Simulating Traffic Control Devices in a Sub-Area Network

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In a sub-area network, stop signs and signals at intersections can be a significant influence on travel paths. The presence of such devices often must be simulated in computerized highway networks so as to obtain more realistic assignments. One common way of doing this is to use "turn penalties." This is very resource-intensive, and has been known to confuse the path-building logic of some programs, resulting in poor assignments. An alternative method has been developed to avoid these problems. This method is based on theoretical models of delay, as a function of the V/C ratio of the controlled approach. Given the link's distance, the uncontrolled free speed, and the type of control device, a new "zero-volume" link speed and capacity are calculated to account for the delay induced by the control device. Further, the characteristics of the link are modified to account for delay caused by queuing: as traffic is assigned to the link, its constrained speed drops at a faster rate than if it had no control device.

A county-wide travel demand model using this technique was implemented using MINUTP, and the control device simulation method was applied with a FORTRAN program which modifies the speed and capacity of controlled links. A comparison of assigned volumes to ground counts by control device type showed reasonable results, and the constrained speeds on controlled links were also found acceptable.

Most highway network analyses do not attempt to simulate the presence of traffic control devices. This is mainly because highway networks have most often been used in regional studies, where intersection delay is usually not a significant part of total zone-to-zone travel time. Also, many planners are not satisfied with the usual methods of representing control devices: turn penalties or "microcoding." UTPS has had a history of difficulties in path building when turn penalties are used, and the documentation of at least one microcomputer package (MINUTP) suggests that this could still be of concern (*1*). Finally, the implementation of properly calibrated turn penalties on even a moderate scale would require resources well beyond the limit of most sub-area studies.

However, it is becoming much more common these days for computer-based highway network planning techniques to be applied to smaller analysis areas, such as sub-areas of a region or neighborhoods. One of the main difficulties in using planning software for such smaller areas is in defining the appropriate level of network detail. Generally, the smaller the area, the more significant intersection delay becomes in defining realistic travel paths. Since control devices are a powerful influence on delay at that scale, it thus becomes more important for a sub-area network to include them in some way.

This was the situation in the recently-completed Somerset Expressway Alternatives Study, a study of corridor highway alternatives in Somerset County, N.J. The analysis focused on a subsection of the county and was particularly concerned with future peak-hour traffic volumes. A very detailed network was used, covering almost all roads in the study area. The sub-area was small enough so that intersection delay was judged to be an important influence on path selection. However, the area was too large to permit a detailed investigation of intersection delay, so the use of turn penalties or microcoding would have been inappropriate. Thus, the project sought an alternative methodology that would permit the network to be sensitive to the presence of control devices.

Although there are numerous types of traffic control devices, this project dealt only with traffic signals and stop signs. Each signalized intersection was defined in terms of its major and minor approaches, based on known roadway and traffic characteristics. For intersections with stop signs, it was assumed that only the minor approaches were controlled. An inventory of the control device types for all intersection approaches in the study area was quickly prepared.

Thus, a method was needed that would permit the simplified simulation of intersection delay in a highway network with a minimum of new data required. The method would also have to be easily implemented within the MINUTP software package, which was being used for the Somerset Expressway project. The following sections of this paper describe the development of this method.

THEORY

The theory behind this project's simulation of control devices is that such devices affect link travel times in two ways. First, they reduce free-flow times by their mere presence. That is, the existence of a control device introduces a certain amount of delay, thus increasing link travel time and reducing effective speeds even if there is no traffic congestion on the link. A fixed delay value is associated with each control device type. This "zero-volume" delay would occur to a single vehicle as it approaches the intersection.

Second, it is theorized that as the volume grows, a link with a control device "behaves" differently than if that link had no such device, explained as follows. In the normal MINUTP capacity restraint calculation, the link running times are recalculated after each iteration as a function of volume using the standard default Bureau of Public Roads (BPR) curve, defined as follows:

$$T = T_0 \cdot \{1 + [S_c \cdot (V/C)^4]\} \quad (1)$$

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where

T = new link time,
T_0 = free-flow link time (in MINUTP, this can optionally be taken as the time from the previous iteration),
S_c = sensitivity parameter (MINUTP default value = 0.15), and
V/C = ratio of volume to capacity (previous iteration).

