Accommodating Transit in TRANSYT

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Although the TRANSYT traffic model simulates transit vehicles in mixed traffic operation, it does not adequately consider the effects of bus or streetcar stops on the traveled roadway near signalized intersections. Specifically, it assumes that transit vehicles loading and unloading passengers do not delay other vehicles. This reduces the validity of TRANSYT evaluations for cycles in which buses stop at or very near signalized intersections. The overall TRANSYT predictions and optimizations for an average cycle will be seriously threatened if total bus or streetcar dwell time per hour is significant. Therefore, an alternative type of network formulation, which uses dummy nodes and dummy links with appropriate link costs, is proposed for modeling the effects of transit stops on intersection performance. Although it requires one dummy node and four or six dummy links for each transit stop that delays traffic, it significantly improves TRANSYT's realism for such operations. Parameters for these dummy links have been tested over a wide range, and a set of operational values is recommended. Flow profiles illustrating the need for and effects of the recommended formulation are presented in this paper.

There are a number of models of varying quality for optimizing fixed-time traffic signal splits and offsets on an arterial or a network with signalized intersections. Among these, TRANSYT (*1*) has become the most accepted internationally, on the basis of theoretical evaluations and field tests. TRANSYT attempts to model on-street performance through the use of integrated flow profiles and platoon dispersion. It then calculates initial splits based on equalized saturation and applies a hill-climbing technique in attempting to minimize a weighted combination of delay, stops, and more recently energy consumption. It does this by adjusting offsets and, to a lesser extent, splits at each step of the hill-climbing process.

TRANSYT is quite user-friendly, providing useful echo prints, link- and node-related statistics, and especially graphs of flow profiles for simple visual pictures of how it is dispersing platoons and recombining the flows at intersections.

RECENT MILESTONES IN TRANSYT RELATIVE TO TRANSIT VEHICLES

In 1975, a version of TRANSYT was described (*2*) that allowed the modeling of buses traveling in mixed traffic. This version, called TRANSYT/5 and commonly known as Bus TRANSYT, provided up to five links using each shared stopline. It allowed buses to travel at their own speed, stop for passengers along the way, and be superimposed into a common First-In-First-Out (FIFO) queue at the traffic signal.

In TRANSYT it is assumed that buses travel independently from other traffic between intersections, even though they use the same lanes, and the program allows one to specify differential flow characteristics to represent and simulate any overtaking by or of the buses. Unfortunately, this shared stopline provision only allows buses to queue with other traffic for the traffic signal. It does not allow buses to hold up traffic while loading and unloading passengers in a traveled lane at an intersection. TRANSYT assumes that bus stops are all midblock and clear of intersections, that is, that they do not reduce intersection capacity.

Although this may be the way that buses operate on other continents (which is not fully conceded), bus and streetcar stops in North America tend to occur at intersections in order to facilitate transfers among different transit routes. Although this is not efficient from a traffic-flow standpoint, it is nevertheless a common method of operation and must be so represented in models that purport to represent transit. Even with bus bays, some time is lost as the bus decelerates into the bay from the traveled lane.

In the early 1980s TRANSYT-7F (which stands for Florida) was created by the Transportation Research Centre at the University of Florida (*3*) for the Office of Traffic Operations of FHWA. The data inputs and outputs of TRANSYT 7 were modified to create a North American version. This is now the accepted and most commonly used version in North America, partly because it is free, and it is therefore the version used in this paper. However, TRANSYT-7F did not alter the basic representation of TRANSYT to allow for transit stops at intersections.

TRANSYT/8 (*4*), introduced in 1980, allows for "give-way" situations, but in the context of YIELD or STOP signs rather than of traffic signals. Although this feature might conceivably be altered to represent the effects of buses loading and unloading at traffic signals, there would seem to be major problems of compatibility with variations during the TRANSYT cycle, and so this has not been explored.

TRICKING TRANSYT-7F

An immediate need to test bus and streetcar priority schemes on arterials in Toronto required that appropriate modeling

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formulations be fed into TRANSYT-7F to represent the effects of transit vehicles and other traffic on one another. This was accomplished through the use of dummy nodes and links that had appropriate travel times and capacities. These are described and discussed below.

