ASSESSMENT OF SIGNALIZED INTERSECTION CAPACITY IN RESPONSE TO DOWNSTREAM QUEUE SPILLBACK

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ABSTRACT

The congestion of urban signalized intersections is a major issue and severe traffic congestion also causes unnecessary and excessive energy consumption, deteriorates the quality of life and creates many safety concerns. The most direct and intuitive approach to alleviate the intersection-wide congestion is to increase the traffic supply at bottleneck intersection by analyzing capacity constraints. Traffic engineers who aim to mitigate intersection congestion usually need to conduct a capacity analysis of signalized intersection in order to measure vehicle delay and level of service. Highway Capacity Manual (HCM) method is the most popular approach in signalized intersection capacity analysis.

Because HCM method doesn't take account for the effect of queue spillback from a downstream signal and is unable to provide accurate estimation if the spillback is present, recent practices in signalized intersection capacity analysis based on HCM method does not consider potential queue spillback of adjacent signalized intersections. However, most of intersection, especially in urbanized area, cannot be considered as an isolated intersection and the queue spillback from closely spacing downstream intersection can adversely affect the upstream throughput. This study was conducted to provide traffic engineers with a simple, practical and step-by-step analysis method to identify the occurrence of queue spillback and to determine the effects of downstream queues on upstream intersection capacity. The theory and method presented in this paper are developed based on HCM method but expanded the application of HCM method in addressing the consequence of downstream queue spillback on intersection capacity assessment. A computational tool was developed to assist in the process of capacity calculation and a case study is presented to demonstrate the practical use of the analysis method.

1. INTRODUCTION

Signalized intersections are key elements in the urban transportation network and carry heavy traffic of motorized and non-motorized vehicles and pedestrians, which, in turn, generate many conflicts among crossing, turning and merging maneuvers. For a variety of reasons such as population, economic and auto ownership growth, increasing traffic demand can exceed the carrying capacity of the intersection during peak periods. As a consequence, traffic condition deteriorates and safety risk worsens. Congested and hazardous traffic conditions increase fuel consumption, emission, accidents and noise, therefore a city's quality of life, world energy resources and global atmospheric conditions deteriorate.

Intersection congestion is expressed in terms of level of service (LOS) as defined by the Highway Capacity Manual (HCM) *(1)*. HCM specifies an operational procedure for determining the LOS at signalized intersections in terms of the average total vehicle delay of all movements through an intersection. Intersection capacity is the maximum rate at which vehicles can pass through the intersection in an hour under prevailing conditions and it accounts for roadway conditions such as lane configuration, lane utilization, grade and signalization conditions *(2)*. Intersection capacity or volume-to-capacity ratio is one of the operational measures of effectiveness used in measuring signalized intersection LOS in HCM procedure. However, the procedure does not take into account the potential impact of downstream congestion on intersection operation and may not be applicable to closely spaced signalized urban arterials if queue spillback occurs from a downstream signal. Queues can grow long at a saturated intersection and block driveways, access roads and adjacent major intersections, so intersection capacity assessment and associated LOS quantification by assuming isolated intersection operation may not reflect reality and are likely underestimate the severity of bottleneck congestion.

A simplified example as indicated in Figure 1 is used to demonstrate the queue spillback between two closely spacing intersections (Intersection I and II). Assuming the capacity of intersection I eastbound through is 2,000 veh/h and intersection II eastbound through is 1,200 veh/h estimated by using HCM method. Please note that the capacity for the entire intersection is not explicitly defined in HCM and the capacity condition in this example is defined by a composite volume/capacity ratio for the critical lane groups in the intersection.

