Operational Impacts of Copenhagen Left as Alternatives to Diagonal Left-Turns of Bicycles at Signalized Intersections

Xiaoming Chen, Ph.D.
Senior Associate
Traffic Engineers, Inc.
8323 Southwest Freeway, Ste 200
Houston, TX 77074
Phone: 1-713-270-8145
E-mail: sammychen@trafficengineers.com

Chunfu Shao, Ph.D.
(Corresponding Author)
Distinguished Professor, Department of Traffic Engineering
Director, MOE Key Laboratory for Urban Transportation
Complex Systems Theory and Technology
Beijing Jiaotong University, Beijing, China 100044
Phone: 86-10-5168-2236
E-mail: cfshao@bjtu.edu.cn

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ABSTRACT

At signalized intersections, diagonally left-turning bicyclists impede through automobile traffic and may experience significant delay. As an alternative to diagonal left-turns, Copenhagen Left operations can be used, in which left-turning bicyclists are required to go straight along with through automobiles from the same approach, stop, wait for the green interval for the cross street, and then go straight along the cross street to finish the maneuver. The objective of this study was to compare Copenhagen Left with diagonal left-turn maneuver in terms of impacts on capacity of automobile traffic and delay of bicyclists. To this end, an analytical capacity model was developed based on the observed behavioral patterns of automobiles when impeded by diagonally left-turning bicyclists. Micro-simulation models were used to assess delays incurred to bicyclists under both Copenhagen Left and diagonal left-turn operations. Numerical results evidenced that the capacities estimated by the proposed model were consistent with micro-simulation method. While Copenhagen Left enhances capacities of automobiles, it is not universally appropriate for all situations. Copenhagen Left can considerably increase delay for left-turning bicyclists at low-volume, small-sized intersections, which may lead to low compliance rate by bicyclists. A successful implementation of Copenhagen Left does not rely only on proven operational benefits, but also on sufficient storage space for the resulting standing bicyclists, clear pavement striping and signage, and effective education for the traveling public.
INTRODUCTION

The use of bicycles for commuting is common in many European and Asian countries, such as Netherlands, Denmark, Germany, China, and Japan. It complements the local transportation systems and offers an alternative to automobiles in helping reduce congestion and air pollution. Even in those cities where bicycle is not an integral part of the planned transportation system, increasing importance has been attached to bicycle as a healthy, sustainable transportation alternative. Therefore, many dedicated/protected bicycle facilities (e.g. dedicated bicycle lanes) have been constructed or planned to keep urban roadways bicyclist-friendly while reducing the impacts upon automobiles traffic (1).

At signalized intersections without dedicated bicycle lanes, a left-turning bicyclist has to be positioned at the left-turn lane (or the center-most lane) and follow the signal indicated for left-turn automobiles. This type of operation, which is very common in North America, is applicable for roadways with rare presence of bicycles. This paper deals primarily with signalized intersections with dedicated bicycle lanes installed (FIGURE 1), where the bicycle lanes and storage areas are placed to the right of the rightmost vehicle lanes. Given this geometry, it is common practice in many Asian countries (e.g. China) that bicyclists do not merge left before the intersection or use the left-turn/center-most lane with automobiles. FIGURE 1 presents conflict zones between diagonal left-turn bicycles and automobiles at an intersection operated by a simple two-phase signal. Such diagonal left-turn maneuver is generally challenging and unsafe, and bicyclists may experience significant delay and result in a considerable loss in capacities of automobiles.

FIGURE 1 Conflicts between automobiles and bicyclists turning left diagonally at signalized intersection
To mitigate potential issues associated with these conflicts, “Copenhagen Left” operations can be used to reroute the left-turning bicyclists, in which the bicyclists are required to go straight with through movement of automobiles, stop (Stage I in FIGURE 2), wait for the green interval for the cross street, and then go straight along the cross street to finish the maneuver (Stage II in FIGURE 2), without having to cross any through traffic of automobiles. Some potential benefits of Copenhagen Left can be summarized as follows.

Potential Impacts on Traffic Safety: Since left-turning bicyclists do not have to cross through automobiles but only to cross right-turn automobiles, the severity of traffic conflicts is potentially lowered. In addition, when diagonally left-turning bicyclists wait for crossing through traffic, some bicyclists may have to rely on the yellow and all-red clearance period, which is a stressful situation and may lead to collisions with conflicting automobiles that rush to cross during the clearance period. By contrast, Copenhagen Left normally utilize the green intervals.

