Modeling Capacity of Through Movement at Signalized Intersection Impacted by Short Left-Turn Bay under Different Signal Settings

Zihang Wei
Graduate Student
Zachry Department of Civil and Environmental Engineering
Texas A&M University
3136 TAMU, College Station, TX 77843-3136
Email: wzh96@tamu.edu

Yunlong Zhang, Ph.D.
Professor
Zachry Department of Civil and Environmental Engineering
Texas A&M University
3136 TAMU, College Station, TX 77843-3136
Email: yzhang@civil.tamu.edu

Xiaoyu Guo*
Ph.D. Student
Zachry Department of Civil and Environmental Engineering
Texas A&M University
3136 TAMU, College Station, TX 77843-3136
Email: xiaoyuguo@tamu.edu

Xin Zhang
Graduate Student
Zachry Department of Civil and Environmental Engineering
Texas A&M University
3136 TAMU, College Station, TX 77843-3136
Email: zhangxin@tamu.edu

*Corresponding Author

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ABSTRACT

Through movement capacity is an essential factor used to reflect intersection performance, especially for signalized intersections where a large proportion of vehicle demand is in the vehicles making through movements. Generally, left-turn spillback is considered a key contributor to affect through movement capacity, and blockage to the left-turn bay is known to decrease left-turn capacity. Previous studies focused primarily on estimating through movement capacity under a lagging protected only left-turn (lagging POLT) signal setting, as left-turn spillback is more likely to happen under such condition. However, previous studies contained assumptions (e.g., omit spillback), or dedicates to one specific signal setting. In this study, through movement capacity models based on probabilistic modeling of spillback and blockage scenarios are established under four different signal settings (i.e., leading protected only left-turn (leading POLT), lagging POLT, protected plus permitted (leading PPLT) and permitted plus protected (lagging PPLT)). Through microscopic simulations, the proposed models are validated, and compared with existing capacity models and the one in the HCM. The results of the comparisons demonstrate that the proposed models have significant advantages over all the other models and have high accuracies in all signal settings. Each proposed model for a given signal setting maintains consistent accuracy across various left-turn bay lengths. The proposed models of this paper have the potential to serve as useful tools, for practicing transportation engineers, when determining the appropriate length of a left-turn bay with the consideration of spillback and blockage, and the most appropriated cycle length with a given bay length.

Keywords: Through Movement Capacity, Left-turn Signal Setting, Signalized Intersection, Short Left-turn Bay, Spillback, Blockage
INTRODUCTION

In the Highway Capacity Manual (HCM) (1), capacity is defined as the maximum hourly rate at which vehicles can reasonably travel through a point or a segment during a given period under a prevailing roadway, traffic and control condition. As most of the traffic passing an intersection are through vehicles, adequate capacities of through movements are essential for intersection operation and performance. The theoretical capacity of a through movement at a signalized intersection is determined by its saturation flow rate and the allocated green time. However, studies have demonstrated that a short left-turn bay can significantly decrease the capacity in the adjacent through lanes because left-turn spillback can frequently occur (2)(3)(4). Left-turn bays are present at intersections to store left-turn vehicles. These are also referred to as left-turn storage lanes or left-turn pocket lanes. The length of left-turn bays are inadequate at some signalized intersections mainly due to the following two reasons: one, because of the physical space or cost constraints when these bays were constructed; and two, because of the increasing traffic demand of left-turn vehicles, through vehicles, and increased adjusted signal cycle length after the left-turn bays were constructed. Signal settings, particularly the left-turn signal settings, have significant impacts on the actual capacity of the through movements adjacent to the left-turn bay. This is due to different spillback or blockage situations the left-turn vehicles create (5).

At intersections where left-turn spillback frequently occurs, different left-turn strategies can result in different spillback and blockage probabilities. It is believed that the lagging protected only left-turn (Lagging POLT) leads to a larger probability of left-turn spillback than leading protected only left-turn (Leading POLT) (2), because vehicles in the left-turn bays need to wait longer until the through movement green duration ends. Higher spillback probability means there will be a larger negative impact brought on the adjacent through capacity. Thus, when spillback occurs, the adjacent through capacity under lagging POLT tends to be lower than that under leading POLT. Moreover, if permitted left-turns are allowed, the probability of spillback and blockage will also change, as a few more left-turn vehicles can pass the intersection during the through movement green duration. The introduction of permitted left-turn will increase the left-turn capacity and, as a result, decrease the probability of left-turn spillback.

Researchers have analyzed intersection capacities with different area types (6), or under different green splits and cycle lengths (7). However, for a signalized intersection at a given location and with fixed green splits for a fixed cycle length, different left-turn signal settings will have different impacts on the capacity of the adjacent through movement when the left-turn bay is short. For example, under the leading POLT signal setting, blockage can occur, leaving some left-turn vehicles waiting in the through lane, affecting the capacity of the through movement. Under a lagging left-turn signal setting, left-turn vehicles spilling out of the left-turn bay could block the adjacent through lane and directly reduce the capacity of the through movement. The impacts of different signal settings on the through movement capacity impacted by a short left-turn bay have not been studied comprehensively. In this study, four left-turn signal settings are considered: (1) leading protected-only left-turn (POLT); (2) lagging POLT; (3) leading protected-permitted left-turn (PPLT); and (4) lagging PPLT. Note that this study only considers undersaturation scenarios.
LITERATURE REVIEW

This literature review section first documents the existing capacity models with the left-turn bay spillback and blockage and their relations to different left-turn bay lengths. Then, it reviews existing studies with different left-turn signal settings.

Kikuchi et al. (8) studied the probability of left-turn vehicles overflowing from the turning lane, and the probability of left-turn-related blockages caused by vehicles on the adjacent through lane. Later in the 2000s, Kikuchi and Kronprasert (9)(5) studied the length of right-turn bays and left-turn bays respectively under different signal strategies based on probabilistic models. Reynolds et al. (10) developed a macroscopic model to predict turn pocket blockage and spillback probability. Cao et al. (11) developed models to estimate left-turn spillback probability in a connected vehicle environment and used the result from spillback probability to improve signal control strategy. According to these studies, the design criteria of left-turn bays should be avoided large spillback and blockage probabilities. However, these probabilities are just indirect standards of intersection performance. The negative effect of spillback and blockage on through and left-turn movement capacity really matters. When designing left-turn bays, it is important to mitigate this negative effect as much as possible.