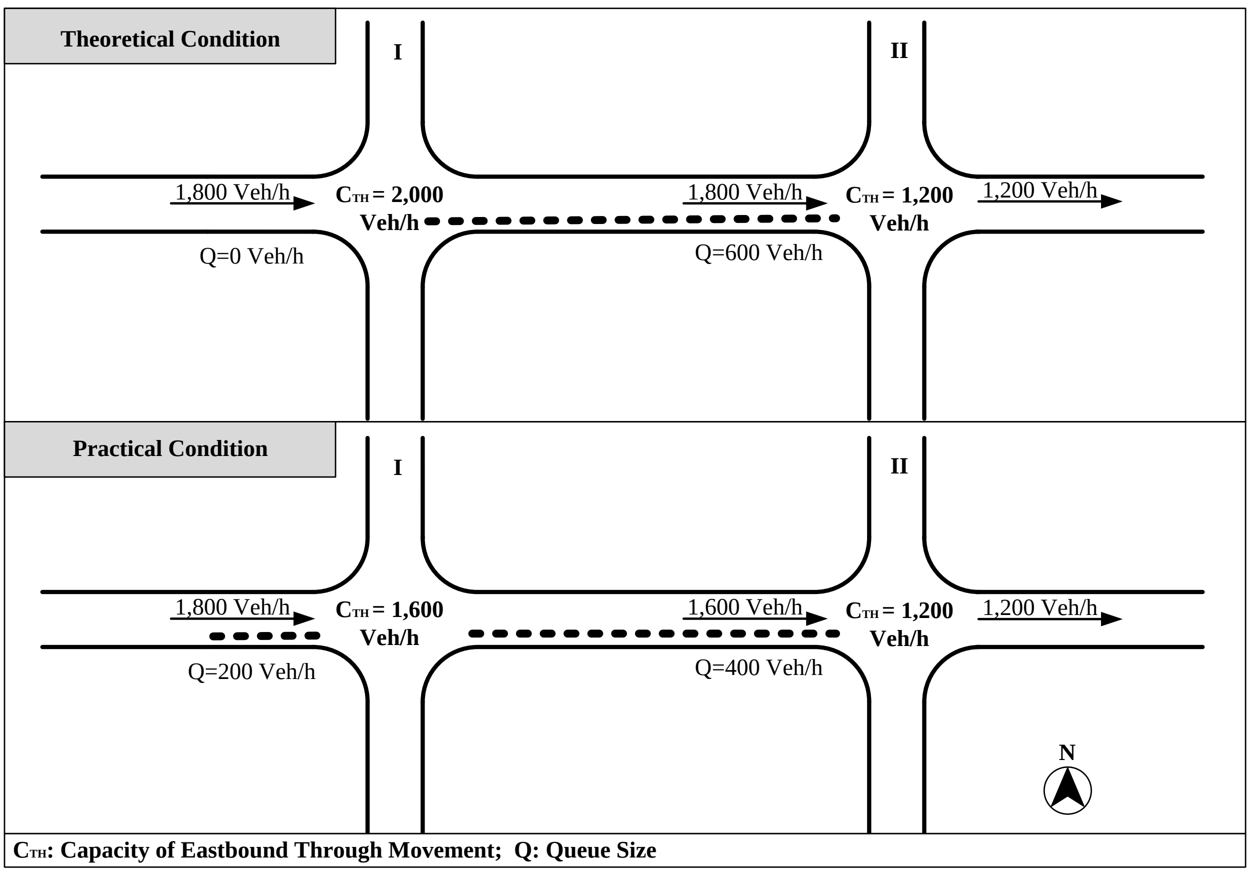

Figure 1. Demonstration of Queue Spillback between Paired Intersections

Assumed the peak hour eastbound through traffic at Intersection I is 1,800 veh/h, which theoretically is under capacity. Therefore, the back-of-queue due to oversaturation on eastbound through at Intersection I should not occur. Because of insufficient capacity at bottleneck intersection II, the queue size that aggregated on the downstream approach would be approximately 600 veh/h, if the portion of through traffic that turns into and out of the perpendicular streets and driveways between the two intersections is negligent. However, the theoretical estimate of capacity and queue size can be incorrect if intersection queue spillback occurs between intersections. Provided that the maximal queue storage between these two intersections is only 400 veh/h. The rest of queuing vehicles (200 veh/h) are unable to enter Intersection I and remain on its upstream segment, resulting in the practical carrying capacity of Intersection I eastbound through is down to 1,600 vehicles per hour and 200 vehicles queue can be observed at upstream Intersection I every hour.

As shown in the example above, upstream throughput may potentially exacerbate the congestion of adjacent downstream intersections and the congested downstream traffic would generate queue spillback, in turn, trim down the upstream capacity. Therefore, assessment of intersection capacity should consider the queuing conditions at downstream signals. Simulation models such as VISSUM, AIMSUM and CORSIM, are recommended and also generally accepted by traffic engineers for modeling intersection operation when the interaction between two closely spaced signalized intersections and queue spillback are suspected. Although simulation can effectively measure the interactions of individual vehicles, conduct network-wide analysis of queue evolvement and provide visual information about queue occurrence, growth and dissipation, it is always a time and resource consuming and data-intensive endeavor. There is a lack of practical and systematic approaches available to assist traffic engineers in determining whether queue spillback would occur under certain traffic conditions and whether significant additional resources for traffic network simulation should be expended.

