**Table 9. Reduction in fuel consumption, four-lane arterial.**

| Driveway Density[a] (no./mile) | ADT | Reduction in Fuel Consumption (gal/vehicle) by Left-Turn Volume[b] | | |
|---|---|---|---|---|
| | | 35 vehicles/ h/1000 ft | 70 vehicles/ h/1000 ft | 105 vehicles/ h/1000 ft |
| 30 | 7 000 | 0.000 14 | 0.000 10 | 0.000 38[c] |
| | 14 000 | 0.000 10 | 0.000 47 | 0.000 68 |
| | 21 000 | 0.000 52 | 0.000 65 | 0.003 44 |
| 60 | 7 000 | 0.000 07 | 0.000 16 | 0.000 43[c] |
| | 14 000 | 0.000 13 | 0.000 35 | 0.000 92 |
| | 21 000 | 0.000 50 | 0.000 78 | -[d] |
| 90 | 8 000 | 0.000 04 | 0.000 06 | 0.000 22[c] |
| | 16 000 | 0.000 04 | 0.000 15 | 0.000 49 |
| | 24 000 | 0.000 45 | 0.001 50 | 0.003 48 |

[a] Total number of driveways on both sides of street.
[b] Volume in each direction.
[c] Quantities under these lines exceed 0.000 29 gal/vehicle, the estimated savings from RTORAS.
[d] Jammed flow in the no-TWLTL case. Simulation incomplete.

The Institute of Transportation Engineers (ITE) published a report in 1980 by Wagner (10) on fuel-conservation impacts of various transportation improvement measures. The most widely implemented measure included in the report is the introduction of right-turn-on-red-after-stop (RTORAS). Fuel savings from RTORAS were calculated for a hypothetical area of 1 million population. It was estimated that an annual traffic volume of 5530 million vehicles will save 1.62 million gal. This corresponds to saving 0.000 29 gal/vehicle. Because RTORAS is considered to be a significant energy-conservation policy, the selection of the above 0.000 29 gal/vehicle fuel savings could be considered a valid yardstick with which to evaluate fuel savings from TWLTLs.

The annual fuel savings shown in Table 8 were therefore recalculated in gallons per vehicle, as shown in Table 9. The steplike heavy line within the table separates the quantities that exceed the savings from RTORAS from those that do not. The following observations can be made from the data presented in Table 9:

1. At a given driveway density, potential fuel savings increase as total volumes (ADT) increase. This increase is more rapid at higher left-turn volumes.
2. Fuel savings change as driveway density changes at a given ADT level and given left-turn volume. This is not unexpected, since changing driveway density changes the average left-turn volumes per driveway. However, no clear pattern can be identified. More research is needed in this area.

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# Effect of Bus Turnouts on Traffic Congestion and Fuel Consumption

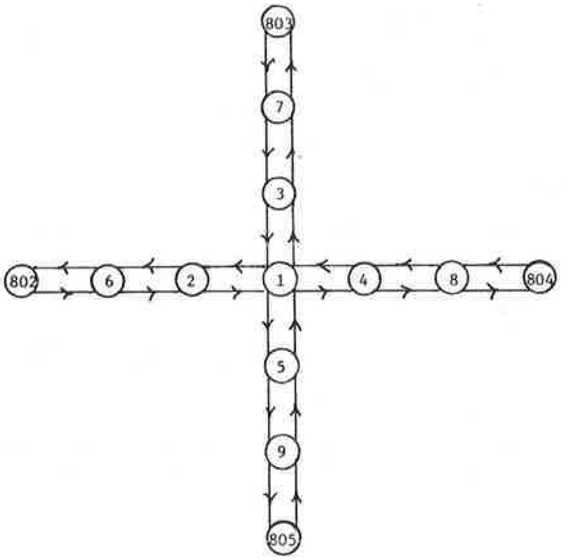
S.L. COHEN

**The NETSIM simulation model was employed to determine the energy impacts of using bus turnouts. Two sets of computer runs were made. The first one consisted of 80 runs of a single intersection with different values of independent variables. The second consisted of six runs of three different networks. The result was that bus turnouts were found to have some potential for improving the fuel efficiency of the general traffic stream but only at high values of volume-to-capacity ratios, high bus volumes, and long bus-loading times.**

There have been a number of papers written in the past few years concerning the effect of various traffic engineering alternatives on automotive fuel consumption. One set of measures studied include such traffic-flow improvements as right-turn-on-red (1), improved signalization (1,2), one-way versus two-way street patterns (2), cycle length (3), and exclusive turn bays (4).

