reflect the official views or policies of the Federal Highway Administration. This paper does not constitute a standard, specification, or regulation.

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# Determining Capacity and Selecting Appropriate Type of Control at One-Lane Two-Way Construction Sites

PANOS G. MICHALOPOULOS AND ROGER PLUM

**The problem of determining the most appropriate type of traffic control at one-lane two-way construction sites (i.e., on two-lane two-way roadways where one lane is temporarily closed for repairs and the other must be shared by both directions of traffic) is addressed. Capacity and performance tables and figures are presented for stop-sign, signal, or flagger control. These were developed by a microscopic simulation program that was adjusted and calibrated from field data. Following safety and visibility constraints, selection of the most appropriate control type can be made from the capacity and performance estimations obtained from the methodology presented here along with some practical considerations. An overview of existing practices followed by most states is also presented.**

Traffic control at construction and maintenance zones has become particularly important in recent years, especially in view of increased government liability for accidents and incidents on public road systems and the reduced tolerance for inefficient operating conditions. Despite the attention recently given to the development of design standards and improved traffic control at construction and maintenance zones, few guidelines are currently available for determining capacity and the most appropriate type of control at two-lane two-way roadways where one lane is temporarily closed and the other must be shared by both directions of traffic. Such is frequently the case for two-lane two-way bridges during deck repairs.

The Minnesota Department of Transportation, recognizing the need for further research in this area, sponsored a research project to (a) determine capacity and select the most appropriate type of control (including optimal timing plans in the case of signal control) and (b) develop guidelines for increasing safety by appropriate signing. In this paper only the first issue is addressed, but it should be noted that all the results of this study are described in a final report (1), which may be consulted for further details not included here due to space limitations.

Selection of the most appropriate type of control (i.e., among stop sign, pretimed or actuated signal, and flagger) requires performance evaluation of each alternative, which in turn is dependent on capacity estimations. An extensive literature search combined with a survey of practices in all states revealed the absence of any well-established methodology for dealing with problems of capacity, performance evaluation, and selection of the most appropriate type of control. For this reason, a more systematic procedure was developed and is described here. It should be kept in mind that although the basic research was geared toward one-lane bridges during the construction or maintenance operations, the results are general and apply to any similar situation in which a single lane is alternately used by both directions of travel.

The problems of capacity determination and performance evaluation with stop-sign control were resolved by generating tables based on simulation, whereas the signal-control case (pretimed or actuated) was treated both analytically and by simulation. Finally, flagger control was assumed to be similar to actuated-signal control, at least from the capacity and performance points of view (i.e., excluding visibility and safety aspects), and therefore it was not treated separately. Naturally this assumption is only an approximation, but in view of the difficulties involved in realistically modeling flagger control, it was felt that such approximation should suffice. It should be pointed out that the simulation programs and their results were tested against actual data collected at 15 sites by time-lapse photography, and model calibrations and adjustments were made. Similar comparisons were also made with the analytical results.

**Table 1. Observed capacities for various expressway lane-closure conditions and work activities.**

| Work Activity | No. of Lanes in One Direction: In Normal Operation | No. of Lanes in One Direction: In Work Area | Observed Capacity (vph) |
|---|---|---|---|
| Median barrier or guard-rail repair | 2 | 1 | 1500 |
| | 3 or 4 | 2 | 3200 |
| | 4 | 3 | 4800 |
| Pavement repair, mud-jacking, pavement grooving | 2 | 1 | 1400 |
| | 3 or 4 | 2 | 3000 |
| | 4 | 3 | 4500 |
| Striping, resurfacing, slide removal | 2 | 1 | 1200 |
| | 3 or 4 | 2 | 2600 |
| | 4 | 3 | 4000 |
| Installation of pavement markers | 2 | 1 | 1100 |
| | 3 or 4 | 2 | 2400 |
| | 4 | 3 | 3600 |
| Middle lanes (for any reason) | 3 or 4 | 2 | 2200 |
| | 4 | 3 | 3400 |

## BACKGROUND

Although considerable progress has been made in recent years in improving traffic operations at construction zones, very little is known about the capacity of the one-lane situation, described earlier; this information is needed for selecting the most appropriate type of control. In this section, only the existing literature on capacity considerations is reviewed. Existing signal-timing practices are omitted due to space limitations; pertinent information on this subject can be found elsewhere (2,3).

The factors that affect roadway capacity can be divided into two categories: roadway and environmental factors and traffic factors. In the first category one may include items such as lane width, lateral clearance, horizontal and vertical alignment, pavement conditions, and weather conditions. Traffic factors in general include the percentage of large vehicles (trucks, buses, etc.), fluctuation of the demand, conflicts, lane distribution, flow interruptions, etc. Although in current literature most of these factors have been taken into account for surface streets and highways during normal operations, only a few were considered at construction sites. Table 1 (2,4) shows observed capacities of expressways with lane closures. The table suggests single-lane capacity ranging from 1100 to 1500 vehicles per hour (vph). The Highway Capacity Manual suggests that maximum capacity per lane at construction zones is 1500 vehicles/h. These figures refer to saturation-flow estimates; i.e., they assume uninterrupted flow. Experience in Europe (3) indicates lower values, which vary slightly among countries. The guidelines developed in Germany appear to be the most conservative and take speed into account. According to these guidelines, the per-lane saturation flow in a construction area is 1200 vph if average speed in the construction zone is greater than 30 mph. The above figure decreases by 5 percent when average speed drops to 25 mph and by 20 percent for speeds less than 20 mph.

The figures given above assume only one-way operation, and although they might seem unrelated to alternate use of the same lane by both directions of travel, they are in fact needed for estimating capacity when signal control is imposed. Before this section is concluded, it is noted that, to the best of our knowledge, no additional information is available in the literature concerning the capacity of the situation in question; i.e., no information was found for determining capacity at one-lane two-way construction sites. The only exception is the case of pretimed signal control, which is partly covered by the guidelines of the Organization for Economic Cooperation and Development (OECD) (3). Even in this case, however, the capacity estimations are rather crude.

## CAPACITY ESTIMATION

Capacity is the most crucial measure for determining the best type of control. This is because in most practical applications the simplest type of control is sought, provided that it can handle the demand without causing serious disruptions to adjacent intersections or resulting in excessive delays to the users. Furthermore, as will be seen in subsequent sections, knowledge of capacity is essential for estimating the performance of each type of control. In addition to the type of control, capacity is affected by geometric factors (including visibility), traffic factors, environmental conditions, speed, and length of the construction zone. The geometric factors (excluding length) can be taken into account by appropriate estimation of saturation flow (by field measurement, earlier experience, or from the literature presented in the previous section). Traffic factors can be considered by converting demands to passenger-car units (PCUs) and by incorporating the appropriate peak-hour factor or probability distributions. Finally, speed and length of the construction zone can be considered by measuring or estimating the traverse (or crossing) time (i.e., the time required to travel the entire construction zone). In the absence of empirical data, the report by Michalopoulos and others (1) may be consulted for estimating the average crossing time analytically.