PROBLEMS WITH TRANSYT'S REPRESENTATION

TRANSYT allows the user to specify dwell times for buses. Therefore, if one specifies 14 sec of dwell time, say, TRANSYT will delay the arrival of the bus at the signal by 14 sec, whether it stops at a midblock location or at the intersection stopline. It will therefore artificially alter the bus's position in the traffic stream and underestimate the delay to cars and other traffic. TRANSYT's procedure in this regard is described below.

TRANSYT estimates the time for a bus to join the queue at the downstream stopline after leaving the previous intersection as the sum of its cruise-related travel time plus dwell time at bus stops. It will therefore assume that cars pass the bus during its dwell time wherever this dwell time occurs, even if it is at the intersection stopline. It then assumes that the bus pulls back into the traffic stream as soon as passengers have been loaded or unloaded and continues to the intersection at its own cruise speed to queue for the signal in mixed lanes of traffic. The basic assumption in TRANSYT is that buses pull off into bays to load or unload, taking 16 sec to travel a distance of 200 ft while accelerating and decelerating for the stop, even if the bus crawls to its loading point in a queue at a traffic signal. It also assumes that buses do not delay traffic in the through lanes during their specified dwell time. This latter assumption is especially critical if TRANSYT is used to model streetcars instead of buses. Streetcars usually travel in the center lanes and therefore stop traffic in all lanes to allow passenger access and egress. Such is the case on Queen Street in Toronto, where the need for the alternative modeling provisions described in this paper originated.

Although effective closure of one or more lanes at midblock locations can also delay traffic, this can be accounted for in the link's cruise speed or travel time, and would in fact be inherent in data collected for this purpose. However, lane blockage during the green phase at an intersection reduces capacity proportionately and keeps other traffic from passing buses and streetcars. TRANSYT does not make adequate provision for these.

MODELING TRANSIT DWELL TIMES

Through the use of dummy nodes and links, TRANSYT can be made to represent the effects of buses or streetcars blocking one or more lanes when they stop to load or unload passengers at an intersection (Figures 1 and 2).

Figure 1 shows the standard TRANSYT representation for a simple signalized intersection (Node 1), which has streetcars and a shared stopline in each direction on the east-west road. The convention used for assigning numbers to links is one or two digits for the downstream node number, followed by one digit to represent possible parallel links, followed by one digit to represent direction of movement. For example, the 1 in Link 104 means flow into Node 1, the 0 means a car-and-truck link, and the 4 means an eastbound flow. Parallel transit links are given numbers in the fifties and are shown as dashed lines (e.g., 152 and 154). TRANSYT allows the user to specify that the parallel Links 104 and 154 share a stopline in order to remerge their flow profiles after they have had their own, independent cruise speeds and platoon dispersions along the link. Because there is no provision for transit vehicles that are loading passengers on Link 154 to delay traffic on one or more lanes of Link 104, the effects of delayed vehicles and reduced capacity are lost. Therefore, alternative modeling procedures are described below for approximating the delays to cars and trucks.

Figure 2 represents an expanded model for Node 1, which allows for streetcars or buses to hold up traffic on all lanes in their direction while they are loading and unloading passengers. The dummy Node 21 and the dummy links leading into and out of Node 21 are used to represent the delaying effects in the eastbound lanes, that is, of Link 154 on Link 104. Similarly, dummy Node 41 and its as-