Another set of traffic engineering alternatives that have potential for fuel savings involves changes in bus operations. These alternatives include such measures as near side versus far side

Figure 1. Single intersection.



stops, bus priority signal strategies, and bus turnouts. The issue of near side versus far side bus stops has been studied by a number of authors (5-7), who arrived at contradictory conclusions. Bus priority signal strategies have also been studied in both field tests (8) and simulations (9). Results indicate that bus service may be slightly improved at the expense of greater delay to the other traffic. By comparison, bus turnouts, the subject of this paper, have received very little attention. Only two rather limited studies (10,11) have been done. Pignataro and others (10) used the NETSIM (formerly UTCS-1) simulation model (12) to study the effect of bus turnouts on general traffic. However, the results of this study may be questionable because it is not made clear whether the authors recognized that the action of a bus pulling out of a turnout is not modeled in NETSIM. In the report by Richards (11), a number of bus turnout designs were studied in the field to determine their effect on bus exit times. This study, however, was limited to two-lane roads (one lane in each direction) with the bus stop not in the vicinity of traffic signals. Thus, it would not be particularly applicable to urban bus operations.

## METHODOLOGY

This study used the NETSIM model (12), which was suitably modified, as described in the next section. The use of simulation has a number of advantages. A large number of comparisons that involve before-and-after studies can be performed at a relatively low cost. The cost of performing such studies in field situations would be quite prohibitive. In addition, simulation experiments have repeatability, which is very difficult, if not impossible, to achieve in the field.

Two experiments were performed. In the first, a single intersection with four approaches, in which each approach had one bus stop and a different number of lanes, was simulated under different passenger car volumes, bus volumes, bus stop locations, and bus loading-time conditions. In the second, three urban networks, one in Washington, D.C., and two in Chicago, were simulated on NETSIM. The purpose of the first experiment was to compare the condition of a bus turnout with the condition of no bus turnout under a limited set of independent variables. The purpose of the second experiment was to indicate what might be expected to occur in an actual street network if unprotected bus stops were replaced with bus turnouts.

## NETSIM CHANGES

NETSIM does not model the exit of a bus from a turnout by using a gap acceptance algorithm. Instead, the user is supposed to input a value of mean dwell time that accounts for time spent in a turnout in addition to passenger loading time. At the end of this dwell time, the bus is then inserted back into the traffic stream whether or not a gap exists. This procedure has two drawbacks from the point of view of this study:

1. The value of dwell time is not known if one is modeling a turnout where one does not exist, and
2. Inserting the bus back into the traffic stream without checking for a gap will cause an overestimate of the delay to the other traffic because, in the model, the bus interferes with the stream, whereas in the real world the bus would wait until there was sufficient room to exit the turnout.

For these reasons, the NETSIM model was modified so that a bus turnout looks for a gap in traffic in the adjacent through lane. Unfortunately, no specific data are available on gap acceptance distributions for buses in turnouts. Richards (11) found that the excess dwell time (i.e., time spent after passenger loading and waiting for a gap) was dependent on the shape of the bay. Observations of some turnouts in the Washington area indicated that the access dwell time is time dependent. Bus drivers appeared more aggressive about forcing their way into the through traffic stream in the morning peak than in the evening peak or off peak. In the absence of any data, the following criterion was used. It was assumed that a bus will exit a bay if a space gap of one bus length plus 2 ft is available in the target lane. If, in fact, larger minimum gaps are observed, the consequence is that turnouts will cause a greater increase in bus travel times than predicted in this work. On the other hand, larger reductions in delay to the other traffic will occur because of less disruption due to slowly accelerating buses.

## SINGLE INTERSECTION SETUP

The first set of experiments involved a total of 80 simulation runs of the single intersection network shown in Figure 1. Approach links 2-1, 3-1, 4-1, and 5-1 had 2, 3, 4, and 5 lanes, respectively. There were four bus routes, one on each of the four directions, and each had a stop on the approach link to node 1. Nodes 1, 2, 3, 4, and 5 were signalized with an 80-s cycle and equal splits. Nodes 6, 7, 8, and 9 were unsignalized. Volumes on each of the entry links were chosen so that the volume-to-capacity ratios (V/C's) on all approach links to 1 were approximately equal for each volume level.

The independent variables--V/C, bus loading time, bus volume, and station position--were selected as likely to have the greatest bearing on the effect of turnouts. Thus, one would expect no effect if volumes are low and/or if bus volumes are low and/or if loading times are short. It would also be expected that the effect of a turnout at the stop line could differ from midblock because, in the former case, buses may be blocked from exiting by a standing queue.