As mentioned earlier, capacity with signal control can be estimated analytically; however, with stop-sign control, best solutions can only be given by either extensive data collection or simulation. In the absence of extensive data, the second approach was followed in this study. The program prepared for simulating one-lane construction sites and employed for determining capacity and evaluating control performance is described in the following sections.

For the problem of estimating saturation flow, Table 1 can be used as a guideline in the absence of field data. Based on this and the suggestion of the OECD report (3), a value of 1200 vph is recommended as more realistic than that recommended in the previous section, especially at one-lane bridges. This figure is rather conservative and could easily be exceeded under ideal conditions or it could vary according to the type of work activity as Table 1 suggests. It is also stressed that conversion of the demands to PCUs is needed for signal timing and estimating the performance of the various control alternatives. A number of suggestions are available in the literature, but in the absence of personal experience the following factors are suggested (3):

1. Trucks or buses with three axles or more, 2.25 PCU;
2. Two-axle trucks, 2.00 PCU; and
3. Motorcycles, 0.5 PCU.

These values can be increased or decreased by 3 percent for each 1 percent downhill or uphill grade accordingly.

### ONELANE Computer Simulation Program

Analytical techniques for determining capacities and

measures of effectiveness at one-lane construction sites generally fail to account for the randomness of arrivals and the variability of travel times in the construction area. Consequently, computer simulation of traffic by using a random-arrival generator and a probability distribution for travel times was developed for evaluating capacities at such locations.

Previously existing computer programs that simulate traffic controlled either by stop signs or by traffic signals were designed to accommodate standard intersections, where two or more roadways intersect. Initially, employment of existing programs was attempted by proper data manipulation (e.g., by employing long clearance and extension intervals or assuming dummy phases) in order to avoid costly development of new software. However, after some experimentation two of the most widely known simulation programs [NETSIM (5) and TRAFLO (6)] proved not to be adaptable to the case under consideration. This inability to be adapted was primarily caused by the longer clearance intervals required at construction sites and/or the particular characteristics of such areas. For instance, the case of a one-lane site controlled by stop signs, where vehicles are discharged one or two at a time from alternating approaches, did not conform with either of the existing programs. Thus, a new simulation program called ONELANE was developed specifically to accommodate the particular characteristics of one-lane sites.

Following are some of the general input requirements of the ONELANE program:

1. Type of control--stop-sign, pretimed, or actuated signal control--must be specified.
2. Demand on each approach must be converted to PCUs per hour.
3. Saturation flow rate of the common lane during construction is required in passenger cars per hour.
4. Average lost time (during transitions) to reach saturation flow is given in seconds.
5. Mean traverse interval in seconds is derived empirically or by using the methods described earlier.
6. SDs of the actual traverse intervals are calculated. It is assumed in the program that actual traverse intervals are distributed normally about the mean.
7. If stop-sign control is being simulated, a maximum platoon size is chosen. This is the maximum number of vehicles that traverse the construction site at a time as a group. Under ideal conditions only one car should be crossing at a time. However, it was observed that this condition is not always met; i.e., two or more cars could be departing from the same approach as soon as it receives priority. Thus, one must measure or assume the maximum number of cars that are likely to depart at a time. The program allows maximum platoon size to depart if the queue on the approach that has priority is long enough; otherwise, fewer cars are released according to the actual demand when the approach under consideration receives priority and traffic starts moving.
8. If signal control has been selected, the user has the option of specifying the traffic signal settings or allowing the program to determine the optimum settings as described in the next section. For pretimed control, the settings include cycle length and green, amber, and all-red times for both approaches. For actuated signal control, the settings include minimum and maximum green times, amber, and all-red times as well as extension intervals.

ONELANE is a microscopic simulation program; i.e., each vehicle is followed from the time it arrives on an approach until the time it departs the single-lane portion of the construction area. Arrivals are assumed to be random; a minimum headway is determined by the user-specified saturation flow rate and the average arrival headway is determined by the demand on each approach.

During the simulation, vehicles are discharged from an approach only if opposing vehicles have cleared the one-lane portion of the construction site. With stop-sign control, if vehicles are waiting on both approaches, it is assumed that platoons passing through the one-lane section will alternate between approaches. If vehicles are waiting on just one approach, platoons from that approach will discharge consecutively until a vehicle arrives on the opposing approach. With signal control, it is assumed that no vehicles violate the signal by departing the stop line while a red signal indication is displayed.

As each vehicle is discharged from the stop line, the delay and the number of stops encountered by the vehicle are calculated along with the current queue size (in vehicles) on that approach. Actual traverse time for each vehicle is obtained from a normal distribution of clearance intervals with the constraint that a faster vehicle cannot pass a slower one.

As the simulation progresses, the average delays and number of stops on each approach are constantly updated. At the end of the simulation, these values as well as the maximum queue size and the average energy consumed on each approach are printed along with the number of cars serviced and the final queue size. Before we conclude, it should be noted that the ONELANE program was tested against the field data collected and calibrations were made accordingly. The details of testing and calibration have been presented elsewhere (1).

## Estimation of Capacity with Signal Control

Once the saturation flow and the optimal signal settings have been determined, the capacity on each approach can be estimated from

$$Q = s(g/c) \tag{1}$$

where

Q = hourly capacity flow rate [passenger cars per hour (pcph)],
s = one-lane saturation flow rate (PCUs/h),
g = effective green interval of approach being considered (s), and
c = cycle length (s).

The cycle length is the sum of the green, amber, and all-red times on both approaches. Effective green interval g can be determined from

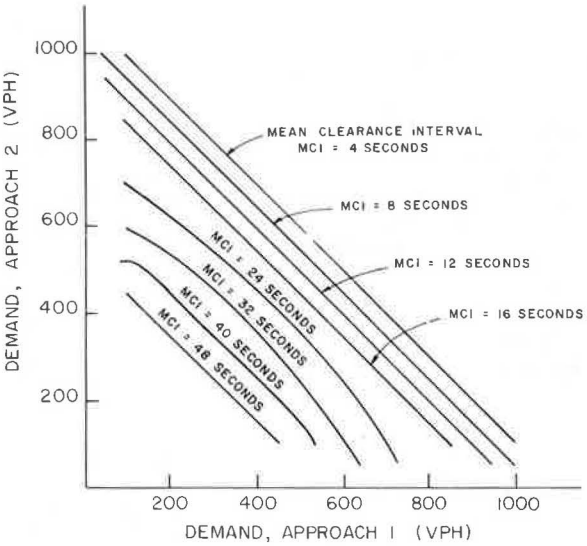
$$g = G + A - LT \tag{2}$$

where

G = actual green time (s),
A = amber time (s), and
LT = lost time (s).

It should be noted that this method for determining capacity is valid for both pretimed and traffic-actuated signal systems. However, in the case of traffic-actuated control, the equations must be modified slightly. Since in actuated signals capacity is achieved when both the cycle length and the green time are maximized, maximum cycle length

Figure 1. Capacity of signal control at one-lane construction sites.




($c_{max}$) and maximum green time ($G_{max}$) should be substituted for c and G in the equations. These maxima can be determined by using the methods outlined in the next section.