Potential Impacts on Accessibility: Implementation of Copenhagen Left can provide easier access than a diagonal turn (i.e., permissive maneuvers) and lead to a significantly shorter crossing distances each time when bicyclists cross.

FIGURE 2 Rerouted left-turn bicyclists under Copenhagen Left operations
OBJECTIVES

Copenhagen Left are being implemented in a large number of European and Asian cities, as well as in several U.S. and Canada cities, e.g., Portland, Salt Lake City, Toronto, and Vancouver. While Copenhagen Left is implemented primarily out of traffic safety considerations, better understanding is also necessary of its operational impacts on bicycle and automobile traffic, so that engineers can make informed decisions. The objectives of this study include:

- Investigating the effectiveness of the Copenhagen Left in reducing impedance to automobile and increasing capacity of automobile traffic, and
- Studying the impacts of using Copenhagen Left on left-turning delays.

For fulfilling the objectives, two sets of analyses were performed as follows:

- **Comparison of automobile capacity between diagonal left-turn and Copenhagen Left**
  Capacity, defined as the maximum flow rate at which vehicles/pedestrians/bicyclists can cross stop lines during an hour under given conditions, is a key measure of effectiveness (MOE) in evaluating quality-of-service and the effectiveness of operational strategies at signalized intersections. The common width of an on-street bicycle lane ranges between 1.2 m and 1.8 m [4 ft and 6 ft]. A wide range of capacities and saturation flow rates have been reported by many countries and may be as high as 2,600 bicycles/h on the basis of research observations (2). Therefore, bicycle lanes are normally not the critical lane/movement at an intersection, and thus in this study, the focus of capacity analysis was placed on automobile traffic only. To enable the comparison, an analytical model was proposed and validated for estimating the capacity of through vehicular movements impeded by bicyclists turning left diagonally.

- **Comparison of bicyclists delay between diagonal left-turn and Copenhagen Left**
  Delay is another widely accepted MOE for evaluating intersections. For automobile traffic, it is normally modeled by estimating delay components including uniform delay, random-arrival delay, and initial queue delay (e.g. HCM recommended methods). Estimation of delays for bicycles can be even more complex due to different behavioral patterns of bicyclists. Therefore, VISSIM simulation models were used in this study to estimate the delays experienced by left-turning bicycles under various traffic conditions before and after the Copenhagen Left is used.

The comparisons conducted are presented through a numerical example based on a hypothesized intersection operated under a simple two-phase signal. Finally, discussions and recommendations were provided regarding implementing Copenhagen Left.
ESTIMATING CAPACITY OF THROUGH VEHICULAR MOVEMENTS IMPEDED
BY DIAGONALLY LEFT-TURNING BICYCLES

The pedestrian-bicycle adjustment factor in HCM (2000 and 2010) is a representative method for characterizing the effects of bicycles on capacity of automobiles at signalized intersections (2-4). The adjustment factor is based on the occupancy of the conflict zones, and provides deep insights and excellent resources. On the other hand, this data-driven model focuses only on effects of bicyclists on capacity of right-turning automobiles, and implicitly assumed that left-turning bicyclists have no impacts on through movements of automobiles, which is normally not the case. In this study, an analytical model was developed based on the observed patterns of how bicyclists impeded through movements of automobiles. The model was used in this study, and may also provide a potential tool for future modeling efforts in characterizing the impacts of left-turning bicyclists on signalized intersections and supplement the HCM method.