There are a large body of research exists highlighting the effects of queue spillback in urban road network. Queue spillback is one of the most common causes of flow restriction at congested intersections according to Kittelson & Associates‘s research *(3)*. ASSHTO *(4)* and Traffic Timing Manual *(5)* recommended the performance measures of intersection treatments should include queue lengths in order to minimize the time period during which the queue spillback or spillover exists and to manage queue interaction between intersections during oversaturated conditions. Dr. Papageorgiou presented that for intersection group, over-saturation’s forward transfer can’t alleviate the global saturation degree, hence, the deteriorating increase in travel delay of an intersection group and the risk of capacity loss do exist *(6)*.

Although the potential capacity cutoff due to downstream back-of-queue has being discussed by traffic engineers and researchers over the past several decades, to our best knowledge, there is only a limited amount of studies focusing on developing planning level and practical methods to measure the intersection capacity under the condition of downstream queue spillback. Most of existing methods, such as EMME/2 micro-simulation model *(7)*, genetic algorithm (GA)-based program *(8)*, and TRAF-NETSIM *(9)*, are either data-intensive and network-wide simulation model or compute-intensive and system-wide mathematical programming model. It may be unrealistic and expensive to conduct network or system wide investigation and information collection, especially in the early stage of intersection bottleneck screening or for a minor/temporary intersection improvement project with limited budgets.

2. METHODOLOGY

In HCM 2010, the capacity condition for an intersection is defined by a composite volume/capacity ratio for the critical lane groups and the adjusted volume and saturation flows for each lane group are combined in the approach analysis. For example, the capacity of lane group *i* at one approach of a signalized intersection is shown in Eq (1).

$$c_i = s_i \frac{g_i}{C_{\text{int}}} \tag{1}$$

Where

c_i is capacity of though lane group

s_i is prevailing saturation flow of through lane group

g_i is effective green time allocated to the lane group

C_{int} is the subject intersection cycle length

The HCM methodology of capacity assessment doesn't consider interactive queuing effects of adjacent intersection. An improved method is developed based on the queue accumulation and intersection capacity estimation methods introduced in the new released HCM 2010. The queuing calculation in HCM 2010 is derived from Akcelik's research *(10)* which provided a method to estimate the full stop rate at signalized intersection for uniform arrivals. Akcelik's methods was extended by Olszewski *(11)* for platoon arrival type and Texas Transportation Institute *(12)* for coordinated-actuated intersection and eventually adopted by HCM 2010. In addition, the estimation techniques of back-of-queue length were refined by eliminating slowing and partially stopped vehicles. The acceleration-deceleration delay d_a term is used to distinguish between a fully and a partially stopped vehicle *(1)*.

$$d_a = \frac{1.47(S_a - S_s)^2}{2S_a}\left(\frac{1}{r_a} + \frac{1}{r_d}\right)$$

Where

S_a is average speed on the intersection approach (mi/h), it can be estimated by posted speed limit S_{pl} with the equation $S_a = 0.90(25.6 + 0.47S_{pl})$

S_s is Threshold speed defined a stopped vehicle = 5.0 (mi/h)

r_a is acceleration rate = 3.5 (ft/s^2)

r_d is deceleration rate = 4.0 (ft/s^2)

The idea behind the derivation of this method is to investigate capacity constraint from downstream queuing by reversing and integrating the HCM procedures of intersection capacity and queue size estimation. According to HCM 2010 *(1)*, the queue size in any lane of a certain lane group can be estimated by accounting for the queue caused by the signal cycling through its phase sequence and the effect of random and cycle by cycle fluctuations in over-capacity demand. Provided that maximal queue storage space between intersections is given, through solving the inverse function of arrival rate element in the queuing size and intersection capacity estimation formula in HCM, the upstream arrival rate contributing to a certain lane group queue and delay at downstream intersection can be calculated with the equation below.

$$\begin{cases} q_i = \dfrac{gQs}{C((Q-d_a s)P - gs(P-1))} & \left(Q < s\left(d_a \dfrac{P}{P-1} + g\right)\right) \\ q_i = \dfrac{g(P-1)(CQ+450gs)}{C^2(d_a P + g(P-1)) + 450Cg(P-1)} & \left(Q \geq s\left(d_a \dfrac{P}{P-1} + g\right)\right) \end{cases} \quad (2)$$