Since the above method of calculating capacity is deterministic and does not take the variability of arrivals and travel times into account, the capacity of one-lane construction zones with signal control was also estimated and tabulated by using the ONE-LANE simulation program. This was accomplished by using the following approach: increments of 4 s were employed for clearances (traverse times) from 4 to 48 s. For each clearance interval, a range of volumes from 100 to 1200 pcph, in increments of 100 pcph, was assumed on each approach. Each combination of demands and clearance interval was simulated for 1 h 10 times to dampen the effect of any single extraordinary simulation. The results from the 10 simulations were then averaged to arrive at a reliable estimate of each measure for that combination of clearance interval and demands. Demands were judged to exceed capacity if the actual volume serviced on either approach was less than 95 percent of the demand on that approach, which indicated a final queue size of at least 5 percent of demand. It should be noted that signal timing for each set of volume combinations was determined first (i.e., prior to simulation) by using the methodology of the next section.

Curves were developed from the simulations for each mean clearance interval. These curves were combined in Figure 1, which can be used as a guideline. It should be noted that a saturation flow of 1200 pcph and a total lost time (excluding all-red) per cycle of 7.4 s (3.7 s per approach) were used in all simulations. The latter as well as the variance in travel times were derived from the collected data.

A single set of curves is presented in Figure 1 despite the fact that two types of signal control, pretimed and actuated, were simulated. This is because the capacity results from the two types of control were so similar in most cases as to be nearly indistinguishable. This is not an unexpected result, since at volumes greater than or equal to capacity, actuated signals operate as pretimed, and if properly timed, they should yield the same capacity. Consequently, one set of results effectively serves for both methods of control.

To use the curves in Figure 1, one simply enters from the bottom of the figure with the demand on one approach and from the left side of the figure with the demand on the opposing approach. One then proceeds vertically from the bottom and horizontally from the left to the intersection of the two demands, which indicates the maximum allowable mean clearance interval (MCI) by interpolation between the curves for various MCIs. If the actual (or estimated) MCI at the one-lane site exceeds the value found in the figure, signal capacity is exceeded. An actual MCI less than or equal to that found from Figure 1 indicates that traffic-signal control is capable of accommodating the demands without significant delays or queueing.

A final consideration in evaluating capacity estimates for traffic-signal control is determining how well the analytical methods described at the beginning of this section approximate the simulation results. If we assume a fifty-fifty split (i.e., equal demands on both approaches), a mean clearance interval of 12 s, and lost times equal to those indicated earlier (3.7 s/phase/cycle), effective green time (with the maximum cycle length) would be 71.3 s on each approach. This assumes an amber time of 3 s and an all-red time of 9 s to accommodate the 12-s clearance interval. By using Equation 1, the capacity per approach would be (1200 x 71.3)/168 = 509 pcph. As can be seen in Figure 1, this analytical result compares very favorably with the results of the simulations. Further comparisons between the analytical approach and points from different curves confirmed the consistency between the two capacity-determination methods; i.e., inclusion of random effects did not (on the average) alter significantly the results of Equation 1.

## Estimation of Capacity with Stop-Sign Control

As mentioned earlier, no reliable analytical methods existed for determining the capacity of one-lane construction sites controlled by stop signs. For this reason, the use of the simulation program proved to be essential.

By proceeding as in evaluating the capacity under signal-controlled conditions, a range of demands on each approach was simulated for MCIs in increments of 4 s. In addition, maximum platoon sizes of one to five vehicles were tested. A maximum platoon size of one vehicle means that every vehicle discharged comes to a complete stop at the stop line. A maximum platoon size of two vehicles means that in a queue of two or more vehicles, the first vehicle in line will stop at the stop line and then depart, whereas the second vehicle in the queue will follow the first without coming to a complete stop at the stop line. Then it is assumed that the next vehicle in line (if any) will stop. A maximum platoon size of three vehicles implies that up to two vehicles will follow the first in the platoon without coming to a full stop at the stop line, etc.

The simulation of each combination of MCI, maximum platoon size, and demands was repeated 10 times to avoid random noise possibly resulting from a single simulation. Any case in which the average actual volume for the 10 simulation runs was less than 95 percent of the demand on either approach was judged to be operating under oversaturated conditions; i.e., the combination of demands exceeded the capacity of the site.

As was done for traffic-signal control in the previous section, a series of curves was constructed that represent the demand limits that can be accommodated by using stop-sign control (1). Depicted in Figure 2 is the set of capacity curves found for a maximum platoon size of two vehicles and a saturation flow of 1200 vph. Capacity from this figure is simply found as before (Figure 1) or by entering

Figure 2. Capacity of stop-sign control at one-lane construction sites: maximum platoon size of two vehicles, s = 1200 vph.

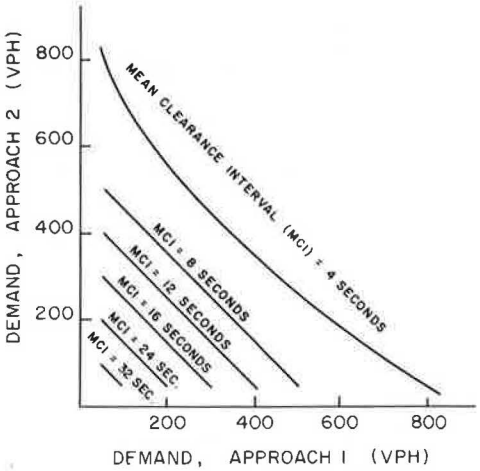
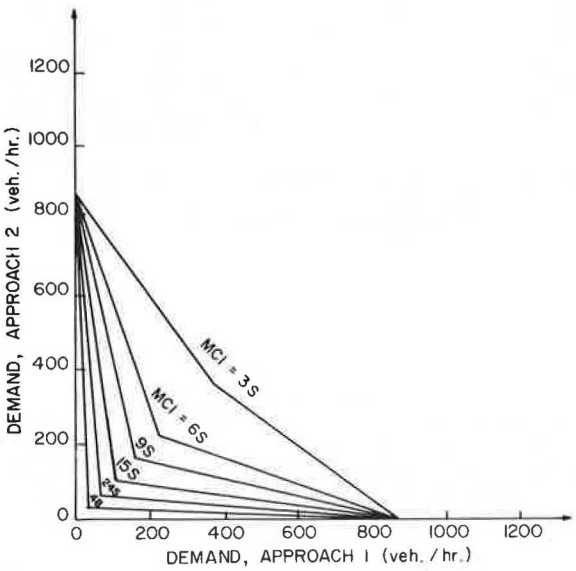
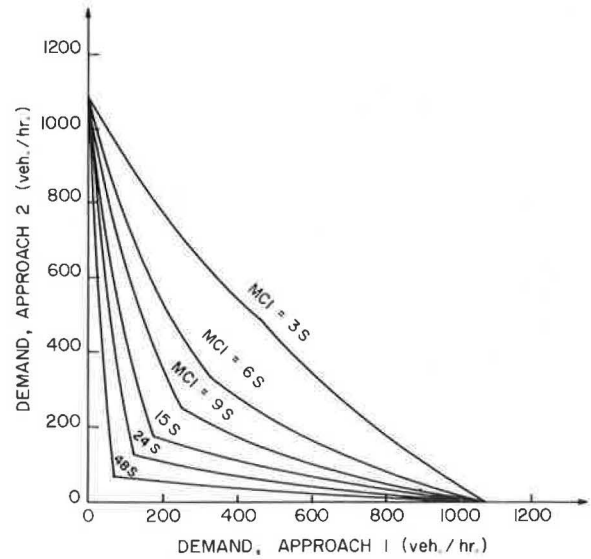