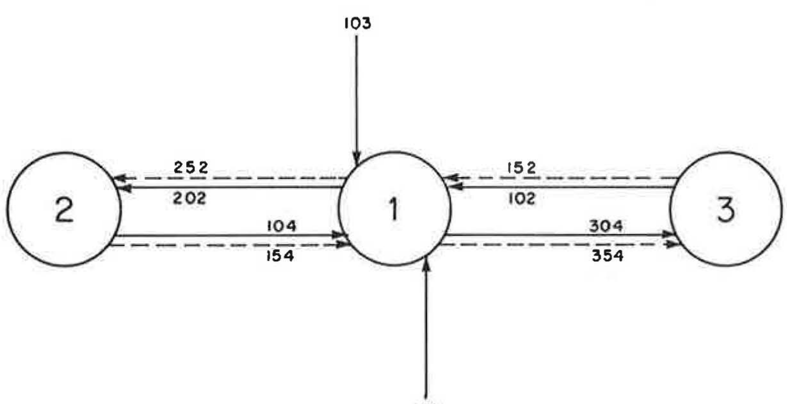

FIGURE 1 Intersection with shared stoplines eastbound and westbound.

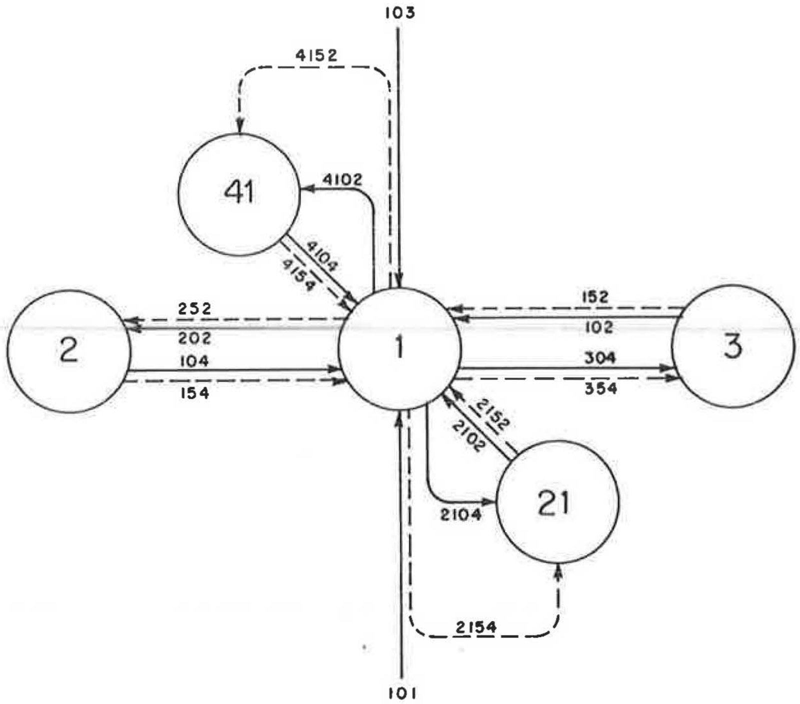

FIGURE 2 Addition of dummy nodes and links to represent full blockage of approach by bus or streetcar loading or unloading passengers.

sociated dummy links are used to stop all westbound traffic while transit is loading and unloading passengers. Note that all dummy links are coded with the number of the dummy node, whether it is their upstream or downstream node, in order to avoid confusion with the real links. The last two digits of dummy links entering a dummy node represent the direction of flow (e.g., 4102 is for westbound cars into dummy Node 41). To draw attention to the fact that dummy links out of a dummy node have the prefix of that originating dummy node, the opposite direction is used for the suffix of the dummy return links (such as 4104) for the westbound flow (i.e., as if Link 4102 had taken vehicles west from Node 1 and Link 4104 was bringing them back east to Node 1). Although somewhat confusing, this convention was adopted after other possibilities had been considered, for lack of a better one.

The key to making this formulation work is in the parameters specified for the dummy nodes. The purpose of the formulation is to require cars and trucks to wait while streetcars load and unload passengers. The procedure is described below for eastbound traffic, and the parameters are listed in Table 1 for both eastbound and westbound links.

Links 104 and 154 queue together at a shared stopline for the eastbound green at Node 1, having traveled from Node 2 at their respective cruise speeds. Cars and trucks from Node 104 then take Links 2104 and 2102 in sequence to Link 304. Because Link 2102 has the same green time as Link 104, the traffic from Link 104 continues through the intersection to Link 304 if Link 104 has a green indication, unless there is a streetcar loading. Link 2104 is red to this car-and-truck traffic when, and only when, the streetcar on Link 2154 is loading or unloading. This is accomplished by giving Link 2154 preemptive priority at Node 21 (through the highest possible weight of 9999), a minimum green time of only 1 or 2 sec, and an amber time that reflects the dwell time while the streetcar is loading or unloading.

