The primary objective of this study was to evaluate the impact of the use of two bus priority techniques on the operation of bus and nonbus traffic in a simulated environment. The strategies studied were (a) contra-flow bus lane on a downtown street and (b) signal settings based on minimizing passenger instead of vehicle delays. The operational setting reflected actual observations on a Chicago downtown street where a contra-flow bus lane was installed in the summer of 1980. It was found that predicted bus operation improved significantly as a result of dedicating an exclusive lane to bus traffic, as demonstrated by an increase in overall bus speed on the route. The signal priority technique implemented by means of the TRANSYT-7F model enhanced bus operation even further. The degree of bus operation improvement, however, was dependent on whether the buses operated in mixed traffic or on exclusive lanes. It was also noted that total vehicle-miles of travel for nonbus traffic decreased after the implementation of the bus lane. Some improvements in nonbus traffic operation on the study section may be attributed to that factor. Finally, a limited field study was conducted to test bus performance indices predicted by the TRANSYT model. The observed and simulated overall bus travel speeds were found to compare favorably at the 5 percent significance level.

In August 1980 Chicago created two contra-flow bus lanes on the downtown portion of Adams Street and Jackson Boulevard. These bus lanes (the first of four such installations in the Loop) were implemented as part of an overall plan aimed at reducing carbon monoxide emissions in Chicago's central business district. Other techniques included the implementation of a real-time traffic signal control system and a reduction of on-street parking opportunities.

The separation of bus traffic from automobile traffic was viewed as an effective means of decreasing automobile delays caused by buses stopping along the route, as well as of improving bus transit operation and reliability.

A review of accident frequency after the implementation of the bus lanes indicated that bus-vehicle accident rates dropped, while bus-pedestrian accident rates sharply increased. It appeared that pedestrians were still accustomed to the previous one-way operation on the street where the bus lanes were introduced. Strategies are presently being studied to tackle the problem of enforcement of priority treatment for buses. That work, however, was beyond the scope of this study, which considers only operational impacts of the bus lane implementation.

STUDY OBJECTIVES AND SCOPE

This study was aimed at evaluating two preferential bus treatments applied to a downtown Chicago street from a strictly operational standpoint, using the tool of digital simulation.

The basis for the evaluation procedure is that buses (as well as automobile traffic) operate in a signalized control environment and their performance is greatly affected by the signal settings adopted on the bus route. Levinson et al. (3), for example, stated that bus delays at traffic signals constitute 10 to 20 percent of overall bus trip time and are the cause of almost 50 percent of all delays.

The relationship between bus performance and priority techniques such as the use of an exclusive lane or signal settings is therefore the focus of this study. The following specific objectives were addressed:

1. To identify signal-related and geometric-related bus priority techniques on Jackson Boulevard in the Chicago Loop and to develop a set of distinct priority strategies.
2. To evaluate each strategy developed in Objective 1 using existing traffic analysis techniques.
3. To recommend a set of actions for enhancing bus operations on the study section.

Only operational indices such as delays, stops, and speeds were investigated. No attempt was made to study the short- and long-term safety impacts of the contra-flow bus lane project.

SITE DESCRIPTION

Schematic representations of the study site before and after the installation of the contra-flow bus lane are shown in Figures 1 and 2, respectively.

Originally, Jackson Boulevard was a one-way eastbound arterial from Jefferson Street (not shown) to Michigan Avenue (not shown). Total pavement width of

FIGURE 1 1975 network and link-node scheme.
minimum vehicular delays and stops; and
describes traffic conditions and controls similar to
conditions and controls in existence approximately 1
year after the contra-flow bus lane was installed
traffic conditions and controls similar to those of
BL, except that signal settings are adjusted for
minimum passenger delays and stops.

