# Modeling of Shared Lane Use in TRANSYT-7F

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**The TRANSYT family of programs continues to be one of, if not the most, widely used computer programs in the world for traffic signal timing and traffic flow analysis. In the past this program was excellent for modeling protected or unopposed traffic movements from separate lanes; however, it did not have the capability to model several different movements, for example, unprotected left turns and through movements from a shared lane. A project to incorporate a model to explicitly deal with this condition in TRANSYT-7F is described. The model is based on the 1985 Highway Capacity Manual. Its implementation in TRANSYT-7F and the user interface are reviewed.**

The Traffic Network Study Tool (*1*), Version 7, Federal (TRANSYT-7F) (*2*) is one of the most useful tools available to the traffic engineer for traffic operations analysis and traffic signal timing optimization. The traffic model is a deterministic, macroscopic time scan simulation model, which is quite realistic in modeling homogeneous flows unencumbered by other traffic.

The applicability of the model was, in the past, somewhat limited when one traffic movement had to yield to another, for example, when permitted left turns were opposed by traffic traveling in the opposite direction. If the permitted left turn movement had its own lane or bay, this could be approximated roughly by estimating a reduction in the saturation flow rate to represent left turners yielding to opposing traffic and by delaying the start of effective green to reflect the delay due to the departure of the opposing through queue. However, if the unprotected left turn movement was from a common or shared lane with the through traffic, no reasonable way to model this condition existed in TRANSYT.

To overcome the limitations, the Federal Highway Administration (FHWA) awarded a contract to the University of Florida Transportation Research Center (TRC) to develop and implement Enhancements to the TRANSYT-7F Program. The specific objectives of the first phase of the project are summarized as follows:

1. Develop a permitted movement algorithm that will enable TRANSYT-7F to model permissive and protected plus permitted left-turn phasing, including "sneakers" that turn at the end of the permitted phase.
2. Develop algorithms that will enable TRANSYT-7F to explicitly model stop sign control and shared left and through lanes.

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The first objective was reported earlier (*3*). The stop control model was handled in TRANSYT by simply estimating a minimum delay to sign controlled traffic, equal to the time requirements to decelerate from the coded speed to a stop, then accelerate to the speed when the permitted model indicated available capacity.

This paper deals with the selection and implementation of the shared lane model. It describes the development of the model and its implementation in TRANSYT-7F.

## EXISTING TRANSYT TREATMENT OF SHARED LANES

TRANSYT-7F, like its predecessors, is a deterministic macroscopic time scan simulation model intended specifically for unencumbered traffic flow. Traffic movements are modeled according to a very simple rule of flow. Periodic flow patterns are modeled in an upstream-to-downstream order. A flow pattern representing the periodic departure as a function of time during a typical cycle is

$$OUT(t) = \begin{cases} 0, \text{ if the link's signal is effectively red;} \\ GO(t), \text{ if the signal is effectively green and a queues exists; and} \\ IN(t) \text{ if the signal is effectively green and no queue exists.} \end{cases} \quad (1)$$

where

$OUT(t)$ = the "output" flow rate at time interval $t$, in vph;
$GO(t)$ = the maximum flow, or "go" rate (vph), which is the saturation flow at time $t$; and
$IN(t)$ = the arrival, or "input," rate (vph) at the reference point of the link at time $t$, which is a product of TRANSYT's platoon dispersion model, or a uniform rate for "external" links.

In TRANSYT's simulation model the IN pattern is known. It is predicted by the platoon dispersion model for "internal" links or is a uniform distribution for "external" links. Thus, the key to incorporating a shared lane model in TRANSYT is to calculate the GO pattern.

The earlier versions of the model had no provision for permitted movements, which must filter through opposing flows. As mentioned previously, recent work (*3*) has been undertaken to provide for permitted movements from exclusive lanes. Models were developed empirically from the data collected around the Washington, D.C., area and have been installed.

