Operational Efficiency Evaluation of Selected At-Grade Intersections

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The purpose of this study was to evaluate the operational efficiency of certain types of unsignalized priority-type intersections in terms of average waiting time and average number of vehicles that have to wait in the queue at the minor street approaches. Queuing theory techniques are employed in this study. Four intersections of varying geometrics are investigated. Utilizing the information on critical time gaps for the minor street traffic and peak-hour flows on the major street traffic, delays and queue lengths are calculated. These are then checked with the observed values. A fairly good correlation was found between the theoretical and observed values. The intersections are then rated according to their operational efficiency.

Because urban transportation systems are planned with emphasis on automobile travel, it becomes increasingly important to ensure the optimum operation of the systems. However, as a chain is only as strong as its weakest link, so the overall operation of a highway system is highly dependent on the operations in critical sections. Intersections in the case of a street system and interchanges in the case of a freeway system can be regarded as the weak links. One very important component of the system is the at-grade intersection. It is important that the traffic engineer know which control is best for a given intersection. However, only meager information is available concerning controls below the level of traffic signals. The purpose of this study is to evaluate the operational efficiency of priority-type unsignalized intersections of varying geometrics relative to traffic performance. Priority-type intersections occur where one of the intersecting streets is given a definite priority over other streets. The non-priority or the minor street for such intersection is controlled by either a stop or yield sign, thus ensuring that the vehicles on the street having the priority will suffer little or no delay. The intersections investigated in this study have the minor street approaches controlled by a stop sign.

At unsignalized intersections the arrival rates and individual drivers generally determine the manner of operation. The operational characteristics of these intersections are a function of traffic flow and driver behavior patterns. In simplest terms, at an intersection, one flow of traffic looks for gaps in the opposing flow of traffic. At priority intersections, because the traffic on the major street is given the priority, it is clear that the traffic on the minor street is usually looking for gaps.

OBJECTIVES

This study is an attempt to gain an understanding of the operational efficiency of priority-type unsignalized intersections of varying geometrics relative to traffic performance. It provides traffic and safety engineers a method for evaluating operational efficiency of certain types of unsignalized priority-type intersections in terms of (a) average time a vehicle on the critical minor street approach has to wait in the queue,
as well as in the system, before it is able to merge with or cross the major street traffic stream, and (b) average number of vehicles on the critical minor street approach that have to wait to merge with or cross the major street traffic stream.

STUDY SITES AND DATA COLLECTION PROCEDURE

Site Selection

After consultations with the personnel of the Safety Section of the District of Columbia Department of Highways and Traffic, the following 4 intersections were selected for investigation: Seventh Street and Michigan Avenue, N. E. (Fig. 1); Eleventh and P Streets, N. W. (Fig. 2); Ninth and K Streets, N. W. (Fig. 3); and Twelfth and C Streets, N. E. (Fig. 4).

Each intersection seemed to have unusually high delay to the vehicles on the minor street approaches. All were unsignalized, at-grade priority-type intersections. A brief description of each intersection location is given in Table 1.

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Figure 1. Seventh Street and Michigan Avenue, N. E., intersection.

Figure 2. Eleventh and P Streets, N. W., intersection.
Figure 3. Ninth and K Streets, N. W., intersection.

Figure 4. Twelfth and C Streets, N. E., intersection.

TABLE 1
SUMMARY OF STUDY INTERSECTIONS

<table>
<thead>
<tr>
<th>Intersection</th>
<th>Type</th>
<th>Major Street</th>
<th>Minor Street</th>
<th>Location Within Metropolitan Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seventh Street and</td>
<td>4-legged,</td>
<td>Michigan</td>
<td>Seventh</td>
<td>Outlying business district</td>
</tr>
<tr>
<td>Michigan Ave., N. E.</td>
<td>2-way—2-way</td>
<td>Avenue</td>
<td>Street</td>
<td>Outlying business district</td>
</tr>
<tr>
<td>Eleventh and</td>
<td>4-legged,</td>
<td>Eleventh</td>
<td>P Street</td>
<td>Outlying business district</td>
</tr>
<tr>
<td>P Streets, N. W.</td>
<td>2-way—2-way</td>
<td>Street</td>
<td>Street</td>
<td>Fringe area</td>
</tr>
<tr>
<td>Ninth and</td>
<td>T-type,</td>
<td>Ninth</td>
<td>K Street</td>
<td>Fringe area</td>
</tr>
<tr>
<td>K Streets, N. W.</td>
<td>2-way—2-way</td>
<td>Street</td>
<td>Street</td>
<td>Fringe area</td>
</tr>
<tr>
<td>Twelfth and</td>
<td>4-legged,</td>
<td>Twelfth</td>
<td>Twelfth</td>
<td>Outlying business district</td>
</tr>
<tr>
<td>C Streets, N. E.</td>
<td>C Street 1-way</td>
<td>Street</td>
<td>Street</td>
<td>Outlying business district</td>
</tr>
<tr>
<td></td>
<td>and Twelfth</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Street 2-way</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Data Collection for Peak-Hour Demand