Field Observation

As part of the modeling efforts, field observation was performed in Beijing, China, at the intersection of S. Academy Rd. & Zaojun Temple Rd. It is located in urban areas with a moderate/high level of bicycle volumes and vehicular volumes. It was operated with a cycle length ranging from 120 s to 140 s during different times of day. Videotapes were recorded from the 10th floor of an office building at the corner during three weekdays. With bicyclists turning left diagonally, four behavioral patterns of automobiles were observed when the through automobiles were crossing the conflict zones at different speeds and flow rates, including

- Pattern 1 – At the beginning of green intervals
- Pattern 2 – When no bicycles show up
- Pattern 3 – When scattered bicyclists are crossing
- Pattern 4 – When bicyclists are standing by the conflict zone

Modeling Impedance of Bicycles Turning Left Diagonally

Pattern 1 - At the beginning of green intervals

According to the field observation in Beijing, bicyclists were normally able to speed up faster and earlier than the conflicting automobiles. At the beginning of green intervals, some bicyclists were observed starting up during the all-red intervals of the previous signal phase, occupying the conflict zone before automobiles did, and crossing the conflict zone at saturation flow. Through automobiles were blocked by the conflicting bicyclists, normally having to stop and wait for a very brief period.

The duration of blockage time by conflicting bicyclists is denoted as $T_{SB}$. The bicyclists crossing during $T_{SB}$, are accumulated during the red interval $t_r$ and $T_{SB}$; therefore,
\[(T_R + T_{SB}) \cdot \lambda_n = N_1 \cdot (B - 0.5) \cdot T_{SB}\]  

(1)

where \(\lambda_n\) is the arrival rate of left-turn bicyclists conflicting with through automobiles (bicycles/s), \(N_1\) is the flow rate per second per unit width that left-turn bicycles can cross the conflict zones (bicycles/s·m), \(B\) is the actual width for the bicycles at the conflict zone, and a clearance of 0.25 m [1 ft] is deducted for each side of the conflict zone.

Equation (1) can be reduced to

\[T_{SB} = \frac{\lambda_B \cdot T_R}{N_1 \cdot (B - 0.5) - \lambda_B}\]  

(2)

**Pattern 2 – When no bicycles show up**

After the period of \(T_{SB}\), scattered arrivals of bicyclists were observed. When no bicyclists were present at the conflict zone, automobile traffic crossed the conflict zone at its saturation flow. If we assume the arrival of bicyclists follows a Poisson process, the headway between bicyclists can be represented by a negative exponential distribution. During an analysis interval \(\tau\), the probability that no bicyclists are present at the conflict zone is:

\[P_0 = Pr(X = 0) = e^{-\lambda_0 \tau}\]  

(3)

On a per signal cycle basis, the length of the period when no bicyclists show up at the conflict zone can be estimated as \(P_0 \cdot (T_G - T_{SB})\), where \(T_G\) is the effective green. During the period of \(P_0 \cdot (T_G - T_{SB})\), automobiles can cross the conflict zone at a saturation flow rate of \(q_0\) and a speed of \(v_0\). Thus, the number of automobiles that can cross per hour when no bicyclists show up at the conflict zone can be estimated as

\[C_{P2} = q_0 \cdot P_0 \cdot (T_G - T_{SB}) / 3600\]  

(4)

**Pattern 3 - When scattered bicyclists are crossing**

When scattered bicyclists arrived, they normally stood by the conflict zone before crossing. When the stand-by bicyclists found a gap to cross, the conflicting automobiles were observed slowing down (normally rolling slowly rather than fully stopping). We assumed the automobile traffic flow changed from a state (when bicyclists were standing by) to another (with a lower speed and a higher density of automobile traffic). In light to the Shock Wave Theory, a backward condensing wave formed and the speed can be estimated as

\[V_w = \frac{q_2 - q_1}{k_2 - k_1} = \frac{q_2 - q_1}{q_2 / v_2 - q_1 / v_1}\]  

(5)

where \(q_1\), \(k_1\) and \(v_1\) are the volume, density and speed of the vehicular flow under the
influence of standing-by bicycles, and $q_2$, $k_2$ and $v_2$ are those when bicycles are crossing. The wave takes effects for the period of $T_B$, which is the time needed for bicyclists to cross the conflict zone. After $T_B$, a moving platoon forms with a length of $(V_w \cdot T_B)$ containing $(q_1 - q_2) \cdot T_B$ vehicles.