The shared lane analysis incorporates permissive turners and is therefore an extension of this work. Analytical procedures and simulation were used in lieu of field calibration due to the great resource demand of the latter.

Prior to this work TRANSYT-7F was unable to treat shared lane flow explicitly. The user's manual (*2*) suggested using the shared stopline feature in which vehicles depart from the set of shared stopline links in the order in which they arrive, regardless of the link on which they arrive. All vehicles depart at the lesser of the rate at which they arrive or the saturation flow rate coded for the primary link (saturation flows were not coded for minor links).

Coded saturation flows could either be measured or estimated. Measurements must be taken under "typical" conditions. Because of the many factors which influence the saturation flow in a shared lane, the results would not be as reliable as saturation flow for exclusive through lanes, which are generally only governed by geometrics and driver behavior. Aside from direct measurements, "engineering judgment" could be used, but only when measurements or calculations were infeasible.

The saturation flow rate may also be calculated, for example using the Highway Capacity Manual (HCM) (*4*) procedure. This procedure is somewhat involved, but is possibly the most realistic approach available to obtain a reliable result. If the HCM procedure is used, however, signal timing parameters must be known. In a simulation they are known but must be estimated if an optimization is performed. Unless the initial guess proves correct, this requires a recursive approach that can be quite consuming in resources.

TRANSYT's simulation routine, progressing link by link in a downstream order, is not conducive to permitted flows, especially shared lane flow with permitted elements. Shared lane flow depends on a plethora of variables, the primary elements being opposing flow and left turn volume. Due to this dependence on opposing flow, shared lane saturation flow will vary on a step-by-step basis as opposing flow varies. Unopposed movements, such as exclusive through lanes, are only constrained by intersection geometry and driver behavior. Thus, the saturation flow for a given location is generally constant over time.

If an intersection has shared lanes opposing each other, calculation of saturation flows, particularly on a step-by-step basis, would require simultaneous processing of both approaches as current opposing flows are required to calculate up-to-date saturation flows. Such a computing procedure would require rewriting TRANSYT completely, which was beyond the scope of the FHWA project.

## Modeling Approach

Many analysis methods of traffic movements have attempted to equate vehicles to a standard, typically equivalent through passenger vehicles (ETVs), because they make up the dominant proportion of all movements. Additionally, through vehicles generally make maximum usage of the roadway when compared to oversized vehicles and turning vehicles, particularly those that must filter through an opposing flow. Saturation flows can be expressed in terms of ETVs and remain constant, independent of the traffic mix. Shared lane analysis uses the ETV concept.

Traffic in a shared lane takes two basic forms:

1. Protected left turns (exclusive phase): Vehicles in the shared lane may move freely without impedance from vehicles traveling in the opposite direction. Saturation flows can be readily measured for protected movements, and suggested rates can be found in the HCM (*4*). Protected shared lane saturation flow can be determined using these suggested values.
2. Permissive left turners: ETVs for the left turners are dependent on the opposing volume. Past research provides various forms for the relationship between permissive turners and opposing flow, ranging from a simple linear to a more complex exponential form. The saturation flow of shared lanes is also a function of the composition of traffic in the lane and the vehicles opposing them.

Many previous studies were investigated, including work by Akcelik in Australia (*5, 6*); Peterson et al. (*7*) in Sweden; City of Edmonton, Canada (*8*); Lin et al. (*9*); Lee et al. (*10*) at the University of Texas; and Fambro, Messer, and Anderson (*11, 12*). Most of these methods use at least a variation of the ETV concept and gap acceptance models developed by the authors or others, such as Drew (*13*).

Because a permitted movement model was being added to TRANSYT-7F at the time of this research, and the resources to add the shared lane capability were limited, it was decided to use an approach similar to the HCM.

## Model Considerations

An analytical model was developed by first establishing upper and lower bounds for shared lane saturation flow. A critical lane procedure was used to pinpoint a unique flow rate, within the previously developed bounds.