To ascertain the potential effectiveness of the bus­
lane operation and the impact on nonpriority tra­fic, six distinct signal and geometric control
strategies were formulated for the study section:

1. Base condition (BC) describes traffic condi­
tions and controls in existence before the bus lanes
were installed (1975);
2. Optimized base condition (OBC) describes
traffic conditions and controls similar to those of
BC, except that signal settings are adjusted for
minimum vehicular delays and stops;
3. Priority optimized base condition (POBC) de­
scribes traffic conditions and controls similar to
those of BC, except that signal settings are ad­
justed for minimum passenger delays and stops;
4. Bus-lane operation (BL) describes traffic condi­
tions and controls in existence approximately 1
year after the contra-flow bus lane was installed
(1981);
5. Optimized bus-lane operation (OBL) describes
traffic conditions and controls similar to those of
BL, except that signal settings are adjusted for
minimum vehicular delays and stops; and
6. Priority optimized bus-lane operation (POBL) de­
scribes traffic conditions and controls similar to
those of BL, except that signal settings are ad­
justed for minimum passenger delays and stops.

The cycle length was fixed at 65 sec under all
strategies and, except for one or two cases, all
signalized intersections operated in two-phase mode.
Thus the prescribed treatments cover a wide range
of bus operation improvement techniques, ranging
from a do-nothing alternative as in BC to a combined
signal and right-of-way priority for bus traffic in
POBL. Not included in this analysis are bus signal
preemption techniques that require special bus de­
tection equipment or on-board devices for signal
green time extension or red time truncation.

The analysis tool for this study was a recently
developed version of the TRANSYT model, TRANSYT-7F,
described hereafter.

TRANSYT-7F
Traffic Network Study Tool (TRANSYT) is a tool for
optimizing traffic-signal systems on urban street
networks. The 7F version has been developed recently
in part to accommodate U.S. conventions and termi­
nology. A recent application of TRANSYT-7F has been
to assess the impact of traffic signal coordination
on fuel conservation as part of an 11-city, National
Signal Timing Optimization Project.

Among the most attractive features in TRANSYT,
which had direct application to this study, is the
concept of multiple links sharing one stop line.
Thus a lane carrying mixed traffic (BC, OBC, and
POBC) was entered in TRANSYT as two distinct links,
each carrying one type of vehicle. The concept was
again used to devise signal priority techniques for
bus traffic. This was done by specifying link
weights that were proportional to the average vehi­
icle occupancy on the link. Because the objective
function in TRANSYT is a weighted (by link) function
of vehicle delays and stops, the optimum signal set­
tings automatically incorporated a degree of pri­
ority for the designated priority traffic.

It should be noted that TRANSYT does not guaran­
tee a global optimum solution, in part because
no optimization of cycle lengths or phasing sequence
is carried out. Some of these shortcomings have been
alleviated in later versions of the model.

DATA PREPARATION AND COLLECTION

The following sections summarize the TRANSYT data
needed to carry out the prescribed evaluation
schemes.

Network Geometry
Lane configurations, intersections, geometrics, and
bus links were gathered from street maps provided by
the city of Chicago. The study section was bounded
by Wacker Drive on the west and Wabash Avenue on
the east. Information was coded directly into TRANSYT-7F
via a link-node scheme shown in Figures 1 and 2.

Signal Settings
Copies of the traffic signal timing schedule fur­
nished by the city of Chicago were used to code sig­
nal timing intervals directly into TRANSYT. Some
adjustments were made in the "after" conditions
(i.e., BL, OBL, and POBL) to account for bus traffic
in two-way operation and for the conversion of some
north-south cross streets from two-way to one-way
traffic.
Saturation Flow Rates

Because of the high density of pedestrian traffic in the study section, the TRANSYT-7F default saturation flows of 1,700 vehicles per hour of green (vphg) and 1,600 vphg for through and turning traffic, respectively, could not be applied. Instead vehicle start-up delays and discharge headways were measured directly in the field for various lane types. A summary of the results is given in Table 1.