Although there are few researchers (12) that have studied the effects of a right-turn bay on the capacity of through movement, a majority of existing studies (2)(3)(4) developed mathematical models to estimate through movement at intersections with a short left-turn bay. This is due to the left-turn bay length’s critical role in traffic performance analysis.

Zhang and Tong (2) developed a model that can estimate left-turn capacity and adjacent through capacity. The proposed model improved the HCM in modeling capacity when the left-turn bay is relatively short. This study was widely adopted by many further researchers (13) (3) (11). However, the study by Zhang and Tong did not model the spillback probability comprehensively, thus the through capacity estimation model can be further improved. Haddad and Geroliminis (14) extended the capacity model with left-turn spillback from one intersection to multiple intersections on an arterial corridor. The study revealed that the effect of left-turn spillback observed at a single intersection also appeared at the corridor level. Li and Elefteriadou (15) studied how changing signal phases can maximize the traffic throughput of turn bays. Liu et al. (7) modeled the capacity of intersections with short left-turn bays while considering different signal timing plans.

In addition to different signal timing plans, a POLT or a PPLT within the same timing plan would also introduce differences in mobility (e.g., delay and queue length) and impacts on the safety performance at the signalized intersection (16) (17) (18). Li et al. (18) concluded that the conversion of a PPLT to a POLT had a slight negative impact on mobility while improving the safety performance of the left-turn movement. According to a survey (19) that covered more than 107,000 signalized intersection all over the United States, 83% of PPLT intersections used a leading sequence, another 11% employed a lagging sequence, and the rest using a lead-lag sequence. Lead-lag sequence is not considered in this study as it is the least common signal timing plan. It is known to create significant driver confusion (20). Machemehl and Mechler (21) experimented under the same geometry, signal timing, and traffic demands and revealed that the total delay between leading and lagging POLT was not significantly different. Hummer et al. (22) (23) evaluated leading and lagging left-turn signal settings in terms of safety and delay. The conflict points between left-turn movements and pedestrians were one of the many measurements of safety. Hummer et al. found that the leading sequence was associated with
three times as many conflicts as the lagging sequence. An additional measurement concerning
the number of left-turn and oncoming vehicle accidents was considered. A greater accident rate
at intersections with leading sequences was observed. Under four signal setting, the average
delay (s/veh) for the intersection measured under leading POLT (19.4 s/veh) and lagging POLT
(19.9 s/veh) were larger than leading PPLT (14.7 s/veh) and lagging PPLT (13.5 s/veh).
Although Hummer et al. recommended lagging instead of leading phase sequences when
considering safety, the lagging sequence caused a larger delay than the leading sequence. Lee et
al. (24) reported that there were 42% and 30% increases in delay from leading to lagging
operation at the Phoenix area and the Pima County, respectively. This study again found no
significant difference in left-turn accident history between leading and lagging operation.
Further, the study conducted by Wright and Upchurch (25) shown reductions in both through and
left-turn delays from a leading POLT as well as a leading PPLT.

When analyzing the effects of left-turn spillback on adjacent through movement, most
researchers only focused on a lagging POLT. This is because the lagging POLT tends to cause a
larger probability of left-turn spillback than a leading POLT. Many previous studies overlooked
the fact that under leading POLT, left-turn spillback will still decrease adjacent movement
capacity. Kikuchi and Kronprasert (5) studied left-turn spillback probability under leading
POLT. Cho (13) developed models to estimate the reductions in through capacity with left-turn
spillback under a leading POLT. However, despite the reasonable logic applied in this model, the
model accuracy can be further improved.

In addition to signal settings and sequences, left-turn bay length (i.e., length of the left-
turn lane) is also an influential factor considered by researchers (2)(3)(11)(13) when analyzing
the effect of left-turns on the adjacent through movement. Messer et al. (26) presented that lead-
lead or lag-lag left-turns (i.e., leading POLT/PPLT or lagging POLT/PPL) performed better at
bay lengths of 5 to 10 vehicles. Kikuchi and Kronprasert (5) analyzed a variety of bay lengths
ranging from 4 to 18 vehicles in different left-turn signal settings and compared those to the
lengths listed in the American Association of State Highway Transportation Officials
(AASHTO). It proved that the existing guidelines were useful within certain ranges of
combinations of left-turn and through volumes. Cho and Zhang (13) focused on short left-turn
bays from 4 to 9 vehicles in length, and modeled the capacity of left-turn and through movement
considering blockage and spillback. Yao et al. (27) simulated various combinations of signal
phase plans and bay lengths from 30 meters (equivalent to 4 or 5 vehicle length) to 120 meters
(equivalent to 16 or 20 vehicles length). Leading PPLT had a better performance than lagging
PPLT when the left-turn bay length was short.

OBJECTIVE

Although the majority of the existing studies focused on the impacts associated with the left-turn
movement, few have modeled the capacity of the adjacent through movement and investigated it
under various left-turn signal settings, different left-turn bay lengths, and their combined effects.
Moreover, some studies contained assumptions and oversimplifications by excluding left-turn
spillback scenarios or only considering one left-turn signal setting. Hence, this study proposed
four comprehensive mathematical models to estimate through movement capacity under different
left-turn signal settings at various left-turn bay length levels. All proposed models will be
validated by simulation results. Moreover, the proposed model will be compared with HCM and
two existing models to show how it is stronger across four signal settings and various bay
lengths. Lastly, this study will examine how cycle length can affect through movement capacity when left-turn spillback exists. The object of this paper is to provide transportation practitioners with an analysis tool to help in decision making when the impact of left-turn spillback is known.