To enhance the modeling realism at the first intersection for each direction, the streetcar's flow profile should be compacted into 1 or 2 sec at its original entry into the network by means of a simple dummy intersection providing only 1 or 2 sec of effective green time to the streetcar. This allows a variable number of streetcars (less than or greater than 1 as allowed by TRANSYT) to arrive once per cycle in a small platoon and load or unload for any specified dwell time. If the compacting is not performed that way, before Node 1, for example, Node 21 will accomplish it for downstream nodes, but much of the benefit of this compaction may not be realized at Node 1.

Although it must be assumed that streetcars arrive at the same time in each cycle in order to model fixed-time transit priority, this is believed to be a reasonable requirement in order for fixed-time priority to work at all. It will give some upper bound on the potential benefits from fixed-time priority. If streetcars cannot arrive at about the same point in the cycle for uncongested operation (a requirement of TRANSYT), there is no point in presetting signals to accommodate them. Only tests on Queen Street and other networks can provide some indication of the

TABLE 1 SUMMARY OF PARAMETERS FOR LINKS IN FIGURE 2

Link	Weight	Travel Time	Green Time	Upstream Link
104	1	As Before[2]	As Before	As Before
154	As Req'd[1]	As Before	Shared with 104	As Before
2104	1	0	Cycle Minus Bus Dwell Time	104
2154	9999	0	1 Step (1 or 2 secs)	154
2102	1	0	Same as 104	2104
2152	As Req'd	Dwell Time	Shared with 2102	2154
304	1	As Before	As Before	2102 + Others[3]
354	As Req'd	As Before	Shared with 304	2152 + Others
102	1	As Before	As Before	As Before
152	As Req'd	As Before	Same as 102	As Before
4102	1	0	Cycle Minus Bus Dwell Time	102
4152	9999	0	1 Step	152
4104	1	0	Same as 102	4102
4154	As Req'd	Dwell Time	Shared with 4104	4152
202	1	As Before	As Before	4104 + Others
252	As Req'd	As Before	Shared with 304	4154 + Others

Notes:

(1) As Req'd = The weight accorded to transit vehicles for optimization

(2) As Before = The same values that would have been used if modelled using TRANSYT without the enhancements recommended in this paper

(3) + Others = The flow profile for link 304 now derives its pattern from link 2102 as well as any other links deemed to feed link 304 directly, such as links 101, 103 for turning movements or link 104 for cycles and/or lanes not affected by the transit stops at node 1.

extent to which fixed-time transit priority can improve overall operation.

After the streetcar has passed through Node 21, its travel along Link 2152 takes a time equal to its dwell time. If it gets back to Node 1 while the signal is still green, it can continue to Node 3 on Link 354. Otherwise, it must wait for the next cycle. The entire process at the intersection is realistic, because the streetcar can begin to load or unload into the red period as long as it reaches Node 1 from Link 154 before the end of the green. However, it can only pass through the intersection if the signal is still green when the loading or unloading has finished.

After cars have passed through Node 1 the first time (on Link 104), they simply continue through Node 21 and back to Node 1 via Links 2104 and 2102, instantaneously if there is no streetcar loading. However, if they are following a streetcar, they must wait on Link 2104 until the streetcar has left. The amber time of Link 2154 delays them just enough to allow the streetcar to get back to Node 1 ahead of them. If the signal turns red before the streetcar has finished loading, the vehicles are delayed on Link 2102 until the signal turns green again.