![Diagram](image)

**FIGURE 3**  Platoon due to impedance of crossing bicyclists

After the bicyclists cross, the automobile flow regained its speed and recovered to the state as when there were no bicycles standing by (at a flow rate of $q_0$ and a speed of $v_0$). A backward release wave is anticipated at a speed of $V_w^*$:

$$V_w^* = \frac{q_2 - q_0}{k_2 - k_0} = \frac{q_2 - q_0}{q_2 / v_2 - q_0 / v_0}$$  \hspace{1cm} (6)

The time needed to disperse the moving platoon is estimated as $(V_w / V_w^*) \cdot T_B$, which is normally slightly longer than $T_B$. Numerical tests showed that $T$ (FIGURE 3) can be approximated by $2 \cdot T_B$. The flow rate during $T$ varies with traffic flow speed. For simplicity, the mean value can be approximated by

$$\bar{q}_{12} = \left( \int_{v_1}^{v_2} q(u) \, du \right) / (v_1 - v_2)$$ \hspace{1cm} (7)

where the field observed values of $v_1$ and $v_2$ for through automobiles were $v_1 = 23.0$ km/h (14.2 mph) and $v_2 = 15.3$ km/h (9.5 mph). Reportedly, for right-turning automobiles, $v_1 = 10.0$ km/h (6.2 mph) and $v_2 = 6.3$ km/h (3.9 mph) (5). Generally, because of the heavily mixed traffic in Beijing, the operating speeds of automobiles were observed very low within the intersection. $q(u)$ is the estimated flow rate at which through vehicles can cross, which can be written as a continuous function of mean vehicular speed $u$. The relationship between $q(u)$ and $u$ can be acquired based on field data or simulation data. In this paper, based on calibrated VISSIM models, Greenshields model was used as $q(u) = 56.087 \cdot u + 207.497$ ($R^2 = 0.99$), where $u$ is expressed in kmph.

Each time when the automobiles are impeded by crossing bicyclists, the number of automobiles...
able to cross can be approximated as

\[ n = \bar{q}_{12} \cdot T = 2 \cdot \bar{q}_{12} \cdot T_B \]  

(8)

\( P_{12} \) represents the probability for the presence of bicycles AND the presence of an acceptable gap in automobile flow at the same time. If we assume the occurrences of the events are independent, \( P_{12} \) can be mathematically written as

\[ P_{12} = \Pr(X > 0) \cdot \Pr(H \geq T_{cb}) = (1 - \Pr(X = 0)) \cdot \Pr(H \geq T_{cb}) \]  

(9)

where \( T_{cb} \) is the critical gap for bicyclists – minimum gap for a bicyclist to cross the conflicting automobile flow. We assume the arrivals of the conflicting automobiles follow a Poisson process, during analysis interval \( \tau \), then \( P_{12} \) can be reduced to

\[ P_{12} = (1 - e^{-\lambda_{12} \tau}) \cdot \int_{T_{cb}}^{\infty} e^{-\lambda_{12}(t - t_m)} dt \]  

(10)

On average, \( N_{12}^\tau \) can be expressed as follows to represent how many times bicyclists may possibly cross during analysis interval \( \tau \):

\[ N_{12}^\tau = (1 - e^{-\lambda_{12} \tau}) \cdot e^{-\lambda_{12}(T_m - t_m)} \cdot (\lambda_{12} \tau - 1) \]  

(11)

The average number of automobiles able to cross during Pattern 3 can be estimated as

\[ C_{p3} = n \cdot N_{12}^\tau \]  

(12)

**Pattern 4 - When bicyclists are standing by conflict zone**

During analysis interval \( \tau \), the possibility for presence of bicyclists at the conflict zone can be estimated as

\[ P_1 = P(X > 0) = (1 - P(X = 0)) = 1 - e^{-\lambda_{12} \tau} \]  

(13)

Thus, on a per cycle basis, the length of period when bicyclists are present at the conflict zone is

\[ P_1 \cdot (T_G - T_{SB}) \], then, the length of time period when bicyclists are present but cannot cross should be \( P_1 \cdot (T_G - T_{SB}) - 2 \cdot T_B \cdot N_{12}^* \), where \( N_{12}^* \) denotes how many times left-turn bicyclists can possibly cross the conflict per cycle (during \( T_G - T_{SB} \)).

Under Pattern 4, the average number of through automobiles able to cross can be estimated as

\[ C_{p4} = q_1 \cdot (P_1 \cdot (T_G - T_{SB}) - 2 \cdot T_B \cdot N_{12}^* ) / 3600 \]  

(14)

where \( q_1 \) is the flow rate of the vehicular flow under the influence of standing-by bicycles.