One-hour traffic counts on a 5-minute basis were obtained for all approaches on each intersection study site during the afternoon peak period. Three recorders were found to be adequate for this purpose. Traffic counts for each approach were stratified into left-turn, through, and right-turn maneuvers.

Data Collection for Gap Measurements

To provide a permanent study record and to facilitate desired exactness of measurement, time-lapse photography was selected as the most appropriate means of recording gaps, lags, and headways.

The camera used was a 16-mm Bolex with a wide-angle lens on loan from the District of Columbia Department of Highways and Traffic. The camera was equipped with time-lapse apparatus and was set to take pictures at one-second intervals. Checks were made periodically during the data collection to ensure that the camera was operating accurately. Color movie film was used for ease of distinguishing individual vehicles.

Data collection was performed with the same procedure at all 4 study locations. At each intersection the camera was mounted on a tripod at some vantage point located near the side street approach. The camera was positioned about 50 ft from the main street to view the entire intersection area. A typical field installation is shown in Figure 5.

Data were collected on a weekday during the morning peak period. About 2 hours of filming was done for each intersection. Field data were collected only when the weather was clear and the pavements were dry. The speed of the camera was frequently checked by a stopwatch.

The developed film was viewed by a microfilm projector. The projector has a frame counter, and the film can be advanced or reversed one frame at a time. A stopped vehicle on the minor street approach leg either proceeded straight through the intersection, turned right, or turned left. If a driver went straight through the intersection, the path of movement intersected that of vehicles from both the right and the left. When a right turn was made, the vehicle merged with traffic coming from the left and did not conflict with the traffic from the right. On a left-turn maneuver the path of a main street vehicle approaching from the left was crossed, and the vehicle merged with the major street traffic coming from the right. The property lines on each approach leg were used as reference points to determine lags, gaps, and headways. It was possible to make measurements to the nearest half second.

OPERATIONAL EFFICIENCY ANALYSIS

Delay

This is a significantly important parameter because of its economic importance. In this study, the delay accruing to each vehicle is its idling time, or the time that the vehicle is not in motion. For all 4 intersections studied, the traffic at the minor street approaches was controlled by a stop sign whereas the major street traffic had no traffic control and always had the right-of-way. The only delay
to the major street traffic was caused by a right- or left-turning maneuver. Every vehicle on the minor street approach leg had to come to a complete stop before entering the intersection.

The delay at an unsignalized intersection depends both on the physical layout of the intersection and on the volume of traffic on each approach. The physical layout affects the sight distance, which in turn affects the size of the acceptable lag or gap.

The delay due to traffic flow on each minor approach will increase as the traffic volume on the main route increases because the number of acceptable lags or gaps for entering the intersection will be reduced.

**Headway Distribution**

Several studies (1, 2, 3) have confirmed that the vehicle arrivals at intersection approaches conform to the Poisson law.

Therefore, in the theoretical derivations to obtain the total average delay to a minor street vehicle waiting to cross or merge with the major street traffic and to determine the average number of vehicles waiting on the critical minor street approach, it is assumed that the distribution of major street traffic arrivals is Poisson, i.e., that the probability that a given gap is between \( t \) and \( t + dt \) seconds is given by an expression of the form \( qe^{-qt} \) where \( q \) is the flow.

If the vehicle arrivals follow Poisson distribution, it follows that the headways between the vehicles are exponentially distributed. That is \( P(h > t) = e^{-\lambda t} \) where \( \lambda \) = mean arrival rate in vehicles per time interval.