Expressing this relationship in terms of speed on a link of a given distance, the equation becomes:

$$S = \frac{(D \cdot 3{,}600)/[(D \cdot 3{,}600)/S_0]}{1 + [S_c \cdot (V/C)^4]} \qquad (1.1)$$

where

S = new link speed (mph),
S_0 = free-flow link speed (mph), and
D = link distance (mi).

Thus, as volume increases on a given link, its speed is reduced. This function generates a curve of speed reduction factors that begin to decline sharply at V/C ratios above 0.75.

The second theory being explored is that the presence of a control device should reduce speeds even more sharply than equation (1.1) estimates. Not only does a control device reduce a link's capacity at each end (i.e., at the intersections), but it introduces additional delay based on queuing and increased friction from conflicting traffic. This additional delay should also be related to the V/C ratio, but the hypothesis is that the curve should be steeper than the default curve.

Of course, actual delay at nodes (intersections) is a function of many factors, not the least of which are the number of approach lanes, turning volume, opposing turns, signal progression, and cross-street volume. However, the challenge in this project was to develop a delay estimate for each link's B node based only on the characteristics of that link: length, free-flow speed, capacity, assigned volume, and control device type. No resources were available to modify the MINUTP software or write substantial new programs to access other network information. Thus, the main hypothesis of this method was that the delay at each intersection could be reasonably estimated from just the "known" data for each link.

In order to test these theories, detailed models of traffic delay were obtained from other sources. Specifically, the 1985 *Highway Capacity Manual* (*2*) provides an estimate for delay at a signalized intersection, assuming random arrivals. This function is as follows:

$$d = 0.38 \cdot C \cdot \left(\frac{(1 - G/C)^2}{1 - (G/C) \cdot X}\right) + 173 \cdot X^2 \cdot [(X - 1) + \sqrt{(X - 1)^2 + (16 \cdot X/c)}] \qquad (2)$$

where

d = average stopped delay per vehicle (seconds),
C = cycle length (sec),
G/C = ratio of effective green time to cycle length,
X = ratio of volume to capacity, and
c = capacity [vehicles per hour (vph)].

It is theorized that this function can be used to represent network delay at signalized nodes, as a function of volume and capacity. For simplicity, it was assumed in the Somerset project that all signals in the study area could be represented as having a cycle length of 90 sec. Further, it was assumed that the major approach legs all have a G/C value of 0.50 and the minor approach legs all have a G/C of 0.35 (the remaining 15 percent of the cycle is clearance time and was assumed to be unavailable for use by vehicles). This equation further assumes that there is no progression of signal timing. Although these conditions do not hold for every intersection in the study area, it was felt that they are, on average, sufficiently representative for the purpose at hand.

For intersection approaches controlled by a stop sign, it was theorized that delay could be modeled as if the intersection were uncontrolled. For these intersections, the ITE Handbook provides a method of estimating delay (*3*). Research by R. Ashworth indicates that average waiting delay can be estimated by:

$$E(d) = t1 - t2 - B2 + T \cdot \{e^{(q \cdot t2} - e^{[q \cdot (t1 - B2)]}\} \qquad (3)$$

provided that $t2 > t1 - B2$
where

$E(d)$ = delay per vehicle (sec),
$t1$ = critical gap of first driver in queue (sec),
$t2$ = critical gap of second driver in queue (sec),
$B2$ = time for second vehicle to move up to the head of the queue after the first vehicle departs (sec),
q = ratio of volume to capacity, and
T = $1/q$.

For simplicity, the following average values were assumed: $t1 = t2 = 8.5$ sec and $B2 = 3$ sec.

MODEL DEVELOPMENT

As noted above, MINUTP offers one method of determining link delay as a function of volume and capacity: the BPR equation [equation (1)]. After each traffic assignment iteration, the MINUTP ASSIGN program determines the V/C ratio for each link, and then calculates a new link time for the next iteration, using this equation. ASSIGN does, however, offer the user the opportunity to modify the value of the sensitivity parameter (S_c) in equations (1) and (1.1). This parameter affects the shape of the delay curve. A different value can be used for each of 63 possible speed categories.

