Transportation Research Part C 62 (2016) 171–181

Contents lists available at ScienceDirect

Transportation Research Part C

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

Capacity drops at merges: New analytical investigations

Ludovic Leclercq [a,b,c,*], Victor L. Knoop [d], Florian Marczak [a,b,c], Serge P. Hoogendoorn [d]

[a] *Université de Lyon, Lyon, France*
[b] *IFSTTAR, LICIT, Bron, France*
[c] *ENTPE, LICIT, Vaulx-en-Velin, France*
[d] *Delft University of Technology, Stevinweg 1, Delft, The Netherlands*

ARTICLE INFO

Article history:
Received 31 March 2015
Received in revised form 19 June 2015
Accepted 30 June 2015
Available online 16 July 2015

Keywords:
Active bottleneck
Capacity drop
Freeway merge
Kinematic wave
Heterogeneous vehicles

ABSTRACT

This paper focuses on the derivation of analytical formulae to estimate the effective capacity at freeway merges. It extends previous works by proposing a generic framework able to account for (i) heterogeneous vehicle characteristics and (ii) refined description of the physical interactions between upstream waves and downstream voids created by inserting vehicles within the merge area. The provided analytical formulae permit to directly compute the capacity values when the merge is self-active, i.e. when both upstream roads are congested while downstream traffic conditions are free-flow. They show that accounting for vehicle heterogeneity is not necessary when only the mean capacity is targeted. Calculations with the proper mean value for all parameters provide almost the same results as calculations that consider the full distributions for all parameters. This means that calibrating all distributions is not necessary only the mean parameter values are important. Finally, this paper also shows that vehicle heterogeneity plays a major role in the flow dynamics just upstream of the merge.

1. Introduction

Determining the effective merge capacity, i.e. the maximum flow that can be observed just downstream of freeway merges, is crucial for traffic operations. This is not only important for simulation purpose but also to develop better control strategies. Effective capacity is referred in some papers as the queue discharge rate. Experimental findings show that capacity drops are often observed at merges even if downstream traffic conditions are in free-flow (e.g. Cassidy and Bertini, 1999; Kerner, 2002; Chung et al., 2007; Sarvi et al., 2007; Zheng et al., 2011). The magnitude of the capacity drops is mentioned to be between 10% and 30% of the maximal observed flow. The main physical explanations for such a phenomenon are lower speeds for merging vehicles combined with bounded acceleration (e.g. Cassidy and Rudjanakanoknad, 2005; Laval et al., 2005; Treiber et al., 2006; Laval and Daganzo, 2006), and the impacts of driver behaviors (e.g. Cassidy and Ahn, 2005; Coifman and Kim, 2011; Chen et al., 2014). In a nutshell, slower vehicles create voids in front of them that locally reduce the available capacity and lead to temporal flow restrictions. It is important to notice that driver relaxation few hundred meters downstream of the merge point and the related global acceleration process may also trigger capacity drops (Kim and Coifman, 2013; Carlson et al., 2014). In this paper, we will only focus on the physical process close to the merge, i.e. the impacts of merging vehicles combined with bounded acceleration.

---

* Corresponding author at: Université de Lyon, Lyon, France.

E-mail addresses: ludovic.leclercq@entpe.fr (L. Leclercq), v.l.knoop@tudelft.nl (V.L. Knoop), florian.marczak@entpe.fr (F. Marczak), s.p.hoogendoorn@tudelft.nl (S.P. Hoogendoorn).

http://dx.doi.org/10.1016/j.trc.2015.06.025

Except for direct experimental observations, the most common way to determine the effective merge capacity is to use a traffic model able to reproduce the underlying physical mechanisms (e.g. Laval and Daganzo, 2006; Srivastava and Geroliminis, 2013). This requires running a simulation for every new set of parameters and is not really convenient when looking for a first and quick approximation of how a merge behaves or to determine which parameters are the most influential, e.g. for sensitivity analysis. Laval (2006) is one of the first attempt to estimate capacity related to a dynamic and local physical process. To the authors' knowledge, Leclercq et al. (2011) is the only attempt to derive an analytical expression that explicitly relates the merge effective capacity to the different parameters. This expression is derived by considering that inserting vehicles act as moving bottlenecks (Newell, 1998; Leclercq et al., 2004) with bounded acceleration while mainstream vehicles behave according to the kinematic wave model (Lighthill and Whitham, 1955; Richards, 1956) with a triangular fundamental diagram. The central point of this contribution is to handle the interactions between moving bottlenecks when vehicles insert at different location along the on-ramp.

