Vehicle Trajectory-Based Bottlenecks Identification and System-wide Impact Analysis

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ABSTRACT

This paper proposes a vehicle trajectory-based bottleneck identification algorithm that can detect active bottleneck location and duration on freeway corridors. Based on a spatial queueing model, an analytical approach is developed to quantify the system-wide impact of possible capacity enhancement or demand shifting strategies. A case study on a regional network is used to demonstrate how those procedures can be used to rapidly identify bottlenecks and prioritize capacity improvement strategies.

KEY WORDS: Dynamic traffic assignment, bottleneck identification, marginal benefit analysis

1. INTRODUCTION

Population growth and economic development lead to increasing demand for travel and pose mobility challenges on capacity-limited transportation networks. It has been well recognized that the impact of congestion mitigation strategies in a regional network is difficult to evaluate due to the lack of mechanisms to (1) rapidly identify bottleneck locations and duration in a regional network and (2) reliably estimate various strategies to avoid recurring and non-recurring congestion. Thus, there is a great need for developing effective analytical models that can locate the critical locations for possible capacity improvements and/or demand shifting, and accordingly quantify the system-wide benefits of those strategies.

Traffic bottlenecks impact the efficiency of vehicle movements in transportation networks. More precisely, a bottleneck is defined as a condition that restricts the free movement of traffic and creates a point of congestion during specific periods of time. Typical sources for activating bottlenecks include severe weather condition, traffic accidents, work zone. Typically, there are three classes of bottlenecks, (1) merge bottleneck, where if there is a sudden surge in on-ramp demand triggering the downstream section flow to exceed its normal capacity; (2) lane drop bottleneck, where two of upstream lanes become the diverge lane; and (3) short weaving bottleneck regarding short weaving sections with geometric restrictions on lane-changing maneuvers.

Since bottlenecks are responsible for the majority of queuing, congestion, delays and breakdown (a transition condition from an uncongested state to a congested state), the evaluation of different congestion mitigation strategies needs to first systematically identify existing bottlenecks and further estimate the network-wide impacts of those strategies. These following challenging questions place a greater need for flexible and systematic bottleneck identification algorithms and strategies evaluation methodologies.

1) How to identify the location, duration and severity of bottlenecks from traffic assignment or traffic simulation results which include path flow information, detailed trajectories and link-based MOEs?

2) How to identify alternate routes with available capacity? If so, what is the system-wide impact of a capacity enhancement or route switching strategy?

3) How to use existing traffic assignment results to quantify the marginal system-wide benefit of capacity gain due to different strategies?

2. LITERATURE REVIEW

The existing bottleneck identification studies can be categorized in two distinctive groups: simulation/assignment-based approach and measurement-based approach. The simulation-based research typically uses the traditional 4-step travel demand model to predict demand levels in transportation networks over different planning horizons. Static assignment tools typically use high V/C ratios to flag heavily congested links, but they fail to capture dynamics of network flow propagation and dynamic travel behavior in response to real-time information. These approaches may capture the severity of bottlenecks but they cannot provide diagnosis results in terms of the duration of bottlenecks, the total number of impacted vehicles, and the direct and indirect delay caused by the bottleneck. During the last two decades, many simulation-based DTA systems, for example, the DYNASMART (Mahmassani et al., 1992), can allow (1) an explicit description of traffic processes and their time-varying properties, and (2) a richer representation of traveler behavior decisions. With comprehensive assignment results from DTA simulators, transportation planners can identify time-dependent OD, link and path-based measure of effectiveness (MOE). Yet the complexity in analyzing multi-dimensional network flow patterns still calls for a theoretically sound and practically useuful methodologies for bottleneck identification. Based on measurement data from loop detectors, a number of automated algorithms are designed to identify bottlenecks by using speed maps (Chen et al. 2004, Gomes et al, 2004, Ban et al, 2007).

To evaluate the impact of flow switching strategies in the dynamic traffic assignment process, a variety of studies have been conducted for computing local link marginals due to adding or deleting a vehicle from a link. Ghali and Smith (1995) used a deterministic point queue model to describe traffic flows and gave analytical formula to quantify the marginal impact of total link travel time due to a small change in incoming flow. Peeta and Mahamssani (1995) proposed the first path-based formulation and simulation-based Dynamic SO model, in which the path marginal is the sum of the constituent local link marginal. In this paper, we focus on how to quantify the system-wide impact of a major traffic improvement strategy (e.g. adding one lane, route switch), rather than the small change in the traffic flow.