Where

q_i is the arrival flow rate from the subject intersection to a lane group of its downstream intersection (veh/s/ln)
Q is the maximal back-of-queue size, i.e. maximum backward distance in vehicles over which queue extends from stop line of downstream intersection during a typical cycle (veh/ln). It can be estimated by $D+ L_v/ L_v$. D is the specified distance between the exit of the subject intersection and the stop line of its downstream intersection (ft) and L_v is the average spacing between vehicles in a stopped queue, assumed to be 25 ft *(12)*.
s is the adjusted saturation flow per second per lane at downstream intersection (veh/s/ln)
g is the effective green time of the analyzed lane group at downstream intersection (sec)
C is the cycle length of downstream intersection
P is the proportion of vehicles arriving on green

No initial queue at the start of each analysis period is assumed. Similar to the HCM method, the equation is applicable for an individual lane, the flow rate, saturation flow, and capacity for the lane group have to be converted in to individual lane value prior to applying this equation and the unequal lane utilization in a lane group is not reflected in the calculation.

The proportion of all vehicles arriving during green (i.e., Parameter *"P"* in Eq. 2) is recommended to be observed in the field because it has a significant impact on the estimation of queue backup and capacity constraint. It can also be estimated by upstream arrivals type and platoon ratio according to HCM 2010 (i.e., $P= R_p\, g/C$, *"R_p" is* Platoon Ratio and the default value of *"R_p"* can be defined by R_p=*Arrival Type/3*) *(1)*. The progression for the off-peak direction or uninterrupted flow was usually characterized as Arrival Type 3 (i.e., $R_p= 1.00$). If the arrivals are effectively random, the proportion of vehicles arriving on green equals to the green/cycle ratio (i.e., $P=g/C$) and the Eq. 2 can be simplified as below.

$$
\begin{cases}
q_i = \dfrac{Qs}{(C-d_a-g)s+Q} & (Q < \dfrac{gs(C-d_a-g)}{C-g}) \\
q_i = \dfrac{(C-g)(CQ+450gs)}{C(C^2-C(d_a+g-450)-450g)} & (Q \geq \dfrac{gs(C-d_a-g)}{C-g})
\end{cases} \quad (3)
$$

Intersection capacity is defined for each lane group in signalized intersection operational analysis, The arrive rate from the subject intersection calculated by Eq. 2 or Eq. 3 is the proportion of total approaching traffic contributing to the queue found in one lane in a downstream lane groups. Arrival rate from the subject lane group to its downstream approach cannot exceed the allowable rate (q_i) at any higher arrival rate on average signal cycle, because the longest spillback queue generated in a certain lane group of the downstream intersection will prevent upstream vehicles which are approaching to that lane group from entering the intersection, which impose the constraint on the capacity at the subject intersection. Therefore, the restricted capacity (veh/hr) of the subject lane group subject to downstream queuing space can be computed with Eq. 4.

$$c' = 3600q_i \quad (4)$$

Because the capacity constraint estimated by Eq.4 derives from the longest queue at any lane of the approaching lane groups of the downstream intersection, the maximal arrival (capacity) calculated by Eq.4 is a conservative estimation. While the queue spillback occurs and blocks some lanes or movements, some other lanes or lane groups may still have space to accommodate coming traffic. However, it could be more scientific and reasonable to determine the subject intersection capacity by considering the longest queue from downstream in order to minimize the occurrence of queue spillback and associated safety concerns.

The upstream effective capacity should be the minimum of the theoretic capacity based on HCM (c) and the restricted capacity subject to downstream queues (c'). Therefore the effective capacity (c_f) can be estimated with Eq.5

$$c_f = \min(c, c') \quad (5)$$

3. CASE STUDY

A signalized intersection at downtown Honolulu, Hawaii is used to illustrate the practical application of the capacity assessment method. The subject intersection is on the urban arterial Vineyard Boulevard and corridor Queue Emma St (named Int VQ). The eastbound (EB) and westbound (WB) of the subject intersection have been experiencing heavy congestion during peak periods, resulting in frequently observed queue spillback from downstream intersection because of the short intersection spacing and long peak hour cycle length. In order to simplify the case study process, only the capacity of EB and WB through lane groups and morning peak hour traffic condition are considered. The Vineyard Blvd intersects Pali Highway at subject intersection westbound and the signalized intersection is named “Int VP” and EB through downstream intersection at Punchbowl street is “Int VB”. Figure 2 delineates the layout of three intersections.