Figure 3. Capacity of stop-sign control at one-lane construction sites: maximum platoon size of one vehicle, s = 1600 vph.




demand on one approach, proceeding to the appropriate MCI, and finding capacity on the other axis. From the field data it was found that the maximum platoon size of 2 was most common. It is therefore recommended that Figure 2 be used in the majority of cases when employment of stop-sign control is being considered. Similar figures were derived for maximum platoon sizes of one to five vehicles; Figures 3 and 4 present the cases of maximum platoon sizes of 1 and 2, respectively, derived by assuming saturation flow of 1600 vph. Space limitations do not allow inclusion of all figures and tables presented in an earlier report (1). It should be noted, however, that in real life, queued vehicles often do not come to a complete stop at stop signs. The effect of these rolling stops would be to increase the effective capacity of a site to a point above that for the case in which all vehicles come to a full stop. Therefore, capacities found from the simulations that used a maximum platoon size of one vehicle were felt to be low. Further, in many cases the vehicle immediately behind the first one in the

Figure 4. Capacity of stop-sign control at one-lane construction sites: maximum platoon size of two vehicles, s = 1600 vph.




queue will follow that front vehicle past the stop sign without actually stopping or slowing down for the sign. This is especially true when the front of the leading vehicle has come to a stop at some point past the stop sign before proceeding, which leaves less than a full car length between the stop sign and the second vehicle in line. However, rarely will two vehicles in a row follow the leading vehicle without at least one slowing for the stop sign. Consequently, capacities found from the simulations that used a maximum platoon size of three or more vehicles may be a little high.

When the capacities under stop-sign control (Figure 2) are compared with those under signal control (Figure 1), it is apparent that the capacity with stop signs is significantly lower than the capacity with traffic signals, given the same traverse MCI. This result was anticipated, since signals allow for large platoons of vehicles to traverse a construction site as a group, whereas stop signs restrict the platooning effect.

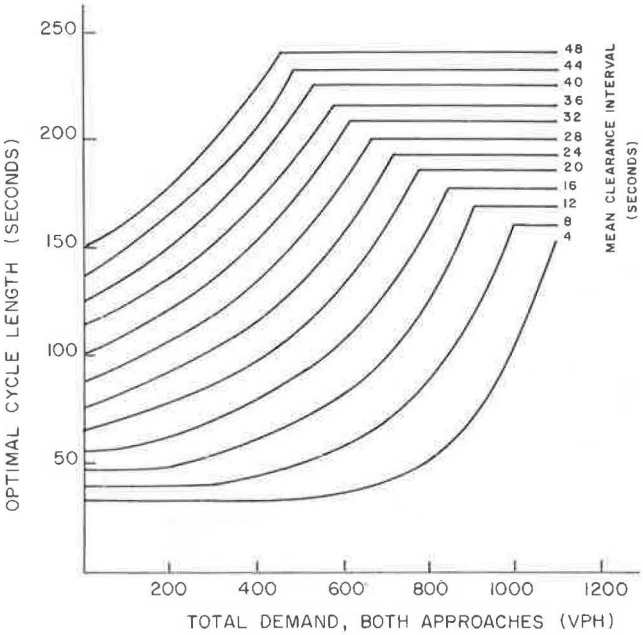
For those combinations of demands and mean traverse intervals where both stop-sign control and signal control are feasible alternatives, selection of one type of control over the other may be based on several different factors. Some guidelines in making such a decision have been included in a later section, although it must be recognized that the criteria for selecting the optimal alternative may depend not only on performance, but also on cost, accident experience, and personal judgment.

Before this section is concluded, it should be pointed out that actual demands at the test sites were insufficient to allow varification of the entire range of capacity tables developed. However, the data collected were useful in adjusting and calibrating the ONELANE program based on the actually observed measures of effectiveness (i.e., delays, stops), traverse time variability, minimum departure headways, capacity at a few locations, etc.

## SIGNAL TIMING

In the previous section, optimal signal settings were required to determine the capacity of a one-lane construction site when traffic-signal control is being evaluated. In addition, after it has been determined that traffic signals are the most appro-

Figure 5. Optimal cycle lengths.




priate type of control, optimum settings are needed for minimizing delays.

In the following two subsections, a procedure for determining the optimal signal settings for both pretimed and actuated signals is presented. The settings derived from these procedures are based on assumptions that are commonly accepted but may not apply in any particular situation. Therefore, when traffic-signal control is implemented, it is advisable to field check the operation of the system and make appropriate adjustments.

## Timing of Pretimed Signals

In order to calculate the optimal cycle length and green times for each approach, the following information is required:

1. Demand on each approach,
2. Estimation of saturation flow rate, and
3. MCI.

In order to accommodate the worst case, the demand used for each approach should be the highest hourly volume during the day. If, for example, different settings are required for the morning, the afternoon, and the off-peak periods, it is possible that three different demands will be used for each approach in calculating all the appropriate settings. In the case of single settings of the signal, the peak-hour volume should be used on each approach, regardless of its time of occurrence. This is common practice in signal timing and ensures that the peak demands will be accommodated in both directions; such treatment, however, will also tend to increase overall delays during off-peak demands. In the following discussion, the acceptable range of signal settings is given as well as an optimal value that minimizes average delay. More specifically, the minimum cycle length (in seconds) is (3)

$$c_{min} = 2\bar{t}/[1 - (q_1 + q_2)/s] \quad (3)$$

where

$\bar{t}$ = MCI (s);
$q_1, q_2$ = demands on approach 1 and approach 2, respectively (pcph); and
$s$ = saturation flow of common lane (pcph).

For safety, the minimum cycle length ($c_{min}$) must be at least 30 s.

If a maximum green interval of 72 s [i.e., a value slightly higher than that used in England (7)] is assumed, the maximum cycle length should be

$$c_{max} = 144 + 2\bar{t} \quad (4)$$

Finally, the optimum cycle length that minimizes average delay is (3)

$$c_{opt} = (3\bar{t} + 5)/[1 - (q_1 + q_2)/s] \quad (5)$$

This is the value that should be used in most cases, subject to the restrictions that the actual cycle length must be greater than or equal to $c_{min}$ and less than or equal to $c_{max}$.

To simplify selection of the proper cycle, calculations for a wide range of demands and clearance intervals were made and are presented in Figure 5. A saturation flow rate of 1200 pcph was employed in developing this figure. To use Figure 5, enter the horizontal axis with the sum of demands on both approaches converted to PCUs. Proceed vertically until the proper MCI is intersected. From that point, proceed horizontally to the left and read the cycle length from the vertical axis.