<table>
<thead>
<tr>
<th>Lane Channelization</th>
<th>Mean Start-Up Delay (sec)</th>
<th>Mean Departure Headway (sec)</th>
<th>Measured Saturation Flow Rate (vphg)</th>
<th>TRANSYT Default Flow Rate (vphg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Through traffic only</td>
<td>3.49</td>
<td>2.98</td>
<td>1,700</td>
<td>1,700</td>
</tr>
<tr>
<td>Through and right(^n) turns, right-turn lanes</td>
<td>4.02</td>
<td>3.53</td>
<td>1,020</td>
<td>1,600-1,700</td>
</tr>
<tr>
<td>Through and left(^n) turns, left-turn lanes</td>
<td>3.82</td>
<td>3.59</td>
<td>1,000</td>
<td>1,600-1,700</td>
</tr>
<tr>
<td>Exclusive bus lanes</td>
<td>3.82</td>
<td>3.59</td>
<td>1,000</td>
<td>600-800</td>
</tr>
</tbody>
</table>

\(^n\) Lane types combined due to the small differences observed in the field.

Average Speed

TRANSYT calculates average speed as the ratio of total travel (in vehicle-miles per hour) to total travel time (in vehicle-hours per hour). Only internal links (i.e., arterial links) are included in calculating speed on the network. When links are designated for bus travel, bus dwell times (assumed to be constant at 20 sec per stop) are incorporated as part of the travel time.

Table 2 gives a summary of the results for average vehicle speed. As anticipated, the simulated network-wide speed increased significantly when optimum TRANSYT signal settings were implemented (OBC, POBC, OBL, and POBL). Automobile traffic speed slightly decreased under the OBL and POBL strategies, compared with OBC and POBC, with turning traffic exhibiting the greatest reduction. This is one result of switching from one-way to two-way operation on the arterial and the associated traffic delays (to left turns) caused by opposing bus traffic and pedestrian interference. The most notable impact given in Table 1, however, is a dramatic increase in the simulated overall bus speeds under exclusive bus lane operation, which ranged from 0.88 to 1.152 mph in mixed traffic and from 4.86 to 6.4 mph with the exclusive lane. The fact that the simulated bus speed decreased under OBL, compared with BL, indicates that additional green time was allocated to the cross-street traffic to minimize over-

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Network-Wide(^a)</th>
<th>All Traffic</th>
<th>Through Traffic</th>
<th>Right Turns</th>
<th>Left Turns</th>
<th>Bus Traffic(^b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base condition</td>
<td>3.63</td>
<td>4.720</td>
<td>4.320</td>
<td>5.944</td>
<td>11.063</td>
<td>0.879</td>
</tr>
<tr>
<td>Bus-lane operation</td>
<td>3.82</td>
<td>10.142</td>
<td>12.642</td>
<td>8.301</td>
<td>10.426</td>
<td>5.236</td>
</tr>
<tr>
<td>Optimized bus-lane operation</td>
<td>6.02</td>
<td>10.177</td>
<td>12.124</td>
<td>7.277</td>
<td>10.104</td>
<td>4.862</td>
</tr>
<tr>
<td>Priority optimized bus-lane operation</td>
<td>5.92</td>
<td>10.251</td>
<td>12.668</td>
<td>8.035</td>
<td>9.366</td>
<td>6.397</td>
</tr>
</tbody>
</table>

\(^a\) Represents average running speed (excluding bus dwell times).

\(^b\) Represents average overall bus speed (including dwell time of 20 sec/stop).

System Configuration Changes

A number of changes occurred on the street system during the 6 years separating the base and bus lane conditions described earlier. These included modifications in network geometry, traffic signal setting, and traffic volume. Geometric changes can be observed in Figures 1 and 2. It was estimated that by removing one lane of traffic from the eastbound approach, the capacity of the eastbound movement would be reduced by 1,100 vphg (see Table 1). The west-bound movement capacity on the other hand is increased by 600 buses per hour (TRANSYT-7F default value). Thus a net capacity loss of 500 vphg occurred in the "after" condition. In addition, both cordon counts and short-term field counts indicated a reduction in automobile traffic using the facility (11,12). Hence, the resulting situation (drop in volume and capacity) offered a unique opportunity for conducting an unbiased evaluation of the traffic signal and geometric priority schemes based on comparable volume-to-capacity ratios in the before and after conditions.