A total of 80 simulation runs were performed.

**Table 1. Tabulation of statistical results, turnouts versus no turnouts.**

| Test No. | V/C | Bus Stop Location | Bus Load Time (s) | Bus Volume (buses/h) | Mean Time Delay (s/vehicle mile) | Mean Passenger Car Fuel Difference (miles/gal) | Mean Bus Speed Difference (miles/h) |
|---|---|---|---|---|---|---|---|
| 1 | All | All | All | All | -35.3[a] | +0.26[a] | -0.21[a] |
| 2 | All | All | 30 | 40 | -80.1[a] | +0.52[a] | +0.043 |
| 3 | All | All | 15 | 40 | -75.0[a] | +0.32[a] | -0.142[a] |
| 4 | All | All | 30 | 20 | -18.1[a] | +0.18[a] | -0.373[a] |
| 5 | All | All | 15 | 20 | -3.2 | +0.037 | -0.387[a] |
| 6 | 0.95 | All | All | All | -51.5[a] | +0.33[a] | -0.21[a] |
| 7 | 0.95 | All | 30 | 40 | -123.5[a] | +0.70[a] | -0.18[a] |
| 8 | 0.95 | All | 15 | 40 | -57.8[a] | +0.40[a] | -0.033 |
| 9 | 0.95 | All | 30 | 20 | -25.6[a] | +0.22[a] | -0.42[a] |
| 10 | 0.95 | All | 15 | 20 | +0.729 | -0.021 | -0.54[a] |
| 11 | 0.75 | All | All | All | -10.8[a] | +0.17[a] | -0.22[a] |
| 12 | 0.75 | All | 30 | 40 | -15.0[a] | +0.22[a] | -0.16 |
| 13 | 0.75 | All | 15 | 40 | -12.3[a] | +0.20[a] | -0.29[a] |
| 14 | 0.75 | All | 30 | 20 | -6.9 | +0.11[a] | -0.29[a] |
| 15 | 0.75 | All | 15 | 20 | -9.1[a] | +0.12[a] | -0.15 |
| 16 | All | Near | All | All | -48.1[a] | +0.30[a] | -0.21[a] |
| 17 | All | Near | 30 | 40 | -119.1[a] | +0.65[a] | +0.22 |
| 18 | All | Near | 15 | 40 | -55.1[a] | +0.40[a] | +0.005 |
| 19 | All | Near | 30 | 20 | -21.9[a] | +0.19[a] | -0.53[a] |
| 20 | All | Near | 15 | 20 | +3.86 | -0.030 | -0.54[a] |
| 21 | All | Midblock | All | All | -22.4[a] | +0.22[a] | -0.22[a] |
| 22 | All | Midblock | 30 | 40 | -41.0[a] | +0.38[a] | -0.14[a] |
| 23 | All | Midblock | 15 | 40 | -24.1[a] | +0.25[a] | -0.28[a] |
| 24 | All | Midblock | 30 | 20 | -14.4[a] | +0.16[a] | -0.21[a] |
| 25 | All | Midblock | 15 | 20 | -10.3[a] | +0.10[a] | -0.24[a] |

[a] Indicates significant difference at 5 percent level.

**Table 2. Tabulation of statistical results, turnout versus no turnout.**

| | | Relative Differences | | |
|---|---|---|---|---|
| Test No. | Test Data Description | Mean Difference of Delay Difference (s/vehicle mile) | Mean Difference of Passenger Car Fuel Difference (miles/gal) | Mean Difference of Bus Speed Difference (mph) |
| 1 | High volume versus low volume | +40.3[a] | -0.13 | -0.01 |
| 2 | Near side versus far side | +24.3 | -0.06 | -0.03 |

[a] Indicates significant difference at 5 percent.

They consisted of the following:

1. A total of 32 runs for two V/C levels, two bus volume levels, two bus loading-time levels, and two bus station locations for the two choices of turnout or no turnout;
2. Thirty-two replicate runs (by using different random number seeds) of 1; and
3. Sixteen replication runs for the higher volume levels in 1.

The V/C levels chosen were V/C = 0.95 and 0.75. Bus volume levels chosen were 40 and 20 buses/h. Loading-time levels chosen were 30 and 15 s. Near side stops located at the stop line and midblock stops located 180 ft from the stop line were tested. The high level of 40 buses/h and 30-s loading times was chosen by using the data from the three networks described in the next section.