Once the actual cycle length has been determined, the green times for both approaches are such that the degree of saturation on each approach is the same; i.e.,

$$G_1 = (c - 2\bar{t})/[1 + (q_2/q_1)] \quad (6)$$

$$G_2 = c - 2\bar{t} - G_1 \quad (7)$$

In addition to green times, an amber clearance interval between 3 and 5 s in duration should be included. Values less than 3 s are not recommended, since vehicles usually require at least 3 s to stop. Values greater than 5 s are not advisable, since longer amber clearance intervals tend to increase the number of violations.

Finally, if the mean traverse time is greater than the amber clearance interval, an all-red interval equal to the difference should be included after the amber interval on each approach. This additional time will help to ensure that vehicles already traveling the one-lane portion in one direction will be cleared before vehicles on the opposing approach receive a green signal indication.

## Timing of Actuated Signals

The use of traffic-actuated signals at one-lane construction sites offers the same basic advantage as at intersections. When demands on the approaching roadways are varying considerably with time, traffic-actuated control will usually decrease the delay and inefficiency.

The guidelines for the yellow and all-red times given in the last section are still valid for actuated control. These guidelines may also be compared with those given by the Department of Transportation in England (7).

The minimum green time should be set to 12.0 s, i.e., the same as in pretimed signals. Any phase duration less than this limit is considered unsafe (7). A vehicle extension interval (following the

minimum green) of 7.0 s per actuation is recommended. The objective here is to allow a vehicle to clear the detector (it takes about 3.0 + 1 s for this at s = 1200 PCU/h) and to allow a reasonable time for another arrival. This is also justified by the long traverse times, which make it unwise to end a phase prematurely (this would result in decreased capacity and increased delay). It is of course assumed that only one detector per approach is employed and that it is placed at the stop line. If more than one detector is employed, the extension interval should equal the travel time from the first upstream detector to the stop line. The maximum green time should be in the range of 12-72 s (7) so that the maximum cycle should not exceed (144 + $2\bar{t}$) s (Equation 4). Calculation of the optimal maximum green interval ($G_{max}$) can easily follow from the design volumes, which can be obtained from the guidelines of the previous section. With the design volumes known, Equations 3-7 can be used for calculating optimum cycle and green times as if the signal were pretimed. The values so obtained can be used as optimal maximum green times provided that they fall within the bounds specified earlier (12-72 s); otherwise, the boundary values should be employed. It should of course be noted that the maximum extension interval is $G_{max}$ - 12 s. In the absence of volume information and/or for comparing the maximum green times calculated from the above guidelines, specific recommendations for initial values of the signal settings as well as for field adjustments have been given elsewhere (7).

## ESTIMATION OF MEASURES OF EFFECTIVENESS

Although in most rural and low-volume situations selection of the simplest type of control subject to capacity considerations may suffice, this is not necessarily the case at urban or high-volume sites. Thus, as the complexity of the construction site increases, control performance becomes important and further analysis is needed. This analysis involves estimation of measures of effectivensss such as delay, queue size, number of stops, and energy consumption. The objective is, of course, selection of a traffic-control strategy that both meets the demands adequately and optimizes the measure(s) of effectiveness judged to be most important in a particular instance.

In the remainder of this section, procedures for estimating the most common measures of effectiveness for different types of control are presented. It should be noted, however, that due to the lack of sufficient information, safety considerations are not included.

### Analytical Methods

For pretimed and actuated signal control, analytical methods exist for estimating the measures of effectiveness mentioned above. These methods were originally developed for use at isolated signals and are also applicable to one-lane construction sites (3). It should be kept in mind, however, that these analytical techniques are only approximations. This is due to the simplifications made in the process of obtaining closed-form solutions of a rather complex process.

Estimation of delay, stops, and maximum queue size with pretimed signal control can be made by employing Webster's methodology (8) as suggested in the OECD report (3). Since this methodology is widely known, it is not presented here; suffice it to mention that further details of this method along with numerical examples may be found in an earlier report (1), which also gives guidelines for saturated conditions [not treated by Webster (8)].

A similar procedure for estimating delays, stops, and maximum queue size (analytically) was developed by Courage and Papapanou (9) for actuated signals, and it was adopted in this study. According to this procedure, average delay at a particular approach of a traffic-actuated signal can be estimated from

$$\bar{d} = 0.9 \left\{ [\bar{c}\,(1-\lambda)^2/2(1-\lambda x)] + [3600\, x_1^2/2q(1-x_1)] \right\} \quad (8)$$

where

- $\bar{d}$ = average delay per vehicle (s);
- $\bar{c}$ = average cycle length under actuated operation, which is cycle length as if signal were pretimed; average cycle can be calculated from Equation 5 subject to maximum and minimum values suggested in that section;
- $\lambda$ = $\bar{G}/\bar{c}$;
- $\bar{G}$ = average green time provided to approach being analyzed calculated from average cycle and Equations 6 and 7;
- q = arrival flow rate at approach under consideration;
- x = degree of saturation = $q/\lambda s$;
- $x_1$ = $(q \approx c_{max})/(G_{max} \approx s)$;
- $c_{max}$ = maximum cycle length at which controller is set determined from guidelines of section on signal timing;
- $G_{max}$ = maximum green time provided by controller to approach being analyzed determined from guidelines given in section on signal timing; and
- s = saturation flow (PCU/h).

As in the case of pretimed signals, Equation 8 is valid for undersaturated conditions, i.e., as long as $x_1 \leq 0.95$. If the average cycle resulting from the computations tends to exceed or equals the maximum cycle, then the signal operates in a pretimed mode. In such a case, the procedures of pretimed control apply.

The maximum queue size under actuated control is (9)

$$N = q(c_{max} - G_{max})/3600 \quad (9)$$

where N represents the maximum queue size in cars that should be expected at the approach being analyzed and the remaining parameters are as defined in Equation 8. Finally, the average number of stops per car, or equivalently the percentage of vehicles stopping, is

$$P = [1 - (\bar{G}/\bar{c})]/[1 - (q/s)] \quad (10)$$

Once delays and stops have been determined, excess energy consumption can easily be estimated by assuming average consumption factors for idling and stops (1,9). In conclusion, it is noted that no reliable analytical estimations of the measures of effectiveness with stop-sign control are available at this time.

### Simulation

In the previous subsection, analytical methods for estimating the measures of effectiveness were presented. Because these analytical methods will yield only approximations, caution must be exercised in applying the results derived from these techniques. Naturally, more accurate results can be obtained by employing the ONELANE simulation program, which is specifically designed for this purpose. In order to

