Effective driving strategies for mitigating capacity drop at sag and tunnel bottlenecks*

Kentaro Wada,[†] Shin-ichiro Kai[‡] and Ryota Horiguchi[§]

Extended Abstract of ISTDM2025

1 Introduction

Once traffic breaks down at a bottleneck, one would logically expect that the queue discharge flow (QDF) rate from the bottleneck to be equal to its traffic capacity. However, in real traffic, the observed QDF rate decreases by an order of 10%. This phenomenon is called "capacity drop" (CD) (Wada et al., 2021). The focus of this study is CD at sag and tunnel bottlenecks.

For these bottlenecks, it is conjectured that a reduction in the QDF rate is caused by a low acceleration and/or delayed response of vehicles that leave from queues or traffic disturbances (e.g., oscillations) (Koshi et al., 1992). One common approach to modeling such sluggish driving behavior is to assume state-dependent car-following styles, i.e., the car-following behavior in congested traffic is described using formulations and parameters that differ from those in free-flow traffic (e.g., Koshi et al., 1992; Goñi Ros et al., 2016). However, this approach essentially imposes CD exogenously; furthermore, although bottlenecks are likely to induce sluggish behavior, their relationship with CD is unclear. In contrast, Jin (2018) and Wada et al. (2020) proposed a continuum traffic flow theory that describes CD endogenously, considering the influence of bottlenecks as a primary factor. With the linkage between the bottleneck and CD, this theory has been successfully applied to the examination of optimal variable speed limit (VSL) zones (Martínez and Jin, 2020).

Building on this theoretical framework, this study explores effective driving strategies for mitigating capacity drop at sag and tunnel bottlenecks. Specifically, unlike VSL, which controls the inflow rate (i.e., demand), we propose two driving strategies designed to enhance the QDF rate (i.e., supply), each corresponding to one of the two main causes of CD in the theory. We then examine the relationship between the penetration rate of (automated) vehicles implementing each of the proposed strategies and the improvement in the QDF rate through a numerical experiment.

2 Theory and Proposed Driving Strategies

In this section, we first provide an overview of the mechanism of CD proposed by Wada et al. (2020).

According to Koshi et al. (1992), at sag and tunnel sections, drivers cannot fully compensate for changes in gradient or surrounding environmental conditions, resulting in drivers attempting to maintain their spacing despite unconsciously slowing down. This "bottleneck effect" can be expressed by a location-dependent speed-spacing fundamental diagram, characterized by an increase in the safety time gap (Jin, 2018), as shown in Figure 1. Since the reciprocal of the safety time gap corresponds to the y-intercept in the flow-density fundamental diagram, changes in the safety time gap along the bottleneck section *spatially* reduce traffic capacity. This is a simple explanation of why sags and tunnels become bottlenecks.

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[†]Institute of Systems and Information Engineering, University of Tsukuba, Ibaraki, Japan. Email: wadaken@sk.tsukuba.ac.jp
[‡]i-Transport Lab. Co., Ltd., Japan
[§]i-Transport Lab. Co., Ltd., Japan