The other parameter in equation (1.1) that can be adjusted is the link capacity (C). Before the assignment process even begins, the original link capacity in the unloaded network can be modified for links that have a control device. In practice, the original link capacity can be multiplied by a factor lower than 1, resulting in a lower effective capacity.

Since the BPR equation is built into ASSIGN and can be adjusted only as described above, it was decided to use this formula, modified as needed, to represent the delay that would be estimated by equations (2) and (3). The basic approach was to plot the values given by each equation as a function of V/C ratio, and then modify the S_c and capacity adjustment values until the BPR equation gave results that were sufficiently close to the theoretically derived values.

According to the theory postulated above, links with control devices should have S_c values greater than 0.15. Such values produce a steeper curve, indicating that speed drops more sharply with increasing V/C, compared to links without control devices. In addition, control devices generally reduce capacity compared to totally free-flow conditions. Thus, there is a sound theoretical basis for reducing the link's original capacity value in the presence of a control device. (Most traffic engineers would observe that signalizing an intersection's minor approach legs actually *increases* their capacity. However, in this case, as in most network models, nodes without traffic control devices have no delay, penalties, or constraints at all. Therefore, adding a control device to such a theoretical intersection would serve to restrict its capacity somewhat.)

Figures 1–3 show the speed reduction equations as a function of V/C ratio for major signalized approach, minor signalized approach, and stop sign control, respectively. In each figure, the upper curve represents the speed reduction that MINUTP would impose by default, based on the link volume and equation (1.1), without any control devices. This is referred to as the "Uncontrolled Speed." (Figures 1–4 and the following discussion demonstrate the methodology for a typical link with a 30 mph original free-flow speed, original capacity of 1,300 vphpl, and a length of 0.5 mi. The specific calculations depend on the link speed and length; 30 mph, 1,300 vphpl, and 0.5 mi are average values.)

Major Signalized Approach

As Figure 1 shows, the theoretical *Highway Capacity Manual* (HCM) curve calculated by equation (2) does have a steeper slope than the Uncontrolled Speed curve, particularly for V/C ratios of 0.8 to 1.5. The HCM curve also includes a factor for zero-volume delay. This is the delay that a signal imposes on a single vehicle, in the absence of any other traffic at the intersection. According to equation (2), when volume is zero, delay is 8.6 sec.

The development of the model, then, consists of fitting another BPR curve to match the HCM curve. This was done by modifying the S_c value in equation (1.1) and reducing the capacity by a fixed percentage until a reasonable match is obtained. This was done by entering the data into a spreadsheet and conducting several iterations manually until the two curves converged sufficiently. The resulting curves are labelled "Mod. BPR" in Figures 1–3.

Since equations (1.1) and (2) are fundamentally different, an exact match could not be obtained. However, in general, the Mod. BPR and HCM curves in Figure 1 are fairly close.