### *Bounds Solution*

As a preliminary investigation of shared lane behavior, upper and lower bounds for the shared lane saturation flow, $S_s$, were addressed.

The saturation flow for a shared lane is primarily dependent on the mix of traffic in the lane, through and left vehicles, and the opposing volume, which interacts with the left turners. The obvious upper bound use of the lane occurs when it is used exclusively by through vehicles, resulting in a saturation flow of $S_{to}$, the base saturation flow for through vehicles. Conversely, the lower bound occurs when the lane operates as an exclusive left turn lane with a saturation flow of $S_l$, the permissive left turn saturation flow rate. In both cases, however, the lane is not operating as a shared lane.

To investigate shared lanes they will be viewed from the perspective of left turners, as Lin viewed them (*9*). Given a through volume of $V_{ts}$, occupying the shared lane, what will be the left turn saturation flow, $S_{ls}$? The shared lane saturation flow can be determined by simply adding $S_{ls}$, the left turn saturation flow from a shared lane and the through volume added to saturate the shared lane, which is equal to $S_{ts}$, the through saturation flow from a shared lane.

An upper bound solution occurs when the through vehicles sharing the lane do not utilize time when gaps occur in the opposing traffic, which otherwise would be available to the permissive left turners. In fact, it is assumed that the left turns are distributed such that they arrive ideally to use all available gaps. It is assumed that all the opposing vehicles arrive together at their saturation flow rate, and move simultaneously with the through vehicles in the shared lane, which are also departing at their maximum flow rate. This allows the maximum number of left turners to use the shared lane. $S_{ls}$ is therefore the minimum of

$$S_{ls} = S_{to} - V_o, \text{ or } S_{to} - V_{ts} \tag{2}$$

where

$S_{ls}$ = left turn saturation flow from a shared lane, vphg;
$S_{to}$ = base through saturation flow from a shared lane, vphg;
$V_o$ = opposing volume, vph; and
$V_{ts}$ = through volume in the shared lane, vphg.

The shared lane saturation flow rate is the lesser of

$$S_s = S_{to} - V_o + V_{ts}, \text{ or } S_{to} \tag{3}$$

where $S_s$ is shared lane saturation flow, vphg; and $S_{to}$, $V_o$, and $V_{ts}$ are as defined before.

If every through vehicle in the shared lane used an otherwise available opportunity for a left vehicle to turn, a lower bound solution would occur. The respective saturation flows are

$$S_{ls} = S_l - V_{ts} \tag{4}$$

and

$$S_s = S_l \tag{5}$$

where $S_l$ is permissive left turn saturation flow, vphg; and $S_{1s}$, $S_s$, and $V_{ts}$ are as defined before.

### *Critical Lane Analysis*

Critical lane analysis was used for signalized intersections in the 1985 HCM. Earlier work by Messer (*12*) formed the foundation for the resultant procedures. Unfortunately, no documentation describing the development of the HCM procedures exists, other than the brief description in the manual itself. With this and the complexity of the shared lane procedures in mind, it was decided not to insert the copious HCM equations into TRANSYT directly, but to use the critical lane procedure to produce a more simplified approach.

Critical lane analysis assigns vehicles equally among available lanes on the basis of their ETV volume. This is predicated on the assumption that drivers strive to minimize delay in their travel.

When permissive turners are converted to ETVs, their numbers increase above their actual on-road volume. In effect, it is assumed that all drivers have "perfect knowledge" about existing traffic conditions and future events. That is, through vehicles arriving at an intersection on a multilane approach, which includes a shared lane, with vehicles already queued in each of the $N$ available lanes, have $N$ possible lane choices. The choice process can be reduced to two basic steps. First there is a choice between the $(N - 1)$ identical through lanes. This is a rather trivial process; obviously the lane with the shortest queue will be chosen. Next the result of the first step is compared to the shared lane.

