18 Congested Patterns at Isolated Bottlenecks

18.1 Introduction

Due to phase transitions at an isolated bottleneck discussed in Sect. 17.2.2 and Sect. 17.3.3, a congested pattern can occur upstream of a bottleneck. In the three-phase traffic theory (Chap. 7) and in empirical observations (Chaps. 10 and 12), if only an F→S transition occurs, then one of the SPs should appear. When the sequence of F→S→J transitions occur, then one of the GPs should emerge.

These conclusions of the three-phase traffic theory and of freeway traffic observations are fully confirmed by numerical investigations of both the microscopic CA model and the spatial continuum and discrete-time model based on three-phase traffic theory [329–331]. In addition, based on these models a microscopic theory of the pinch effect in synchronized flow [329,331] as well as a theory of weak and strong congestion [330] have been developed. Results of these theories are in accordance with empirical results [208,213]. Furthermore, based on model simulations we can find possible regions in the diagram of congested patterns where different types of congested patterns can coexist. The latter means that there should be metastable regions of traffic demand where depending on initial local perturbation at the same traffic demand one of various types of congested patterns emerge. These nonlinear effects of congested pattern emergence and metastability at different freeway bottlenecks will be the aims of this chapter.

Firstly, we consider the diagram of congested patterns at isolated on-ramp bottlenecks. Here, we discuss various types of SPs, certain microscopic features of synchronized flow within these congested patterns, and a theory of the pinch effect in synchronized flow that leads to GP emergence. Secondly, strong and weak congestion conditions in congested patterns are discussed. Thirdly, we study the pattern metastability effects at on-ramp bottlenecks. Further, we will study congested patterns, which can occur at a merge bottleneck associated with a reduction of freeway lanes in the flow direction. We will find that only strong congestion can occur in the pinch region of an GP at the merge bottleneck. In contrast to this feature of the merge bottleneck, in the next consideration we will find that only weak congestion can occur in the pinch region of an GP at an off-ramp bottleneck. Finally, we will analyze results of a numerical study of congested pattern capacity at isolated bottlenecks.
on-ramp bottlenecks. A consideration made in this chapter is based on results of [221, 329, 330].

18.2 Diagram of Congested Patterns at Isolated On-Ramp Bottlenecks

18.2.1 Synchronized Flow Patterns

Numerical examples of the diagram of different congested patterns, i.e., the regions of *spontaneous* occurrence of the patterns in the flow–flow plane whose coordinates are $q_{in}$ and $q_{on}$, have already been considered in Sect. 7.5. It has been mentioned that these diagrams are qualitatively similar to the diagram of congested patterns at an on-ramp bottleneck postulated in the three-phase traffic theory (Fig. 7.13).

In particular, there are two main boundaries in this diagram, $F_S^{(B)}$ and $S_L^{(B)}$ (Fig. 18.1a). Below and left of the boundary $F_S^{(B)}$ free flow occurs. Between the boundaries $F_S^{(B)}$ and $S_L^{(B)}$ different SPs emerge on the main road upstream of the on-ramp (Figs. 18.1b–d). There are three types of SPs: (1) widening synchronized flow pattern (WSP), (2) localized synchronized flow pattern (LSP), and (3) moving synchronized flow pattern (MSP). Right of the boundary $S_L^{(B)}$ wide moving jams occur spontaneously in synchronized flow, i.e., different GPs appear (Figs. 18.1e–g).

SPs exhibit the following common characteristic features (Fig. 18.2):

(i) The downstream front of an WSP is fixed at the on-ramp bottleneck (Fig. 18.1b). The upstream front of the WSP is continuously widening upstream. The WSP occurs above the boundary $W$ in the diagram in Fig. 18.1a.

(ii) Below the boundary $W$ an LSP occurs. As in WSP, the downstream front of the LSP is fixed at the on-ramp bottleneck. However, the upstream front of the LSP is localized on the main road at some distance $L_{LSP}$ upstream of the on-ramp bottleneck (Fig. 18.1c).

(iii) At higher $q_{in}$ and a very low $q_{on}$ an MSP can occur rather than WSP. The MSP occurs spontaneously on the main road at the on-ramp bottleneck because at very low $q_{on}$ the downstream front of synchronized flow can depart from the on-ramp bottleneck. The MSP begins to propagate on the main road as an independent localized structure (Fig. 18.1d), as on a homogeneous road (Fig. 7.4). A sequence of MSPs can also occur on the main road at the on-ramp bottleneck (Fig. 18.3).

(iv) The flow rate in an SP is often only slightly lower than the initial flow rate in free flow (Figs. 18.2a,b,e).\(^1\)

\(^1\) This is a very important feature of SPs that will be used for congested pattern control at freeway bottlenecks (Sect. 23.3.2).