**Total Capacity of Automobile Movements**

The average number of through automobiles able to cross is the sum of Pattern 2, Pattern 3, and
Pattern 4

\[ C_T = (C_{p2} + C_{p3} + C_{p4}) \cdot \frac{3600}{T} \]  

(15)

where \( T \) is the cycle length.

In case that Copenhagen Left is implemented, the conflicts between left-turning bicyclists and through automobiles are eliminated, and thus the traditional equation in HCM (i.e., product of saturation flow and signal split) can be used for estimating capacity of through automobiles:

\[ C_T' = q_0 \cdot T_G / T \]  

(16)

CASE STUDY

Numerical experiments were conducted based on a signalized intersection hypothesized. Each of the approaches included a through lane, a dedicated right-turn lane, and a dedicated left-turn lane. The base saturation flow rates for the lanes were approximately 1,650 veh/h/ln, 1,550 veh/h/ln, and 1,550 veh/h/ln, respectively. Right-turn-on-red was allowed on all of the four approaches. Simple two-phase timing was used with permissive left-turn phasing for automobiles, and the cycle length \( T \) was 90 s. An effective green of 45 s was allocated to the northbound and southbound approaches, and 39 s to the westbound and eastbound approaches. The green indication for bicycles/pedestrians was terminated 4 s before terminated for through vehicles (FIGURE 4). The traffic lanes were 3.3 m [11 ft] wide, the bicycle lanes were 3.5 m [11.5 ft] wide, and the terrains of the approaches were level. The automobile volumes were given as to maintain a v/c of 0.7. The bicycle volumes were assumed 300 bicycles/h, 20 percent of which were turning left and the others were traveling through. These conditions were inputted into both the proposed model and VISSIM micro-simulation model.

![FIGURE 4 Signal timing used in the numerical experiments](image)

Validation of Proposed Capacity Model

To test the effectiveness of the proposed capacity model, varying volumes of the northbound bicycle movement was inputted to the model, and the outputs of the model were compared with the micro-simulation benchmarks for validation. As shown in FIGURE 5, the results indicated
that the calculated, total capacities of the northbound and southbound through automobile 
movements were consistent with the simulated results (close to the 45-degree diagonal line). The 
squared coefficient of correlation ($R^2$) was 0.69 and the mean absolute percentage error (MAPE) 
was 3% as opposed to the simulated capacities. The results indicated that the proposed capacity 
model provides an alternative method to micro-simulation, which is effective in estimating the 
effects of left-turning bicyclists on through automobile traffic.

![Graph showing calculated vs. simulated capacities]

**FIGURE 5**  Proposed capacity model vs. micro-simulation

**Impacts of Copenhagen Left on Capacity of Automobiles**

Varying volumes of northbound bicycles were also used to show the effects of the Copenhagen 
Left operations on capacities of automobiles. The automobile movements associated with the 
northbound left-turning bicyclists included northbound/southbound through movements and 
northbound/southbound right-turn movements.

*Effects on Through Movement of Automobiles*

As presented in **FIGURE 6**, the results of the analytical model revealed that, after Copenhagen 
Left is used, the total capacity of northbound/southbound through vehicles was increased 
significantly in presence of heavy bicycle volumes.
Effects on Right-Turning Movement of Automobiles

At a simple two-phase controlled intersection, multiple traffic streams conflict with a right-turn movement (FIGURE 1). For instance, the northbound right-turn automobiles conflicts with northbound through bicyclists, northbound left-turn bicyclists, and southbound left-turn bicyclists during green intervals, and conflicts with eastbound/westbound automobiles/bicyclists during red intervals. The proposed analytical model may be limited in application and accuracy because the arrival patterns of conflicting vehicles/bicycles may differ vastly from what was assumed (e.g. exponential distribution). Thus, VISSIM micro-simulation models were used for estimating capacity of right-turn automobiles impeded by bicycles before and after using Copenhagen Left.