Choosing between the shared lane and the preferred through lane is not quite as straightforward. At this stage the concept of ETV becomes important. Assuming that only passenger cars use the roadway, permissive turners must be converted to ETV on the basis of their opposing traffic. The actual shared lane queue on the roadway serves as an indicator to approaching drivers of the desirability of the lane. If it is longer than the favored through lane, for example, one would expect the drivers to reject the shared lane.

Problems arise when the shared lane queue is equal to or less than the best through-only alternative. The driver must make a subjective judgment on lane use. Intuitively one would expect the through lane to be favored when the actual queues are the same length, but the risk of joining the marginally shorter shared lane queue and being delayed by a left turner is high. As the actual queue length of the through lane increases, a point of equilibrium is reached when the driver is equally likely to select either lane. In theory this occurs when the ETV queue lengths are identical. Beyond this point the driver would be expected to join the shorter queue in the shared lane.

Of course drivers do not explicitly think in terms of ETV when making lane choices; this is a procedure developed to simulate lane choice. This concept, however, has intuitive appeal, aside from the fact that it is assumed arriving drivers know about the future opposing traffic while at the intersection.

The above interpretation of driver behavior forms the basis of the shared lane model developed below.

## Model Derivation

The calculation of shared lane flow involves two steps:

### *Step 1. Calculation of $V_{ts}$*

It is assumed that vehicles are distributed evenly among the available lanes on the basis of their ETV. Therefore,

$$V_s\,(ETV) = (V_t + EL * V_l)/N \tag{6}$$

where

$V_s\,(ETV)$ = volume in the shared lane, ETV/hr;
$v_t$ = through volume in all approach lanes;
$EL$ = through vehicle equivalent for opposed left turns;
$V_l$ = left turn volume, vph; and
$N$ = number of lanes on the shared lane approach being analyzed.

A check should be performed to see if the shared lane is acting as a de facto left turn lane. The check is as follows:

$$\text{If } V_s\,(ETV) < EL * V_l, \tag{7}$$

then treat as an exclusive left turn lane.

In this case the lane saturation flow is equal to the permissive left turn saturation flow, $S_l$. Otherwise the following analysis procedure is used to determine shared lane saturation flow rates:

$$V_{ts} = V_s\,(ETV) - EL * V_l \tag{8}$$

where $V_{ts}$ is through volume in the shared lane, vph; and the rest were defined previously.

Substituting $V_s$ $(ETV)$ from Equation 6 into Equation 8 gives

$$V_{ts} = [(V_t + EL * V_l)/N] - (EL * V_l)$$
$$= [V_t + EL * V_l * (1 - N)]/N \quad (9)$$

*Step 2. Use $V_{ts}$ to Determine Saturation Flows*

The available capacity of the shared lane, from $S_{to}$, is distributed among the several movements using the lane according to their respective volumes, in ETVs. The left turn saturation flow from a shared lane is as follows:

$$S_{ls}\,(ETV) = S_{to} * (V_l * EL)/V_s\,(ETV) \quad (10)$$

where $S_{ls}$ is left turn saturation flow from a shared lane, ETVphg; $S_{to}$ is base saturation flow for through vehicles, vphg; and the rest as previously defined.

Equation 10 gives the left turn saturation rate in terms of effective through vehicles. If Equation 10 is divided by the equivalent left turn factor, $EL$, as follows, the saturation flow can be expressed in the more familiar units of vphg:

$$S_{ls} = S_{ls}\,(ETV)/EL$$
$$= (S_{to} * V_l)/V_s\,(ETV) \quad (11)$$

where $S_{ls}$ is left turn saturation flow from a shared lane, vphg; and the rest were defined previously.

The through saturation flow rate from a shared lane is as follows:

$$S_{ts} = S_{to} * V_{ts}/V_s\,(ETV) \quad (12)$$

where $S_{ts}$ is through saturation flow from a shared lane, vphg; and the rest were defined previously.