Now, because Links 104 and 2102 could theoretically both be serving queued cars in parallel, the streetcar's effect on intersection capacity could be lost on Link 104. However, the capacity constraint is handled properly on Link 2102. Link 2102 accepts vehicles immediately after Link 104 when there are no streetcars, because Link 2104 would have a red indication and zero travel time. However, when a streetcar stops, cars are queued on Link 2104 and cannot reach the intersection, where the capacity goes begging for the vehicles stuck behind the streetcar. This use of a series of links to model a streetcar stop breaks down the component delays at an intersection as an event-ori-

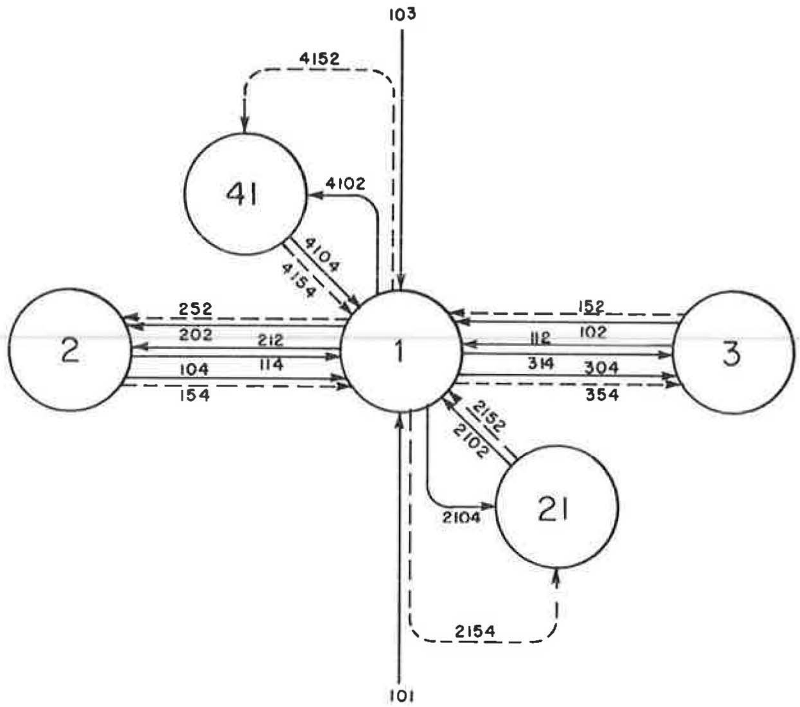

FIGURE 3 Addition of dummy links to allow either full or partial blockage of approach.

ented simulation would do, and actually allows TRANSYT to directly account for carryover to the next cycle, which will be discussed later.

To represent buses that might take up only one lane while allowing traffic on other lanes to pass through, the network of Figure 2 could be expanded by the addition of a through lane for cars not affected by the dummy transit priority considerations. This is represented by Links 114, 314, 112, and 212 in Figure 3. Links 304 and 314 could each have Links 114 and 2102 as partial upstream links to allow for lane changing.

GENERAL AND THEORETICAL DISCUSSION

Varying Saturation Flow

The effective saturation flow for streetcars, in terms of their effect on capacity at a signalized intersection, is very low if they load and unload during the green period; that is, their service headway is very long. For example, if the dwell time and the time taken to accelerate into the intersection are 15 and 3 sec, respectively, the service headway is 18 sec, and the effective saturation flow is 3,600/18 = 200 streetcars per hour of green if this all occurs during the green period. On the other hand, if the streetcar arrives with only 6 sec of green left, it uses up that 6 sec of green time in the loading and unloading process, plus about 3 sec of vehicle service headway time at the beginning of the next green. Now the total service headway is 9 sec, and the effective saturation flow is about 3,600/9 = 400 streetcars per hour of green.

If TRANSYT could accept varying saturation flows during a cycle, or at least different saturation flows for different intervals, one could use an approximation to the curve of effective streetcar saturation flow, as shown in Figure 4, for the foregoing example. Here saturation flow varies monotonically from 200 for streetcar arrivals up to 15 sec before the end of the green to 3,600/3 = 1,200 for streetcar arrivals just at the end of the green.

