Available online at www.sciencedirect.com

ScienceDirect

IFAC-PapersOnLine 49-3 (2016) 159–164

Off-Ramp Blockage on Freeways

Yibing Wang, Yuqi Pang, Xinyao Chen, Yuheng Kan

Institute of Transportation Engineering, Zhejiang University
Hangzhou, China, 310058

wangyibing@zju.edu.cn; sevenpangyuqi@163.com; chenxy_sclz@163.com; kanyuheng@zju.edu.cn

Abstract: Freeway congestion in many cases may spill back for several kilometers, blocking a number of on/off-ramps upstream of the congestion origin. As a result, the total off-ramp flow may substantially reduce, and vehicles bound for the blocked off-ramps are trapped in the mainstream congestion, causing the continuing spillback of congestion that blocks more off-ramps at the further upstream with similar effects and so forth. The off-ramp blockage effect is readily understood and its impact is empirically recognized, but there is a lack of analytical results to provide more insights. In this paper some flow conditions on bottleneck activation are first established, and the mechanism of the off-ramp blockage is theoretically explored. Macroscopic and microscopic simulations are conducted to demonstrate the analytical results obtained. To demonstrate the off-ramp blockage effect in particular, general relations between the total demand, total inflow, total off-ramp outflow, and the number of vehicles within the considered freeway system is examined in simulation. This work can shed some light on a side of traffic network dynamics that was not given enough attention before.

Keywords: freeway network, bottleneck, shockwave, off-ramp blockage.

1. INTRODUCTION

From a system point of view, traffic operation in a road network is a game between the traffic demand and network supply, with the outcome reflected in the resulting network traffic conditions and outflows. When the total demand is less than the network capacity, the total outflow is equal to the total demand, in spite of some time delay between the inflows and outflows. When the total demand exceeds the network capacity, congestion sets in and the outflows decline. If the total inflow is further increased, the number of vehicles in the network increases, which in turn decreases the network outflows even more (Geroliminis, 2008 and Geroliminis, 2011). Some works are briefly reviewed on this global image of network traffic dynamics. Daganzo (2005) modeled an urban system as a set of interconnected reservoirs, and investigated the effect of gridlock on urban mobility. Arnott (2013) proposed a bathtub model, in which water flowing into the bathtub corresponds to cars entering the traffic stream, water flowing out of the bathtub to cars exiting from the traffic stream, and the height of water in the bathtub to traffic density. The idea of applying some fundamental-diagram-alike “device” to the analysis of traffic conditions of an urban network was long conceived, but only in the recent years, some strong evidence for implementing the idea was found (Geroliminis, 2008 and Geroliminis, 2011). For freeway networks, Papageorgiou (1997) studied the relation between the total time spent by drivers and total exit flow. Daganzo (1996) examined the gridlock problem for a city ring road. Using macroscopic fundamental diagrams, Haddad, et. al. (2012) studied traffic control of a mixed network of both arterial roads and freeways. In these works, the total exit flow of the addressed networks is of a major interest.

The total exit flow of a road network, representing the network productivity, is an important performance metric of network operation. In an early report, Papageorgiou (1997) proved that the total time spent by all drivers in an isolated freeway system is linearly related to a weighted sum of the exit flows. In a later report, he demonstrated that a traffic control measure is beneficial for the whole driver population if it facilitates the increase of the total network exit flow. In other words, increasing the total exit flow serves to attenuate traffic congestion in the network. This paper focuses on the issue of freeway off-ramp blockage, which can be seen as a specific example as to how the performance of a freeway network deteriorates with the decrease of the total exit flow due to congestion.

Normally freeway congestion is initiated at a bottleneck such as an on-ramp, a tunnel, or an incident location. In many cases, congestion may spill back for several kilometers, blocking a number of on/off-ramps upstream of the bottleneck. This causes the off-ramp blockage; that is, flows exiting from the off-ramps that are dominated by the mainstream congestion substantially reduce. As a consequence, vehicles bound for the blocked off-ramps are trapped in the mainstream congestion, contributing to the further spillback of congestion that blocks more off-ramps at the further upstream with similar effects and so forth. The off-ramp blockage can cause severe infrastructure degradation. In fact, a lasting and unendurable congestion in a freeway network during a peak period may not necessarily be due to the total arriving demand much exceeding the total capacity. Instead, an initial congestion spills back and its propagation can be accelerated and intensified with the consecutive occurrence of the off-ramp blockage. Eventually, the formed congestion may cover a

Peer review under responsibility of International Federation of Automatic Control.
10.1016/j.ifacol.2016.07.027

significant part of the freeway and even spill over to other freeways. It should be emphasized that the off-ramp blockage under discussion is caused by congestion in the freeway mainstream rather than congestion spillback from an arterial road at the downstream of the off-ramp (see e.g. Spiliopoulou, et. al. 2014).

Although off-ramp blockage is readily understood and the resulting impact has been empirically recognized by some researchers, it was only discussed in a couple of papers. Papageorgiou (2009) addressed off-ramp blockage while dealing with ramp metering. Recently Iordanidou (2015) mentioned the same issue to the end of variable speed limit control. This paper addresses the theoretical exploration and simulation demonstration of the off-ramp blockage issue. The rest of the paper is organized as follows. Section 2 examines flow conditions on bottleneck activation and explores the mechanism of off-ramp blockage. To demonstrate the theoretical results, both macroscopic and microscopic simulations were conducted with typical results presented in Section 3. Section 4 concludes the paper.

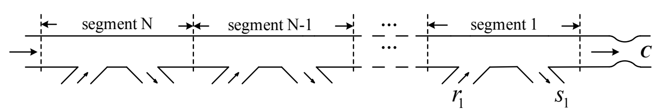

Fig. 1 A freeway stretch with a bottleneck.