According to Adams (4), the proportion of time occupied by intervals greater than \( t \) seconds is given by the expression

\[
P(h > t) = e^{-\lambda t} (\lambda t + 1)
\]

where \( \lambda \) = vehicles per second.

Conversely, the proportion of time occupied by intervals less than or equal to \( t \) is

\[
P(h \leq t) = 1 - e^{-\lambda t} (\lambda t + 1)
\]

In one hour the expected number of intervals greater than or equal to \( t \) is \( Te^{-\lambda t} \) where \( T \) = vehicles per hour.

Similarly, the expected number of intervals greater than \( t + dt \) is

\[
Te^{-\lambda(t + dt)} = Te^{-\lambda(t + \lambda dt)} = Te^{-\lambda t} e^{-\lambda dt}
\]

by the rule for addition of indexes.

The cumulative frequency curves in Figures 6 and 7 show the theoretical relationship between gap availability and the critical gap, assuming that the distribution of headways on the main street is described by the exponential distribution.

**Gap and Lag Acceptance**

The acceptance or rejection of a time gap is a binomial response and is dependent on the size of the gap. The minimum time gap that a driver accepts is fixed for that driver. He will reject all gaps smaller
than that time interval and accept all gaps larger than that time gap. There is an evidence that this minimum acceptable time gap would decrease with time pressure and the number of vehicles in the major traffic stream.

A lag at an intersection may be defined as the time interval between the arrival of the minor street vehicle, and the arrival thereafter of the first vehicle on the major street at a reference point.

A gap at an intersection is defined as each time headway formed by successive crossings of a reference line by major street vehicles, regardless of direction of travel. If the minor street vehicle moves through the intersection before the arrival of the first major street vehicle, the driver of the minor street is said to "accept" the lag. If he remains until after the first vehicle passes, he has "rejected" the lag. After rejecting a lag, he then evaluates the gaps between the successive vehicles. Each gap that he fails to accommodate his vehicle into is said to be rejected. The gap that the driver finally moves into is said to be accepted.

Critical Gap or Lag

The method developed by Bissell (5) and Raff (6) to determine the value of a critical lag or gap for a minor street approach was used in this study. In this method, 2 cumulative distributions are plotted on the same graph. One curve describes the number of gaps or lags accepted shorter than a time interval, and the other shows the rejected number of gaps or lags longer than this interval. The value of the critical gap is the time at which the 2 curves intersect. A single value of critical gap was determined for left-turn and through movements for each study intersection. This was done after field observations indicated that there was no significant difference in the gap acceptance characteristics for these 2 maneuvers. A separate value of critical gap was determined.
for the right-turn maneuver for each study intersection. A typical graph showing the determination of critical time gap, $T_c$, is shown in Figure 8. The critical time gaps, $T_c$, for the selected intersections are given in Table 2. It is seen from the table that the critical time gaps are different for different intersections depending on the sight distance, traffic volume, and speed.

**Crossing and Merging Delays**

Delay is useful in describing the level of service at an intersection or in a system of streets. Also, it lends itself to economic analysis.

In an operation where a minor stream of traffic has to yield right-of-way to the major street traffic, it is important to determine the average time a vehicle has to wait before entering the intersection. The waiting driver measures each time gap, $t$, in the major street traffic until he finds an acceptable gap, $T$, that he believes to be of sufficient length to provide him a safe entry into an intersection. If he accepts the first gap ($t > T$), his waiting time is zero. If he rejects the first gap ($t < T$) and accepts the second gap, his waiting time is equal to one time gap interval. Queuing theory methods can be applied to establish the probability for the number of time gap intervals that a vehicle will have to wait before it can enter the intersection safely.

Thus we can write the probability, $P_n$, for the driver that he will have to wait for $n$ intervals each less than $T_c$ (critical time gap) seconds before entering the intersection as

$$P_n = (1 - \rho)\rho^n \text{ for } n > 1 \quad (1)$$

where $n = \text{number of time intervals that a vehicle has to wait}$ and $\rho(\text{traffic intensity}) = \lambda/\mu$. We can also express the mean number of time intervals for which a vehicle has to wait as

$$E(n) = \frac{\rho}{1 - \rho}, \rho < 1 \quad (2)$$

$$\rho = P(t < T_c) = \int_0^{T_c} f(t) dt \quad (3)$$

### Table 2

<table>
<thead>
<tr>
<th>Intersection</th>
<th>Maneuver</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Right Turn</td>
</tr>
<tr>
<td>Seventh Street and Michigan Avenue, N. E.</td>
<td>5.5</td>
</tr>
<tr>
<td>Eleventh and P Streets, N. W.</td>
<td>5.5</td>
</tr>
<tr>
<td>Ninth and K Streets, N. W.</td>
<td>5.7</td>
</tr>
<tr>
<td>Twelfth and C Streets, N. E.</td>
<td>4.0</td>
</tr>
</tbody>
</table>