One might expect that in attempting to minimize the performance index TRANSYT would tend to try to have streetcars either pass through the intersection during a

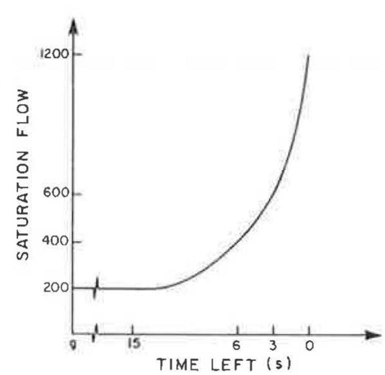

FIGURE 4 Effective streetcar saturation flow versus time left in green phase when streetcar arrives.

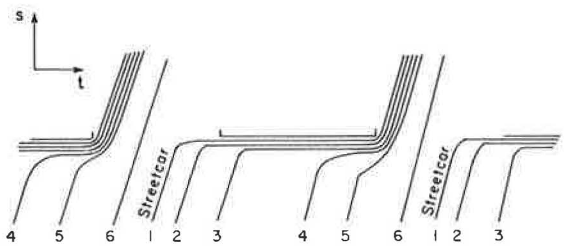

FIGURE 5 Overflow effects of streetcar loading beyond end of green phase.

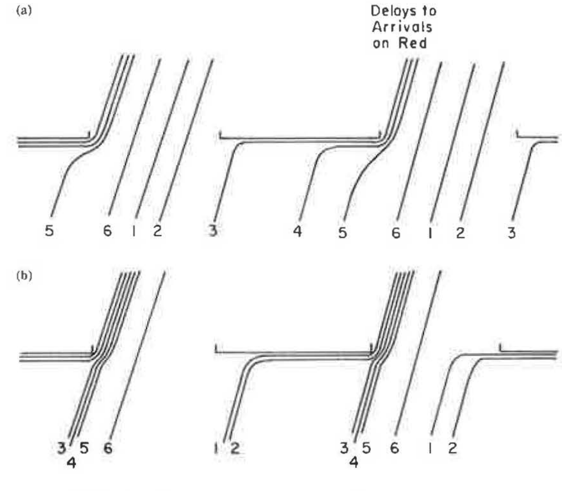

FIGURE 6 Component delays for westbound traffic at Node 1. (a) Delays represented at original shared stopline; (b) queueing of vehicles that arrived during red behind overflow vehicles at return shared stopline at beginning of green.

single green phase or arrive at the very end of one green phase and leave at the beginning of the next one. The latter scenario is the best for streetcars, given that they cannot reach the stopline and load and unload all passengers during a single green phase. It also maximizes the total capacity of the shared approach, as suggested in Figure 4.

Varying Passenger Demand at Streetcar Stops

Some streetcars will not have to stop for passengers at a given stop. If only a small percentage do not have to stop, it can be ignored. If it is large enough that one must represent both stopping and nonstopping streetcars on a link, additional parallel links could be used, similar to those added to Figure 2, creating Figure 3. These streetcars would simply pass through as cars do and would not be disturbed by other streetcars, which would presumably generally not arrive during the same cycle. They could also be given the weights accorded to streetcars. An intricate combination of parallel links could now be employed, as was done with buses to represent partial blocking of the intersection. Again, to simplify the modeling, one might reasonably assume that the probability that a given streetcar would stop at a given stop was independent of whether it had stopped at the previous stop, in determining its relative flows from the modeled parallel upstream streetcar links.

Platoon Dispersion

One need not specify a bus or streetcar link in order to give vehicles higher weights. The provision for using transit

```
LINK  8102   MAX FLOW    242   VEH/H         LINK  8152  MAXFLOW  1326   VEH/H

00000000000000000000000000000000000                S
00000000000000000000000000000000000                S
00000000000000000000000000000000000                S
00000000000000000000000000000000000                S
00000000000000000000000000000000000                S
00000000000000000000000000000000000                S
00000000000000000000000000000000000                S
00000000000000000000000000000000000                S
00000000000000000000000000000000000                S
00000000000000000000000000000000000                S
00000000000000000000000000000000000                S
00000000000000000000000000000000000                S
00000000000000000000000000000000000                S
00000000000000000000000000000000000                S
00000000000000000000000000000000000                S
00000000000000000000000000000000000                S
00000000000000000000000000000000000                S
00000000000000000000000000000000000                S
00000000000000000000000000000000000                S
00000000000000000000000000000000000                S
00000000000000000000000000000000000                S
00000000000000000000000000000000000                S
00000000000000000000000000000000000                S
00000000000000000000000000000000000          IIIIIOOIIIIIIIIIIIIIIIIIIIIIIIIIIII

---------+---------+---------+-----          ---------+---------+---------+-----
12345678901234567890123456789012345          12345678901234567890123456789012345
```