Bus Flow Data

Information about bus routes, schedules, and stops on Jackson Boulevard was provided by the Chicago Transit Authority. The data were subsequently coded into TRANSYT-7F.

Traffic Volume Data

A complete set of directional and turning movement counts was not available for the "before" study period. This constituted a serious obstacle to the evaluation process because there was no possibility of collecting volume data that had not already been obtained. A logical procedure was devised to produce realistic estimates of missing counts on the basis of available turning movement, directional, and cordon counts in the study area (9). The final volume estimates were subsequently reviewed by traffic personnel in Chicago and coded into TRANSYT-7F. It is interesting to note that previous work by Kneer (10) indicated that TRANSYT measures of effectiveness are not very sensitive to errors in traffic volume estimations. It was shown that it was the introduction of a random deviate with mean 1 and standard deviation 0.2 on each link volume resulted in variations of less than 5 percent in the performance index in TRANSYT.

No such difficulties were encountered in the "after" condition because there were adequate volume counts in that particular period and missing counts were obtained directly from field measurements.
FIELD VALIDATION OF RESULTS

A limited field study was conducted to validate the predicted bus performance measures obtained from the TRANSYT simulation runs. Overall bus travel speed was the targeted performance measure. In addition, bus operating parameters, such as occupancy and dwell times, were gathered to verify the original assumptions about their values in the TRANSYT runs.

Two observers on board the transit vehicle were used to gather the required data. One observer collected transit riding data, such as the number of passengers boarding and alighting at each station and dwell time at each bus stop. The second observer collected travel time, running time, and traffic-related delays on each link on the bus route. A total of five independent bus runs in the evening peak hour was conducted. This sample size gives estimates of mean travel speed within ±3 mph of the expected value (13). The results of these runs are summarized in Tables 4 and 5. Bus dwell times, which are comprised of passenger boarding and alighting times away from bus stops, were not considered in this analysis.

TABLE 4  Bus Operation on Jackson Boulevard—Field Measurements

<table>
<thead>
<tr>
<th>Link</th>
<th>Bus Occupancy (passengers)</th>
<th>Dwell Time at Bus Stop (sec)b</th>
<th>Traffic Delays on Link (sec)</th>
<th>Overall Travel Time on Link (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>31.8</td>
<td>14</td>
<td>16</td>
<td>47</td>
</tr>
<tr>
<td>2</td>
<td>30.0</td>
<td>11</td>
<td>22</td>
<td>46</td>
</tr>
<tr>
<td>3</td>
<td>31.4</td>
<td>11</td>
<td>22</td>
<td>54</td>
</tr>
<tr>
<td>4</td>
<td>32.2</td>
<td>14</td>
<td>5</td>
<td>42</td>
</tr>
<tr>
<td>5</td>
<td>31.8</td>
<td>30</td>
<td>5</td>
<td>44</td>
</tr>
<tr>
<td>6</td>
<td>31.2</td>
<td>40</td>
<td>11</td>
<td>71</td>
</tr>
<tr>
<td>7</td>
<td>21.2</td>
<td>38</td>
<td>24</td>
<td>72</td>
</tr>
<tr>
<td>Total</td>
<td>29.9</td>
<td>15.8</td>
<td>105</td>
<td>376</td>
</tr>
</tbody>
</table>

a Includes average of five independent bus runs.
b Includes passenger boarding/alighting times away from bus stops as well.