Four measures of effectiveness (MOEs) were chosen for comparing the turnout and no turnout situations:

1. Total delay per vehicle mile in seconds per vehicle mile--all vehicles;
2. Fuel efficiency in miles per gallon--passenger cars;
3. Average route speed in miles per hour--buses; and
4. Fuel efficiency in miles per gallon--buses.

## STATISTICAL ANALYSIS OF SINGLE INTERSECTION EXPERIMENTS

In order to make the most efficient use of the available computer runs, it was decided to use the matched-pairs signed-rank test described by Wilcoxon (13). This test is particularly useful in cases where the effect of a single treatment (here the use of a bus turnout) is being determined and where varying values of independent variables (e.g., bus loading times) are not expected to reverse the direction of the effect (i.e., it is not expected that a bus turnout would improve traffic at long loading times and make it worse at short loading times). Details of the test are as follows. The Wilcoxon matched-pairs test consists of the following:

1. Arrange the data in two columns: column 1, which consists of data from the turnout case, and column 2, which consists of data from the no-turnout case.
2. Pair off the elements of columns 1 and 2 based on identical values of independent variables.
3. Subtract, pairwise, column 2 from column 1 and rank the differences independently of the signs.
4. Form the rank sums of the positive differences and the rank sums of the negative differences.
5. If the number of matched pairs that have nonzero differences is less than 16, compare the

Table 3. Network results.

| Network | Protected Stops | Networkwide Delay per Vehicle Mile (s/vehicle mile) | Networkwide Passenger Car Fuel Efficiency (miles/gal) | Networkwide Bus Delay (s/vehicle mile) | Networkwide Bus Fuel Efficiency (miles/gal) |
|---|---|---|---|---|---|
| K Street | No | 215.4 | 7.54 | 118.2 | 4.23 |
| | Yes | 202.8 | 7.69 | 121.1 | 4.23 |
| North Michigan Avenue | No | 237.6 | 7.58 | 183.6 | 4.07 |
| | Yes | 231.2 | 7.75 | 203.4 | 4.08 |
| South Halsted Street | No | 61.2 | 12.91 | 73.2 | 4.76 |
| | Yes | 55.8 | 13.27 | 76.2 | 4.81 |

smaller of the positive and negative rank sums against the table values in Snedecor and Cochran (13).

6. If the number of matched pairs that have nonzero differences is 16 or greater, compare the statistic Z given by the following equation with the standard normal table, i.e.,

$$Z = [|\mu - T| - (1/2)]/\sigma \quad (1)$$

where

$$\mu = n(n + 1)/4 \quad (2)$$

and

$$\sigma = [\mu(2n + 1)/6]^{1/2} \quad (3)$$

where n is the number of pairs that have nonzero differences and T is the smaller of the positive or negative rank sums.

Two types of analysis were made:

1. A determination of whether the presence of a bus turnout had a statistically significant effect on MOEs for different sets of values of the independent variables, and
2. A determination of whether the magnitude of the effects of bus turnouts differed significantly from one set of independent variables to another.

Table 1 gives the results for tests of significance of bus turnout effects. It should be noted that a positive sign for a mean difference indicates that the value of the MOE for the case with a turnout is larger than the value for the case without a turnout. Thus, a negative value for a delay difference indicates that bus turnouts improved delay; a positive value for a fuel-efficiency difference indicates that bus turnouts improved fuel efficiency.

Table 2 gives the results for tests of significance for the effect of independent variables on the relative effects of bus turnouts. Here, for example, we try to discern whether bus turnouts give a greater reduction in delay at higher rather than lower V/C's.

## DISCUSSION OF SINGLE INTERSECTION RESULTS

A number of conclusions can be drawn from looking at Tables 1 and 2:

1. There is some potential for fuel savings for nonbus traffic where bus turnouts are used. However, the savings are rather small, as the overall saving of 0.26 mile/gal is about 4 percent of the mean fuel efficiency experienced by passenger car traffic.
2. The V/C has a substantial effect on the benefits obtained from turnouts. The mean delay reduction of all traffic went from 51.5 s/vehicle-mile at V/C = 0.95 to 10.3 s/vehicle-mile at V/C = 0.75. The fuel-efficiency benefit for passenger cars went from 0.33 mile/gal at V/C = 0.95 to 0.17 mile/gal at V/C = 0.75.
3. Benefits derived from turnouts are strongly dependent on high bus volumes and loading times. No significant improvement in MOEs was found at the lowest combined bus volume and loading-time level.
4. No significant difference was found in benefits derived from turnouts at either near side or midblock stops.
5. Turnouts decreased average bus speed; however, the reduction was small, being only about 1-3 percent.