The results showed that the capacities of the southbound right-turn movements remained almost the same after the use of Copenhagen Left. The underlying reason is: the right-turn capacity were composed of capacity for right-turn-on-green and right-turn-on-red. The benefits from eliminating northbound left-turning bicyclists, which would conflict with southbound right-turn automobiles during right-turn-on-green, were offset by the added conflicting through bicycles during the second stage of the Copenhagen Left. The northbound right-turn movements of automobiles basically had the same volumes of conflicting bicycles before and after the use of Copenhagen Left; therefore, the capacity was not changed.
Combining the results for through and right-turn movements of automobiles, the total capacity of the intersection were significantly enhanced due to eliminating impedance to through automobile movements under Copenhagen Left operations.

**Delays Experienced by Left-Turning Bicyclists**

In the simulation experiments, three levels of automobile volumes ($v/c = 0.3, 0.7,$ and $0.9$) were used, and three levels ($100, 500, $ and $1000$ bicycles/h) of bicycle volumes were used, which led to nine combinations of traffic conditions. The results are shown in TABLE 1.

<table>
<thead>
<tr>
<th>Traffic Volumes</th>
<th>Delays of Left-Turn Bicycles</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DLT $^1$ (s)</td>
</tr>
<tr>
<td>Low Low</td>
<td>17.4</td>
</tr>
<tr>
<td>Low Median</td>
<td>16.6</td>
</tr>
<tr>
<td>High Low</td>
<td>16.8</td>
</tr>
<tr>
<td>Low Median</td>
<td>22.1</td>
</tr>
<tr>
<td>Median Median</td>
<td>22.2</td>
</tr>
<tr>
<td>High Median</td>
<td>23.9</td>
</tr>
<tr>
<td>Low High</td>
<td>27.0</td>
</tr>
<tr>
<td>Median High</td>
<td>29.8</td>
</tr>
<tr>
<td>High High</td>
<td>34.9</td>
</tr>
</tbody>
</table>

Note: $^1$ DLT = diagonally left-turning bicycles; $^2$ LOS is determined based on the threshold in HCM (2)

The number of stops was simulated from when bicyclists arrived at the stop line to when they finished crossing the intersection (TABLE 2). The use of Copenhagen Left led to an increased number of stops for left-turning bicycles, especially for intersections with low vehicular volumes.
### TABLE 2  Changes of number of stops of northbound left-turn bicycles after Copenhagen Left

<table>
<thead>
<tr>
<th>Traffic Volumes</th>
<th>Number of Stops by Left-Turn Bicycles % of Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left-Turn Bicycles</td>
<td>Automobiles</td>
</tr>
<tr>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Median</td>
<td>High</td>
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<tr>
<td>High</td>
<td>High</td>
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<td>Low</td>
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<td>Median</td>
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<td>High</td>
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<td>Low</td>
<td>Low</td>
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<tr>
<td>Median</td>
<td>Low</td>
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<tr>
<td>High</td>
<td>Low</td>
</tr>
</tbody>
</table>

### RECOMMENDATIONS ON USE OF COPENHAGEN LEFT

#### Consideration for Four-/Six-Lane Streets

Turning left from four-/six-lane streets to side streets, bicyclists may need to cross more lanes permissively compared to the case described before. Thus, the crossing distance is longer, and delay for bicyclists turning left diagonally may be longer. The change of delays due to implementing Copenhagen Left was estimated using micro-simulation models. As shown in TABLE 3, when there are more through lanes (with the same v/c) for left-turning bicyclists to cross, Copenhagen Left were increasingly preferable. Where three or more through lanes were provided and high volumes of automobiles were present, the use of Copenhagen Left reduced delay experienced by left-turning bicyclists.

### TABLE 3  Number of through-traffic lanes on increase of bicycle delay due to Copenhagen Left

<table>
<thead>
<tr>
<th>Traffic Volumes</th>
<th>Number of through lanes for automobiles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left-Turn Bicycles</td>
<td>Automobiles</td>
</tr>
<tr>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Median</td>
<td>High</td>
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<tr>
<td>High</td>
<td>High</td>
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<td>Low</td>
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<td>High</td>
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<td>Median</td>
<td>Low</td>
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<tr>
<td>High</td>
<td>Low</td>
</tr>
</tbody>
</table>

Collectively, for bicycles turning left from two-/four-lane streets to side streets, the decisions associated with whether Copenhagen Left should be used depend on several factors, such as
safety concerns, whether the impedance to automobiles needs to be mitigated, and how well the bicyclists will comply with Copenhagen Left. The use of Copenhagen Left is especially recommended for wide intersections where bicyclists turning left diagonally have to cross six or more through-traffic lanes permissively.

