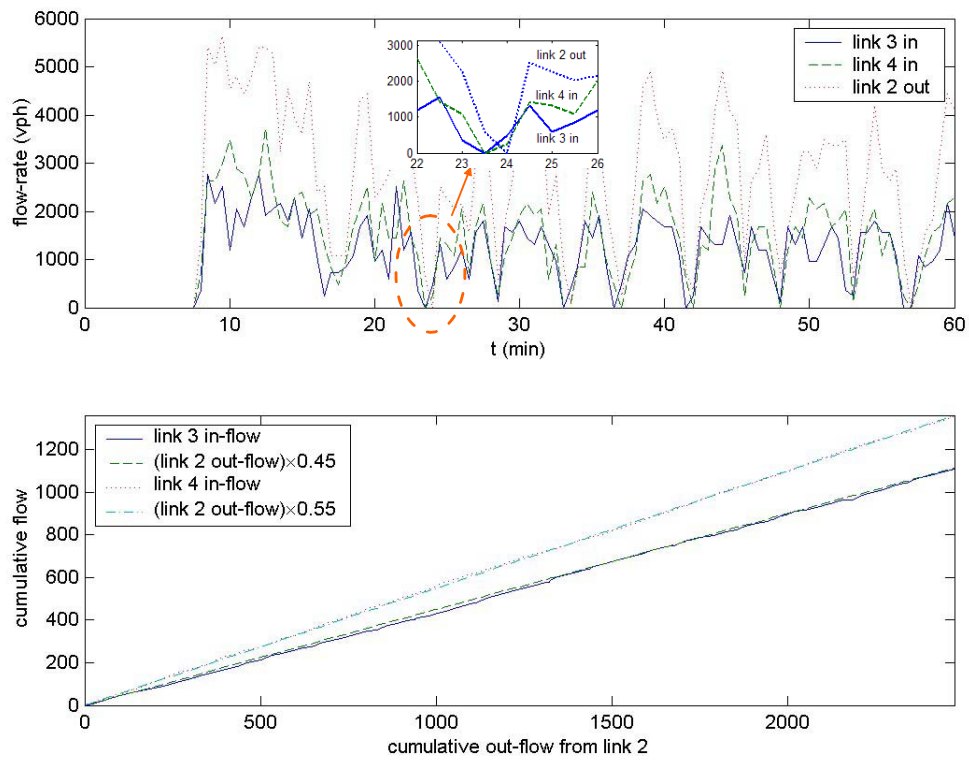


Figure 4. Simulation results around the diverge

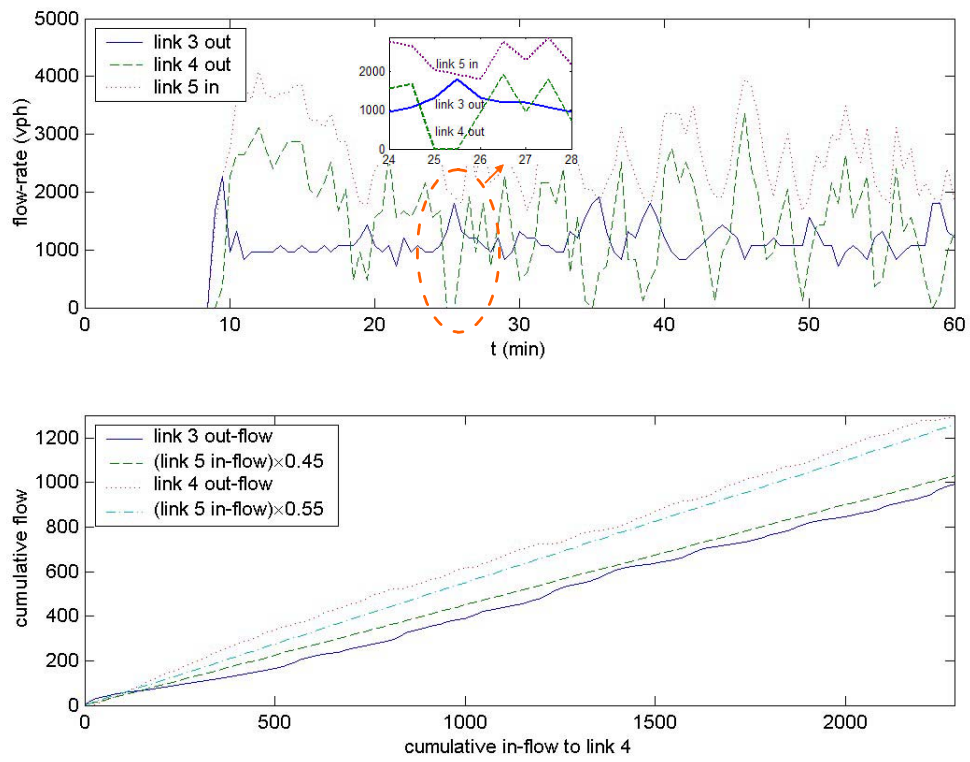