The objectives of this article are twofold. The first is to develop a methodology capable of identifying bottlenecks through vehicle trajectory-based DTA models on freeway corridors. The second is to quantify the marginal cost analysis to evaluate the impact of traffic management strategies related the significant change of link capacity or demand.

3. VEHICLE TRAJECTORY-BASED BOTTLENECK IDENTIFICATION CONCEPTUAL MODEL

The vehicle trajectory-based bottleneck identification algorithm aims to overcome limitations of link-based studies, and better recognize queue propagation due to a bottleneck along a corridor. A vehicle trajectory, determined by start time, end time and speed on each link along its path for each vehicle, is used to find 1) total waiting time/delay associated with each bottleneck, 2) number of impacted vehicles and 3) average waiting time.

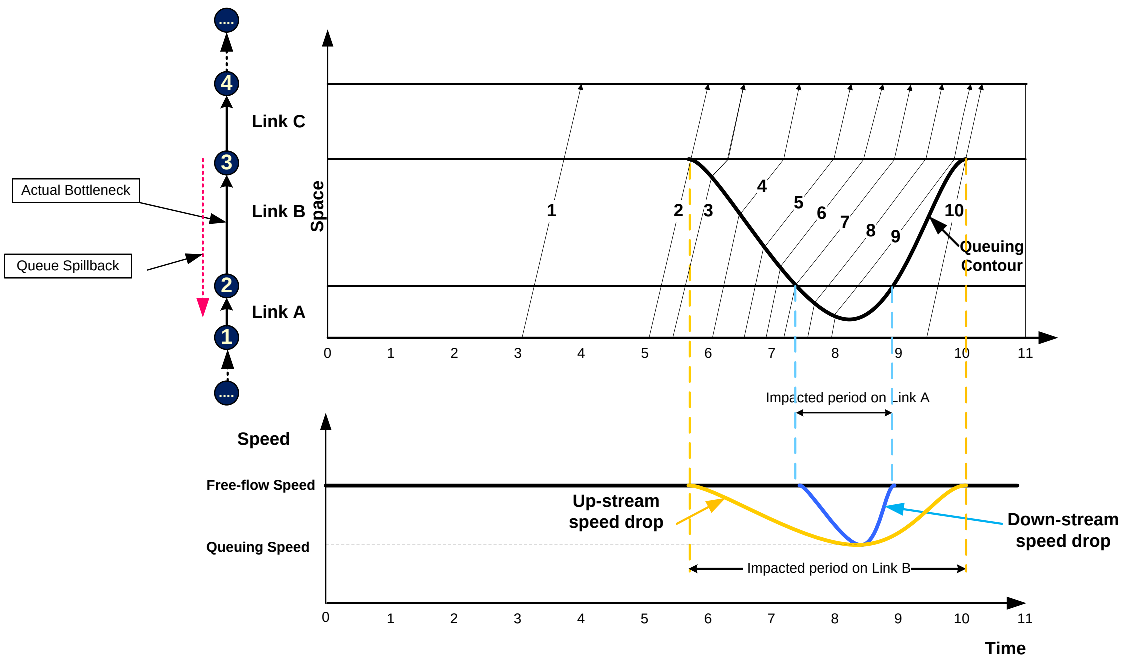

Figure 1 Vehicle trajectory-based bottleneck identification

An example shown in Fig. 1 is used to illustrate the vehicle trajectory-based approach. The polyline in the lower part represents the vehicle trajectory graph of each vehicle. Links are numbered as A, B, C…, and the vehicles are numbered as 0, 1 … The horizontal axis represents the time t (unit hours). The vertical axes of upper portion and lower portion represent the corridor segments and vehicle speed, respectively. The vehicle positions from the trajectories are mapped to the time-speed graph to infer the presence and the duration as well as the severity of a bottleneck in the corridor. More specifically, three vehicles (#1, #2, and #10) drive at free-flow speed. Other vehicles (#3 ~ #9) suffer from varying degrees of congestion from 6 am to 10 am. Due to the queue spillback effect from the down-stream link B, the upstream link A also experience delays. While there is a speed drop in link A, the actual bottleneck and resulting vehicular delay should be attributed to link B, which propagates congestion to upstream links. The total waiting time associated with each bottleneck and the number of impacted vehicles can also be obtained by scanning vehicle trajectories. The delays associated with the bottleneck cover all the delay from the first congested link to the last congested link by tracing the link speed and travel time of different links on a vehicle's path. The traditional link-based strategy, however, cannot find the total delay associated with the bottleneck. The following algorithm further details an implementable procedure to calculate the above statistics.