TABLE 5  Comparison of Overall Bus Travel Speeds (mph)

<table>
<thead>
<tr>
<th>Bus Link</th>
<th>Field Runs</th>
<th>TRANSYT Runa</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7.02</td>
<td>5.63</td>
</tr>
<tr>
<td>2</td>
<td>4.84</td>
<td>5.02</td>
</tr>
<tr>
<td>3</td>
<td>4.88</td>
<td>6.38</td>
</tr>
<tr>
<td>4</td>
<td>5.29</td>
<td>6.47</td>
</tr>
<tr>
<td>5</td>
<td>5.87</td>
<td>6.42</td>
</tr>
<tr>
<td>6</td>
<td>4.57</td>
<td>5.35</td>
</tr>
<tr>
<td>7</td>
<td>5.00</td>
<td>5.18</td>
</tr>
<tr>
<td>Average</td>
<td>6.09</td>
<td>5.27</td>
</tr>
</tbody>
</table>

a Includes average of five independent bus runs.
b Adjusted for variable dwell time on bus links.
 ranging from 11 to 40 sec, were found to vary from one stop to another, with an average of 22.5 sec per stop. Although the average dwell time varied by only 2.5 sec per stop from the assumed value in TRANSYT (20 sec per stop), adjustments on individual link travel times in TRANSYT were made in order to reflect the observed changes in overall bus travel speeds on the individual links caused by dwell time variations. Mathematically, the adjusted link travel time is calculated as follows: Adjusted link travel time (vehicle-hours per hour) = TRANSYT-derived travel time + (Observed dwell time for bus stop on link in seconds) x (Hourly bus volume)/3600.

The adjusted link travel speed is then calculated as:

\[ \text{Speed on link} = \frac{\text{Total travel on link (vehicle-miles per hour)}}{\text{Adjusted link travel time (vehicle-hours per hour)}} \]

A comparison of observed and simulated link travel speeds is given in Table 5. A t-test for matched pairs was conducted on the difference between observed and simulated link travel speeds in each run (14). The results indicated that the two sets of speeds were not statistically different at the 5 percent significance level. That conclusion held true for all five pair-wise comparisons.

No formal validation effort was undertaken to verify automobile traffic performance in TRANSYT. However, floating car runs conducted by the city of Chicago in 1975 gave an estimated evening peak-hour traffic speed of 5.68 mph on the study section. This value compares favorably with the TRANSYT's estimate of 4.72 mph given in Table 1.

SUMMARY AND CONCLUSIONS

Bus priority techniques on urban street networks have been adopted in many U.S. cities to increase the person-moving capacity of major travel corridors. This study has focused on evaluating two techniques for bus priority, namely a reserved contraflow bus lane on a downtown street and bus priority consideration in signal timing calculations at each intersection along the bus route.

The results of a simulation analysis applied to a downtown Chicago street indicated that the potential effectiveness of each strategy in improving bus performance depends on many factors, including the magnitude of nonbus traffic, capacity reductions for nonbus movements after implementing the reserved lane, bus dwell times, and, of course, the traffic signal settings along the bus route.

In general, simulated bus speeds increased when the signal settings incorporated some degree of priority for high-occupancy bus operations (1.146 to 1.152 mph) but considerable under the reserved lane configuration (4.82 to 6.397 mph).

It was also noted that the TRANSYT optimized settings did not always result in improved bus performance because the objective function in TRANSYT considers all vehicle delays and stops on the network, not just those experienced on the bus route. The most consistent result, however, is a dramatic increase in predicted overall bus travel speeds under the reserved bus lane configuration, regardless of the signal control strategy adopted.

Finally, all of the prescribed impacts were concomitant with an observed reduction in nonbus traffic volume 1 year after the implementation of the contraflow bus lane. Whether a route shift by motorists who originally traveled on Jackson Boulevard occurred as a result of the increased congestion for nonbus traffic after the bus lane was installed is yet to be thoroughly investigated. Nevertheless, it is imperative that both route and modal shifts be monitored regularly after the implementation of bus priority techniques so that a comprehensive impact assessment analysis beyond the bus path may be undertaken.

ACKNOWLEDGMENTS

This study was sponsored in part through a University of Illinois, Chicago, Research Board Grant. The author wishes to thank John LaPlante and Jerry Sachno, Traffic Engineers with the city of Chicago, for supplying the data needed to conduct this study. Sincere thanks to Debbie Van Huis, Sandra Wichelecki, and Jeffery Monroe for their assistance in data collection and computer run analysis.

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