![Figure 8. Distribution of accepted and rejected lags and gaps at Twelfth and C Streets, N. E., intersection, right-turn maneuvers.](https://example.com/figure8.png)
where \( f(t) \) is the density function of time gaps in the major traffic stream. Thus we have

\[
E(n) = \frac{\lambda}{1 - \rho} = \frac{\int_0^{T_c} f(t) \, dt}{\int_{T_c}^{\alpha} f(t) \, dt}
\]

(4)

The average time a minor street vehicle will have to wait to find an acceptable gap in order to cross or merge with the major street traffic is the product of expected number of intervals less than \( T_c \), \( E(n) \), and the mean length of time gap. The average length of time gap less than \( T_c \) is, in turn, equal to the total time less than \( T_c \) seconds divided by the number of time gaps less than \( T_c \) seconds.

\[
\text{Average length of time gaps < } T_c = \frac{q \int_0^{T_c} t \times f(t) \, dt}{q \int_0^{T_c} f(t) \, dt}
\]

(5)

where \( q \) is the rate of flow.

Multiplying Eqs. 4 and 5 yields the average waiting time for a minor street vehicle to merge or cross.

\[
d = \frac{\int_0^{T_c} t \times f(t) \, dt}{\int_{T_c}^{\alpha} f(t) \, dt}
\]

(6)

We recall that the percentage of minor street vehicles actually delayed is given by Eq. 2. It is evident that the average waiting time of those vehicles that are actually delayed is given by the expression

\[
d' = \frac{d}{\int_0^{T_c} f(t) \, dt}
\]

(7)

It should be remembered that the delays expressed in Eqs. 5 and 6 are for single vehicles approaching the minor street to merge or cross the main street.

Adams (4) and Tanner (8) have obtained theoretical derivations for vehicles attempting to merge or cross on the assumption that the major street traffic is exponentially distributed.
\[ f(t) = q e^{-qt} \]  
\[ \text{(8)} \]

Substituting Eq. 7 in Eq. 5, the mean delay, \( d \), for a critical time gap, \( T_c \), and major street traffic flow, \( q \), is

\[
d = \frac{\int_0^{T_c} t \times q e^{-qt} \times dt}{\int_0^{T_c} q e^{-qt} \times dt} = \frac{tq}{q} \left( \int_0^{T_c} e^{-qt} \times dt \right)
\]

\[ \text{(9)} \]

Equation 9 is shown in Figure 9, where delay, \( d \), is shown as a function of major street volume, \( q \), for various values of critical time gaps, \( T_c \).

**Determination of Total Delay to Minor Street Traffic**

Our discussion up to now has been primarily concerned with average delay to the vehicle on the minor street and in a position to cross or merge with the major street traffic. It is important to determine how many vehicles on the average are waiting on the minor street to enter the intersection and also average waiting time for a queue of minor street vehicles waiting to merge or cross major street traffic. We can also use these 2 values as figures-of-merit to evaluate the operational efficiency of intersections.

In our case, a sequence of vehicles arrives at the minor street approach legs to merge or cross the major street traffic. If and when there is a suitable lag or gap available in the major street traffic, a vehicle from the minor street is able to enter the intersection, and thus a minor street vehicle is discharged. Usually there are variations in the regularity of vehicle arrivals or in the waiting time required to "put through" a vehicle from the minor street, or both; hence, there will be fluctuations in all aspects of intersection operation. More vehicles may arrive on the minor street than the major street can immediately accommodate, and a queue of varying length will be formed. The variables associated with the operation will be stochastic variables and will fluctuate with time above and below some average value or rate. Morse (9) explains that instead of
trying to predict in detail how the state of the system changes with time, we can calculate the probabilities that the system is in each of the possible states. These probabilities facilitate calculations of average queue length and average time that the vehicle has to wait in the system.