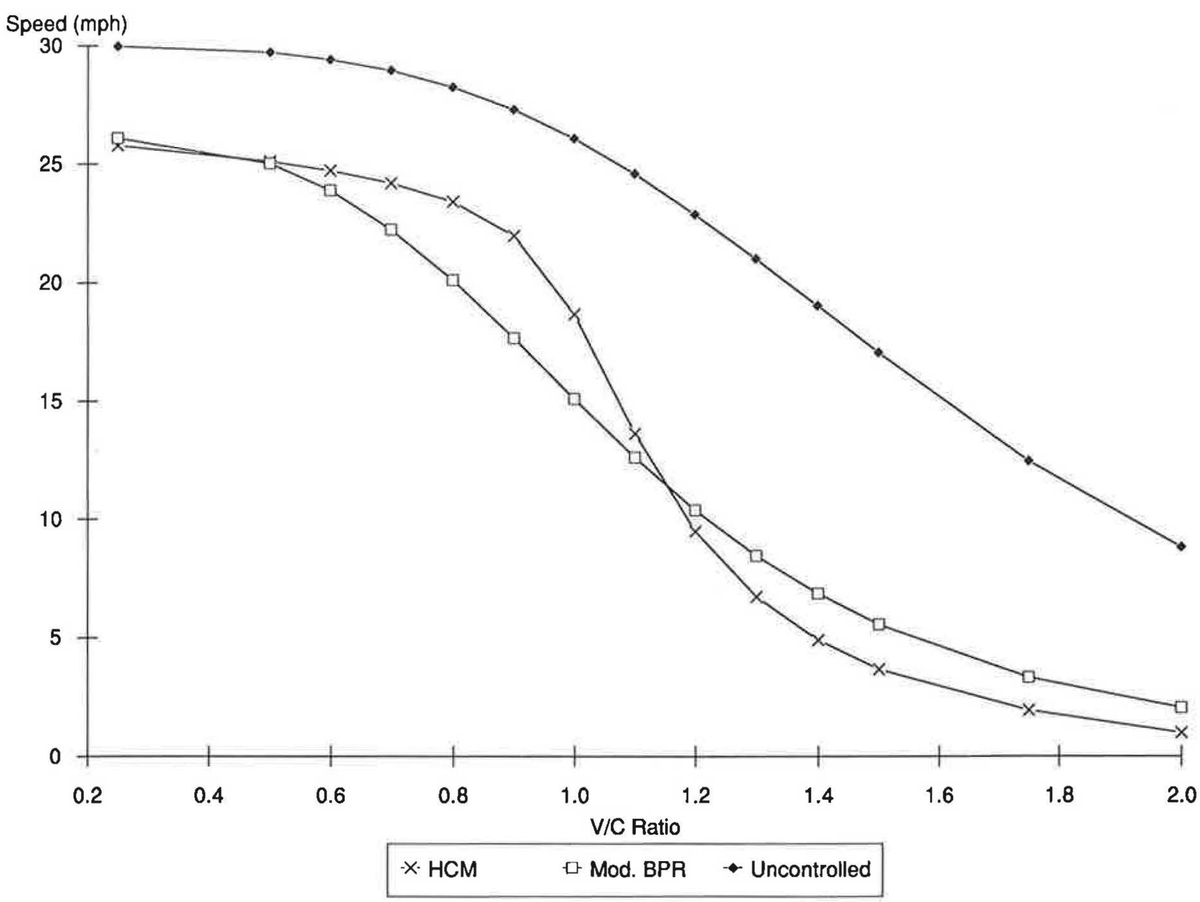

FIGURE 1 Signallized major approach speed reduction.