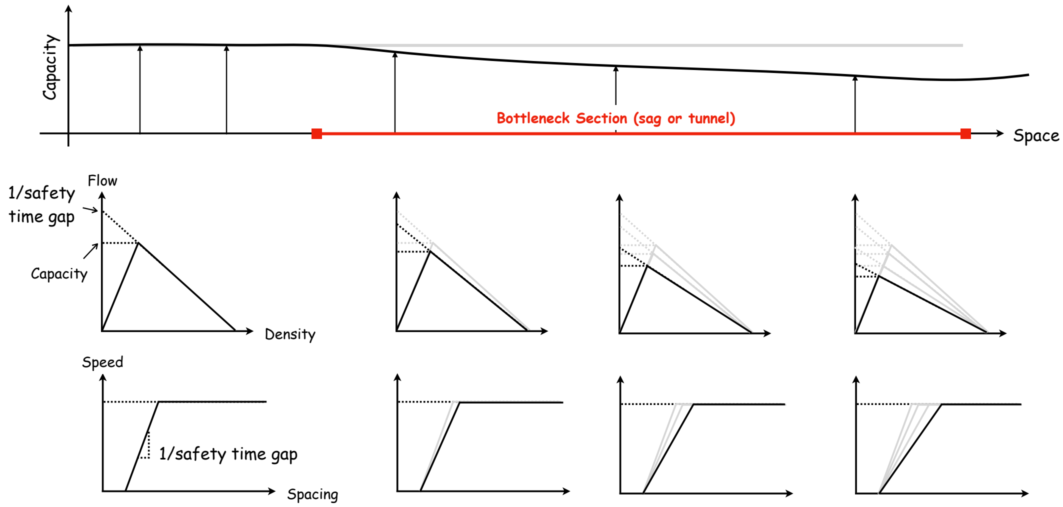

Figure 1: Location-dependent fundamental diagrams

We illustrate the mechanism of CD, demonstrating how the increase in the safety time gap ("bottleneck effect") can serve as a primary factor in CD (i.e., a *temporal* reduction in traffic capacity). Figure 2 presents a time-space diagram for a lead vehicle problem. According to Newell's simplified car-following theory (Newell, 2002), the trajectory of a following vehicle is a parallel shift of the trajectory of the preceding vehicle by the safety time gap horizontally and the minimum headway distance vertically (see blue trajectory). However, as shown by the black trajectory, the second vehicle (the first following vehicle) experiences a delay in speed recovery (i.e., amplifies the speed reduction of the lead vehicle) due to the increase in the safety time gap inside the bottleneck section. Furthermore, since the vehicle's acceleration is bounded, it cannot recover to free-flow speed instantaneously; the behavior is referred to as bounded acceleration (BA), which describes the sluggish behavior in which drivers cannot immediately recognize that they have passed the bottleneck. This leads to a further speed reduction of the third vehicle, which simultaneously implies an increase in the headway (i.e., the QDF rate becomes lower than the bottleneck capacity). The decrease in the QDF rate due to this vicious cycle persists until the system stabilizes in a stationary congested state. In summary, there are two types of behavioral delays due to the increase in the time gap and bounded acceleration, and their feedback causes CD.

Based on the above CD mechanism, we propose two types of CD mitigation driving strategies: one aims to prevent the increase in the safety time gap inside bottlenecks, while the other focuses on improving acceleration upon exiting bottlenecks. The former can be provided by a vehicle capable of compensating for gradient changes (referred to as a Gradient Compensation (GC) strategy), while the latter can be achieved by a vehicle that quickly detects when it is no longer in a car-following state (referred to as a Quick Acceleration (QA) strategy). As for the effects, the GC strategy is expected to increase the speed at the downstream end of the bottleneck by preventing delays in speed recovery. On the other hand, the QA strategy enables following vehicles to pass through the bottleneck earlier by accelerating rapidly upon exiting the bottleneck. However, if the acceleration capability of the following vehicles is limited, they may fail to follow the preceding vehicle, potentially becoming a moving bottleneck.

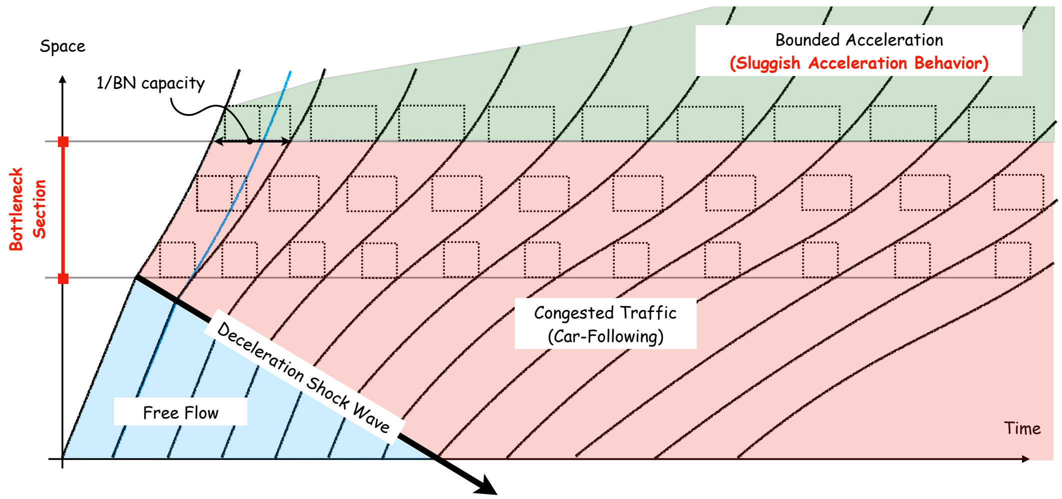

Figure 2: The mechanism of capacity drop

3 Results and Discussions

The quantitative effects of the proposed strategies are analyzed using the continuum car-following model (a continuum model in Lagrangian coordinates) proposed by Wada et al. (2020):