Notation

v = vehicle id

i = link index

t = time index, time interval is 1 minute

b = bottleneck link id

FL(*v*,*b*) = first congested link id for vehicle *v* at bottleneck *b*
LL(*v*,*b*) = last congested link id for vehicle *v* at bottleneck *b*

W(*b*) = total bottleneck delay (waiting time) at bottleneck b
N(*b*) = total number of impacted vehicles at bottleneck b
CI(*b*, *t*) = congestion indicator of bottleneck b
T(*b*) = congestion duration of bottleneck b

Step 0: Initialization
For each link *i* (potential bottleneck)
  W(i) = 0, *N*(i) = 0, *CI*(i,t) = 0, *T*(i) = 0.
End for each link

For each vehicle *v* // Outer loop

Step 1: Calculate link delay and identify all congested links along vehicle path
  Link delay = link travel time – free-flow travel time

Step 2: Identify first and last congested links of all bottlenecks: FL(v,b) and LL(v,b)
  Bottleneck *b* = link index of last congested link LL

  For each bottleneck *b along vehicle path*
    Step 3: Calculate bottleneck delay

    For each link from *FL* to *LL // Inner loop*
      add the link delay from *FL* to *LL* to total bottleneck delay *W*(*b*)
    Endfor each link

    Step 4: Count total number of impacted vehicles and mark delay duration
    Increase the total number of impacted vehicles *N*(*b*) by 1
    Record congested time point at the bottleneck
    CI(*b*, *t*) = 1, where *t* is the arrival time of vehicle *v* at bottleneck *b*

  End for each bottleneck *// Inner loop*
End for each vehicle // Outer loop

Step 5: Identify congested time period for each bottleneck
T(*b*) = Sum of *CI*(*b*, *t*) over peak hours

Potential congestion on a sequence of links may essentially suffer from the same sources of congestion, which arises from queue propagation on a downstream freeway link. For bottleneck-oriented traffic improvement analysis, there are critical needs to distinguish critical bottlenecks and impacted links. In our study, a critical bottleneck is defined as those bottlenecks caused by over-saturated traffic conditions at the freeway segments; while an impacted link is regarded as those links suffering from queue spillback of downstream critical bottlenecks. By grouping successive congested links according to the first and last congested links of a bottleneck, the above algorithm can clearly identify the critical bottleneck and its corresponding impact. Furthermore, those detailed bottleneck statistics (such as 1) total waiting time; 2) number of impacted vehicles; and 3) congestion duration) can be provided to planning agencies to evaluate congestion mitigation strategies and maximize operational improvements with limited resources constrains.

4. CONCEPTUAL MODEL FOR QUANTIFYING MARGINAL BENEFIT

When adding one unit capacity to an existing road facility, the marginal benefit of each additional capacity enhancement depends on a number of interrelated factors such as the existing congestion duration, total number of impacted vehicles, and possibly total exiting delay.

In the input-output queuing diagram shown as Figure 2, curves A and D represent vehicle upstream arrival pattern and downstream departure pattern respectively. All the curves are expressed in terms of cumulative numbers of vehicles, where the slop of a curve indicts the capacity of inflow/outflow of vehicles. If the first-in-first out rule (FIFO) is assumed, the horizontal distance between curves A and D shows the waiting time of a vehicle, and the vertical distance between curves A and D shows the number of vehicles accumulated in the queue. The area between two curves, A and D in Figure 2, represents the total queuing delays of all vehicles. As shown by Ghali and Smith (1995), the marginal improvement with respect to adding or deleting a vehicle is approximately proportional to the time interval from a vehicle entering time t_v to the end of congestion t_2.

Notation

t_0 = beginning time of congestion period

t_2 = ending time of congestion period

t_3 = ending time of congestion period after capacity improvement

A(t) = cumulative arriving vehicles into the bottleneck

D(t) =cumulative departing vehicles from the bottleneck

C = original capacity

C' = improved capacity after traffic improvement strategy

In this study, we focus on two typical strategies aiming at alleviating congestion levels: (1) demand reduction (through tolling or detour) and (2) capacity enhancement (adding a lane and reversible lane management. The measure of interest is the magnitude of marginal improvement in terms of the system cost (i.e. the total travel time).