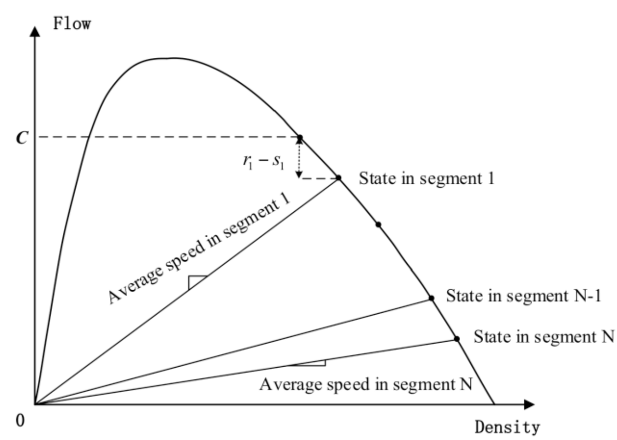

Fig. 2 A fundamental diagram illustration of congestion propagation in an idealized case (Cassidy and Mauch, 2001).

2. THEORETICAL ANALYSIS

In this section some general conditions on bottleneck activation are first developed to set a basis for the subsequent theoretical discussion of the off-ramp blockage issue.

2.1 Flow conditions for bottleneck activation and congestion propagation

With reference to Fig. 1, if a queue forms at the bottleneck due to overflowing and the resulting shockwave propagates backward over the entire freeway stretch, then the flows on all segments would be constrained by the bottleneck capacity. As suggested by Newell (1993) and Cassidy (1999), if the ramp inflow exceeds the ramp outflow in each segment (Fig. 1), the flow of a segment can be simply determined by the flow of its immediately downstream segment minus the net ramp inflow there. As illustrated in Fig. 2, each reduction in queued flow that occurs over space is accompanied by a rise in density. This means that densities in a long freeway queue that are highest at its tail and get smaller over space towards each successive downstream segment. However, since there is no guarantee that every segment would have a net ramp inflow, the picture of Fig. 2 is not always valid. In what follows, we establish some general conditions on bottleneck activation and congestion propagation.

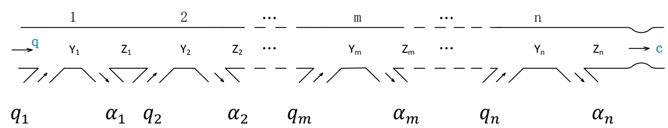

Fig. 3. A freeway stretch with a downstream bottleneck: the no congestion case.

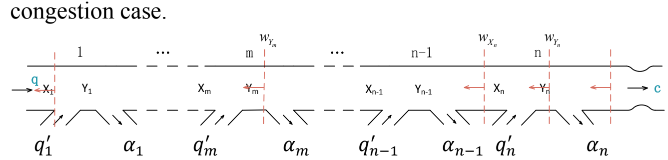

Fig. 4. A freeway stretch with a downstream bottleneck: the congestion case.

Fig. 3 displays a freeway stretch including n couples of on/off-ramp and a bottleneck at its downstream end. The upstream demand is q, the on-ramp inflows are q_m ($m = 1, 2, \dots, n$), the exit rates at the off-ramps are $0 \le \alpha_m \le 1$ ($m = 1, 2, \dots, n$), and the bottleneck capacity is C. For the m-th couple of on/off-ramps, denote the location between the on-ramp and off-ramp as Y_m, and the location right downstream of the off-ramp as Z_m; denote the mainstream flows at these locations as Q_{Y_m} and Q_{Z_m}. Then, the condition on bottleneck activation is:

$$q \prod_{i=1}^{n}(1-\alpha_i) + \sum_{i=1}^{n} q_i \prod_{j=i}^{n}(1-\alpha_j) > C \qquad (1)$$

Notice that

$$Q_{Y_1} = q + q_1 \qquad (2)$$

$$Q_{Z_1} = Q_{Y_1}(1-\alpha_1) = q(1-\alpha_1) + q_1(1-\alpha_1) \qquad (3)$$

$$Q_{Y_2} = Q_{Z_1} + q_2 = q(1-\alpha_1) + q_1(1-\alpha_1) + q_2 \qquad (4)$$

$$Q_{Z_2} = Q_{Y_2} \cdot (1-\alpha_2) = q(1-\alpha_1)(1-\alpha_2) + q_1(1-\alpha_1)(1-\alpha_2) + q_2(1-\alpha_2) \qquad (5)$$

By simple induction, we then have for $2 \le m \le n$,

$$Q_{Y_m} = q \prod_{i=1}^{m-1}(1-\alpha_i) + \sum_{i=1}^{m-1} q_i \prod_{j=i}^{m-1}(1-\alpha_j) + q_m = \frac{q \prod_{i=1}^{m}(1-\alpha_i) + \sum_{i=1}^{m} q_i \prod_{j=i}^{m}(1-\alpha_j)}{1-\alpha_m} \qquad (6)$$

And for $1 \le m \le n$,

$$Q_{Z_m} = Q_{Y_m} \cdot (1-\alpha_m) = q \prod_{i=1}^{m}(1-\alpha_i) + \sum_{i=1}^{m} q_i \prod_{j=i}^{m}(1-\alpha_j) \qquad (7)$$

Then, condition (1) reads: $Q_{Z_n} > C$.

With reference to Fig. 4, assume that (1) is satisfied and congestion propagates backward over the entire stretch of freeway. Also, denote by X_m the location right upstream of on-ramp m. Comparing the congestion case (Fig. 4) to the congestion-free case (Fig. 3), we see two differences. First, no distinction is made in Fig. 3 on q_i ($m = 1, 2, \dots, n$) between on-ramp demands or inflows, since there is no congestion. In