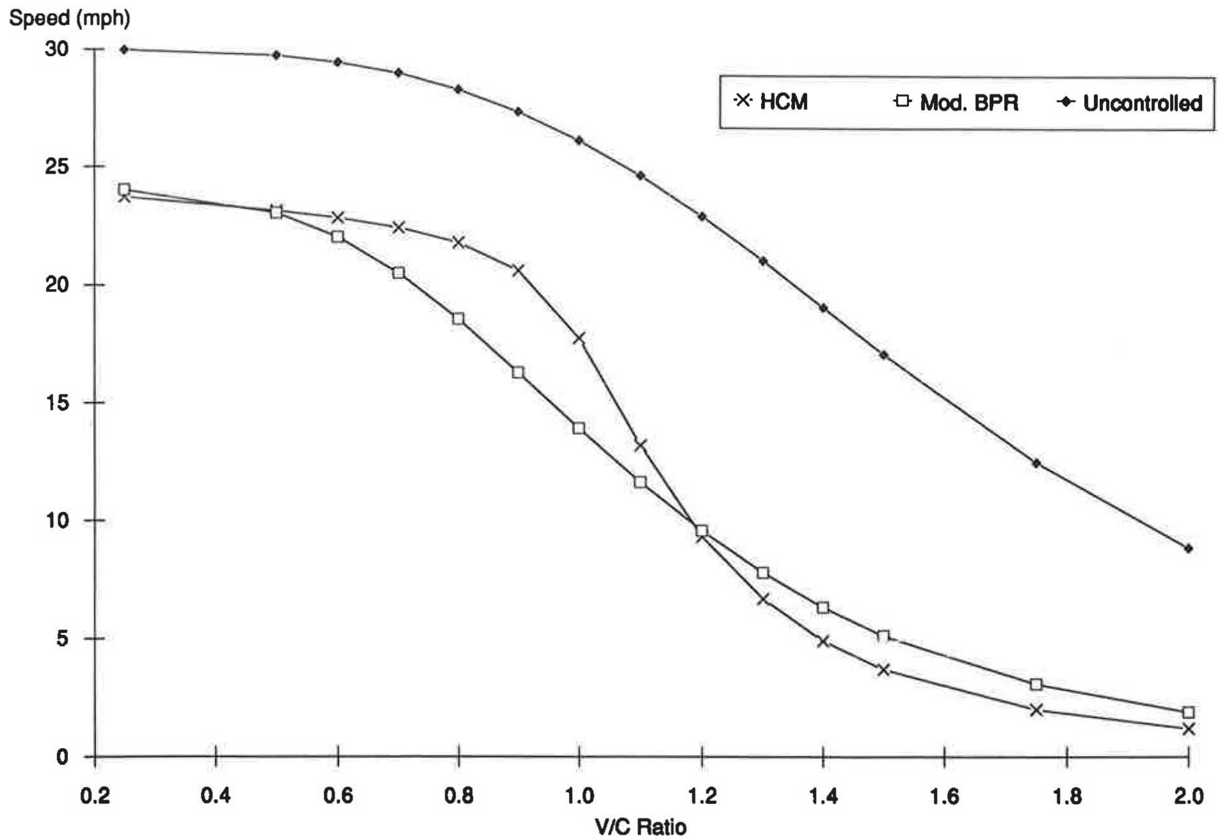

FIGURE 2 Signalized minor approach speed reduction.