4 METHODOLOGY

In this methodology section, four mathematical models are established to estimate through movement capacity under four different left-turn signal settings. First, an improved model under lagging POLT is established based on previous studies by different researchers. Second, the model under the leading POLT is introduced. Blockage and spillback cases are more complicated under leading POLT, so the model is created on the basis of the lagging POLT model. Lastly, models under lagging and leading PPLT are established using the concept of equivalent left-turn bay forward extension.

Adjacent Through Capacity with Lagging Protected Only Left-Turn (Lagging POLT)

Under a lagging POLT, when a left-turn bay is short, the adjacent through lane will be blocked by left-turn queue spill out of the left-turn bay in some cycles, and as a result, the adjacent through capacity will be affected. Zhang and Tong (2) proposed a model to determine the adjacent through capacity with a lagging protected left-turn phase. They introduced that the probability of left-turn spillback can be presented as Equation (1):

\[ P_{spill} = P(X_{LT} \geq N + 3) \cap P(X_{TH} \leq N + 1) \]  

(1)

Where:

- \( P_{spill} \): Left-turn spillback probability
- \( X_{LT} \): Number of left-turn vehicles per cycle
- \( X_{TH} \): Number of through vehicles in the adjacent through lane per cycle
- \( N \): Length of the left-turn bay in vehicles length

The transitional (taper) area of a left-turn bay is assumed to be able to store two extra vehicles. Thus, N+2 left-turn vehicles can be stored without spillback. Left-turn spillback will happen when at least N+3 left-turn vehicles arrive at the intersection and, at the same time, no more than N+1 through vehicles arrive. Later, Osei-Asamoah et al. (4) proposed that there are three different left-turn spillback conditions: (1) normal spillback, (2) delayed spillback and (3) no spillback. Normal spillback happens during the red phase of the through movement when the N+1 left-turn vehicle arrives before the Nth through vehicles. Delayed spillback means that during the red phase of the though movement, left-turn spillback does not happen either because less than N+1 left-turn vehicle have arrived or because the N through vehicle arrives before the N+1 left-turn vehicle. Left-turn spillback will happen during the green phase of the thought movement. After combining these two spillback scenarios (normal spillback and delayed spillback), it can be concluded that once the number of left-turn vehicles reaches N+1 during the left-turn red duration, spillback will certainly happen and the adjacent through capacity will be affected. Left-turn arrival is assumed to follow a Poisson distribution. Thus, according to Osei-Asamoah et al. (4), the probability of left-turn spillback can be written as Equation (2):

\[ P_{spill} = P(X_{LT}(r_{LT}) \geq N + 1) = 1 - \sum_{i=0}^{N} e^{-\lambda_{LT}} \frac{(\lambda_{LT} r_{LT})^i}{i!} \]  

(2)

Where:
$P_{\text{split}}$ : Left-turn spillback probability

$X_{LT}(r_{LT})$ : Number of left-turn vehicles arriving during the red duration of left-turn movement

$\lambda_{LT}$: Left-turn vehicles arriving rate (veh/h)

$r_{LT}$: Left-turn red duration (h)

Once the number of left-turn vehicles arriving during the red phase exceeds N, spillback will happen. Only the through vehicles arriving before the N+1 left-turn vehicle on the adjacent through lane can pass the intersection during the through movement green duration. All the other through vehicles behind it will be blocked by the left-turn vehicles spilling out of the left-turn bay into the adjacent through lane.

However, Osei-Asamoah et al. (4) did not consider the arriving sequence of the left-turn vehicles and the through vehicles in the adjacent through lane in their model. They used the average number of through vehicles arriving before the N+1 left-turn vehicle to determine the through capacity. The actual number of vehicles arriving before the spillback varies from cycle to cycle. In order to model the left-turn capacity more precisely and comprehensively, the arriving sequence of left-turn vehicles and through vehicles in the adjacent lane will be considered in the proposed model of this paper.

Kikuchi and Kronprasert (9) studied the length of right-turn lanes. They considered the arriving sequence of through and right-turn vehicles to determine the probability of blockage and overflow. Similar ideas can be applied here to left-turn spillback. For a certain cycle, during the left-turn red duration, when left-turn spillback occurs, supposing that $i$ left-turn vehicles and $k$ through vehicles arriving in the adjacent through lane and $t$ through vehicles arrive before the left-turn spillback (the N+1 left-turn vehicles arrives) during the left-turn red duration ($i \geq N + 1, k \geq 0$ and $t \leq k$). The probability of this scenario ($i, k, t$) happens can be calculated as Equation (3):

$$ P(i, k, t) = e^{-\lambda_{LT}r_{LT}} \frac{(\lambda_{LT}r_{LT})^i}{i!} e^{-\lambda_{TH}r_{LT}} \frac{(\lambda_{TH}r_{LT})^k}{k!} \left(\frac{N+t}{t}\right) \left(\frac{N-1+k-t}{k-t}\right) $$

(3)

Where:

$P(i, k, t)$: The probability of scenario ($i, k, t$) happens

$\lambda_{TH}$: Through vehicles arriving rate per lane (v/h/l)

Under this case in the adjacent through lane, only $t$ through vehicles and the through vehicles accumulated during the left-turn green duration of the previous cycle can clear the intersection during the through movement green duration. The equivalent through movement capacity in an hour can be written as Equation (4):

$$ c(i, k, t) = n(t + \lambda_{TH} g_{LT}) + (N_{TH} - 1) \frac{s_{TH} g_{TH}}{C} $$

(4)

Where:

$c(i, k, t)$: through movement capacity of scenario ($i, k, t$) in an hour

$n$: number of cycles per hour

$N_{TH}$: number of through lanes

$s_{TH}$: saturation flow rate of through movement per lane (veh/h/ln)

$g_{LT}$: left-turn green duration per cycle (h)

$g_{TH}$: through green duration per cycle (h)

$C$: cycle length (h)

The through movement capacity can be estimated with Equation (5):
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\[ c_{TH | \text{lagging POLT}} = \sum_{t=0}^{\infty} \sum_{k=0}^{\infty} \sum_{i=N+1}^{\infty} \frac{(N+i+k-t)}{t} e^{-\lambda_{LT}g_{LT}} \left( \frac{\lambda_{LT}g_{LT}}{t!} \right)^i e^{-\lambda_{TH}g_{TH}} \left( \frac{\lambda_{TH}g_{TH}}{k!} \right)^k \]

(5)

Where:

- \( c_{TH | \text{lagging POLT}} \): Through movement capacity under lagging protected only signal settings (veh/h)
- \( c_i \): The numbers of through movement vehicles arriving before the \( i+1 \) vehicle vary from cycle to cycle, so Equation (5) considers all possible arrival scenarios by combining vehicle arrival sequences. Moreover, if the distribution of vehicle arrivals becomes something other than a Poisson distribution, Equation (5) can be revised accordingly.