**Uniform Implementation Preferable**

It should be noted that uniform and consistent implementation of Copenhagen Left along a corridor can reduce the level of informational complexity placed on bicyclists.

**Accounting for Compliance by Bicyclists**

At large-sized intersections with heavy traffic, the operating speed of automobiles is relatively high. Out of safety considerations, left-turning bicyclists were normally observed voluntarily performing a Copenhagen Left at multiple locations in Beijing, even if Copenhagen Left was not implemented yet. At small-sized intersections with light automobile traffic, to avoid excessive delay, left-turning bicyclists may not comply with the Copenhagen Left even if it is mandated. Therefore, traffic engineers need to take into account the bicyclist's behavioral patterns when making decisions on Copenhagen Left operations. In addition, a successful implementation of Copenhagen Left depends on effective education for the traveling public.

**Providing Waiting Areas for Standing Bicyclists**

In implementing Copenhagen Left, waiting areas are necessary for the bicyclists to stop temporarily, waiting to be served in Stage 2 of the maneuver (FIGURE 2). On one hand, the size of waiting areas for Copenhagen Left bicyclists can be restricted by the size of the intersection. Placement of the waiting areas for Copenhagen Left should not encroach on the path of the RTOR movements in Stage 1 (FIGURE 2) or the path of through movements in the upcoming Stage 2 (FIGURE 2). When the number of bicyclists exceed the capacity of the waiting areas, the bicyclists performing a Copenhagen Left may encroach the path of the automobile movements. On the other hand, dense standing crowds of bicyclists can be uncomfortable, and a certain level-of-service should be maintained for the waiting area. So far, there are few research focused on the LOS for bicyclist waiting areas. A standing bicyclist normally occupies an area of 1.14 m$^2$ [12.3 sf] (the length is 1.9 m [6.3 ft] and the width is 0.6 m [2.0 ft]). According to our field experiments, bicyclists could follow the crowd and slowly start at the beginning of a green interval given an area of 1.14-2.20 m$^2$/bicycle [12.3-23.7 sf/bicycle]; thus, the use of Copenhagen Left is only recommended when this minimum area (i.e., 1.14-2.20 m$^2$/bicycle) can be provided. In addition, pavement markings for the waiting areas should be properly provided.

**Protected Left-Turn Phases for Automobiles**
Where protected phasing is used for left-turning automobiles, diagonal left-turns of bicycles may raise following concerns:

- Since left-turning bicyclists need to cross abreast of left-turn automobiles during the protected phases, a longer minimum green may be required because bicycles have a lower speed and have to travel longer distance (outer circular path).
- Sideswipe/off-path crashes between left-turning automobiles and bicyclists may become potential safety issues when they turn abreast.

In response to these concerns, Copenhagen Left can be considered as alternatives to diagonal left-turns. In addition, the use of Copenhagen Left is recommended for the intersections where left-turns are not allowed for automobiles, e.g., at restricted-area intersections or innovative intersections such as “Michigan U” intersections.

**CONCLUSIONS**

Based on the results of this study, the following conclusions were drawn:

(1) The analytical capacity model developed provides an alternative tool for future modeling efforts in characterizing the impacts of bicycles on through automobiles, which may supplement the HCM methods that cannot deal with impedance of bicycles on through automobiles.

(2) Capacities of through automobiles can be increased significantly due to the use of Copenhagen Left. On the other hand, the use of Copenhagen Left has no significant effects on the capacity of right-turn automobiles.

(3) At small-sized intersections (e.g. turning left from a two-lane street), the use of Copenhagen Left may be associated with considerable increases of delay for left-turn bicyclists during off-peak or under low-volume conditions. At large-sized intersections where diagonally left-turning bicyclists need to permissively cross more than three through-traffic lanes, the use of Copenhagen Left may reduce the delay for bicyclists. Under these conditions, the use of Copenhagen Left is recommended.

Importantly, a successful implementation of Copenhagen Left does not only rely on proven operational benefits, but also depends on the safety considerations, availability of storage space for the resulting standing bicyclists, clear pavement marking/signage, and effective education for the traveling public. Future studies will be focused on safety impacts of Copenhagen Left.
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REFERENCES


