Transportation Research Part B 77 (2015) 88–102

Contents lists available at ScienceDirect

Transportation Research Part B

journal homepage: www.elsevier.com/locate/trb

Impact of stop-and-go waves and lane changes on discharge rate in recovery flow

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ARTICLE INFO

Article history:
Received 14 October 2014
Received in revised form 23 March 2015
Accepted 24 March 2015
Available online 11 April 2015

Keywords:
Capacity drop
Lane change
Stop-and-go wave
Discharge rate
Asymmetric traffic flow theory

ABSTRACT

In an effort to uncover traffic conditions that trigger discharge rate reductions near active bottlenecks, this paper analyzed individual vehicle trajectories at a microscopic level and documented the findings. Based on an investigation of traffic flow involving diverse traffic situations, a driver's tendency to take a significant headway after passing stop-and-go waves was identified as one of the influencing factors for discharge rate reduction. Conversely, the pattern of lane changers caused a transient increase in the discharge rate until the situation was relaxed after completing the lane-changing event. Although we observed a high flow from the incoming lane changers, the events ultimately caused adverse impacts on the traffic such that the disturbances generated stop-and-go waves. Based on this observation, we regard upstream lane changes and stop-and-go waves as the responsible factors for the decreased capacity at downstream of active bottlenecks. This empirical investigation also supports the resignation effect, the regressive effect, and the asymmetric behavioral models in differentiating acceleration and deceleration behaviors.

1. Discharge rate reduction near active bottleneck

Sudden and pronounced declines in discharge rates accompanied by the activation of bottlenecks have long been observed worldwide (Hall and Agyemang-Duah, 1991; Hall et al., 1992; Ringert and Urbanik, 1993; Cassidy, 1998; Chung et al., 2007) and have been the subject of traffic modeling efforts (Laval and Daganzo, 2006; Siebel et al., 2009; Leclercq et al., 2011; Srivastava and Geroliminis, 2013). Even in the absence of any physical block downstream of a bottleneck, 2–16% reductions in the discharge rate are commonly observed at isolated freeway bottlenecks (Oh and Yeo, 2012). This phenomenon has long been a subject of interest for many transportation researchers.

One of the first studies that reported on this capacity loss was carried out by Edie and Foote (1958), who studied the outflow from New York City's Lincoln Tunnel. Edie and Foote observed 16% reductions in the discharge rate with the activation of a bottleneck inside the tunnel. They postulated that the capacity drop could be prevented by controlling the inflow to the tunnel. To evaluate this postulation, Edie and Foote controlled the inflow to the tunnel, and the findings from their experiment supported their hypothesis. Some later studies argued that the capacity drop could be an inherent result of a discontinuity embedded in the "reverse-λ" shape flow-density relationship (Koshi et al., 1983; Greenshields, 1935; Hall and Agyemang-Duah, 1991; Hall et al., 1992; Ringert and Urbanik, 1993; Cassidy, 1998).

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http://dx.doi.org/10.1016/j.trb.2015.03.017

These earlier studies, however, did not fully provide a precursor state that can be monitored and signal for the capacity drop. To understand the mechanism by which some portion of the capacity is lost, a micro-level discussion is required because the capacity drop is closely linked with other traffic phenomena such as traffic breakdowns, stop-and-go traffic, and traffic instability. Traffic breakdown refers to the transition from free flow to congestion; immediately afterward, a drop in capacity can be observed downstream of the active bottleneck. After the breakdown, stop-and-go traffic is frequently observed as a repeated pattern of deceleration-acceleration inside a congestion region. It often begins around a merging location near an active bottleneck point and influences capacity drop. The traffic instability issue is also related to both traffic breakdown and stop-and-go traffic. Capacity drop, which involves these microscopic traffic issues, is strongly related to driver behavior (Saifuzzaman and Zheng, 2014).

There have been numerous studies that attempted to explain traffic phenomena related to capacity drop. To address the mechanism of traffic breakdown and traffic instability, Kerner and Rehborn (1996a, 1996b) introduced the concept of "spontaneous breakdown" caused by drivers overreacting to deceleration under unstable traffic conditions and argued that it was one of the contributing factors of capacity drop. However, Daganzo et al. (1999) and Ahn and Cassidy (2007) contended that the spontaneous breakdown theory for both formation and growth of oscillation was limited to minor cases and that traffic breakdown was primarily triggered by lane-changing events. More recently, Zheng et al. (2011a) demonstrated the capabilities of wavelet transform in analyzing bottleneck traffic. By identifying the origins of oscillations through a wavelet transform on NGSIM data (in case of US 101 – uphill segment), Zheng et al. (2011b) found that approximately 34% of a traffic wave was triggered by lane changing while the remainder (66%) was generated by traffic instability. Moreover, detailed studies on driving behavior convinced that the instability can be one of the major factors inducing traffic oscillations (Chen et al., 2012a). As for the primary factor for stop-and-go wave generation, it appeared that both traffic instability and lane-changing maneuvers influenced this wave generation.