Adjacent Through Capacity with Leading Protected Only Left-Turn (Leading POLT)

For leading POLT signal settings, it is believed that the adjacent through capacity is less affected because left-turn vehicles receive green light before the through movement green duration. However, left-turn spillback can still happen if too many left-turn vehicles arrive at the intersection. One major problem of leading POLT is shown in the blockage to the left-turn bay by through vehicles in the adjacent through lane. When this occurs, the blockage will affect the left-turn spillback probability. Thus, in order to model the probability of left-turn spillback, two different scenarios need to be considered: (1) blockage to the left-turn bay does not occur and (2) blockage to the left-turn bay occurs.

(1) Blockage to the left-turn bay does not occur

Similar ideas used in left-turn spillback probability calculation can be applied here to represent the probability of blockage to left-turn bays. During the red duration of through movement, once there are more than \( N \) through vehicles arriving on the adjacent though lane, blockage will happen. The probability of blockage can be calculated as:

\[ P_{\text{blockage}} = P(X_{TH}(r_{TH}) \geq N) \]

(6)

Where:

- \( P_{\text{blockage}} \): The probability of blockage to the left-turn bay
- \( X_{TH}(r_{TH}) \): Number of through vehicles arriving during the red duration of through movement

If a left-turn bay is not blocked by the through vehicles during through movement red duration, all left-turn vehicles can clear the intersection at the end of the left-turn green duration because oversaturation is not considered in this study. This means that when the signal for the through movement phase turns green, there will be no left-turn vehicles in the left-turn bay. During this green phase of the through movement, left-turn vehicles will begin to queue in the left-turn bay. Once the number of vehicles exceeds the length of the bay, spillback occurs and affects the adjacent through capacity. If the blockage to the entrance of left-turn bay condition does not occur, the through movement capacity can be estimated as:

\[ c_{TH \text{ no blockage}} = \sum_{t=0}^{\infty} \sum_{k=0}^{\infty} \sum_{i=N+1}^{\infty} \frac{(N+i+k-t)}{t} e^{-\lambda_{LT}g_{LT}} \left( \frac{\lambda_{LT}g_{LT}}{t!} \right)^i e^{-\lambda_{TH}g_{TH}} \left( \frac{\lambda_{TH}g_{TH}}{k!} \right)^k \]

(7)

Where:

- \( c_{TH \text{ no blockage}} \): Through movement capacity when no blockage to left-turn bay entrance occurs
\( P^{\text{no blockage}}_{\text{spill}} \): Probability of left-turn spillback when no blockage to left-turn bay entrance occurs

\( T \): Average number of through vehicles arriving at the intersection during the red duration of through movement (calculation detail as in Equation (8)):

\[
P^{\text{no blockage}}_{\text{spill}} = P(X_{LT}(g_{TH}) \geq N + 1) = 1 - \sum_{i=0}^{N} \frac{e^{-\lambda_{LT}g_{TH}} \lambda_{LT}^{i} g_{TH}^{i}}{i!}
\] (8)

T is the average number of through vehicles arriving at the intersection during the red duration of through movement. These vehicles can also pass the intersection in the green duration of through movement. If no blockage occurs in this case, there might be 0 to N through vehicles in the blocked lane. T can be calculated as:

\[
T = \sum_{i=0}^{N} i \cdot e^{-\lambda_{TH}r_{TH}} \frac{(\lambda_{TH}r_{TH})^{i}}{i!}
\] (9)

(2) Blockage to the left-turn bay occurs

For cycles where blockage to the left-turn bay occurs during the red duration of both left-turn and through movements, only a limited number of left-turn vehicles can clear the intersection during the left-turn green duration because the entrance of the left-turn bay will be blocked. When the left-turn green duration ends, there will still be some left-turn vehicles left at the intersection. Let \( \epsilon \) be the average number of left-turn vehicles that can clear the intersection during left-turn green duration when blockage happens. When calculating the spillback probability, these vehicles can be considered the extra capacity of a left-turn bay and thus \( \epsilon \) can be considered as a forward extension of the left-turn bay. Left-turn spillback probability should be calculated considering the duration of the entire cycle. Kikuchi and Kronprasert (9) applied a similar idea about equivalent forward extension when analyzing the probabilities of spillback and blockage to right-turn pocket by right-turn vehicles when right-turn on red is allowed (RTOR).

In this case, the equivalent length of the left-turn bay is \( N + \epsilon \). The probability of left-turn spillback under this scenario can be written as:

\[
P^{\text{blockage}}_{\text{spill}} = P(X_{LT}(C) \geq N + \epsilon + 1)
\] (10)

Where:

\( X_{LT}(C) \): The number of vehicles arriving at the intersection within an entire cycle.

\( \epsilon \): The average number of left-turn vehicles that can clear the intersection during left-turn green duration when blockage happens.

Note that if blockage to the left-turn bay occurs during a cycle, some left-turn vehicles will miss the left-turn green period in this cycle because left-turn bay entrance is blocked. After this, when the through movement receives green light, all through vehicles which block the left-turn bay entrance will clear the intersection. Thus, when the left-turn vehicles left over from this cycle receive green light again in the next cycle, these vehicles can clear the intersection because there is not any through vehicles ahead. Therefore, when calculating the probability of left-turn spillback in this condition, the model only needs to consider the left-turn vehicles arriving during the current cycle. This is true because this study does not consider oversaturation scenario.

