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Stochastic modeling of breakdown at freeway merge bottleneck and traffic control method using connected automated vehicle

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ABSTRACT

This paper proposes a novel breakdown probability model based on microscopic driver behavior for a freeway merge bottleneck. Extending Newell's car following model to describe the transition from free-flow to congested regimes, two elements of breakdown, *trigger* and *propagation*, are derived in terms of vehicle headway. Combining these elements, a general breakdown probability is derived in terms of various parameters related to driver behavior and traffic conditions – other than flow – that can be treated as constants or stochastic with probability distributions. The proposed model is validated with real data. It was found that the theoretical breakdown probability distribution accords well with the empirical counterpart within reasonable ranges of parameter values. Our model suggests that the breakdown probability (i) increases with flow (both mainline and merging) as expected, and the merging spacing, (ii) decreases with the merging speed and aggressive driver characteristics, and interestingly, (iii) increases with the deviation in headway. A proactive traffic control method to achieve uniform headway is developed considering low penetration rates of connected automated vehicle technologies.

1. Introduction

Traffic breakdown is one of the most significant issues in traffic science and engineering. Numerous empirical studies show that traffic breakdown is often accompanied by the capacity-drop phenomenon, in which bottleneck discharge rates diminish significantly (5–25%) after the onset of congestion (Banks, 1991; Bertini and Leal, 2005; Cassidy and Bertini, 1999; Cassidy and Rudjanakanoknad, 2005; Hall and Hall, 1990; Leclercq et al., 2016, 2011; Maggi et al., 2015; Yuan et al., 2015, 2014). To prevent or remedy traffic breakdown and the ensuing capacity drop, various traffic control strategies have been developed. Variable speed limit (VSL) control is one of the promising methods (e.g., Carlson et al., 2010a; D. Chen et al., 2014a; Chen and Ahn, 2015; Hegyi et al., 2008; Hegyi and Hoogendoorn, 2010), and novel extensions have been developed exploiting the emerging connected vehicle (CV) or connected automated vehicle (CAV) technologies (Grumert et al., 2015; Han et al., 2017; Hegyi et al., 2013; Müller et al., 2016). Through speed limitation, VSL control regulates inflow into a bottleneck (or a moving jam) below its capacity to prevent/resolve traffic breakdown and capacity drop. Similarly, ramp metering (RM) strategies are widely implemented to control merging flows via freeway on-ramps to prevent or minimize traffic breakdown (Kan et al., 2016; Kerner, 2007; Kotsialos and Papageorgiou, 2004; Papageorgiou et al., 1991; Papamichail et al., 2010).

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Nomenclature

Speed

u	free flow speed
v_{in}	merging speed
v_{tr}	triggered speed by traffic disturbance for following vehicle

Spacing

$S_F^*(v)$	equilibrium spacing at speed v for following vehicle
$S_M^*(v)$	equilibrium spacing at speed v for merging vehicle
s_F	observed spacing between following and merging vehicles at merge
s_M	observed spacing between merging and leading vehicles at merge
$s_M(u)$	observed spacing between merging and leading vehicles after the merging vehicle accelerates to u

Time

t_a	necessary time to accelerate from v_{in} to u for merging vehicle
t_d	necessary time that the spacing between merging and leading vehicles reaches to $S_M^*(u)$
t_{in}	duration of travel at v_{in} for merging vehicle
t_{tr}	duration of travel at v_{tr} for following vehicle
t_M	interval between merge

Headway (Time headway)

h	headway between leading and following vehicles before merge in free flow state
h_i	observed headway between vehicle i and its leading vehicle
b_i	buffer headway (time that h_i is larger than minimum headway) for vehicle i
h_{cr}	critical headway between leading and following vehicle that the merge does not affect to the following vehicle
h_{I}, h_{II}, h_{III}	bound headways between leading and following vehicle for each trigger type

Combined strategies of VSL and RM have also been developed to increase control efficiency (Carlson et al., 2010b; Hegyi et al., 2005; Lu et al., 2011; Papamichail et al., 2008).

A critical parameter for many traffic control strategies, particularly model-based strategies, is bottleneck capacity, which can vary by various traffic features (Banks, 1991; Brilon et al., 2005; Elefteriadou et al., 1995; Evans et al., 2001; Hall and Agyemang-Duah, 1991; Lorenz and Elefteriadou, 2001; Ozguven and Ozbay, 2008; Persaud et al., 1998; Shiomi et al., 2011; Xie et al., 2014). Therefore, when the control scheme is developed based on the constant (deterministic) bottleneck capacity, it has the latent possibility of capacity underutilization if the control is too conservative, or control failure if too aggressive. Several studies suggested remedies to deal with uncertainty in bottleneck capacity, which can be largely divided into two categories: referred to as “proactive” vs. “reactive” strategies in this paper. Proactive strategies attempt to prevent traffic breakdown at freeway bottlenecks (and thus capacity drop). For example, Carlson et al. (2011, 2010a, 2010b) developed mainstream traffic flow control (MTFC) schemes of VSL and/or RM. These methods use the parameter, “critical bottleneck density”, which is observed to be more stable than the bottleneck capacity (Papageorgiou et al., 2008). Furthermore, Carlson et al. (2011) proposed a local-feedback scheme to further optimize bottleneck operations. Hegyi et al. (2005) applied a model predictive control (MPC) framework to predict network evolution based on the current traffic state. They showed that the VSL control with MPC can prevent congestion in coordination with RM.

With reactive strategies, control is actuated after the occurrence (or confirmation) of congestion or a jam to maximize the bottleneck discharge rate. For example, Kerner (2007) introduced “congested pattern control approach (ANCONA)” based on the three-phase traffic theory (Kerner, 2004), where traffic at a bottleneck is initially allowed to enter congestion, more specifically “synchronized” state, but then is controlled via RM to prevent emergence of wide-moving jams and recover a free-flow state. D. Chen et al. (2014a) developed VSL schemes for both steady and oscillatory queues near fixed freeway bottlenecks. In their control framework, the first VSL control is imposed upstream of a bottleneck to resolve the existing queue around the bottleneck, and the second less restrictive VSL is followed to dissipate the controlled queue induced by the first VSL and to regulate the inflow to the bottleneck. Similar but more efficient VSL strategies were developed by Han et al. (2017), considering the CV technology. They also developed an adaptive scheme to resolve possible control failures and restore the maximum stable discharge rate. Considering greater uncertainty in non-recurrent bottleneck capacity, Chen and Ahn (2015) suggested an upward correction strategy - gradual parameter increases for bottleneck capacity, and imposing additional VSL control for the case of underestimation (i.e., control failure). Since breakdown is allowed to occur with reactive strategies, the system presumably has a better sense of the uncertainty in bottleneck capacity. Furthermore, they are able to remedy control failures, and thus, control parameters can be set more aggressively. However, it could take some time to resolve existing congestion and incur significant delays if the control is not actuated timely.