FIGURE 7 Flow profiles for dummy entry links.

```
LINK   102    MAX FLOW   3380  VEH/H    LINK   152    MAX FLOW   1365  VEH/H

S                                       S
S                                       IS
S                                       IS
S                                       IS
S                                       IS
S                                       IS
S                                       IS
S                                       IS
S                                       IS
S                                       IS
S                                       IS
S                                       IS
S                                 S     IS
S                                 S     IS
S                                 S     IS
S                                 S     IS
S                                 S     IS
SS                                S     IS
SS                                S     IS
SS                                S     IS
SS                                S     IS
SS                                S     IS
000000000000IIIIIIIIIIIIIIIIIIIIII0     IS
000000000000IIIIIIIIIIIIIIIIIIIIII0     IO

---------+---------+---------+-----     ---------+---------+---------+-----
12345678901234567890123456789012345     12345678901234567890123456789012345
```

FIGURE 8 Flow profiles for initial shared stopline.

links is merely a convenience to the user in specifying transit speeds and dwell times. However, if one does use TRANSYT's representation of transit speeds and travel times, one must also accept TRANSYT's estimate that typically about one in eight or so buses will not stop, which is used to increase the variance and reduce travel time on bus links. However, it is easier for the user to understand what is happening to transit flow profiles and to control them if the percentage of nonstopping buses is handled directly through the use of parallel links as shown in Figure 3. Because one also wishes to control the dispersion of the single transit vehicle in a cycle, it is easier to tell TRANSYT that it is just a car, albeit on a very important link, which can be given an appropriate level of priority. In giving this link zero dispersion, one should also reduce its speed to 80 percent of actual cruise speed, because TRANSYT takes it to be the lead vehicle in its platoon, traveling at 125 percent of the specified cruise speed.

Modeling Carryover for Loading into the Red Phase

Dummy links were used to ensure that any cars that were delayed sufficiently behind loading and unloading streetcars to miss the green phase would have to wait for a green after the streetcar had loaded. Figure 5 shows the effect of cars queueing behind a streetcar that is loading and unloading passengers during the last few seconds of green time. These cars must spill over to the next cycle, therefore further delaying the departure during the next green phase of other vehicles that arrive during the red phase. The component delays are represented as follows:

Vehicle 1: streetcar delayed on Link 2152 while loading and then while waiting for green signal;

Vehicle 2: car delayed on Link 2104 until streetcar has loaded; if signal has turned red, Vehicle 2 waits on Link 2102 until signal has turned green again and streetcar has passed through;

Vehicle 3: car waiting on Link 104 for green signal; it passes through Link 2104 and waits on Link 2102 until Vehicles 1 and 2 have been served;

Vehicle 4: car that follows Vehicle 3;

Vehicle 5: car that follows Vehicle 4; and

Vehicle 6: car that is not delayed (has green on Links 104, 2104, and 2102).

Figure 6a and b shows how the component delays are represented at the original shared stopline and the shared stopline for the return dummy links, respectively. In Figure 6a the only delays are to Vehicles 3, 4, and 5, which arrive during the red phase. In Figure 6b, Vehicles 3, 4, and 5 must wait until the overflow Vehicles 1 and 2 leave at the beginning of the green phase. The delays during the streetcar loading are not shown in Figure 6. The proposed disaggregated modeling technique allows TRANSYT to directly account for these delays of queue spillover, as well as represent the transit loading effect on car delays.