The value of \( \epsilon \) (number of left-turn vehicles arrive at the intersection before the blockage to the left-turn bay occurs) varies from cycle to cycle, and it is very complicated to calculate.
However, the average number of left-turn vehicles arriving before the N through vehicle can be
determined. The probability density function of the time when the N through vehicle arrives at
the intersection on the adjacent through lane is given by:
\[
f(\eta) = \lambda_{TH} e^{-\lambda_{TH}\eta} \left(\frac{\lambda_{TH}\eta}{N-1}\right)^{N-1} (N-1)!
\]
(11)

Where \(\eta\) is the arrival time of the N though vehicle arriving at the intersection (in
second). The probability of \(X_{LT}\) left-turn vehicles arriving at the intersection during time \(\eta\) is
given by:
\[
P(X_{LT}) = \int_0^{r_{TH}} e^{-\lambda_{LT}\eta} \times \frac{(\lambda_{LT}\eta)^{X_{LT}}}{X_{LT}!} \times \left\{ \lambda_{TH} \times e^{-\lambda_{TH}\eta} \times \frac{(\lambda_{TH}\eta)^{N-1}}{(N-1)!} \right\} d\eta
\]
(12)

Thus, the average number of left-turn vehicles arriving at the intersection before the
blockage to the left-turn bay happens (\(\epsilon\)) can be calculated as:
\[
\epsilon = E(X_{LT}) = \sum_{X_{LT}=0}^{\infty} X_{LT}P(X_{LT})
\]
(13)

\[
\epsilon = \sum_{X_{LT}=0}^{\infty} X_{LT} \times \int_0^{r_{TH}} e^{-\lambda_{LT}\eta} \times \left\{ \frac{(\lambda_{LT}\eta)^{X_{LT}}}{X_{LT}!} \times \left\{ \lambda_{TH} \times e^{-\lambda_{TH}\eta} \times \frac{(\lambda_{TH}\eta)^{N-1}}{(N-1)!} \right\} d\eta \right\}
\]
(14)

The adjacent through capacity when blockage to the entrance of left-turn bays occurs can
be calculated as follow:
\[
c_{TH}^{blo} = \sum_{i=N+\varepsilon+1}^{\infty} \sum_{k=0}^{\infty} \sum_{t=0}^{k} \frac{(N+\varepsilon+t)}{(i-k-1)!} e^{-\lambda_{LT}C} \frac{(\lambda_{LT}C)^i}{i!} e^{-\lambda_{TH}C} \frac{(\lambda_{TH}C)^k}{k!} \left[ nt + (N_{TH} - 1) \frac{S_{TH}g_{TH}}{C} \right] + (1 - P_{blo}^{spill}) \frac{N_{TH}S_{TH}g_{TH}}{C}
\]
(15)

Where:
\(c_{TH}^{blo}\) : Through movement capacity when blockage to left-turn bay entrance occurs
\(P_{blo}^{spill}\) : Probability of left-turn spillback when blockage to left-turn bay entrance occurs

After combining the through capacity estimation models in Equation (7) and (15), the
overall through movement capacity under leading POLT signal setting can be concluded as
Equation (16):
\[
c_{TH}|_{leading\_POLT} = P_{\text{blockage}} \times c_{TH}^{blo} + (1 - P_{\text{blockage}}) \times c_{TH}^{no\_blo}
\]
(16)

Where:
\(c_{TH}|_{leading\_POLT}\) : Through movement capacity under leading protected only signal setting
(veh/h)

Adjacent through capacity estimation with permitted plus protected left-turn signal setting (PPLT)
When permitted left-turns are introduced to the signal timing plan, several vehicles in the left-
turn bay can move through the intersection during the through movement green duration. Let \(\delta\) be
the number of vehicles passing the intersection during the permitted left-turn phase. In this case, the left-turn bay can hold another $\delta$ vehicles during the left-turn red duration. Thus, the equivalent left-turn bay length becomes $N + \delta$. $\delta$ can be calculated as Equation (17) below.

$$\delta = \frac{c_L}{n} + sne$$  

(17)

$$c_L = \left(\frac{g_u}{C}\right) c_p$$  

(18)

$$c_p = \frac{V_0 e^{-V_0 r_c/3600}}{1 - e^{-V_0 H_f/3600}}$$  

(19)

$$g_u = g_{TH} - \frac{V_0 r_{TH}}{s - V_0}$$  

(20)

Where:

- $V_0$: Opposing through flow rate
- $c_L$: Actual permitted left-turn capacity
- $c_p$: Potential permitted left-turn capacity
- $g_u$: Effective green time after the opposing through queue clears
- $sne$: The number of sneakers and jumpers in each cycle (2 in leading PPLT and 3 in lagging PPLT)
- $T_c$: Critical gap (assumed to be 4.5s)
- $H_f$: Follow up headway (assumed to be 2.5s)

The probability of left-turn spillback for lagging left-turn phase then becomes to:

$$P_{spill} = P(X_{LT}(r_{LT}) \geq N + \delta + 1)$$  

(21)

For case (1) and case (2) of leading left-turn phase, the probabilities of left-turn spillback become to:

$$P_{spill}^{no\,bloc} = P(X_{LT}(g_{TH}) \geq N + \delta + 1)$$  

(22)

$$P_{spill}^{bloc} = P(X_{LT}(C) \geq N + \epsilon + \delta + 1)$$  

(23)

**Method of Highway Capacity Manual for Adjacent Through Capacity**

The HCM method calculates the capacity of through movement as according to Equation 25:

$$c_{TH|_{HCM}} = N_{TH} S_{TH} g_{TH}$$  

(24)

Where:

- $c_{TH|_{HCM}}$: Through movement capacity in HCM
- $N_{TH}$: Number of through lanes
- $S_{TH}$: The saturation flow rate of through movement per lane (v/h/l)
- $g_{TH}$: Through green time per cycle (s)
- $C$: Cycle length (s)

Equation (25) gives a constant value for the given saturation flow rate and green time. This calculated value represents the maximum theoretical capacity, ignoring the impacts of
blockage and spillback situations due to short left-turn lanes. The modeling results for the adjacent through lane considering different left-turn signal settings and left-turn lane lengths will be compared with this theoretical capacity based on HCM.