Figure 5. Simulation results around the merge

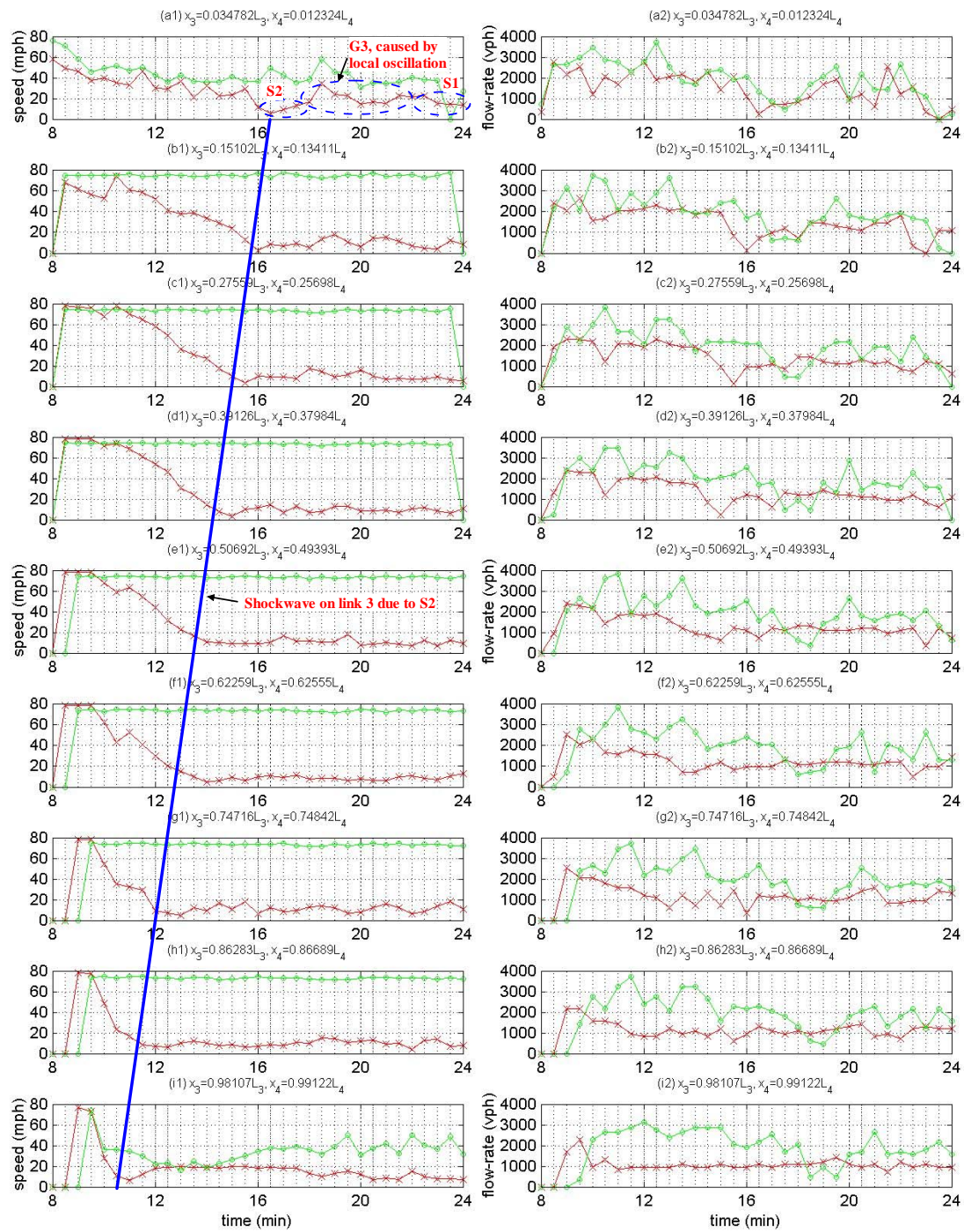


Figure 6. Start of oscillations

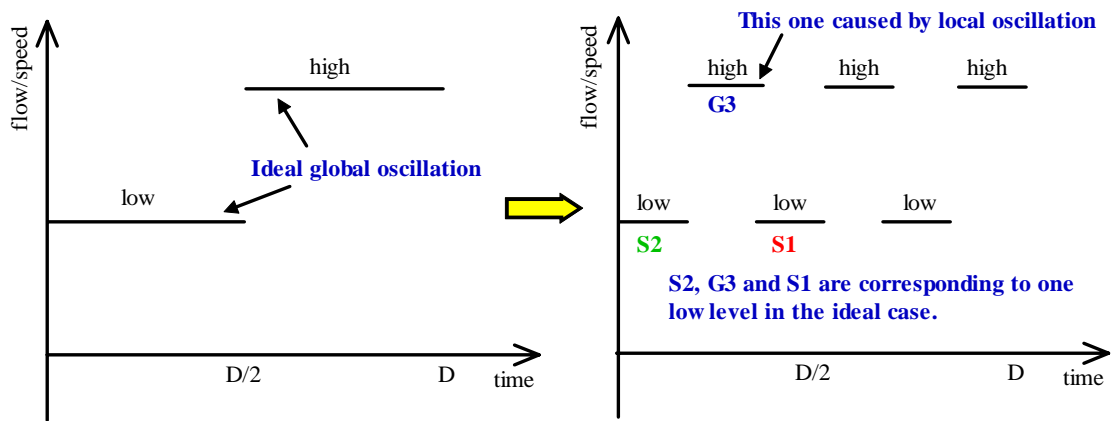