This first attempt has two main shortcomings. First, vehicle characteristics are supposed homogeneous, i.e. same acceleration, same jam spacing... Second, interactions of upstream propagating traffic waves with downstream propagating voids created downstream of moving bottlenecks are neglected. This paper proposes new analytical investigations that tackle these two shortcomings. Notably heterogeneous vehicle characteristics will be introduced to account for traffic composition (trucks and cars) but also for driver behaviors (random maximal acceleration). As a major result an updated expression for the effective capacity defined by Eq. (5) in Leclercq et al. (2011) will be established. In this paper, we will assume that both the on-ramp and the freeway are congested upstream of the merge. Leclercq et al. (2011) provides all the materials to extend the results to situations when the on-ramp is in free-flow. Furthermore, we will consider that the inserting flow q_0 is given when calculating the merge effective capacity C. One more time, the major challenge is to derive an update version of Eq. (5) in Leclercq et al. (2011). Then, all methodology already presented in Leclercq et al. (2011) can be directly applied. Notably, when the merge ratio α is given (Daganzo, 1995), q_0 can be derived by solving Eq. (1). This provides both equilibrium traffic states upstream of a self-active merge, i.e. when the congestion is not coming from downstream. Finally, note that we will restrict our investigations here to a one-lane freeway. Extensions to multi-lane freeways have already been discussed in Leclercq et al. (2011). The corresponding methods are directly applicable to the extended expression of the effective capacity.

$$(1 + 1/\alpha)q_0 = C(q_0) \tag{1}$$

This paper is organized as follow: the first section proposes a generic expression for the effective capacity. Section 2 deals with proper consideration of voids downstream of moving bottlenecks while Section 3 addresses the question of heterogeneous vehicle characteristics. The main work in these two sections is to derive the characteristics of the statistical distributions that appear in the generic expression. The main challenge is to maintain analytical tractability from end-to-end. Analytical expressions will be compared to numerical simulations to test the relevance of the required approximations. The last section presents a brief discussion.

2. Generic expression for the effective capacity

Consider a merge with two one-lane roads. Vehicle i inserts from the on-ramp at time t_i and location x_i ($0 \leqslant x_i \leqslant L$), where L is the length of the insertion lane, see Fig. 1a. The time headway $h_i = t_{i+1} - t_i$ between two successive insertions follows an unknown distribution $H(h_0, s_H)$ with mean $h_0 = 1/q_0$ and standard deviation s_H. Inserting vehicles are considered as moving bottlenecks (Newell, 1998; Leclercq et al., 2004) on the freeway with initial speed $v_{0,i}$ and bounded acceleration a_i. The distributions of these parameters are respectively described by $V_0(v_0, s_{V0})$ and $A(a, s_A)$. Note that capital letters will be used for defining the distributions associated to random variables labeled with lower case letters. Platoons of vehicles upstream of each moving bottleneck on the main road are described by the kinematic wave model (Lighthill and Whitham, 1955; Richards, 1956) and a triangular fundamental diagram with wave speed w and jam density κ_i. Free-flow speed has no influence here and it seems reasonable for freeway traffic to assume same wave speeds for all platoons (Chiabaut et al., 2010). A different jam density value is assigned to each inserting vehicles following $K(\kappa, s_K)$. In this paper, we will assume that this value also characterizes the mean jam density of the platoons leaded by the inserting vehicle.

To establish the generic expression for the effective capacity C, vehicles are first assumed to all insert at $x = 0$, i.e. $L = 0$, see Fig. 1b. Let δ_i be the cumulative number of vehicles that have crossed $x = 0$ between time t_i and t_{i+1}. Variational theory (Daganzo, 2005) states that δ_i can be equally calculated on the paths A → B or A → C → B, see Fig. 1b. This can also be seen as a direct application of the Green's theorem. No vehicle can pass the bottleneck between A and C, so δ_i is equal to $w\kappa_i(h_i - \tau_i)$, where τ_i is the time duration between points A and C. The effective capacity C corresponds to the ratio between the sum of δ_i and the total duration of the process, i.e. the sum of h_i, when the number of insertions tends to infinity. It is then given by:

$$\begin{gathered} C = \sum_{i=1}^{n\to\infty} \delta_i \Bigg/ \sum_{i=1}^{n\to\infty} h_i = w \sum_{i=1}^{n\to\infty} \kappa_i (h_i - \tau(h_i, v_{0,i}, a_i)) \Bigg/ \sum_{i=1}^{n\to\infty} h_i \\ \tau = \frac{1}{a_i}(-w - v_{0,i} + v); \; v(h_i, v_{0,i}, a_i) = \sqrt{(w + v_{0,i})^2 + 2wa_i h_i} \end{gathered} \tag{2}$$