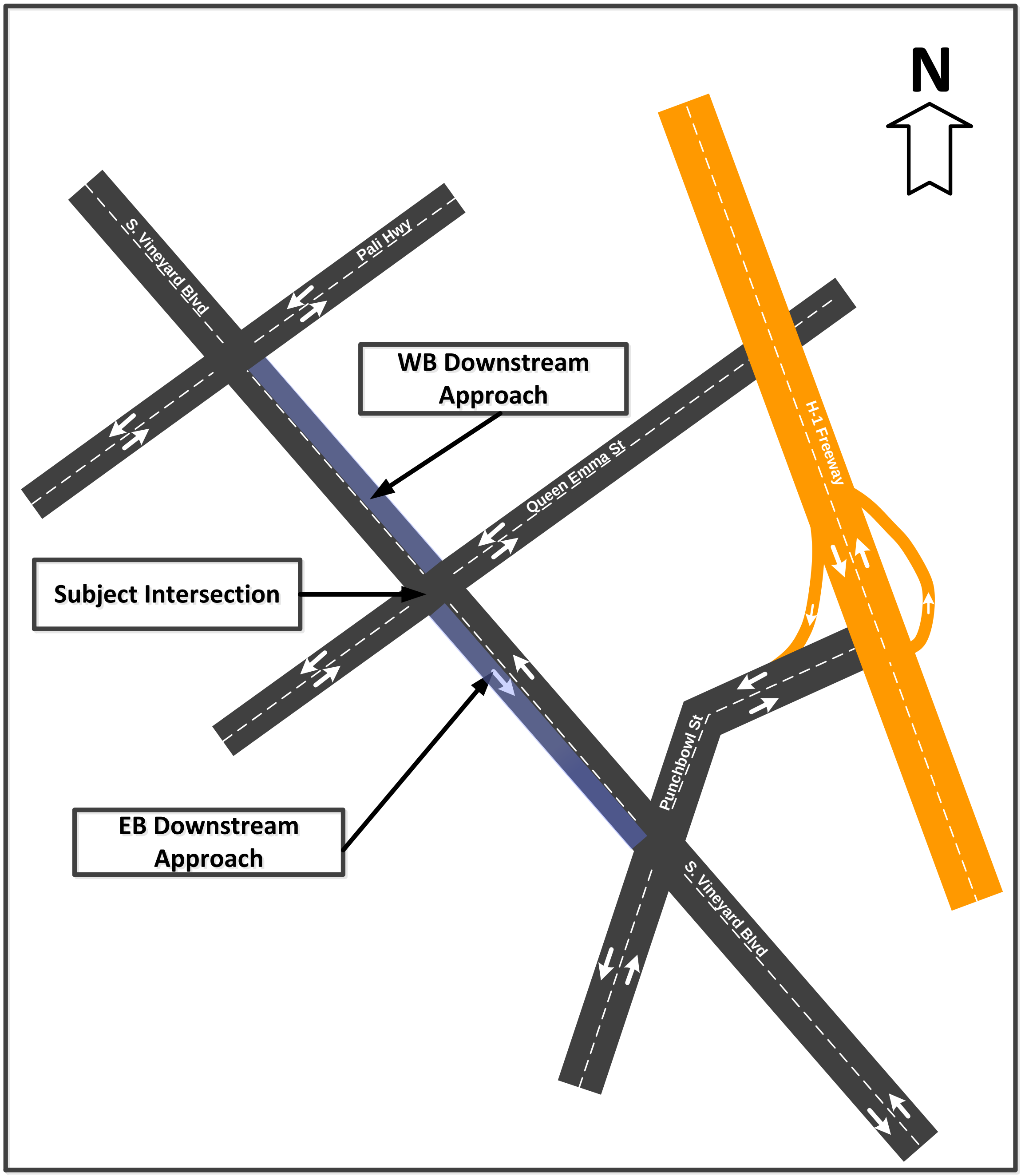

Figure 2. Demonstration of Intersection Layout

In addition to the information required in HCM 2010 method, addition information is needed to conduct improved capacity analysis including the intersection spacing between signals, downstream approach lane configuration, downstream cycle length, road segment posted speed and green time allocation. The information of intersections required by the HCM 2010 and proposed method is summarized in Table 1. Note that only through traffic information is provided due to the case study scope.