Figure 7. Illustration of three sets of oscillations caused by local ones

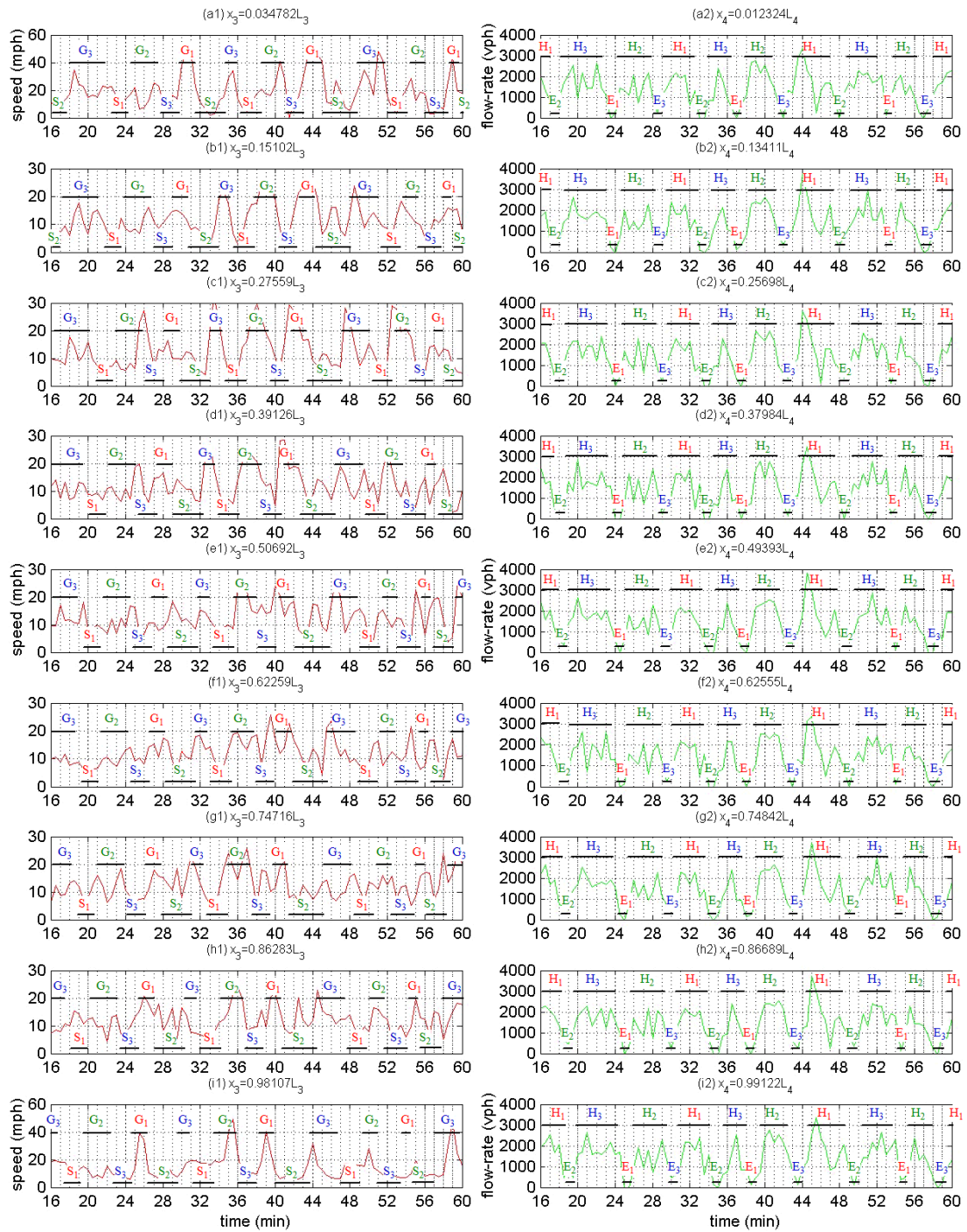