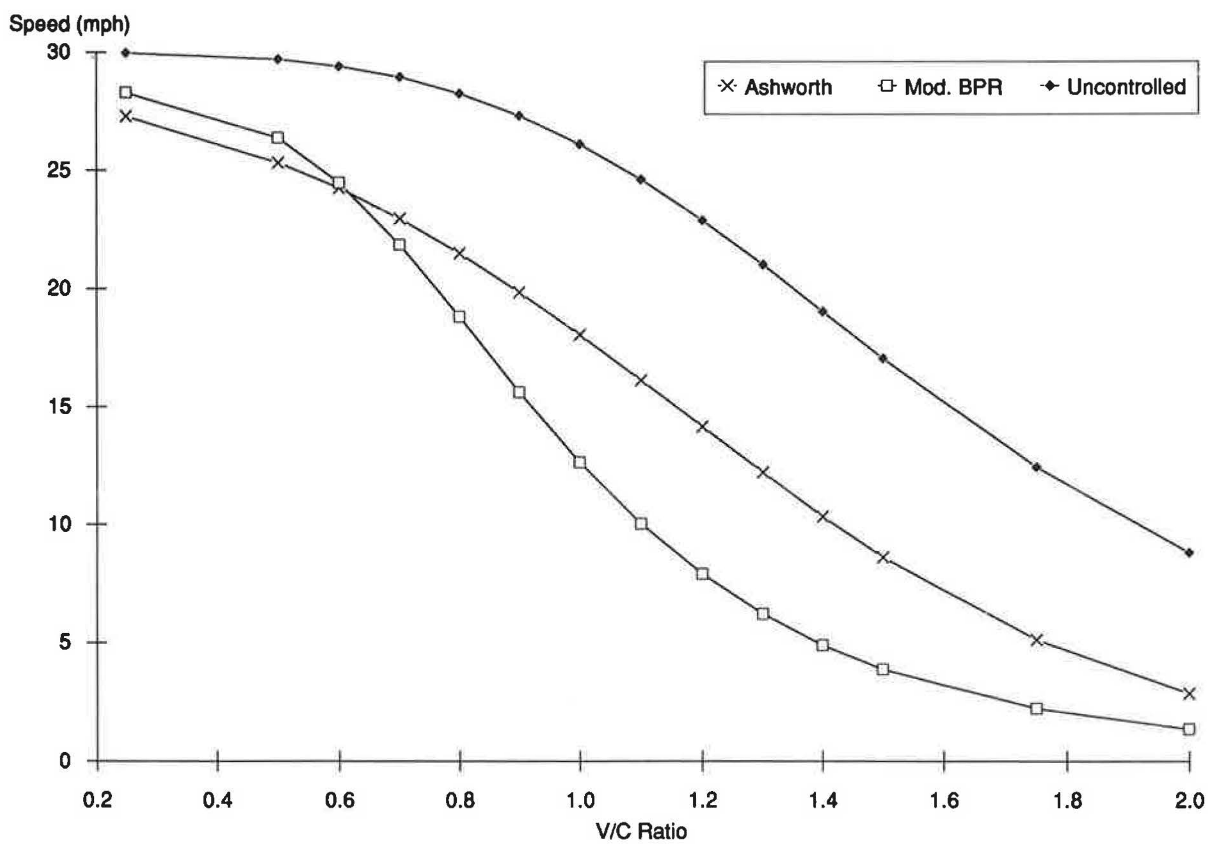

FIGURE 3 Stop sign speed reduction.

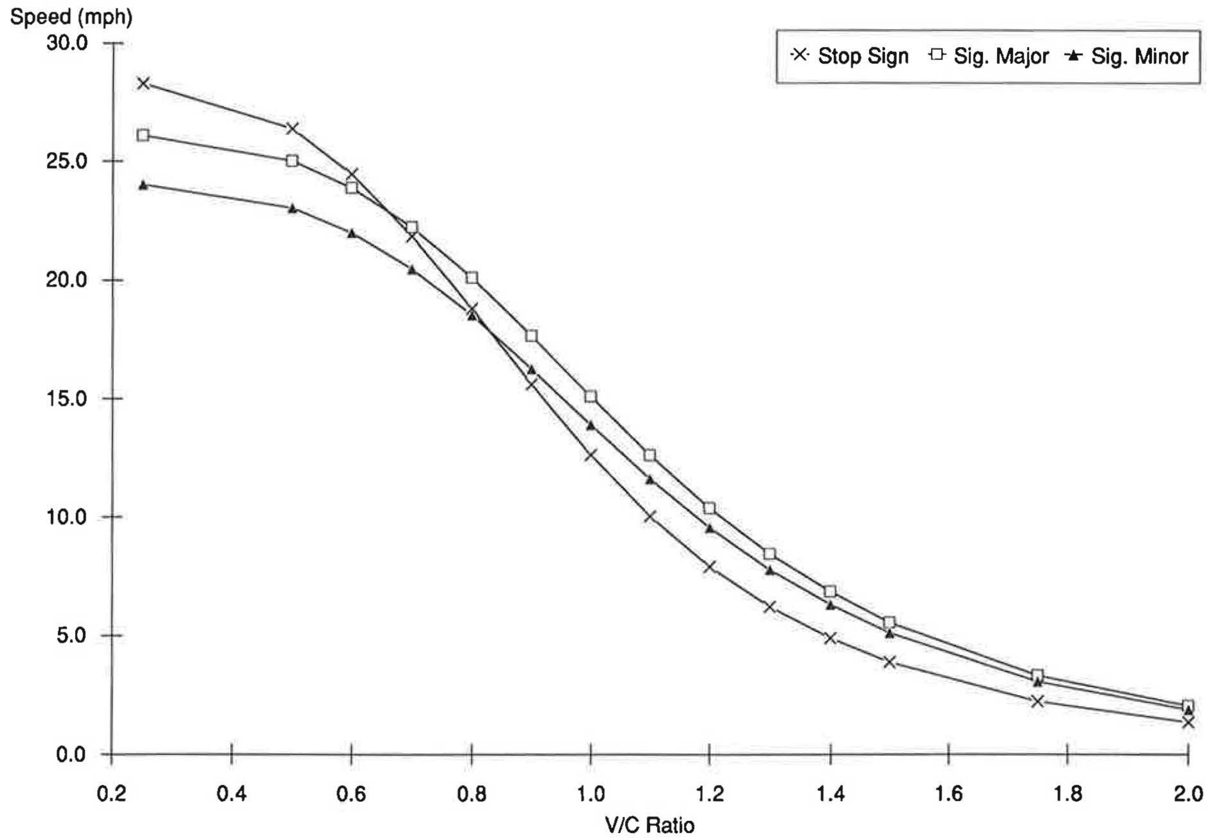

FIGURE 4 Speed reduction for all control devices.