## NETWORK DEMONSTRATION RUNS

Although the intersection results described in the previous sections are of interest, it was felt that practitioners would profit from demonstrations of the effects of bus turnouts in actual urban street systems. Three networks with actual bus data were available in the form of input cards to the NETSIM program. They included a network from Washington, D.C., centered around K Street, N.W. (shown in Figure 2); a network from Chicago centered around North Michigan Avenue (shown in Figure 3); and another network from Chicago centered around South Halstead Street (shown in Figure 4). These three networks include a wide variety of conditions with differing values for the independent variables tested in the previous sections.

Six runs were performed, one of each network for each situation: all bus stops with turnouts or no bus stops with turnouts. Results are given in Table 3.

## DISCUSSION OF NETWORK RESULTS

A number of conclusions can be drawn from looking at Table 3. In particular, it is evident that the results obtained through use of a turnout for the single intersection hold up when aggregated over a network. Thus, there is some improvement in fuel efficiency, although small, and some reduction in delay for the nonbus traffic. Again little, if any, change in bus fuel efficiency was seen, but generally a small increase in bus travel times was observed.

## CONCLUSIONS

From the results of this work, it can be concluded that installing turnouts for buses has the potential to reduce traffic congestion and thus increase fuel efficiency. However, the congestion reductions become substantial only at high V/C's, high bus volumes, and high passenger loading times. It can also be concluded that the relative improvement due to turnouts is not dependent on the location of the bus

Figure 2. K Street network.

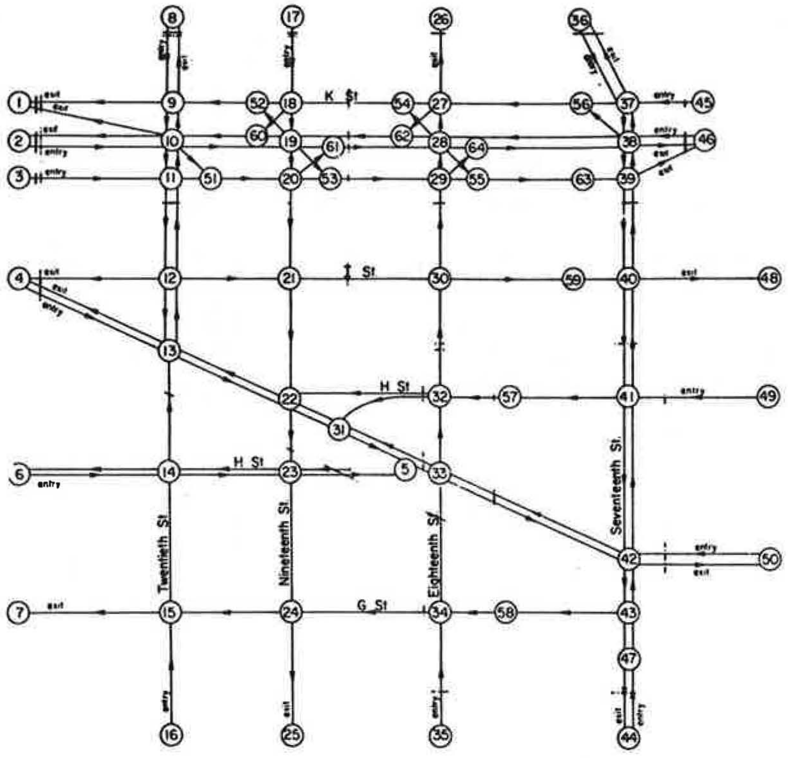


Figure 3. North Michigan Avenue network.