The state of the intersection operation is dependent on the average arrival rate on the minor street, \( \lambda \), and the average service rate, \( \mu \), on the major street. The traffic intensity factor, \( \rho \), is the ratio of the vehicle rate, \( \lambda \), and service rate, \( \mu \), and represents the fraction of the time the service channel is used; i.e., either a merging or crossing operation from the minor street traffic can be performed. If \( \rho > 1 \), there is no "steady-state" solution, and arriving vehicles join an ever-increasing queue; if \( \rho < 1 \), steady-state solutions can be determined if \( \lambda \) and \( \mu \) are known.

Let \( q_a \) be the average rate of arrival on a critical approach of the minor street. The minor street approach with the highest arrival rate is considered as the critical approach. The vehicles arriving on the critical approach must stop, and the main street traffic has the right-of-way. They form a single-lane queue waiting for a vehicle at the head of the queue to merge with or cross the major street traffic. For a Poisson distribution of arrivals and exponential distribution of service rate,

\[
\text{Expected number of units in the system, } E(n) = \frac{\lambda}{\mu - \lambda} \tag{10}
\]

\[
\text{Expected number of units in the queue, } E(m) = E(n) - \rho \tag{11}
\]

\[
\text{Expected waiting time in the system, } E(y) = \frac{1}{\mu - \lambda} \tag{12}
\]

\[
\text{Expected waiting time in the queue, } E(w) = E(y) - \frac{1}{\mu} \tag{13}
\]

Major and Buckley (10) have interpreted the service time for the queue, \( \mu \), as identical to the summation of the rejected lags and gaps for a minor street approach vehicle in position to merge. This is the same as the delay, \( d \) (Eq. 9, Fig. 9), in this study. Based on the assumption that the average service time is equal to the average merging delay and the distribution of service times is of the exponential form, the peak-period operational efficiency of each study intersection is obtained in terms of queue lengths and waiting times at the minor street approaches.

1. Seventh Street and Michigan Avenue, N.E. intersection, left-turn and through maneuvers, critical approach at Catholic University entrance.

\[
\text{Arrival rate } = 81 \text{ vph} = \frac{81}{3,600} = 0.0225 \text{ vps}
\]

\[
\text{Service rate } = 35 \text{ sec/vehicle}
\]

(from Fig. 9, for critical time gap, \( T_c \), equal to 7 sec, and major street traffic flow, \( q \), equal to 1,450 vph) or

\[
\frac{3,600}{35} = 103 \text{ vph} = \frac{1}{35} = 0.0286 \text{ vps}
\]

\[
\rho (\text{traffic intensity}) = \frac{\lambda}{\mu} = \frac{0.0225}{0.0286} = 0.7867
\]
Expected time in the system, \( E(\gamma) = \frac{1}{\mu - \lambda} = \frac{1}{0.0286 - 0.0225} = \frac{1}{0.0061} = 164 \text{ sec} \)

Expected time in the queue, \( E(w) = E(\gamma) - \frac{1}{\mu} = 164 - \frac{1}{0.0286} = 164 - 35 = 129 \text{ sec} \)

Expected number in the system, \( E(n) = \frac{\lambda}{\mu - \lambda} = \frac{0.0225}{0.0286 - 0.0225} = \frac{0.0225}{0.0061} = 3.69 \text{ vehicles} \)

Expected number in the queue, \( E(m) = E(n) - \frac{\lambda}{\mu} = 3.69 - 0.79 = 2.90 \text{ vehicles} \)

2. Seventh Street and Michigan Avenue, N. E. intersection, right-turn maneuver, critical approach at Seventh Street.

\( \lambda(\text{arrival rate}) = 141 \text{ vph} = \frac{141}{3,600} = 0.0392 \text{ vps} \)

\( \mu(\text{service rate}) = 15 \text{ sec/vehicle} \)

(from Fig. 9, for critical time gap, \( T_c \), equal to 5.5 sec, and major street traffic flow, \( q \), equal to 1,450 vph) or

\[ \frac{3,600}{15} = 240 \text{ vph} = \frac{1}{15} = 0.0667 \text{ vps} \]

\( \rho(\text{traffic intensity}) = \frac{\lambda}{\mu} = \frac{0.0392}{0.0667} = 0.5877 \)