Daganzo (2002) explained traffic breakdown by using a behavior theory with two different behaviors. He sought to explain this traffic phenomenon by assuming that drivers fall into two distinct classes—rabbits (aggressive drivers with higher free-flow speed) and slugs (timid drivers with lower free-flow speed). Daganzo proposed that the rabbits and slugs would remain separated while the traffic was freely flowing and that the rabbits would change their lanes to the slugs' lane when a queue began to form in their lane. This migration of rabbits to the slugs' lane could trigger the onset of congestion as well as capacity drop. Chung (2004) also reported evidence of lane changing contributing to capacity drop from different types of bottlenecks. Chung found a strong link between a capacity drop and the number of vehicles in the vicinity of a bottleneck. His findings indicated that although the sequence of events leading to a capacity drop may have differed among bottlenecks, the number of vehicles in the vicinity of the bottleneck triggering the capacity drop were reproducible at each site. These findings were further confirmed by Cassidy and Rudjanakanoknad (2005) and Chung et al. (2007). Laval and Daganzo (2006) explained capacity drop with a hybrid model that created a void between an incoming vehicle from an adjunct lane and the leading vehicle in the existing lane. The hybrid model suggested that the void was caused by the acceleration performance limitation and maximum speed capability of the lane changer. The authors ascribed the cause of the capacity drop to this void, which was an additional headway to the normal headway. For validation, Laval et al. (2005) compared the travel times, the number of lane-changing maneuvers, and the capacity drop observed from empirical data with the results of a simulation based on the hybrid model. The results showed a positive relationship between the number of lane changes and the capacity drop and a mitigation effect of on-ramp metering on lane changes and the shoulder lane's queue. Their study reported consistency between the simulation and the empirical data. Laval and Leclercq (2008) and Leclercq et al. (2011) subsequently adopted and extended the theory. Leclercq et al. (2011) proposed an analytical model of the capacity drop at merges with an extension of the Newell–Daganzo model. This model incorporated the merging mechanism described in the hybrid model in Laval and Daganzo (2006). The theory explains the impact of slow lane changers on the reduction of traffic efficiency for active bottlenecks in merging areas, particularly for outer lanes.

We should also consider other explanations for the reduction in discharge rate. Newell (1962) used two distinct driver behaviors in acceleration and deceleration that assumed that the spacing in the acceleration state was larger than that in the deceleration state. Daganzo et al. (1999) explained transition curves by using a simple Markovian model for traffic behavior caused by disturbances with the flow-density plane. They demonstrated the potential explanatory power of asymmetric traffic theory. As for this theory, Yeo (2008) and Yeo and Skabardonis (2009a) developed an asymmetric driving behavior theory consisting of five phases that considered changes in gap acceptance among drivers with respect to the passage of kinematic waves. The drivers changed their gap acceptance pattern from aggressively short spacing in the deceleration state (D-state) to a less aggressive pattern with larger spacing in the acceleration state (A-state), as shown in Fig. 1. Furthermore, Laval and Leclercq (2010) incorporated different driver characteristics (aggressive and timid branches) and proposed a parsimonious theory that extended Newell's car-following model to explain traffic oscillations. Through a simulation study, Laval and Leclercq concluded that two different drivers' behaviors in reaction to a deceleration wave can explain traffic oscillations, thus explaining capacity drop from the driver's behavioral perspective. The asymmetric behavioral model was enhanced by Chen et al. (2012a) capturing the non-equilibrium behavior. Using the model, the authors revealed the feature of hysteresis in Chen et al. (2012b). Treiber et al. (2006) empirically observed two distinct behaviors from Dutch A9 and compared time gaps in two speed regimes by using single-vehicle data. Based on observations showing a larger time gap in the free-flow speed regime than in the congested regime, the authors ascribed the capacity drop to a resignation effect by providing a theoretical explanation of human aspects related to driving behavior. In addition, the driver tendency of decreased accelerations and increased time gaps after passing congested traffic (resignation effect) resulted in a