The modified BPR formula underestimates speed for V/C of 0.5 to 1, and slightly overestimates speed for V/C above 1.2.

The final BPR Speed curve shown in Figure 1 was produced by modifying equation (1.1) as follows:

$$S = \frac{(D \cdot 3{,}600)/\{[(D \cdot 3{,}600)/S_0] + 8.6\}}{1 + 0.30 \cdot [V/(0.8 \cdot C)]^4} \qquad (4)$$

where

S = new link speed (mph),
S_0 = free-flow link speed (30 mph in this example),
D = link distance (0.5 mi in this example),
V = link volume (from the previous iteration),
C = link capacity (1,300 vph in this example).

As predicted, the S_c value of 0.30 indicates a steeper curve, compared with the default value of 0.15 for other links. The capacity is reduced by 20 percent, also confirming the above hypothesis. Thus, this equation was judged acceptable for estimating network speed reductions.

Minor Signalized Approach

A similar method was followed in developing the speed reduction function for the minor approach of a signalized intersection. The theoretical delay was calculated using equation (2), and the resulting reduction in speed was plotted as a function of V/C ratio (see the HCM curve in Figure 2). As noted above, the cycle length was assumed to be 90 sec and the minor approach G/C ratio was assumed to be 0.35. The only difference between the delay calculated for the major and minor approaches is that the zero-volume delay, based on equation (2), is approximately 14.5 sec.

As Figure 2 shows, the HCM curve (equation (2)) is somewhat parallel to the Uncontrolled Speed curve for V/C ratios of less than about 0.8. Above that point, the HCM curve shows a very sharp speed reduction with increasing volume, leveling off at a V/C of 1.5 and higher.

The fit of a BPR-type function to the curve calculated by equation (2) is also shown in Figure 2. The equation of this modified BPR Speed curve is

$$S = \frac{(D \cdot 3{,}600)/\{[(D \cdot 3{,}600)/S_0] + 14.5\}}{1 + 0.30 \cdot [V/(0.8 \cdot C)]^4} \qquad (5)$$

As Figure 2 shows, the modified BPR curve matches the HCM curve well at V/C below 0.6. From 0.6 to 1.3, the modified BPR curve underestimates the HCM speed. Above 1.3, the two curves are similar. Overall, this fit was judged to be acceptable. The sensitivity factor (S_c) and the capacity reduction factors are the same as for the major signalized approach, with the only difference being the higher zero-volume delay.

Stop Sign Control

The same procedure was followed for the stop sign model, but using equation (3) as the theoretical basis. As Figure 3 shows, the "Ashworth" speed curve calculated by equation (3) also has a steeper downward slope than the Uncontrolled Speed, for V/C values below 1.0. Above 1.0, the two curves are just about parallel. However, this does not mirror actual field conditions, in which stop sign control starts to break down as the V/C approaches 1.0. In addition, comparing Figures 1, 2, and 3 suggests that the theoretical delay at stop signs is less than delay at signalized intersections for V/C above 1. This also seems illogical.

It was felt that at a V/C of about 0.75, the speed should drop even faster than equation (3) suggests. Thus the parameters of equation (1.1) were adjusted so as to produce the bottom curve of Figure 3. Note that the Mod. BPR and Ashworth curves begin to converge again at V/C ratios above 1.2.

The Mod. BPR curve also include a factor representing zero-volume delay. This is the delay that a stop sign imposes on a single vehicle, in the absence of any other traffic at the intersection. This delay is fixed at 3.3 sec, which is calculated assuming an initial speed of 30 mph and a deceleration rate of 4.6 mph/sec. The Ashworth equation does not include a factor for zero-volume delay.