The sum of the shared lane saturation flows, in units of ETVphg, is equal to the base through saturation flow rate, $S_{to}$, or

$$(S_{ls} * EL) + S_{ts} = S_{to} \quad (13)$$

Using a volume division of the available capacity is only an approximation, increasing in accuracy as the shared lane approaches its limit, saturation.

*Through Volume Equivalency and Effective Opposing Volume*

Through volume equivalency used for opposed turns was determined using the HCM procedure:

$$EL = S_{to}/(S_{lo}) \quad (14)$$

where $V_o < S_{lo}$ and $S_{lo}$ is base protected left turn saturation flow rate, vphg.

The HCM uses $S_{lo}$ = 1,400 vphg. In the calculation of this factor 1,800 vphg is used for $S_{to}$. A departure from the manual was made, however, in calculating the opposing volume, $V_o$.

The HCM does not differentiate between opposing flow as a function of the number of lanes, $n$, available. It is assumed that the opposing flow faced by permissive turners is the same, regardless of $n$. Figure 1 illustrates upper and lower bound solutions of the effect of the number of lanes available for

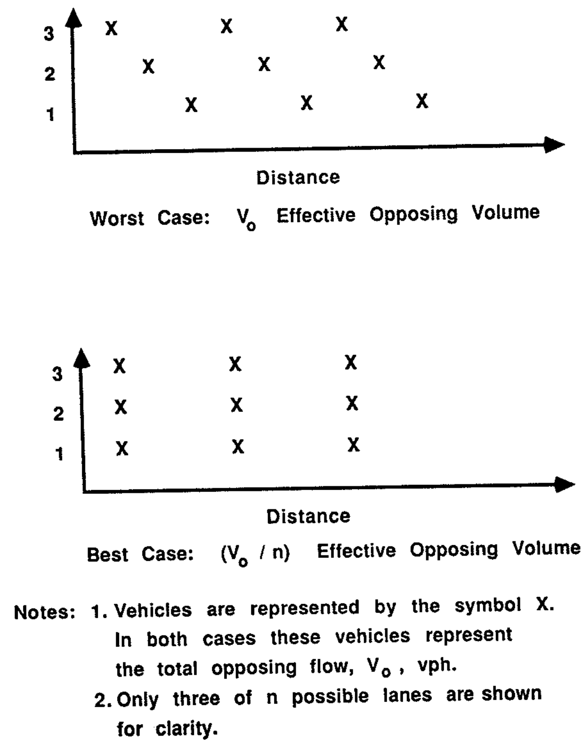


**FIGURE 1 Effect opposing volume bounds; X = total opposing flow ($V_o$) in vph; only three of $n$ possible lanes are shown.**

opposing traffic. At worst the opposing volume, $V_o$, could be distributed entirely uniformly, in such a way that the opportunity for left turners to filter through is the same as if only one lane were available. Conversely, $V_o$ may be distributed in echelon fashion, such that the effective opposing volume is reduced to $V_o/n$. In the absence of specific theory or data, it was decided to use a simple average of these two extremes in calculating the opposing volume corrected for multiple opposing lanes, $V_o'$. That is:

$$V_o' = [V_o + (V_o/n)]/2$$
$$= (V_o * (n + 1))/(2 * n) \quad (15)$$

where $V_o'$ is opposing volume corrected for multiple opposing lanes, vph; and $n$ is number of opposing lanes.

No adjustment is necessary if the opposing approach itself includes a shared lane. Clearly the number of opposing lanes is less than $n$. This question is left to future research.

Second, the HCM only uses $EL$ when permissive turners are filtering through opposing flow, $g_u$, which by this time is assumed to have returned to the random arrival rate, because opposing vehicles that queued during the preceding red period have cleared during $g_q$. Figure 2 illustrates the calculation of the unsaturated portion of the permissive green phase. This behavior is reasonable for an isolated intersection where vehicles will in fact arrive in a random manner. However, when signalized intersections are closely spaced and coordinated, random arrivals cannot be assumed, because platooning will tend to occur.