$$X(t+\Delta t, n) = X(t, n) + \min\{V(x, s(t, n)), v(t, n) + A(x)\Delta t\}\Delta t$$
$$\text{where} \quad V(x, s) = \min\{u, (s-d)/\tau(x)\},$$
$$s(t, n) = \{X(t, n-\Delta n) - X(t, n)\}/\Delta n,$$

where $X(t, n), s(t, n)$, and $v(t, n)$ denote the position, spacing, and speed of vehicle n at time t, respectively. The location-dependent speed-spacing fundamental diagram $V(x, s)$ is characterized by the free-flow speed u, minimum spacing d, and location-dependent safety time gap $\tau(x)$. $A(x)$ represents the location-dependent acceleration bound, which may depend on the gradient. If $\Delta n = 1$, $s(t, n)$ corresponds to the conventional headway, and this model becomes a BA version of Newell's simplified car-following model. However, to avoid numerical errors associated with the location-dependent safety time gap, a sufficiently small Δn must be used. For details, see Wada et al. (2020).

In this model, the GC strategy is represented by a vehicle with a constant safety time gap, while the QA strategy is modeled as a vehicle with an extremely high acceleration parameter. The constant safety time gap for GC strategy vehicles is set to be equal to the safety time gap of normal vehicles at the downstream end of the bottleneck (i.e., the longest safety time gap). This ensures that the bottleneck capacity remains constant regardless of the strategy or vehicle penetration rate, allowing for a fair comparison of the CD ratio, which indicates the extent to which the QDF rate decreases.

In the numerical experiment, we use the parameters that reproduce the congestion phenomenon at the Kobotoke tunnel in Japan, as demonstrated in Wada et al. (2020). The CD ratio in this congestion is approximately 10%. The experiment was conducted with vehicle penetration rates of 0%, 5%, 10%, 20%, 30%, 50%, 90%, and 100% for each strategy. The acceleration for the QA strategy is set to 1 [m/s^2], which is sufficiently large for acceleration in congested conditions. Additionally, to ensure high simulation accuracy, $\Delta n = 0.04$ [veh] and $\Delta t = 0.05$ [s] were used.

Figure 3 presents the penetration rate of each vehicle type and the corresponding CD ratio. From this, it can be observed that for the GC strategy, the increase in penetration rate and the resulting improvement are nearly proportional. In contrast, for the QA strategy, even a penetration rate of 90% results in only a 0.3% improvement. These findings indicate that enhancing car-following behavior inside the bottleneck section is significantly more critical than improving acceleration behavior upon exiting the bottleneck.

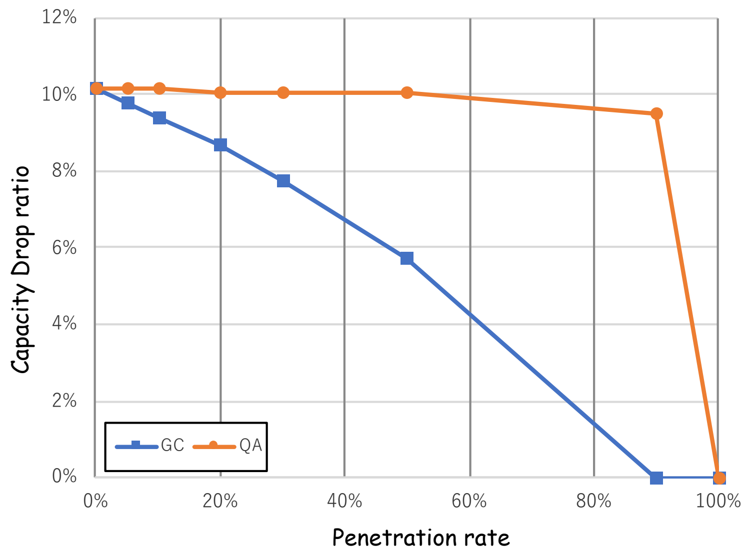

Figure 3: Penetration rate vs capacity drop ratio

These results can be explained theoretically as follows. First, the mixed traffic of GC strategy vehicles and normal vehicles can be regarded as a traffic flow with heterogeneous fundamental diagrams. According to the theory (Wada et al., 2020), in such cases, the QDF rate can be approximately described using the expected values of the parameters, which implies that the GC strategy affects the entire traffic flow on average. On the other hand, the mixed traffic of QA strategy vehicles and normal vehicles forms a traffic flow with heterogeneous acceleration bounds. Unlike the previous case, the QDF rate cannot be described using the expected values, because, as previously mentioned, following vehicles are constrained by the low acceleration performance of preceding vehicles.

At the conference, we will present examples of traffic control measures that align with the conclusions obtained here, as well as the results of a demonstration experiment conducted based on these findings.

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