For example, Figures 7 to 11 are flow profiles for the westbound flows from Node 3 to Node 2 on the network in Figure 2, which represents the eastern portion of an arterial network in Toronto. Flow profiles are shown separately for the car-and-truck and the streetcar links.

Although Node 1 is the entry node from the east, dummy Node 3 was inserted. It has parallel Links 8102 and 8152

```
LINK  4102    MAX FLOW  3380  VEH/H     LINK  4152   MAX FLOW  1365   VEH/H

I                                       0
I                                       0
I                                       0
I                                       0
I                                       0
I       S                               0
I       S                               0
I       S                               0
I       S                               0
I       S                               0
I       S                               0
I       S                               0
0      SS                         0     0
0      SS                         0     0
0      SS                         0     0
0      SS                         0     0
0      SS                         0     0
0I     SS                         0     0
0I     SS                         0     0
0I     SS                         0     0
0I     SS                         0     0
0I     SS                         0     0
0IIIIII00000                      0     0
0IIIIII00000                      0     0

---------+---------+---------+-----     ---------+---------+---------+-----
12345678901234567890123456789012345     12345678901234567890123456789012345
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FIGURE 9 Flow profiles for transit priority.

entering. The purpose of inserting dummy Node 3 is merely to give streetcars a spiked flow profile, as in Figure 7. It gives them (Link 8152) 2 sec of green and allows the cars to pass through unimpeded. The streetcar in Figure 7 enters Link 152 from Link 8152 at time step 7 and reaches the downstream end of Link 152 at time step 1 of a later cycle. There it joins the queue of cars on Link 102 and is delayed for one step, as shown in Figure 8, which gives the effect of a westbound shared stopline at Node 1, where Links 102 and 152 must be served by the common east-west green. Note that in this case, Link 8102 was not necessary, because cars could enter the network directly at a constant rate onto Link 102.

Figure 9 shows the effect of a 12-sec (six-step) loading of a streetcar on Link 4152 on the cars of Link 4102, which are held up in steps 2 to 7. Then Link 4154 delays the streetcar for 12 sec, so that it reaches the signal at the appropriate time (i.e., step 8), as shown in Figure 10.

```
LINK  4104    MAX FLOW   2675  VEH/H   LINK  4154   MAX FLOW   1365  VEH/H

        0                                     0
        0                                     0
        0                                     0
        0                                     0
        0                                     0
        0                                     0
        0                                     0
        0                                     0
        0                                     0
0      00                         0           0
0      00                         0           0
0      00                         0           0
0      00                         0           0
0      00                         0           0
0      00                         0           0
0      00                         0           0
0      00                         0           0
0      00                         0           0
0      00                         0           0
0      00                         0           0
0      00                         0           0
0      00                         0           0
0      00000                      0           0
0      00000                      0           0

---------+---------+---------+-----    ---------+---------+---------+-----
12345678901234567890123456789012345    12345678901234567890123456789012345
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FIGURE 10 Flow profiles for return shared stopline.

```
LINK  202    MAX FLOW    3345   VEH/H   LINK  252    MAX FLOW    1365   VEH/H

              SS                                                0
              SS                                                0
              SS                                                0
              SS                                                0
              SS                                                0
              SS                                                0
              SS                                                0
              SS                                                0
              SS                                                0
              SS                                                0
              SS                                                0
              SS                                                0
              SS                                                0
              SS                                                0
              SSS                                               0
              SSS                                               0
              SSS                                               0
              SSS             I                                 0
              SSS             IIII                              0
I             SSS     0       IIIII                             0
III           SSS    000     IIIIII                             0
IIIIIII       SSS    000000IIIIIIII                             0
IIIIIIIIIIIIIISSS    000000IIIIIIII                             0

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12345678901234567890123456789012345     12345678901234567890123456789012345
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FIGURE 11 Flow profiles for arrivals to downstream shared stopline.

Because the signal is still green at step 8, the streetcar can go onto Link 252 toward Node 2. Figure 11 shows the effects of platoon dispersion on the arrival of cars at downstream Node 2 via Link 202 and the preserved spike for the streetcar Link 252.

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