Operational Evaluation of Bus Priority Strategies

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ABSTRACT

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 (1).

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 (2). 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:

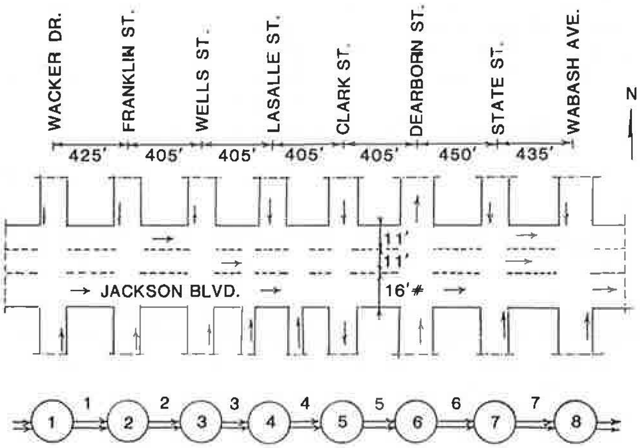
1. To identify signal-related and geometric-related bus priority techniques on Jackson Boulevard in the Chicago Loop and to develop a set of distinct priority strategies,
2. To evaluate each strategy developed in Objective 1 using existing traffic analysis techniques, and
3. To recommend a set of actions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



*INCLUDES 7' PARKING LANE

FIGURE 1 1975 network and link-node scheme.

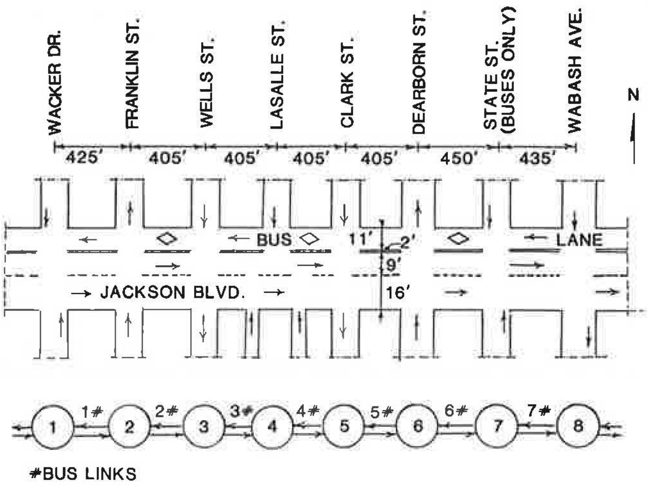


FIGURE 2 1981 network and link-node scheme.

38 ft was provided, including a 7-ft parking lane on the south side of the street and a three-lane travel section throughout. Twenty-four-hour counts taken between Dearborn and Clark streets gave an estimated 1975 average daily traffic (ADT) count of 13,277 vehicles, of which approximately 5 percent were buses operating in mixed traffic lanes.

After the creation of the bus lanes, the eastbound traffic was confined to two lanes, each 9 ft wide. Bus lanes were designed by 2-ft-long painted medians and had a width of 11 ft. Appropriate signing and signaling changes were also introduced. A 1980 count on Jackson Boulevard between Dearborn and Clark streets showed a 17 percent drop from the 1975 counts, down to 11,042 vehicles per day.

The subsequent evaluation schemes were simulated for representative weekday evening peak-hour (4:00 to 5:00 p.m.) traffic on Jackson Boulevard in 1975 (before bus lane) and 1981 (after bus lane).

BUS PRIORITY SCHEMES

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

1. Base condition (BC) describes traffic conditions 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) describes traffic conditions and controls similar to those of BC, except that signal settings are adjusted for minimum passenger delays and stops;
4. Bus-lane operation (BL) describes traffic conditions 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) describes traffic conditions and controls similar to those of BL, except that signal settings are adjusted 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 detection equipment or on-board devices for signal green time extension or red time truncation (4).

The analysis tool for this study was a recently developed version of the TRANSYT model, TRANSYT-7F, described hereafter (5).

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 terminology. 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 (6).

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 vehicle occupancy on the link. Because the objective function in TRANSYT is a weighted (by link) function of vehicle delays and stops, the optimum signal settings automatically incorporated a degree of priority for the designated priority traffic.

It should be noted that TRANSYT does not guarantee a global optimum solution (7), 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 (8).

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 furnished by the city of Chicago were used to code signal 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 1 Saturation Flow Study Results

Lane Channelization	Mean Start-Up Delay (sec)	Mean Departure Headway (sec)	Measured Saturation Flow Rate (vphg)	TRANSYT Default (vphg)
Through traffic only	3.49	2.98	1,200	1,700
Through and right[a] turns, right-turn lanes	4.02	3.53	1,020	1,600-1,700
Through and left[a] turns, left-turn lanes	3.82	3.59	1,000	1,600-1,700
Exclusive bus lanes	—[b]	—[b]	—[c]	600-800

[a] Lane types combined due to the small differences observed in the field.

[b] Inadequate sample size.

[c] Inadequate sample size; default value 600 buses per lane per hour of green was used.

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 Kreer (10) indicated that TRANSYT measures of effectiveness are not very sensitive to errors in traffic volume estimations. It was shown that 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.

RESULTS

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 volumes. 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 westbound 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.