**Table 2. Measures of effectiveness for stop-sign control.**

| Avg Clearance Interval (s) | Demand (pcph) | | Avg No. of Stops per Vehicle | | Avg Delay per Vehicle (s) | | Maximum Queue Size[a] (vehicles) | | Energy Consumed (gal/1000 vehicles) | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Approach 1 | Approach 2 | Approach 1 | Approach 2 | Approach 1 | Approach 2 | Approach 1 | Approach 2 | Approach 1 | Approach 2 |
| 4 | 100 | 100 | 1.0 | 1.0 | 2.3 | 2.2 | 1 | 1 | 10.4 | 10.4 |
| | 200 | 100 | 1.0 | 1.0 | 2.4 | 2.7 | 2 | 2 | 10.4 | 10.4 |
| | 200 | 200 | 1.0 | 1.0 | 2.9 | 2.9 | 2 | 2 | 10.5 | 10.5 |
| | 300 | 100 | 1.0 | 1.0 | 2.5 | 3.5 | 2 | 2 | 10.4 | 10.4 |
| | 300 | 200 | 1.0 | 1.0 | 3.4 | 3.7 | 2 | 2 | 10.6 | 10.6 |
| | 300 | 300 | 1.0 | 1.0 | 4.9 | 5.2 | 3 | 3 | 11.0 | 11.0 |
| | 400 | 100 | 1.0 | 1.0 | 2.7 | 4.0 | 2 | 2 | 10.5 | 10.4 |
| | 400 | 200 | 1.0 | 1.0 | 4.3 | 4.9 | 3 | 2 | 10.8 | 10.7 |
| | 400 | 300 | 1.4 | 1.0 | 14.5 | 8.3 | 7 | 4 | 16.1 | 12.9 |
| | 400[b] | 400 | 7.6 | 8.0 | 141 | 148 | 32 | 33 | 99.6 | 104 |
| | 500 | 100 | 1.0 | 1.0 | 3.4 | 4.7 | 4 | 2 | 10.7 | 10.6 |
| | 500 | 200 | 1.4 | 1.0 | 11.2 | 6.4 | 7 | 3 | 15.5 | 11.9 |
| | 500[b] | 300 | 15.5 | 1.1 | 252 | 9.6 | 72 | 4 | 197 | 52.6 |
| | 600 | 100 | 1.1 | 1.0 | 5.3 | 5.7 | 5 | 2 | 11.7 | 10.9 |
| | 600[b] | 200 | 13.2 | 1.0 | 170 | 7.5 | 58 | 3 | 161 | 38.3 |
| | 700 | 100 | 5.8 | 1.0 | 58.2 | 6.8 | 24 | 2 | 67.6 | 19.7 |
| | 800[b] | 100 | 25.5 | 1.0 | 267 | 7.2 | 122 | 2 | 300 | 54.5 |
| 8 | 100 | 100 | 1.0 | 1.0 | 3.5 | 3.3 | 2 | 2 | 10.6 | 10.6 |
| | 200 | 100 | 1.0 | 1.0 | 4.1 | 5.1 | 3 | 2 | 10.7 | 10.7 |
| | 200 | 200 | 1.0 | 1.0 | 7.4 | 7.3 | 3 | 3 | 11.4 | 11.4 |
| | 300 | 100 | 1.0 | 1.0 | 5.4 | 6.9 | 4 | 2 | 11.2 | 10.9 |
| | 300 | 200 | 1.9 | 1.1 | 33.9 | 14.2 | 9 | 4 | 24.7 | 16.4 |
| | 300[b] | 300 | 9.9 | 9.9 | 265 | 264 | 44 | 44 | 143 | 143 |
| | 400 | 100 | 1.2 | 1.0 | 8.8 | 9.1 | 6 | 2 | 13.0 | 11.5 |
| | 400[b] | 200 | 17.9 | 1.1 | 403 | 15.1 | 88 | 4 | 246 | 77.0 |
| | 500[b] | 100 | 23.8 | 1.2 | 188 | 12.5 | 54 | 3 | 270 | 42.9 |
| 12 | 100 | 100 | 1.0 | 1.0 | 5.1 | 5.3 | 2 | 2 | 10.8 | 10.9 |
| | 200 | 100 | 1.0 | 1.0 | 8.8 | 10.0 | 4 | 3 | 11.9 | 11.5 |
| | 200 | 200 | 2.4 | 2.5 | 69.7 | 75.0 | 9 | 10 | 35.6 | 37.0 |
| | 300 | 100 | 1.5 | 1.0 | 20.4 | 13.6 | 9 | 3 | 18.2 | 13.5 |
| | 300[b] | 200 | 16.7 | 2.8 | 592 | 84.7 | 101 | 10 | 266 | 126 |
| | 400[b] | 100 | 7.1 | 1.0 | 128 | 16.4 | 33 | 3 | 92.3 | 31.5 |
| 16 | 100 | 100 | 1.0 | 1.0 | 9.3 | 8.6 | 3 | 3 | 11.6 | 11.6 |
| | 200 | 100 | 1.3 | 1.0 | 25.2 | 18.9 | 7 | 3 | 17.5 | 14.6 |
| | 200[b] | 200 | 8.6 | 8.3 | 368 | 357 | 42 | 42 | 147 | 145 |
| | 300[b] | 100 | 8.1 | 1.1 | 208 | 23.0 | 37 | 4 | 116 | 45.2 |
| 20 | 100 | 100 | 1.0 | 1.0 | 16.7 | 15.0 | 3 | 3 | 13.2 | 13.1 |
| | 200 | 100 | 4.1 | 1.1 | 136 | 30.5 | 19 | 4 | 64.1 | 33.7 |
| | 200[b] | 200 | 11.7 | 11.8 | 608 | 612 | 67 | 68 | 218 | 219 |
| | 300[b] | 100 | 17.2 | 1.1 | 617 | 31.0 | 103 | 4 | 275 | 114 |
| 24 | 100 | 100 | 1.1 | 1.1 | 32.0 | 29.7 | 4 | 4 | 16.7 | 16.6 |
| | 200[b] | 100 | 10.7 | 1.2 | 522 | 44.4 | 60 | 5 | 194 | 99.2 |
| 28 | 100 | 100 | 1.5 | 1.5 | 66.1 | 68.1 | 5 | 6 | 25.7 | 26.1 |
| | 200[b] | 100 | 12.6 | 1.7 | 835 | 84.4 | 96 | 6 | 266 | 156 |
| 32 | 100[b] | 100 | 3.4 | 3.3 | 235 | 224 | 13 | 12 | 73.3 | 72.0 |

[a]Maximum platoon size is two vehicles. [b]Indicates that demands exceed capacity.

assist the designer, tables and figures for estimating the measures of effectiveness similar to those presented in the earlier sections were also developed by simulation with the same volume and traverse MCI combinations. Signal settings, lost times, saturation flow, and other parameters were the same as in Figures 1 and 2. For stop-sign control different tables were generated for each maximum platoon size. Table 2 can be used for estimating the measures of effectiveness when maximum platoon size is 2. The tables for the remaining maximum platoon sizes and control alternatives are not presented here due to space limitations.

After completion of the tables that estimate the measures of effectiveness, a comparison was made between the analytical and the simulation results for the case of signal control. The following conclusions were drawn from this comparison:

1. In practically every case, the analytical methods tended to overestimate average delay per vehicle. This overestimation ranged from less than 10 percent at demand combinations close to capacity to more than 40 percent at relatively low total demands. In general, the percentage of overestimation was higher for the minor approach than for the major approach.

2. The analytical estimates of the average number of stops per vehicle also were generally higher than the simulation results, although the magnitude of overestimation was significantly less than that for delays. In fact, the analytical methods actually matched the simulation results in several cases. As was found for delays, the tendency to overestimate was more pronounced on the minor approach.