4 MODEL VALIDATION

This model validation section introduces the simulation setup used to validate the proposed capacity models, and briefly describes the measure of effectiveness for evaluation adapted in this study.

Simulation Setup

A four-leg isolated signalized intersection was set up in VISSIM (28), a widely used micro-simulation modeling software (3)(29)(30). Due to its microscopic nature, each vehicle’s movement is tracked in time and space, and spillback and blockage scenarios are explicitly modeled in VISSIM. The simulation results were used to validate the capacity models. For simplicity, the intersection has two 3.7m through lanes on every approach, with one left-turn bay in the northbound, and has the ideal conditions of all passenger cars: no parking, no pedestrians, and no turn right on red. Four left-turn signal settings (i.e., leading POLT, lagging POLT, leading PPLT, lagging PPLT) were considered in the three-phase signal timing plan. The length of the left-turn bay was selected as a numerical variable in the capacity calculation. The length of passenger cars varies from 4.1m to 4.8 ft in VISSIM and the bay length was adjusted by observing the number of vehicles during a simulation. For instance, Figure 1 (a) captured one such scenario when the length of left-turn bay was set at five vehicle lengths long. The main input data for the capacity calculation are as follows:

- Through vehicle volume, 1,700 veh/h;
- Left-turn volume, 400 veh/h;
- Through vehicle green, 50 s;
- Through vehicle red and change time, 54 s;
- Protected left-turn green, 23 s;
- Cycle length, 106 s;
- Opposite through volume, 1,500 veh/h;

These input data and calibration processes were referenced to the simulation setup in (2)(3). Both left-turn spillback and left-turn blockage conditions were included in the scenarios of this study, and examples were shown in Figure 1 (a) and (b) respectively. The authors managed to obtain the capacity results from VISSIM based on its outcome of lane throughput by increasing the demand until the throughput reached its maximum. A detector was coded downstream as illustrated in Figure 1 to measure the throughput.

Accounting for all of the various left-turn bay lengths and left-turn signal settings, there are 44 scenarios (i.e., 11 left-turn bay lengths from 4 to 14 vehicles, 4 left-turn signal settings including leading POLT, lagging POLT, leading PPLT, lagging PPLT) in this study. To address the stochastic nature of VISSIM, a minimum of six simulation runs was recommended to provide an outcome within a 90% confidence interval following the Guidelines for Applying Traffic Microsimulation Modelling Software issued by Federal Highway Administration (31). Hence, each scenario was simulated for seven runs. In total, 308 simulation runs were performed to provide the ground-truth data as accurately as possible. Each run lasted for one hour and 15
minutes. The first 15 minutes of each run was a “warm-up” period to make sure the simulation was running smoothly and so the data collection did not accidentally occur during these periods.

(a) Layout of the intersection for collecting adjacent through capacity with left-turn spillback.

(b) Layout of the intersection for collecting adjacent through capacity with blockage to the entrance of left-turn bays.

Figure 1. The layout of the intersection for collecting adjacent through capacity.

Measure of Effectiveness

In this study, the capacity obtained from VISSIM simulation is assumed to be the ground truth. The absolute percentage error (APE) is as the measure of effectiveness (MOE) in this study. The equation below computes APE between a value estimated by a capacity model (i.e., $c_{TH}^*$) and the value from ground truth (i.e., $c_{TH}$):

$$\text{Absolute Percentage Error (\%)} = \frac{|c_{TH} - c_{TH}^*|}{c_{TH}^*}$$  \hspace{1cm} (25)

The absolute percentage error helps to capture the error regardless of whether the capacity model is overestimating or underestimating the capacity. For instance, in any one scenario, the method used in the HCM may overestimate, while the proposed model may
underestimate. They only become comparable with the scale of absolute percentage error. Moreover, this MOE is independent of the simulation setup. Although Zhang and Tong’s through movement capacity model in 2008 (2) was based on a different simulation tool, the model proposed in this study still can compare to Zhang and Tong’s when using the scale of absolute percentage error.

RESULTS

In the following section, the authors first examined the proposed capacity models under four left-turn signal settings (i.e., leading POLT, lagging POLT, leading PPLT, and lagging PPLT) at different left-turn bay lengths (i.e., 4 to 14 vehicle length given increment at one vehicle length) by comparing the adjacent through capacity results to the capacity values from VISSIM (i.e., ground truth) and HCM model (i.e., conventional method). Then, comparisons in MOE are made between proposed models, the HCM model, and two existing models (2)(13). Lastly, after proving the superiority of the proposed capacity models, the authors used the models at lagging POLT to explore the effect of cycle length on adjacent through capacity among various bay lengths.

Validation of Proposed Adjacent Through Capacity Models

Results from the proposed models and the HCM model are compared with the ground truth (i.e., VISSIM Outputs) results at various left-turn bay lengths in Figure 2. The HCM model does not take left-turn spillback into account, so the capacity stays the same at all left-turn bay length levels. Significant gaps can be observed between the proposed models and the HCM model, especially when left-turn bay lengths are short. The gaps become smaller when left-turn bay lengths increase. The through capacity will reach the same level as HCM when the left-turn bay length is around 11 vehicle lengths under lagging POLT and 9 vehicle lengths for leading POLT. There is a significant improvement in the through capacity when permitted left-turns are introduced and the left-turn bay is short. However, this improvement becomes less apparent when the left-turn bay is long. The proposed models work well under all four left-turn signal settings except under lagging POLT, where the model seems to slightly underestimate the through capacity.
Figure 2. Comparison of adjacent through capacity among proposal model, HCM model, and VISSIM Simulation under four different left-turn signal settings.