Expected time in the system, \( E(\gamma) = \frac{1}{\mu - \lambda} = \frac{1}{0.0667 - 0.0392} = \frac{1}{0.0275} = 36.36 \text{ sec} \)

Expected time in the queue, \( E(w) = E(\gamma) - \frac{1}{\mu} = 36.36 - \frac{1}{0.0667} = 36.36 - 14.99 = 21.37 \text{ sec} \)

Expected number in the system, \( E(n) = \frac{\lambda}{\mu - \lambda} = \frac{0.0392}{0.0667 - 0.0392} = \frac{0.0392}{0.0275} = 1.43 \text{ vehicles} \)

Expected number in the queue, \( E(m) = E(n) - \frac{\lambda}{\mu} = 1.43 - 0.5877 = 0.842 \text{ vehicles} \)

In a similar manner waiting times and queue lengths were determined for other intersections.

In order to evaluate the reliability of the theoretically calculated values of queue lengths and waiting times for the vehicles on the minor street approaches, it was decided to obtain field measurements.
The expected time in the system and in the queue are the average waiting times for a vehicle on the critical minor street approach. It would be almost impossible to obtain waiting times for each vehicle approaching the critical minor street approach; hence a systematic random sampling technique was used. The method consisted of selecting every fifth vehicle at a critical minor street approach and recording its waiting time in the queue and in the system. The waiting times for left-turn and through maneuvers were recorded as one group, and right-turn maneuvers as another group. The data were collected at each location for a period of one hour during the peak period. The mean waiting time was determined from the sample.

The field measurements to obtain the mean number of vehicles waiting in the queue and in the system at the minor street approach were obtained in a similar manner. In this case the number of vehicles in the queue and in the system were observed at exactly 3-minute intervals for a period of one hour during the peak period at each study intersection. Again, the queue lengths were obtained separately for left-turn and through maneuvers in one group and right-turn maneuvers in another group.

The results are given in Tables 3 and 4. It is seen that there is a fairly good correlation between the theoretical and observed values.

Operational Efficiency Evaluation

Data given in Tables 3 and 4 demonstrate the operational efficiency of 4 priority-type at-grade intersections with varying geometrics.

### TABLE 3

<table>
<thead>
<tr>
<th>Intersection</th>
<th>Expected Time in the System (sec)</th>
<th>Expected Time in the Queue (sec)</th>
<th>Expected Number in the System (vehicles)</th>
<th>Expected Number in the Queue (vehicles)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Theoretical</td>
<td>Observed</td>
<td>Theoretical</td>
<td>Observed</td>
</tr>
<tr>
<td>Seventh Street and Michigan Avenue, N. E.</td>
<td>164.00</td>
<td>190</td>
<td>139.00</td>
<td>143</td>
</tr>
<tr>
<td>Eleventh and P Streets, N. W.</td>
<td>277.78</td>
<td>262</td>
<td>247.75</td>
<td>260</td>
</tr>
<tr>
<td>Ninth and K Streets, N. W.</td>
<td>86.95</td>
<td>91</td>
<td>58.91</td>
<td>75</td>
</tr>
<tr>
<td>Twelfth and C Streets, N. W.</td>
<td>6.99</td>
<td>9</td>
<td>1.0</td>
<td>2</td>
</tr>
</tbody>
</table>

### TABLE 4

<table>
<thead>
<tr>
<th>Intersection</th>
<th>Expected Time in the System (sec)</th>
<th>Expected Time in the Queue (sec)</th>
<th>Expected Number in the System (vehicles)</th>
<th>Expected Number in the Queue (vehicles)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Theoretical</td>
<td>Observed</td>
<td>Theoretical</td>
<td>Observed</td>
</tr>
<tr>
<td>Seventh Street and Michigan Avenue, N. E.</td>
<td>36.36</td>
<td>43</td>
<td>21.37</td>
<td>25</td>
</tr>
<tr>
<td>Eleventh and P Streets, N. W.</td>
<td>15.38</td>
<td>13</td>
<td>2.38</td>
<td>3</td>
</tr>
<tr>
<td>Ninth and K Streets, N. W.</td>
<td>80.00</td>
<td>94</td>
<td>68</td>
<td>75</td>
</tr>
<tr>
<td>Twelfth and C Streets, N. E.</td>
<td>2.56</td>
<td>4</td>
<td>0.06</td>
<td>0</td>
</tr>
</tbody>
</table>
The Twelfth and C Streets, N. E., intersection is the most efficient one, both with respect to delay to the vehicles and the number of vehicles that have to wait in line on the minor street approaches. C Street, which is one-way, carries the major street traffic, whereas Twelfth Street is a 2-way minor street approach. The average waiting time for a left-turning or through vehicle on the critical minor street approach is about 7 seconds. The average waiting time in the queue is about one second. There is hardly any queue formed on the minor street approach. A right-turning vehicle has to wait about 3 seconds and has almost no waiting time in the queue. On the average, no queues are formed on the minor street approaches.