3. Estimates of maximum queue size by using the analytical methods were generally lower than those found by using simulation. Regardless of the magnitude of the maximum queue size, the differences between the two methods were consistently between two and four vehicles. One possible explanation for the discrepancy is that the analytical methods do not adequately account for the variability of demand within the control period. The aforementioned difference was only for undersaturated conditions.

4. Because the analytical methods tended to overestimate both the average delay and the average number of stops per vehicle, analytical energy consumption estimates were higher.

Perhaps of greater interest to the reader is the comparison of the measures of effectiveness between stop-sign control and traffic-signal control. This comparison is addressed next along with other con-

siderations for determining the desirable control alternative.

## GUIDELINES FOR DETERMINING MOST APPROPRIATE CONTROL

### Practical Considerations

Although only the few most widely employed control alternatives were analyzed in detail in this study, it should be realized that other options are also available. In what follows, a brief discussion on the practical considerations of each alternative is presented followed by a more rational approach based on operational efficiency.

The self-regulating type of control is generally nothing more than warning signs that allow motorists to determine priority for themselves. This control is generally used only in very short zones and under very low demands. Where there is a potential for conflict, the system breaks down quite easily, especially in terms of legal assignment of right-of-way. Although self-regulating control is used successfully in some states, it was not included among the controls considered during this study.

Yield signs on one or both approaches have also been used in other states. They too offer some advantages under very low volumes and in short construction areas. Where a yield sign is posted on one approach only, the assignment of right-of-way is positive and understandable. When yield signs are posted on both sides, assignment of right-of-way may not be fully understood by motorists. Because the capacity of the yield type of traffic control is limited, it also was not considered.

The posting of stop signs on both approaches to the construction area has been used in Minnesota and several other states. The installation of such signs is inexpensive and requires very little special equipment and time. In theory, the stop control control should provide for a safe environment since all motorists will be stopping in advance of the construction site and therefore reducing their speeds through the construction area. The full stop should also allow motorists to observe and react to any construction equipment or workers that may be present on the site.

In reality, there are many violations of the stop sign, although most are rolling stops where motorists are reacting to the stop-sign control and to the conditions present for traffic and construction. Many of the observed violations were motorists who sought to catch up to a previous vehicle traveling in the same direction rather than stop and wait for traffic from the opposite approach to pass across the bridge. There were very few flagrant violations of the stop sign. The stop-sign control appears to be understood quite well by motorists. Observations at the several sites did not indicate that motorists were confused by the unusual placement of a stop sign compared with that which they normally encounter at intersections. Motorists also tended to react quite well to the need to allow for clearance intervals and to wait for traffic from the other side to clear the site.

Traffic signals are often installed at one-lane sites, primarily because of their positive control of traffic. Both fixed-time and full actuated signals will provide a very visible and positive control over approaching motorists. Full actuated signals can be very efficient in view of the varying demands. Fixed-time signals, although they have very positive control over motorists, are relatively inefficient since they cannot react to any variations in demand. Because of this and the long clearance periods required for bridges, delays can be rather substantial.

In signal control, however, it is necessary to design, install, and remove the traffic signal, at a considerably higher cost than that of stop signs. Signals also require a source of power, which may be a problem in some outlying areas. There is also a continual maintenance responsibility and a potential for equipment malfunctions that could totally upset the positive control of traffic. Fixed-time signals are relatively maintenance free when properly installed. Actuated signals do require some periodic checks to make certain that detectors are working properly and that intervals are properly set. An additional problem with traffic-signal control is that the green light is an invitation for motorists to proceed into the construction zone at a speed that might be greater than desirable. There is also a concern that drivers may speed up to make the green light or to run a yellow light. Perhaps it is worthwile to note that observations indicated that red-light violations were quite infrequent.

Flaggers are probably the most efficient type of traffic control that can be used. They will provide a very positive control over motorists and can react to changing conditions immediately. A flagger can also react to necessary stoppages of traffic for work operations or for equipment maneuvering. Flaggers can react to varying clearance intervals required for traffic and can practically ensure the highest efficiency over any type of traffic control through the construction area. Flaggers, however, are expensive in that their cost is directly related to both size and duration of the project. Further, it is necessary to provide not only flaggers at either end of the site but also periodic relief during their working period. When flaggers are used at night, lighting should be provided that again increases overall cost and requires a source of electrical power.

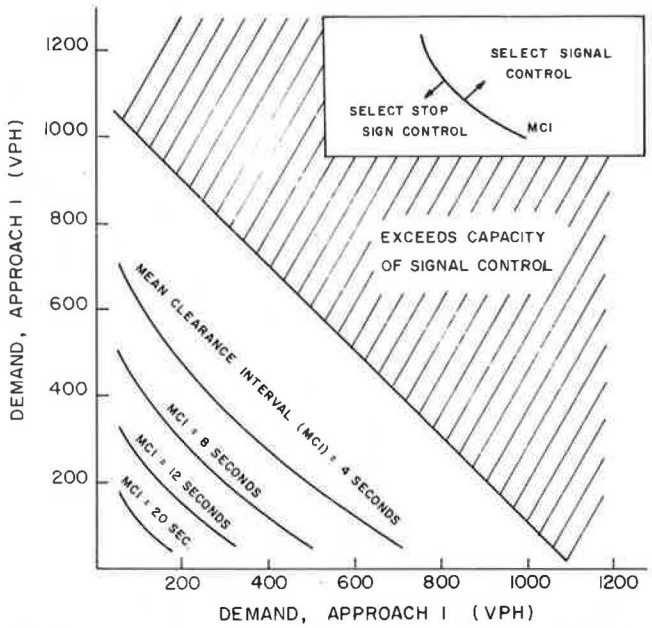
It is also possible to use a combination of controls. A fixed-time traffic signal can be equipped with a remote-control device to override the controller and provide manual control. This would allow manual regulation of traffic during peak hours and higher efficiency. With this option, it is necessary to ensure that the clearance intervals not be modified or that the individual operating the system has a very clear understanding of the operation of the signal and the legality of the clearance intervals.

A similar combination to provide increased efficiency can be made by using stop-sign control supplemented by flaggers during peak hours. This eliminates the need for night-time lighting but provides for a highly efficient method of moving peak-hour volumes. The many advantages of flaggers can be made use of during the day in both peak-traffic and construction periods. The relatively inexpensive stop-sign control can be used at other periods, assuming that the capacity is available. It is also possible to use flaggers during the working day and during the heavier traffic hours but to revert to yield control or self-regulating control during other hours.

### Further Considerations

Perhaps the most important factor in determining traffic control at a one-lane construction site is sight distance. Unless vehicles can see each other at opposite ends of the one-lane section of roadway, stop-sign and possibly signal control should be excluded. The guidelines of the section on capacity estimation could be considered in determining maximum sight distances for stop-sign and signal control. After sight-distance and safety constraints, determination of the most desirable control scheme

Figure 6. Optimal control of one-lane construction site based on minimum total delay.




could be made on capacity considerations alone, which may result in elimination of one or more alternatives; capacity can be determined from the methodology presented in this paper. If sight-distance and capacity requirements are met by more than one type of control, the next determining factor should be a comparison of the costs and benefits of each type of control. Aside from the direct costs of installing and maintaining stop signs or signals or of paying flaggers, the user costs in terms of energy consumption and delay may also be considered.