Table 1. Intersection Information Required in Capacity Assessment

Required Information	Cycle Length (sec)	Green Time Allocation (sec)	No. of Lanes	Intersection Spacing (ft)	Saturation Flow Rate (veh/s)	Posted Speed Limits (mph)
WB Int VQ	120*	25*	2	-	0.46*	35
EB Int VQ	120*	25*	2	-	0.46*	35
WB Int VP	150	30	2	450	0.46	35
EB Int VB	150	20	2	490	0.46	35

* Information required in HCM capacity estimation procedure

Because of the complexity involved in the formulation of the improved capacity assessment method and in order to reduce the chances of error if attempting to calculate by hand, an interactive spreadsheet tool is developed by using Microsoft Excel 2007 to quickly execute the process. The spreadsheet user is taken through this computerized tool where above traffic and geographic information at intersections is collected and the calculation is automatically processed. As shown in Figure 3, the spreadsheet tool is a one-page worksheet containing Input, and Output. User is required to select lane group and enter data including the intersection geographic and signal timing information in the green boxes of the input section. As indicated in Eq. 5, the value of effective lane group capacity presented in the output section of the worksheet is the minimum of HCM theoretic capacity value and restricted capacity estimate subject to downstream queuing effects.

Signalized Intersection Capacity Assessment

Study Intersection	VQ WB TH	-
Analyzed by:	Xin Yu	-
Date and Time:	10-Apr-12	-

Inputs

A. Intersection Condition	Units	
Posted Speed Limit	***mi/hr***	**35**
Distance to Upstream Int	***ft***	**490**
Subject Int Cycle Length	**sec**	**120**
Downstream Int Cycle Length	***sec***	**150**
B. Lane configuration and Signal Timing		
Select Lane Group (LG)	**-**	**TH**
No. of Lanes	**-**	**2**
Saturation flow	***veh/s/ln***	**0.46**
Effective Green at Subject Int	***sec***	**25**
Effective Green at Downstream Int	***sec***	**20**
Arrival Type	**-**	**3**

Output

Lane Group Effective Capacity *(Rounded to the nearest 5)*	***veh/h***	**590**

Figure 3. Spreadsheet Tool of Capacity Assessment

The results of effective capacity analysis are shown in Table 2. According to the results, we may conclude that the capacity of subject intersection WB though lane is determined only by the green/cycle ratio and the downstream queue spillback may not occur and will not likely lead to capacity loss of the through lane group under current signalization and traffic condition.

Table 2. Analysis Results of Case Study

Lane Group	Theoretic Capacity *(c)*	Restricted Capacity *(c')*	Effective Capacity *min (c,c')*
WB VQ TH	**690 veh/h**	**745 veh/h**	**690 veh/h**
EB VQ TH	**690 veh/h**	**590 veh/h**	**590 veh/h**

However, the EB through capacity is adversely affected by the downstream queues, resulting in capacity overestimation by using HCM method based on green/cycle ration. In this case, the downstream queue spillback would occur once the volume-to-capacity ratios on subject intersection EB through is larger than 0.85 (590/690), which means the signalization at subject intersection, especially EB through green allocation, should be revised and optimized. The current intersection timing is not cost-effective at the analysis peak period. Under near or over saturation traffic condition, a portion of the green time assigned to EB through is wasted due to occurrence of downstream queue spillback and traffic blockage at the subject intersection.

4. CONCLUSION

Assessment of signalized intersection capacity should consider the downstream traffic and back-of-queue size, which can reduce upstream capacity through spillback. This issue has been well recognized but there is a lack of practical and systematic approaches available to analyze this problem. The main purpose of this research was to develop a quick and practical analysis method for identifying the potential queue spillback between paired signalized intersections and evaluating the interactive impacts of the downstream queues on the capacity assessment at a non-isolated intersection. The paper presents the development of an improved capacity model for signalized intersection approach with adjacent downstream signals. The method takes into account of the traffic flow arrival type and the effect of queue blockage to the upstream capacity. The proposed model also enhanced to the current HCM methodology where the downstream queuing issue has not been addressed. The research showed that the capacity of a signalized intersection approach with is strongly related to the intersection spacing and downstream signal timing plan.

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