The Ninth and K Streets, N. W., intersection is the second most efficient for left-turn maneuvers from the minor street approach. However, it is the least efficient for right-turn maneuvers from the minor street approach. This is a T-type intersection. Ninth Street is a 2-way major street, and K Street is a single minor street approach. The average waiting time for a left-turn maneuver from the minor street approach is about 87 seconds, whereas average waiting time in the queue is about 59 seconds. The mean number of vehicles waiting to make a left-turn maneuver is two and about one in the queue. The average time a right-turning vehicle has to wait on the minor street approach is 80 seconds, which is almost the same as a left-turn maneuver. The average waiting time in the queue is 68 seconds, which is slightly more than the average waiting time in the queue for the left-turn maneuvers. The average number of vehicles on the minor street approach waiting to make a right-turn maneuver is about six, and the average number of vehicles waiting in the queue to make the right-turn maneuver is about five. Both the queue length and the number of vehicles on the minor street approach waiting to make the right-turn are considerably higher than for the left-turn maneuver. It is noted here that this intersection is least efficient operationally for right-turn maneuvers.

The Seventh Street and Michigan Avenue, N. E., intersection rates the third most efficient for all maneuvers from the minor street approaches. This is a 4-legged, 2-way intersection. However, this is a unique intersection because the minor street approaches are offset by about 100 ft. Also one approach is at a right angle and the other is at about 60 deg to the major street. The average delay to the left-turn and through vehicle on the critical minor street approach is about 164 seconds, and the waiting time in the queue is about 129 seconds. The mean number of vehicles in the system is about four and the number of vehicles in the queue is about three. For right-turn maneuvers, however, the waiting times and the queue lengths are considerably shorter. The mean waiting time in the system and in the queue on the critical minor street approach is about 36 and 21 seconds respectively. The average number of vehicles in the queue and in the system on the critical minor street approaches is about two and one respectively.

The Eleventh and P Streets, N. W., intersection is a typical 4-legged, 2-way—2-way intersection. It is the least efficient for left-turn and through maneuvers, whereas the second most efficient for right-turn maneuvers. The average delay to a vehicle on the critical minor street approach is about 277 seconds, and the time spent in the queue is about 248 seconds. The average number of vehicles in the system and in the queue on the critical minor street approach is eight and seven respectively. The unusually high waiting time and queue formation is due to a considerably high traffic demand on the major street during the peak periods as well as existing moderate demand on the minor street. For right-turn maneuvers, the intersection is the second most efficient. The waiting times in system and in the queue are about 15 and 3 seconds respectively, and queues are seldom formed.

SUMMARY AND CONCLUSIONS

Summary
This investigation has shown how queuing theory techniques can be employed to evaluate the operational efficiency of priority-type at-grade intersections in terms of waiting times in the system and in the queue at the minor street approaches. It also indicates the number of vehicles that have to wait in the system and in the queue at the minor street approaches.
The applicability of this method has been tested for 4 selected priority-type intersections of varying geometrics of a large metropolitan area.

CONCLUSIONS

1. There were some indications that the driver on the minor street tends to accept a shorter gap under pressure (i.e., when a queue of 2 or more vehicles is formed behind him) than the gap he would accept under normal conditions.

2. There was a fairly good correlation between the theoretical and observed values of the mean waiting time in the system and in the queue and of the mean number of vehicles waiting in the system and in the queue for the vehicles on the minor street approaches. The operational efficiency in terms of delay and queue lengths is given in Table 5 in the descending rank order for left-turn and through maneuvers and for right-turn maneuvers.

REFERENCES