Comparisons of Adjacent Through Capacity Models in Different Left-turn Signal Settings

Table 1 provides detailed absolute percentage error (APE) data of the proposed models under four different left-turn signal settings (i.e., leading POLT, lagging POLT, leading PPLT, and lagging PPLT) and at different left-turn bay lengths (i.e., 4 to 14 vehicle length given increment at 1 vehicle length). Moreover, Zhang and Tong’s model (2) under lagging POLT, and Cho and Zhang’s model (13) under leading POLT are also included in Table 1 to compare with the proposed models in this paper. Note than in Zhang and Tong’s model, it only presented data at left-turn bay length levels with 5 to 12 vehicle length, and, in Cho and Zhang’s model, 4 to 9 vehicle length. APE data for leading and lagging POLT signal settings are visualized in two different ways in Figure 3 and Figure 4.
Table 1. Comparisons in Measure of Effectiveness

<table>
<thead>
<tr>
<th>Bay Length</th>
<th>Proposed Model</th>
<th>HCM Model</th>
<th>Cho and Zhang’s Model (13)</th>
<th>Bay Length</th>
<th>Proposed Model</th>
<th>HCM Model</th>
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<tbody>
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<td>POLT</td>
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<td></td>
<td>PPLT</td>
<td></td>
<td></td>
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<tr>
<td>4 (26m)</td>
<td>2.503%</td>
<td>19.466%</td>
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<td>11.927%</td>
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<td>2.228%</td>
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<td>15.094%</td>
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<td>0.177%</td>
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<td>0.236%</td>
</tr>
<tr>
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<td>0.118%</td>
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<td>12 (77m)</td>
<td>0.236%</td>
<td>0.236%</td>
</tr>
<tr>
<td>13 (82m)</td>
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<td>13 (82m)</td>
<td>0.118%</td>
<td>0.118%</td>
</tr>
<tr>
<td>14 (87m)</td>
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</table>

<table>
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<tr>
<th>Bay Length</th>
<th>Proposed Model</th>
<th>HCM Model</th>
<th>Zhang and Tong’s Model (2)</th>
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<td>PPLT</td>
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<td>0.494%</td>
<td>4.880%</td>
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<td>1.255%</td>
<td>1.494%</td>
</tr>
<tr>
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</tr>
<tr>
<td>7 (47m)</td>
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<td>0.650%</td>
<td>0.295%</td>
</tr>
<tr>
<td>8 (52m)</td>
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<tr>
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<td>0.059%</td>
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<tr>
<td>14 (87m)</td>
<td>0.235%</td>
<td>0.000%</td>
<td></td>
<td>14 (87m)</td>
<td>0.059%</td>
<td>0.059%</td>
</tr>
</tbody>
</table>

Note: the unit of bay length is in number of vehicles, the corresponding SI unit is listed in the parenthesis next to each.

Figure 3 presents the advantage of the two proposed models in this study over the HCM model, Cho and Zhang’s model (for leading POLT) and Zhang and Tong’s model (for lagging POLT). The advantage of the proposed models in this study is more apparent when left-turn bays are short. As for leading and lagging POLT signal settings, the HCM model’s estimation differs significantly from the ground truth data. Zhang and Tong’s model (2) alleviates the estimation errors, however, the APEs are still around 5%. The proposed models further improve the
estimation accuracy at short left-turn bay length levels under all four left-turn signal settings. The APEs of proposed models under leading and lagging POLT at all left-turn bay length levels are lower than 3%.

![Comparison of adjacent through capacity model under leading protected-only left-turn (POLT) signal setting](image1)

(a) Comparison of adjacent through capacity model under leading protected-only left-turn (POLT) signal setting

![Comparison of adjacent through capacity model under lagging protected-only left-turn (POLT) signal setting](image2)

(b) Comparison of adjacent through capacity model under lagging protected-only left-turn (POLT) signal setting

**Figure 3. Comparisons of adjacent through capacity models under different left-turn settings**
Comparisons of Adjacent Through Capacity Models with Different Left-Turn Bay Lengths

In Figure 4, two proposed models (leading and lagging POLT) show excellent accuracy and consistency at all left-turn bay length levels compared with the HCM model, Cho and Zhang’s model and Zhang and Tong’s model. HCM models under both leading and lagging POLT signal settings have substantial estimation errors at short left-turn bay length levels, but the accuracy improves when left-turn bays become longer. As for Cho and Zhang’s model under leading POLT, it cannot provide accurate estimation at left-turn bay length levels from 4 to 9 vehicles. For Zhang and Tong’s model, its accuracy improves when compared with the HCM model, however its overall accuracy is still lower than the proposed model in this study.

Figure 4. Comparisons of adjacent through capacity models with different left-turn bay lengths

Effect(s) of Cycle Length on Through Movement Capacity

After validating proposed capacity models with ground truth (i.e., VISSIM) and proving their superiors over two existing models in different left-turn strategies and different bay lengths, the last step is to explore the effect of cycle length on through movement capacity using proposed capacity models. The left-turn signal setting - lagging POLT – will serve as an example here. As shown in Figure 2, it is clear that under the same signal timing plan, the adjacent through movement capacity increases when left-turn bay length increases. Moreover, it would be interesting for engineers of practice to see the potential for increasing capacity by adjusting the cycle lengths. In this section, the authors calculated adjacent through movement capacity values from the proposed model for lagging POLT signal setting under various cycle lengths (from 80 to 130 seconds with an incremental of 10 seconds) and different bay length (from 4 to 14 vehicle
length). In order to make a fair and meaningful comparison, it is necessary to keep the same theoretical through movement capacity (i.e., capacity calculated by HCM model, which is 1700 veh/h/ln in this study) for all scenarios. Thus, the same g/C ratio is kept for both through and left-turn movements among all these scenarios. The list of cycle lengths and their corresponding through green and left-turn green durations are as follows:

- Cycle length = 80s, through green duration = 38s, and left-turn green duration = 17s
- Cycle length = 90s, through green duration = 42s, and left-turn green duration = 20s
- Cycle length = 100s, through green duration = 47s, and left-turn green duration = 22s
- Cycle length = 160s, through green duration = 50s, and left-turn green duration = 23s (setting used in previous section of this study)
- Cycle length = 110s, through green duration = 52s, and left-turn green duration = 24s
- Cycle length = 120s, through green duration = 57s, and left-turn green duration = 26s
- Cycle length = 130s, through green duration = 61s, and left-turn green duration = 28s

Table 2 presents the adjacent through movement capacity under Lagging POLT left-turn signal setting at various cycle lengths and left-turn bay lengths. Table 2 illustrates that an increase in cycle length results in a decrease in adjacent through movement capacity for all left-turn bay lengths. This effect of cycle length is small when left-turn bay length is relatively long. With a theoretical capacity of 1700 veh/h/ln, cycle lengths only lead to a small decrease (< 5%) of capacity for bay lengths from 10 to 15 vehicles in length. Nevertheless, the decrease in adjacent through capacity is larger when left-turn bay length is shorter. The adjacent through capacity decreases to 1368 veh/h/ln (~ 20% decrease from theoretical capacity) on a bay of 4 vehicle length. Overall, a combination of shorter left-turn bays and longer cycle lengths decrease through movement capacity. A combination of longer left-turn bays and shorter cycle lengths increase through movement capacity. This can be attributed to fixed short left-turn bay, where longer cycle length means left-turn vehicles may have to wait for longer at intersections during each cycle. As a result, more left-turn vehicles accumulate in the left-turn bay. Under this condition, the probability of left-turn spillback increases. With shorter cycle lengths, left-turn vehicles have more opportunities to clear the intersection in the same period of time, vehicles accumulation decreases, and the probability of left-turn spillback is decreased. Obviously, with the decrease of the cycle length, the overall capacity of the signalized intersection may be decreased so comprehensive investigation is needed.
Table 2. Adjacent through movement capacity (veh/h/ln) at various cycle lengths and left-turn bay lengths under Lagging POLT

<table>
<thead>
<tr>
<th>Cycle Length (s)</th>
<th>80</th>
<th>90</th>
<th>100</th>
<th>106*</th>
<th>110</th>
<th>120</th>
<th>130</th>
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<tbody>
<tr>
<td>Bay Length</td>
<td></td>
<td></td>
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<td></td>
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<td></td>
</tr>
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<td>1439</td>
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<td>1368</td>
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<td>1533</td>
<td>1498</td>
<td>1488</td>
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</tr>
<tr>
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<td>1689</td>
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<td>1696</td>
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<td>1693</td>
<td>1687</td>
</tr>
</tbody>
</table>

Note: green indicates a larger capacity; red indicates a smaller capacity; * 106-second is the cycle length used prior to this section in this study.

CONCLUSIONS AND FUTURE STUDY

This paper successfully established through movement capacity models under four left-turn signal setting (i.e., leading POLT, lagging POLT, leading PPLT, and lagging PPLT). The modeling results are compared with ground truth data obtained by VISSIM simulation. Results show that the proposed models can estimate the thorough movement capacity precisely and, in fact, even improves on the existing HCM model. This paper also compares the proposed models with through capacity models developed in previous studies (2)(13). Results show that the proposed models present better accuracy over all signal settings while also maintaining consistent accuracies at all left-turn bay length levels. The key findings of this paper include:

1. For a signalized intersection at a given location and with a fixed green split in a fixed cycle length, different left-turn signal settings have different levels of impact on the through movement capacity.
2. Although the impact of leading POLT on through movement capacity tended to be overlooked by previous studies, leading POLT can also present significant impact on the through movement capacity because blockage to the entrance of the left-turn bay can increase the spillback probability which will affect the through movement capacity.
3. Generally, a leading POLT signal setting can alleviate the negative impact caused by left-turn spillback on the through movement capacity compared with a lagging POLT signal setting. However, when left-turn bays are short, a leading POLT may have more negative impacts on the through movement capacity.
4. The introduction of permitted left-turn phase can have a significant improvement in through movement capacity especially when left-turn bays are short. This
improvement by permitted left-turn becomes less obvious when a left-turn bay becomes longer.

(5) When left-turn spillback occurs, the combination of shorter left-turn bay and longer cycle length decreases through movement capacity while the combination of longer left-turn bay and shorter cycle length increases through movement capacity.

It should be noted that Poisson arrivals are assumed in the calculation of spillback and blockage. This is reasonable since left-turn demand is relatively low and arrivals are rarely in platoons. Nevertheless, other types of arrival distribution could be considered in the future. When considering through vehicle arrivals affected by upstream signals for example, vehicles will arrive at the intersection in platoons instead of random arrival. In this case, the arrival distribution of through vehicles needs to be adjusted in the proposed models to reflect this effect.

This study only investigates the effect of left-turn spillback on the adjacent through lane immediately adjacent to a left-turn lane. However, in some scenarios, left-turn spillback can also impact other through lanes. Further studies can explore the impact of left-turn spillback and blockage of the entire through approach (i.e., all though lanes instead of only the one adjacent to the left-turn bay). The impacts of leading and lagging POLT signal settings on adjacent through capacity with short left-turn bays can be studied more comprehensively by including more signal timing plans and different numbers of through lanes and left-turn lanes. The development of through movement capacity models applying to intersections with more complex configurations (multilane left-turn bays and shared lanes with both left-turn and through movement) is also valuable.

AUTHOR CONTRIBUTION STATEMENT

The authors confirm contribution to the paper as follows: study conception and design: Zihang Wei, Yunlong Zhang; data collection: Zihang Wei, Xin Zhang; analysis and interpretation of results: Zihang Wei, Xiaoyu Guo; draft manuscript preparation: Zihang Wei, Xiaoyu Guo, Yunlong Zhang. All authors reviewed the results and approved the final version of the manuscript.

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