The platoon may arrive at any time during the cycle, assuming the traffic is, in fact, grouped; however, the step-by-step

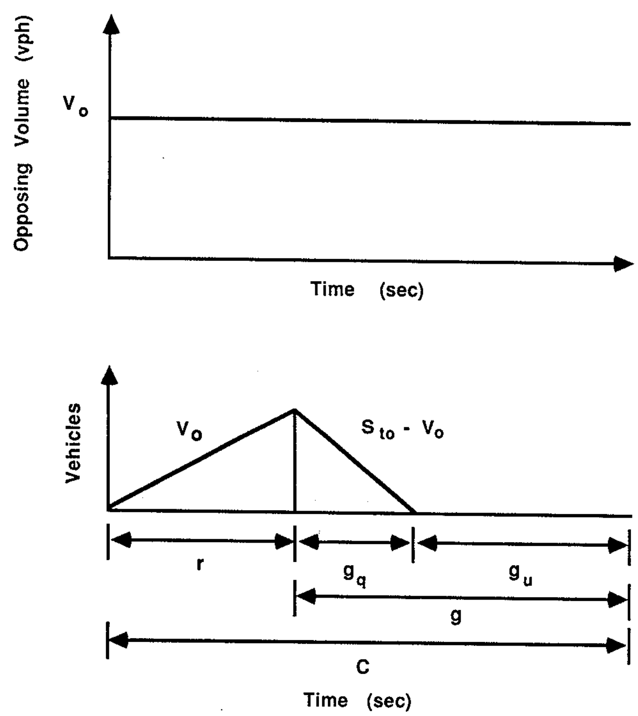


**FIGURE 2 Calculation of unsaturated portion of permissive green phase.**

calculations would require a recursive model which, as stated before, is beyond the scope of this work. The model thus assumes a "uniform" saturation rate, but the opposing flow rate is adjusted as described below.

The opposing flow used is the coded hourly volume $V_o$, multiplied by the $C/g$ ratio, where $C$ is the cycle length and $g$ is the effective green time during which traffic in the shared lane may move. In effect, the opposing flow faced by the permissive turners has been evenly distributed over the available turning time, recognizing that this is an approximation.

### *Finalizing the Model*

Calculations of the shared lane saturation flows were also modified for both multiple opposing lanes and signal timing parameters. The latter is necessary because the adjusted opposing flow ($V_o'$ above) moves only during its effective green; thus, the effective flow rate is found by multiplying $V_o'$ by the $C/g$ ratio, or

$$V_{oeff} = V_o' * (C/g) \quad (16)$$

where $V_{oeff}$ is effective opposing volume, corrected for both multiple opposing lanes and signal timing.

The modified form of $EL$ is thus

$$EL' = S_{to}/(S_{to} - V_{oeff}) \quad (17)$$

$EL'$ is substituted for $EL$ in Equations 6 through 11 to give the resultant saturation flows from a shared lane incorporated into TRANSYT.

The final models are expressed as follows:

$$S_{ls}' = S_{to} * V_l/V_s\,(ETV)' \quad (18)$$

and

$$S_{ts}' = S_{to} * V_{ts}'{}'/V_s\,(ETV)' \quad (19)$$

where

$S_{ls}'$ = modified left turn saturation flow from a shared lane, vphg;
$S_{ts}'$ = modified through saturation flow from a shared lane, vphg;
$V_s(ETV)'$ = modified volume in the shared lane, ETV/hr; and
$V_{ts}'$ = modified through volume in the shared lane, vph; or

$$V_s(ETV)' = (V_t + EL' * V_l)/N \quad (20)$$

and

$$V_{ts}' = V_s\,(ETV) - EL' * V_l \quad (21)$$

$V_l$ and $S_{to}$ are as defined previously. Here $S_{to}$ is the user coded saturation flow rate for the shared lane group, adjusted as appropriate for the number of lanes.