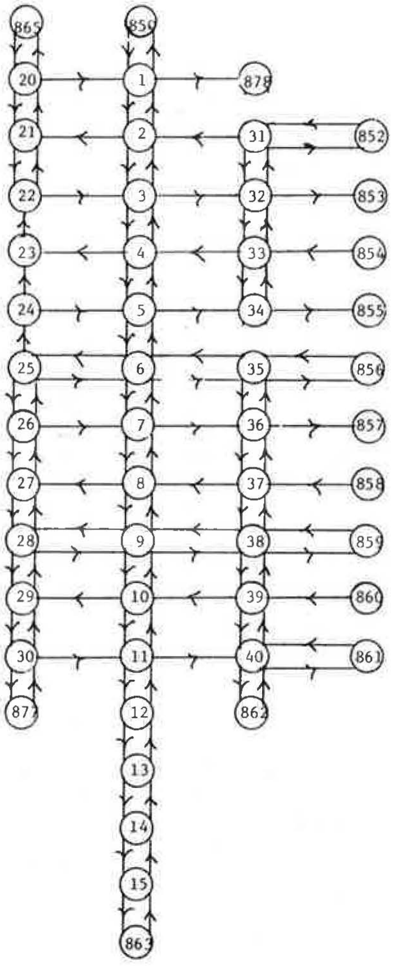
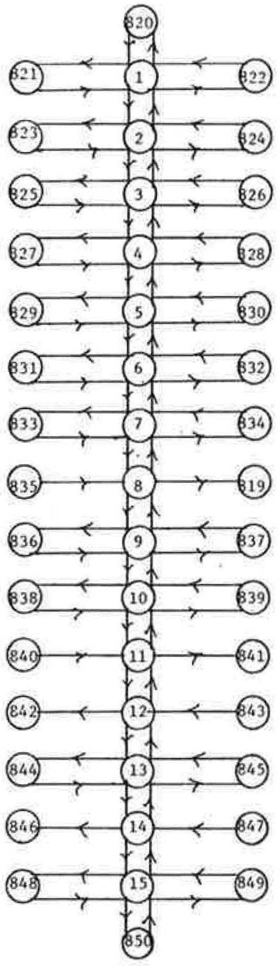


Figure 4. South Halsted Street network.



factors, as discussed elsewhere (5-7).

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# Queuing at Drive-up Windows

W. GORDON DERR, THOMAS E. MULINAZZI, AND BOB L. SMITH

**The development of drive-up windows may cause serious problems, where (a) additional fuel is consumed and pollutants are generated by vehicles, in queue, waiting to be served; (b) serious off-site operational problems may occur due to queued vehicles extending onto adjacent streets; and (c) queued vehicles often interfere with the use of on-site parking spaces. Queuing theory is used in the development of a procedure to identify and quantify the magnitude of the problems associated with drive-up windows. Estimated arrival rates and service rates are used to predict a failure rate, i.e., the percentage of time in which a queue length will exceed a selected length of queue. The average time of vehicles in the system, estimated from arrival and service rates, is used to calculate the amounts of air pollutants generated and the fuel consumed. An example problem is included. A brief description of applicable queuing theory is included. Some geometric design guidelines are suggested for the efficient on-site operation of drive-up windows.**

The fast-food industry is booming. New businesses are springing up everywhere, and older establishments are adding services to stay competitive. One area where this affects the transportation system is in the development of drive-up windows. Many of these businesses seem to feel it is their inalienable right to have a drive-up window. The traffic engineer and planner have had very few tools to combat drive-up-window developments, which may have an adverse impact on area air quality, fuel consumption, smooth flow of vehicles on site and off, and/or use of on-site parking. Although many businesses, new and old, have adequately sized and shaped lots so that the drive-up-window queues can be handled without harm to other area activities, some do not.

The standing of operating vehicles in queue can cause problems, including consuming fuel and producing air pollutants. In addition, the cars in queue may stack up to the point that they block the flow on site. Of greater concern are those times when the queues extend into area streets. An ancillary problem is the loss of use of those on-site parking spaces adjacent to the area of the queue buildup.

The purpose of this paper is to provide tools that will quantify the impacts in terms that will be understandable to decisionmakers and to provide some guidelines for geometric design of facilities. This paper should assist in the development of local guidelines that will help in determining the situations where drive-up windows should or should not be allowed.

## QUEUING THEORY

Queuing theory involves the mathematical study of waiting lines. [General discussions of queuing theory may be found elsewhere (1-3).] Customers show up at some arrival rate ($\lambda$) and then stand in the queue until assisted by a server. Service occurs at some service rate ($\mu$). Both arrival rate ($\lambda$) and service rate ($\mu$) are expressed as the number of activities per hour. The utilization factor ($\rho$) is the ratio of the arrival rate ($\lambda$) to the service rate ($\mu$).

Every queuing situation can be described by using six descriptors. They are

1. Arrival time distribution--a mathematical description of the times between arrivals;
2. Service time distribution--a mathematical description of the times taken to serve customers;
3. Number of servers--in this case, number of service lanes;
4. Service discipline--in what order will the customers be served; the most popular is first come, first served;
5. System storage capacity--how many vehicles can fit in the area where the queue is located; and
6. Size of the customer population--how many vehicles there are in the community.