Figure 8. Formation of periodic oscillations

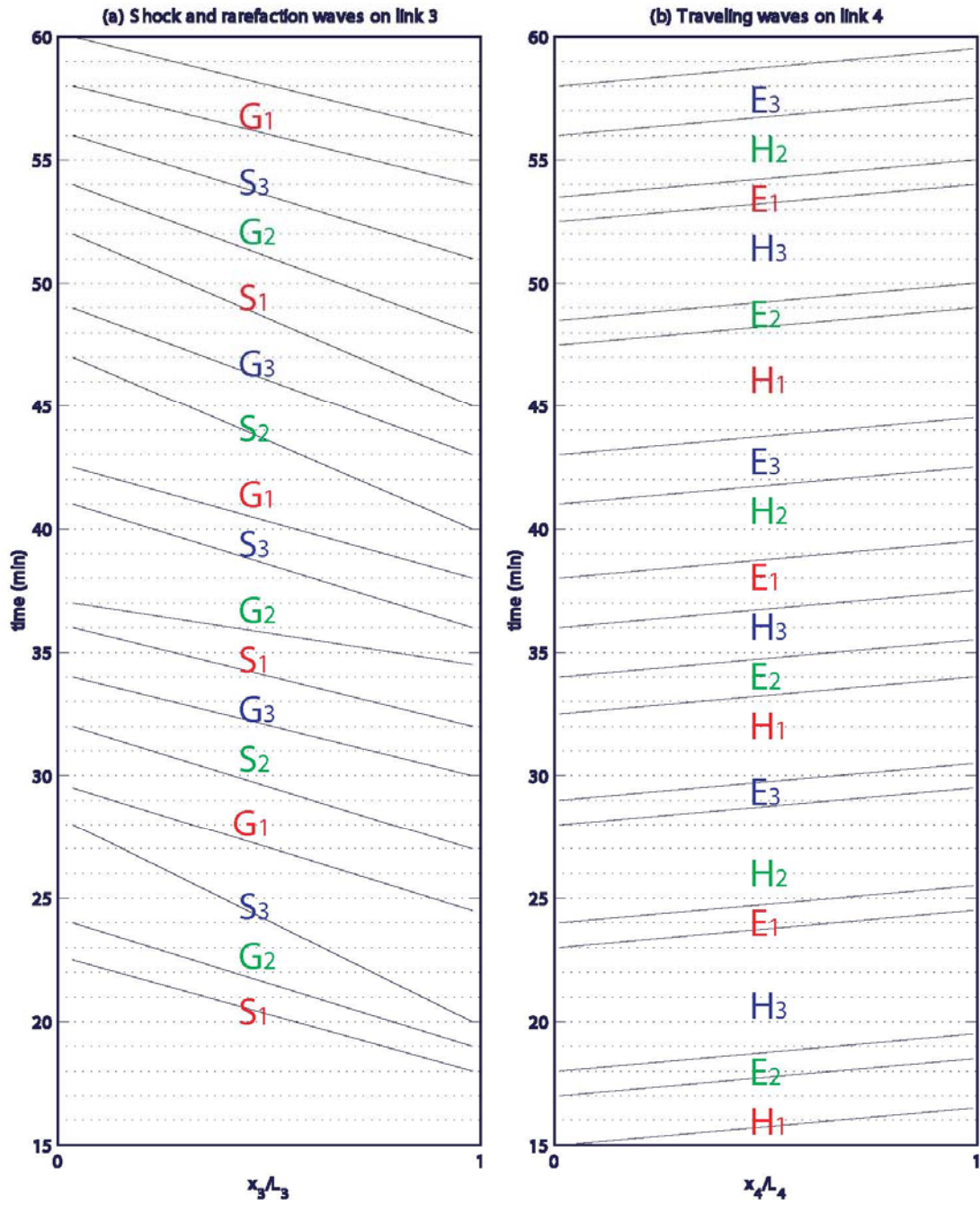


Figure 9. Waves on links 3 and 4 and patterns of oscillations