A comparative analysis between stop-sign and signal control was performed for each of the measures of effectiveness. Based strictly on total delay during the design hour (the hour for which the signal settings were determined), Figure 6 was derived. To use this figure, find the point of intersection of the demands of the two approaches. If this point of intersection lies to the left and below the appropriate MCI curve, stop-sign control will yield lower delays than will signal control. On the other hand, if the point lies to the right and above the MCI curve, signal control will yield lower delays than stop-sign control. From this figure, it can be seen that for MCIs greater than about 20 s and demands greater than 200 vph, the total delay when stop-sign control is used will always be higher than that for signal control.

When the average number of stops and the average energy consumed for the two types of control were compared, it was found that in all cases signal control yielded a lower number of stops and a lower energy consumption than stop-sign control. This result is at least partly attributable to the platooning effect of signals, in which queued vehicles rarely are required to stop more than once, whereas queued vehicles controlled by stop signs often stop several times before being discharged.

## CONCLUSIONS

Safety along with demand-capacity considerations constitute the basic criteria for selecting the most appropriate type of control at one-lane construction sites. The guidelines presented here allow estimation of capacity for each control scheme so that exclusion of one or more options that fail to accommodate demand is now possible. Among the control strategies that pass the basic capacity and visibility tests, further screening can be accomplished from safety considerations. Lack of sufficient experimental data did not allow recommendation of safety guidelines sufficient for detailed design. Thus, in addition to visibility one could adopt the OECD recommendations (3) concerning the maximum lengths of the construction zone for stop-sign and signal control (60 and 250 m, respectively). Although no specific data are available for accident predictions, it should be expected that accidents decrease as the sophistication of the control strategy increases.

After the basic capacity and safety tests, further screening can be accomplished from the practical considerations of the previous section, cost-effectiveness analysis, and performance evaluation following the procedures described earlier. It should be kept in mind that for situations out of the realm of the tables and charts presented here, employment of the simulation program developed is highly advisable. This program can also be used for further accuracy or experimentation and it was originally run on a Cyber 730 computer at an average cost of less than $5/h of simulation (the low cost is due primarily to the event scan structure of the program). Recently the program was rewritten in BASIC, and it can run on an Apple II microcomputer (at a considerably higher execution time but at practically zero cost). Employment of the program is particularly recommended for simulating saturated conditions, which are not covered here.

As mentioned earlier, prediction of accident and safety performance in general was not studied in sufficient detail due to the lack of sufficient data. This subject along with further testing of the program results for the entire volume-capacity range were left for future research. Further, it should be noted that calibration of the program was based on the data collected at rural situations. Adjustments of certain program parameters may be needed for urban conditions.

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*Abridgment*

# Single-Lane Capacity of Urban Freeway During Reconstruction

ROBERT E. DUDASH AND A. G. R. BULLEN

**Lane capacities of an urban freeway under various traffic-flow configurations during reconstruction are determined. The urban freeway studied was the Penn-Lincoln Parkway, Interstate 376, located in Pittsburgh, Pennsylvania. The study locations on the freeway were in the vicinity of the entrance and exit portals of the Squirrel Hill Tunnel. Traffic flows were studied in the right lane of a two-lane section of the highway for three distinct operating conditions. The first condition consisted of both lanes traveling in the same direction. For the second condition, the left lane was closed because of construction, which left only a single lane open to traffic. In the third condition, the left lane had a single lane of traffic traveling in the opposite direction. The results of this study determined the flow, average speed, and density at capacity for each of the operating conditions. A comparison of the data indicated that the single-lane capacity of both sides of the tunnel was significantly lower during the second and third operating conditions; during the third condition, the lowest level of capacity was attained. Generally, for a two-lane, two-way facility under forced flow, the sustained capacity for a single lane was about 1200 vehicles/h. With both directions under forced flow, a two-way flow of 2400 vehicles/h could be sustained.**

Various procedures have been published through the years to evaluate the capacity of a roadway. These include, in the United States, the 1950 Highway Capacity Manual (1), the 1965 Highway Capacity Manual [Highway Research Board Special Report 87 (2)], and, most recently, Interim Materials on Highway Capacity [Transportation Research Circular 212 (3)].

These evaluations of capacity, however, do not consider the effect on traffic flow of construction work zones adjacent to a roadway. Within the past several years, the trend of constructing new highways has decreased, and the trend of reconstructing inadequate highways has increased. Unfortunately, the development of the evaluation of traffic flow through construction work zones has not developed at the same rate. The main examination of the subject has been by Dudek (4), who reports on capacity studies at urban freeway maintenance and construction work zones in Houston and Dallas, Texas, for five-, four-, and three-lane freeway sections.

## CONSTRUCTION WORK-ZONE EVALUATION

A study was conducted to compare lane capacities of an urban freeway while it was under various traffic-flow configurations during reconstruction. The urban freeway studied was the Penn-Lincoln Parkway, Interstate 376, located in Pittsburgh, Pennsylvania. The locations chosen for comparison were in the vicinity of the entrance portal (site A) and exit portal (site B) of the Squirrel Hill Tunnel.

The parkway is a four- to six-lane divided urban freeway traversing east and west. It has an average daily traffic volume of 92 000 vehicles. The Pennsylvania Department of Transportation embarked on a 2-year safety improvement project to update the facility for a length of 6 miles; this consisted of the placement of a new 8-in concrete overlay road surface, new shoulders and concrete median barrier for the entire length of the project, and the rehabilitation of both tubes of the Squirrel Hill Tunnel.

The construction phasing consisted of reconstructing the westbound lanes during the 1981 construction season and the eastbound lanes during the 1982 construction season. The construction required that the westbound and the eastbound lanes be completely closed during various stages of their reconstruction. Since no convenient alternative route was available to detour parkway traffic, it was necessary to maintain two-way opposing traffic on the lanes opposite those being reconstructed.

Traffic flows were studied for the two locations in the right lane of a two-lane section of the highway for three distinct operating conditions. The first condition was for both lanes traveling in the same direction (two lanes, one way). For the second condition, the left lane was closed to traffic because of construction, which left only a single lane of traffic (one lane, one way). In the third condition, the left lane had a single lane of traffic traveling in the opposite direction (two lanes, opposing). Figures 1, 2, and 3 depict the three traffic conditions.

The horizontal alignment at the sites consisted of horizontal curves that were designed for vehicle speeds of more than 65 mph. The vertical alignment, traveling west to east, consisted of 0.5 mile of +4.5 percent grade approaching site A and 1 mile of -2.5 percent grade approaching site B.

The roadway section for sites A and B varied for each condition. During the two-lane one-way condition, two lanes, each 12 ft wide, existed. The right edge of pavement was paralleled by a curb 6 in high and a beam guardrail. The left edge of pavement was paralleled by a 6-in mountable curb and a grass median.

For the one-lane one-way condition, one lane 12 ft wide existed. The right edge of pavement remained unchanged for the two-lane, one-way condition. The left edge of roadway was paralleled by 55-gal drums spaced 100 ft center to center.

The two-lane opposing condition consisted of one lane 12 ft wide for the eastbound traffic and one