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Driver relaxation impacts on bottleneck activation, capacity, and the fundamental relationship ☆

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ABSTRACT

This study examines traffic behavior in the vicinity of a freeway bottleneck, revisiting commonly held assumptions and uncovering systematic biases that likely have distorted empirical studies of bottleneck formation, capacity drop, and the fundamental relationship (FR). This simulation-based study examines an on-ramp bottleneck using Newell's lower order car following model with a driver relaxation factor added for the vehicles that enter or are immediately behind an entering vehicle (termed "affected vehicles"). The affected vehicles will tolerate a truncated headway for a little while after an entrance but slowly relax back to their preferred speed–spacing relationship. All other vehicles remain on their preferred speed–spacing relationship throughout.

Simulating conventional detector measurements, we show that flow is supersaturated in any sample containing an affected vehicle with a truncated headway, i.e., the flow is higher than the underlying FR would predict. This systematic bias is not readily apparent in the detector measurements, during the initial queue formation speeds remain close to free speed and the supersaturated states can exceed the bottleneck capacity. As the affected drivers relax, the high flows become unsustainable so a queue initially forms downstream of the on-ramp (consistent with earlier empirical results) only later receding upstream past the on-ramp. This initial phase of activation often lasts several minutes. Without any evidence of queuing upstream of the ramp, the conventional point bottleneck model would erroneously indicate that the bottleneck is inactive. Thus, an empirical study or traffic responsive ramp meter could easily mistake the supersaturated flows to be the bottleneck's capacity flow, when in fact these supersaturated flows simply represent system loading during the earliest portion of bottleneck activation. Instead of flow dropping "from capacity", we see flow drop "to capacity" from supersaturation. We also discuss how the supersaturated states distort empirically observed FR. We speculate that these subtle mechanisms are very common and have confounded the results of many past empirical studies.

1. Introduction

Empirical bottleneck studies are encumbered with the difficult challenge of simultaneously measuring *bottleneck capacity* (BCap), identifying the time that the bottleneck becomes active (i.e., starts restricting flow), and establishing where the bottleneck actually forms. In this paper we show that an on-ramp bottleneck's activation may occur several minutes earlier than

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conventional bottleneck models would detect, and that unsustainably high flows after the true activation time could easily be mistaken for BCap, leading to an overestimate of capacity. In the present case these discrepancies arise due to driver relaxation, whereby a driver will accept a short headway for some time (often 20 s or more, e.g., Smith, 1985) so that they can enter a lane that is constrained by downstream conditions and then will slowly "relax" to their preferred headway (e.g., Newman, 1963; Cohen, 2004; Leclercq et al., 2007; Wang and Coifman, 2008; Xuan and Coifman, 2012). Likewise, the driver immediately behind an entrance will slowly relax in response to their newly shortened headway. Of course average headway is the reciprocal of flow, q, so as drivers relax q should drop.

Typically BCap is defined as the highest sustained throughput and it is usually observed immediately prior to activation. Many researchers have observed a *capacity drop* where discharge flow drops immediately after the bottleneck becomes active (e.g., Banks, 1990; Hall and Agyemang-Duah, 1991; Persaud et al., 1998; Cassidy and Bertini, 1999; Zhang and Levinson, 2004; Chung et al., 2007; Duret et al., 2010; Leclercq et al., 2011). Several studies have stressed the importance of measuring BCap downstream of the bottleneck to avoid including demand in excess of capacity upstream of a growing queue and doing so without any intervening ramps to ensure that the entire throughput is measured (e.g., Hurdle and Datta, 1983; Hall and Agyemang-Duah, 1991; Cassidy and Bertini, 1999). Most contemporary studies employ the point bottleneck model, wherein the bottleneck process is assumed to occur over a negligible distance along the roadway (e.g., Daganzo, 1997; Zhang and Levinson, 2004). In this case an active bottleneck is defined as a point on the network with queuing upstream and unqueued conditions downstream (see, e.g., Bertini and Leal, 2005). A few studies model the bottleneck process over space, either by assuming multiple point bottlenecks (e.g., Banks, 1989; Hall and Hall, 1990) or that the bottleneck process itself occurs over an extended distance (e.g., Hurdle and Datta, 1983; Hall et al., 1992; Coifman and Kim, 2011). There are also many different techniques used to determine when a bottleneck is active:

[$a1$] some studies look for a speed drop upstream of the bottleneck, indicative of queuing (e.g., Banks, 1990; Hall and Agyemang-Duah, 1991);

[$a2$] some look for a positive correlation between flow and occupancy, indicative of the traffic state falling in the unqueued regime of the fundamental relationship (e.g., Hall and Agyemang-Duah, 1991). Both $a1$ and $a2$ have latency, requiring the queue to grow back to the detection location before the queuing can be detected;

[$a3$] More recently Cassidy and Bertini (1999) used rescaled cumulative arrival curves to construct a queuing diagram and measure accumulation between detector stations (thus identifying queuing before the queue reaches a detector station) and verified that the locally observed conditions at the stations were consistent with $a1$ and $a2$.

Most bottleneck studies do not account for driver relaxation and this paper seeks to demonstrate that driver relaxation is an important factor that can confound the results of empirical studies if it is not accounted for. We argue that if drivers are perpetually entering the freeway from an on-ramp, then the maximum sustainable throughput should drop as a function of distance downstream of the on-ramp due to driver relaxation. Although throughput becomes more constrained as drivers relax, traffic downstream of the on-ramp should be traveling at or near free speed, v_f, even after this relaxation starts limiting throughput. The simulations presented herein show that this relaxation process can extend at least 1.8 mi downstream of the on-ramp, much further beyond the ramp than most empirical studies contemplate. The initial period of activation is characterized by very minor accumulations downstream of the on-ramp that are below the sensitivity of $a1$–$a3$. Then as congestion worsens, these downstream accumulations dissipate as the queue moves largely upstream of the on-ramp. A detailed discussion of these impacts will be presented in Section 3. Needless to say, this view implicitly assumes that the on-ramp bottleneck process occurs over an extended distance and should not be modeled as a single point bottleneck.

A few empirical studies have explicitly considered driver relaxation at on-ramps and support the general need to account for driver relaxation. Cohen (2004) demonstrated that applying different sensitivity values into the existing FRESIM model to account for the relaxation process can yield better consistency with field data compared to the un-relaxed procedure. Leclercq et al. (2007) studied an on-ramp that was subject to queuing from a downstream bottleneck and found impacts from driver relaxation similar to those that we find herein when the on-ramp is the source of the bottleneck (Laval and Leclercq, 2008, subsequently developed a model of Leclercq et al.'s observations). Daamen et al. (2010) found evidence of driver relaxation at an on-ramp bottleneck, but only undertook a detailed study of the vehicles in the merge area while the relaxation process extended beyond the downstream end of their study segments.

1.1. Overview

The remainder of this paper is as follows. Section 2 reviews the underlying models used in the study. We seek the simplest model that can demonstrate the effects, and to this end we extend the lower order car following model by Newell (2002) to include driver relaxation for those affected drivers directly involved with an entrance maneuver (an entering driver or the driver immediately behind an entering vehicle). Section 3 uses simulation to investigate the systematic impact of driver relaxation at an on-ramp bottleneck on a one-lane freeway. As such, we explicitly exclude other important factors, e.g., lane change maneuvers within the bottleneck (Coifman et al., 2003; Laval and Daganzo, 2006; Duret et al., 2010; Coifman and Kim, 2011). So the present work should not be viewed as a complete model of the very complicated bottleneck process, rather, these results are intended to highlight the impacts of what we believe to be an important factor that has previously gone largely overlooked. The paper closes with a discussion in Section 4 and conclusions in Section 5.