The modified BPR speed curve in Figure 3 is represented by this equation:

$$S = \frac{(D \cdot 3{,}600)/\{[(D \cdot 3{,}600)/S_0] + 3.3\}}{1 + 0.30 \cdot [V/(0.7 \cdot C)]^4} \qquad (6)$$

Although the fit between the modified BPR and Ashworth curves is not as good as for the other models, the overall result is still consistent with the other models. The sensitivity factor is the same (0.30) as for the signalized approaches, but the capacity adjustment factor is slightly lower (0.7 vs. 0.8), properly suggesting that replacing a stop sign with a signal increases capacity for a minor approach.

OVERALL COMPARISON

Figure 4 presents the curves for equations (4), (5), and (6) in one graph. Below a V/C of about 0.7, the signalized approaches show a higher delay (lower speed) than the stop sign approach. Above 0.7, the stop sign-controlled link starts to break down faster, resulting in lower speed that either signalized approach. At very high V/C ratios, all three equations provide similar results.

Another test of the validity of the control device model is the comparison of assigned volumes to counts for the sub-area. The Somerset Expressway project focused on hourly volumes. Table 1 provides a comparison of the total of estimated vs. observed a.m. and p.m. peak hour traffic volumes, by type of control device, for all sub-area links which had counts posted in the network.

As this table shows, the control device model did not, by itself, lead to perfect assignments. However, neither did it unduly distort the network. These results suggest that more time could have been spent to fine tune the methodology for this project. For example, the parameters for the signallized approaches (zero-volume delay, capacity factor, BPR sensitivity) could have been adjusted to decrease the delay associated with the minor approaches to signallized intersections and slightly increase the delay for the major approaches. The stop sign delay function would appear to need no further changes.

TABLE 1 ASSIGNED VERSUS COUNTED VOLUME FOR DIFFERENT CONTROL DEVICES

	AM			PM		
Control Device	Counted	Assigned	Difference	Counted	Assigned	Difference
Signallized Major Approach	44,000	51,400	+17%	51,800	52,030	0%
Signallized Minor Approach	6,740	5,200	-23%	9,540	7,130	-25%
Stop Sign	5,680	5,830	+4%	7,940	7,160	-10%

IMPLEMENTATION

This model was implemented in MINUTP as follows:

- The highway network was coded as usual in MINUTP, with speed and capacity look-up table values coded in the SPDC and CAPC fields.
- A new data field was added to the network, called "CDEV."
- For each link, by direction, if there is a control device at the link's B node, a number was entered into the CDEV field: 1 for stop sign, 3 for major signallized approach, and 4 for minor signallized approach.
- A short FORTRAN program was written to read the binary network file and see if a control device was coded. If so, then the link's capacity was reduced and a new speed calculated based on the link's distance and original free-flow speed. (This could also have been done using the MINUTP NETMRG program, but the flexibility of FORTRAN was needed for other reasons.)
- In the batch file of set-up commands to run the ASSIGN program, the value of S_c for the links with control devices was changed from the default of 0.15 to 0.30.

From this point forward, the assignment process proceeded as usual in MINUTP. It should also be possible to implement this procedure, or a variation thereof, using other planning software packages.

CONCLUSIONS

The presence of traffic control devices is rarely simulated in regional network modelling. This is mainly because (1) such networks are not detailed enough that control devices would make a difference, and (2) the available means of simulating such devices (e.g., turn penalties or microcoding) are usually cumbersome or otherwise unsuitable. In sub-area networks, however, it is often desirable to represent the effects of intersection delay, and specifically delay associated with traffic control devices, in order to obtain more realistic paths and assignments.

This analysis demonstrates that an alternative approach is available. The normal BPR-based link capacity restraint function built into MINUTP can be modified to provide an approximation of the delay associated with traffic control devices. This estimate of delay is based on detailed, theoretical models of delay and is internally consistent among control device types. The method is relatively simple and can be implemented within existing planning software systems. This method provides an adequate compromise between data and resource limitations, and theoretically proper delay models, and should be useful in other sub-area network applications.

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