## IMPLEMENTATION INTO TRANSYT

A major aim of the shared lane enhancement was to ensure that minimal additional coding would be required by the user, and if possible all changes could be incorporated into the existing input data file. Additionally, the shared lane capability was only one component of a variety of changes being undertaken, so it had to be compatible with the other modifications, namely, permissible turners, stop-control, and sneakers. Through the implementation of a simplified analytical procedure, these aims were met, in addition to modeling the shared lane behavior somewhat realistically.

### User Interface

In regard to user input data, no new data are required to use the shared lane facility per se. All user interface either existed previously, or resulted from the addition of the permitted movement model. In short, the following three items summarize how the user informs TRANSYT-7F of a shared lane condition:

1. The shared stopline facility (card type 7) is used for the shared lane group, just as before. The through, unopposed movement must be the primary link and the permitted, opposed link (only one allowed) is one of perhaps several other secondary links.
2. The permitted opposed link is identified on the phase data card (card type 2X) with a negative number, as required for the permitted movement model. A secondary maximum flow rate to override the permitted movement model is optional (card type 29).
3. Sneakers and the opposing link numbers, with an optional percentage, are coded on the link data continuation card (card type 29).

### Model Implementation

The foregoing model was incorporated directly into TRANSYT's traffic simulation routine, in close coordination with the permitted movement model referred to previously (*3*).

To clarify how the permitted model is used, a typical simulation run of TRANSYT-7F will now have three iterations, or passes, through the simulation model (for "normal," nonshared lanes):

1. In Pass 1 all links are simulated, but permitted links are modeled with a uniform maximum flow rate based on the HCM.
2. In Pass 2 only permitted links are simulated, using the permitted movement model reported by Wallace (*3*). This provides a more realistic estimate of traffic performance as a function of opposing traffic.
3. Finally, in Pass 3 all nonpermitted links are resimulated to correct their flow patterns for any changes which occurred as a result of Pass 2.

In the case of a shared lane the above is slightly different. In Passes 2 and 3, the through link saturation flow rate is calculated as in Equation 19, and the left turn link's saturation flow rate is calculated according to Equation 18. During Pass 2, the latter's maximum flow rate is the lesser of the value calculated by Equation 18 or the rate calculated step by step by the permitted movement model.

During any simulation, a check is first made to see if the shared lane is acting as an exclusive left turn lane. If this is the case, the lane is treated as a permissive left and the approach through maximum flow rate, *TMFR*, reverts to

$$TMFR = LSATF_i * (N - 1)/N \tag{20}$$

where $LSATF_i$ is link saturation flow (total for all lanes), vphg; and $N$ is number of approach lanes as defined previously.

If, however, the lane is shared, the respective saturation flows are as follows:

$$S'_{ts} = (LSATF_i/N) * (V'_{ts}/V_s(ETV)') \tag{21}$$

and

$$S_{ls} = (LSATF_i/N) * (V_l/V_s(ETV)') \tag{22}$$

where

$S'_{ts}$ = modified through saturation flow from a shaded lane, vphg;
$S_{ls}$ = modified left turn saturation flow from a shared lane, vphg;
$V'_{ts}$ = modified through volume in the shared lane, vphg;
$V_s(ETV)'$ = modified volume in the shared lane, ETV/hr;
$V_l$ = left turn volume, vph; and $LSATF_i$ and $N$ are as previously defined.

Both saturation flows are assumed to be constant over their effective greens. In reality both flows vary over time as opposing flow varies; however, to model this would require a recursive approach, which was beyond the scope of this enhancement. The adopted procedure emulates traffic on a cycle-by-cycle rather than a step-by-step basis.