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 2 Predicted Travel Speeds (mph) for Jackson Boulevard Traffic

Strategy	Network-Wide[a]	All Traffic	Through Traffic	Right Turns	Left Turns	Bus Traffic[b]
Base condition	3.63	4.720	4.320	5.944	11.063	0.879
Optimized base condition	6.27	11.395	11.133	13.519	13.287	1.146
Priority optimized base condition	6.19	11.889	11.436	13.805	13.949	1.152
Bus-lane operation	3.82	10.142	11.642	8.301	10.426	5.236
Optimized bus-lane operation	6.02	10.117	12.124	7.277	10.104	4.862
Priority optimized bus-lane operation	5.92	10.251	12.668	8.035	9.366	6.397

[a] Represents average running speed (excluding bus dwell times).

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

TABLE 3 Predicted Delays in Vehicle-Hours per Hour (passenger-hours per hour) for Jackson Boulevard Traffic

Strategy	Network-Wide	All Traffic	Through Traffic	Right Turns	Left Turns	Bus Traffic	Cross-Street Traffic
Base condition	115.501 (304.178)	90.701 (267.474)	78.480 (249.387)	8.223 (12.170)	3.998 (5.917)	9.114 (145.824)	24.800 (36.704)
Optimized base condition	58.428 (122.688)	26.736 (65.784)	21.510 (58.050)	2.488 (3.682)	2.738 (4.052)	1.812 (28.992)	31.692 (46.904)
Priority optimized base condition	59.464 (118.840)	23.960 (59.294)	19.339 (52.455)	2.198 (3.253)	2.423 (3.586)	1.633 (26.606)	35.504 (52.546)
Bus-lane operation	(76.504) (138.373)	24.424 (61.295)	16.800 (24.864)	1.872 (2.770)	4.020 (5.949)	1.732 (27.712)	52.080 (77.087)
Optimized bus-lane operation	44.247 (96.384)	23.206 (65.243)	15.132 (22.395)	2.114 (3.129)	3.832 (5.671)	2.128 (34.0480)	21.041 (31.141)
Priority optimized bus-lane operation	45.204 (86.851)	20.578 (50.405)	13.502 (19.983)	1.805 (2.671)	3.897 (5.767)	1.374 (21.984)	24.626 (36.446)

all delays and stops on the network. Because the total available green time is fixed (cycle = 65 sec), an inevitable decrease in bus green times, and subsequently in simulated overall bus travel speed, occurred.

Finally, optimum bus performance was attained when passenger delays were considered in developing the signal-timing plans. The improvement in bus performance, however, was less than 1 percent under mixed traffic operation (POBC versus OBC) but more than 30 percent with the exclusive lane.

Vehicle and Passenger Delays

Delay in TRANSYT is defined as the stopped time on the link due to signal timing only, including bus traffic. Table 3 gives a summary of the results for simulated vehicle and passenger delays associated with each of the six strategies under study. Whereas vehicle delay is obtained directly from TRANSYT output, some calculations were necessary to estimate passenger delays. The latter were based on average vehicle occupancies on each link, as obtained from cordon counts taken at the Jackson Boulevard Bridge on the Chicago River. Values of 1.48 persons per car, 1.90 persons per taxi, and 16 persons per bus were derived. The average link occupancy was determined as

$$\text{Link } (j) \text{ occupancy} = \sum_{i=1}^{3} O_i P_{ij}$$

where O_i is vehicle occupancy for vehicle type i and P_{ij} is percentage of traffic volume on link j consisting of vehicle type i.

As indicated in Table 3, simulated vehicle delays decreased significantly as TRANSYT-7F optimum signal settings were implemented. The OBL operation resulted in the lowest network-wide vehicle delays, whereas the POBL operation resulted in the lowest overall passenger delays. It should be noted that the passenger-related performance measures are valid only for the set of vehicle occupancies stated previously. Another set of occupancies will probably result in different conclusions. Simulated delays on Jackson Boulevard did not vary considerably under the TRANSYT optimized signal settings, even under bus-lane operations (i.e., strategies OBC, POBC, OBL, and POBL), except for left-turn traffic delay, which increased as a result of the opposing bus traffic in the "after" condition.

Finally, simulated bus delays were generally lower under the exclusive bus lane, with optimum delays occurring with the POBL strategy.

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,

TABLE 4 Bus Operation on Jackson Boulevard—Field Measurements[a]

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

[a] Includes average of five independent bus runs.
[b] See link designations in Figures 1 and 2.
[c] Includes passenger boarding/alighting times away from bus stops as well.

TABLE 5 Comparison of Overall Bus Travel Speeds (mph)

Bus Link[a]	Field Runs 1	2	3	4	5	Mean	TRANSYT Run[b]
1	7.02	6.15	7.44	6.73	2.89	6.06	5.71
2	4.84	5.02	10.50	5.02	4.93	6.06	5.82
3	6.88	6.38	6.16	6.50	6.50	6.48	6.53
4	5.92	6.47	6.95	8.59	9.59	7.50	5.59
5	8.37	6.42	6.14	5.31	5.21	6.29	5.05
6	4.57	2.35	5.01	4.50	5.37	4.36	4.02
7	5.00	2.75	5.18	3.20	5.09	4.24	4.21
Average	6.09	5.08	6.76	5.71	5.65	5.86	5.27

[a] Link designations are shown in Figure 2.
[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 - 20) x (Hourly bus volume)/3600. The adjusted link travel speed is then calculated as

Speed on link = Total travel on link (vehicle-miles per hour)/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 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 contra-flow 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 vehicles. That increase, however, was barely noticeable under mixed traffic 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 contra-flow 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.

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