Consider a long-term capacity improvement project (e.g. adding a lane) that increases capacity from C to C' , the departure time curve during the congestion period is constrained by the capacity (i.e. maximal discharge rate) before the capacity change:

$$D(t_2) = C \times (t_2 - t_0) + D(t_0) \tag{1}$$

the departure time curve during the congestion period after the capacity change is also constrained by the capacity

$$D'(t_3) = C' \times (t_3 - t_0) + D(t_0) \tag{2}$$

For simplify, we use t_2 as an approximate of t_3, then Eq. (2) – Eq. (1) leads to

$$D'(t_3) - D(t_2) \approx (C' - C) \times (t_2 - t_0) \tag{3}$$

Because the total system-wide waiting time is the area between the cumulative curves A(t) and D(t), the change of total waiting time (due to capacity change) can be approximated by

$$\frac{1}{2} \times [D'(t_3) - D(t_2)] \times (t_2 - t_0) \approx \frac{1}{2} \times (C' - C) \times (t_2 - t_0) \times (t_2 - t_0) \tag{4}$$

where $D'(t_3) - D(t_2)$ is the height of the "change" triangular and $t_2 - t_0$ is the width of the "change" triangular.

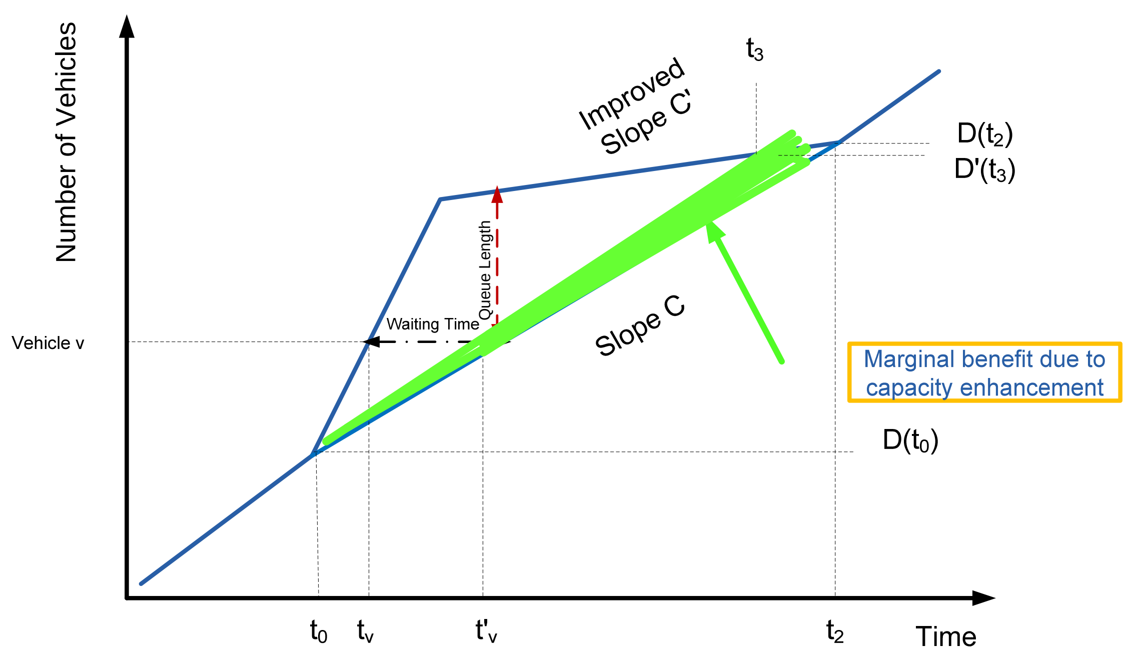

Figure 2 Marginal benefit of capacity gain at bottleneck (shown by the green triangular)

In summary, the marginal benefit of capacity improvement is proportional to the capacity change $(C' - C)$ and the quadratic function of congestion duration $(t_2 - t_0)^2$. Chen et al. (2004) suggested that the bottlenecks should be ranked in terms of their frequency of recurrence and the magnitude of their delay impact. Based on our analytical model, the marginal benefit of link capacity improvement is highly dependent on the congestion duration of a bottleneck: $(t_2 - t_0)$. Therefore we suggest to use congestion duration as the major indicator as to rank the magnitude of potential capacity improvements and the effectiveness of different strategies. A corridor-based and network-based algorithm will be further presented in the full paper to illustrate the calculation process.

5. CONCLUSION

The proposed approach aims to provide a rigorous bottleneck identification algorithm in a network, and assist benefit estimation and prioritization of operating capacity improvement strategies.

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