## CONCLUSIONS AND RECOMMENDATIONS

The procedure divided the available shared lane capacity among its tenants on the basis of ETVs. This is an approximation approaching the actual saturation flows as the lane nears capacity. In fact, capacity represents the limit when the analytical and actual saturation flows meet.

Shared lanes can now be modeled explicitly by using the existing or only slightly modified inputs. Inclusion of an explicit treatment into TRANSYT represents a significant enhancement, filling a previous void in the package. This procedure may be considered for adoption in other traffic analysis models as well.

Field validation of the adopted shared lane saturation flow models should, however, be undertaken. Only through such testing can it be assured that they are reproducing "real world" results.

An iterative procedure for shared lane analysis should be investigated if the current model proves inadequate, but such a procedure would require a major revision of TRANSYT, possibly a rewrite of the entire program. Such an undertaking would be resource consuming; therefore, the benefits would need to be weighed against this cost.

The enhanced version of TRANSYT-7F is referred to as Release 5, made available in the fall, 1987. The mainframe version is available from FHWA, HTO-23, 400 Seventh Street, S.W., Washington, D.C. 20590. The microcomputer version is available from the McTrans Center, 512 Weil Hall, Gainesville, Florida 32611.

## ACKNOWLEDGMENT

The authors gratefully acknowledge FHWA's sponsorship of this project.

## REFERENCES

1. D. I. Robertson. *TRANSYT: A Traffic Network Study Tool.* Road Research Laboratory LR 253, Ministry of Transport.
2. C. E. Wallace, K. G. Courage, D. P. Reaves, G. W. Schoene, G. W. Euler, and A. Wilbur. *TRANSYT-7F User's Manual.* rev. ed. FHWA, U.S. Department of Transportation, 1987.
3. C. E. Wallace, F. J. White, and A. Wilbur. A Permitted Movement Model for TRANSYT-7F. Presented at 66th Annual Meeting of the Transportation Research Board, Washington, D.C., 1987.
4. *Special Report 209: Highway Capacity Manual.* TRB, National Research Council, Washington, D.C., 1985.
5. R. Akcelik. *Timing Signals: Capacity and Timing Analysis.* Research Report ARR No. 123, Australian Road Research Board, 1981.
6. R. Akcelik. *SIDRA Version 2.2 Input and Output.* Technical Manual ATM No. 19, Australian Road Research Board, 1986.
7. B. E. Peterson, A. Hanson, and K. L. Bang. Swedish Capacity Manual. In *Transportation Research Record 667*, TRB, National Research Council, Washington, D.C., 1978, pp. 1–27.
8. *Saturation Flow Manual.* City of Edmonton Traffic Operations Section; University of Alberta Transportation Engineering Group, April 1980.
9. H. J. Lin, R. B. Machemehl, C. E. Lee, and R. Herman. *Guidelines for Use of Left-Turn Lanes and Signal Phases.* Center for Transportation Research Report CTR 3-18-80-258-1. University of Texas at Austin, Jan. 1984.
10. C. E. Lee, G. E. Grayson, C. R. Copeland, J. W. Miller, T. W. Rioux, and V. S. Savur. *The TEXAS Model for Intersection*

*Traffic—User's Guide*. Research Report 184-3. Center for Highway Research, The University of Texas at Austin, July 1977.
11. D. B. Fambro, C. J. Messer, and D. A. Andersen. Estimation of Unprotected Left-Turn Capacity at Signalized Intersections. In *Transportation Research Record 644*, TRB, National Research Council, Washington, D.C., 1977, pp. 113–119.
12. C. J. Messer and D. B. Fambro. Critical Lane Analysis for Intersection Design. In *Transportation Research Record 644*, TRB, National Research Council, Washington, D.C., 1977, pp. 26–35.
13. D. R. Drew. *Traffic Flow Theory and Control*. McGraw-Hill, New York, 1968.

*Publication of this paper sponsored by Committee on Highway Capacity and Quality of Service.*