A Permitted-Movement Model for TRANSYT-7F

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The TRANSYT-7F program has become one of the most widely used tools for traffic flow analysis and traffic signal timing optimization in the United States and several other countries. Although the model is one of the most useful, it is currently limited to the modeling of protected or unopposed traffic movements. Permitted-only left-turn operations can be approximated by adjusting the maximum flow rate and delaying the start of the effective green phase, but it is the user's responsibility to determine the appropriate values of these parameters. Permitted plus protected operations cannot be modeled at all. A project to develop an algorithm that will allow the explicit modeling of opposed, permitted traffic movements is described. The model was calibrated with field data collected in the suburban areas in and around Washington, D.C., by personnel of the FHWA Office of Traffic Operations. The field data were analyzed using multiple regression to produce the model. In addition, explicit treatment of left-turn "sneakers" has also been developed. Development of both algorithms and their implementation in the TRANSYT-7F program is described.

The Traffic Network Study Tool, Version 7, Federal (TRANSYT-7F) *(1)* 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 that is quite realistic in modeling homogeneous flows that are unencumbered by other traffic.

The applicability of the model is somewhat limited when one traffic movement must yield to another, for example, when permitted left turns are opposed by traffic traveling in the opposite direction. The current TRANSYT traffic model has remained essentially unchanged in this regard since the original version *(2)*. Traffic movements, represented as links, follow a simple rule of flow. A flow pattern representing the periodic departure rate as a function of time in a typical cycle is defined as follows:

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

where

$OUT(t)$ = output flow rate at time interval t, in vehicles per hour (vph);
$GO(t)$ = maximum flow, or go, rate (vph), which is the saturation flow rate at time t, normally expressed in vehicles per hour of green (vphg); 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.

It is clear from Equation 1 that no consideration is given to any opposing flow. This simply means that opposed, permitted movements are not explicitly modeled in TRANSYT-7F (or any prior version). Common traffic movements such as permitted left turns, right turns on red, and sign-controlled movements cannot be modeled directly.

Permitted left-turn operations can be approximated by reducing the *GO* pattern, reflecting the higher headways of such movements, and delaying the start of the effective green phase. The latter recognizes the fact that left turners must wait for the departure of the opposing queue before they can possibly execute their maneuver.

There are two major problems with this approach, aside from requiring the user to estimate the parameters. First, this approximation still assumes a uniform maximum flow rate, the *GO* pattern in Equation 1. In reality, the opposing flow rate fluctuates, thus the availability of gaps will vary with time. This is even more significant for sign-controlled traffic that may have to yield to several opposing flows.

Secondly, the combined protected and permitted control, such as protected plus permitted left turns and right turns on green (RTOG) and red (RTOR), cannot be modeled using this approximation. In these cases there are really two maximum flow rates required: (a) the saturation flow rate during the protected period, and (b) a rate dependent on the opposing flow, which varies with time as previously noted, during the permitted period.

The absence of explicit modeling of permitted movements has been one of the most serious limitations of the TRANSYT family of programs. The British Transport and Road Research Laboratory (TRRL) has installed a give-way model in TRANSYT-8 *(3)*; however, a change in the British government policy that became effective about the same time TRANSYT-8 became available requires each end user to purchase a license to use TRANSYT-8. Consequently, TRRL's enhancements reflected in that and future versions are unavailable in the public domain.

TRANSYT-7F is a public domain program, thus the only feasible solution to the previously described limitation in the United States is to modify TRANSYT-7F. In April 1986, FHWA awarded a contract to the University of Florida Transportation Research Center (TRC) to develop and implement the Enhancements to the TRANSYT-7F Program. The specific

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objectives of the first phase of the project are summarized as follows:

1. Develop a "gap acceptance" 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.

Development of the gap acceptance and sneakers algorithms and their implementation in TRANSYT-7F are described in this paper. The shared-lanes model is the subject of another paper *(4)*.

MODEL SELECTION

One of the prime objectives of the FHWA was to develop a model that was supported by current field calibration. Thus, no existing model could be adopted outright, but a review of previous work was useful in providing insights.

Past Research

Much research has been conducted in the area of gap acceptance. A good review of past work is given by Lin et al. *(5)*, and is paraphrased in the following.

The most notable early work was probably that of Tanner *(6)*, which dealt with minor street traffic interacting with a free flow traffic stream on a priority roadway. Webster and Cobbe *(7)* adopted Tanner's model to typical conditions at signalized intersections. Drew *(8)* and Fambro *(9)* applied assumptions to the earlier work to specifically predict left-turn capacity at signalized intersections.

Michalopoulos et al. *(10)* tested these methods and found that none of them were satisfactory in all cases. Consequently they developed a model derived from their field data. Following the review of the existing models, Lin et al., and Machemehl and Mechler *(5, 11)* derived a new model based on simulations using the TEXAS *(12)* model.

Naturally, the model used in TRANSYT-8 *(3)* is of interest. It deals directly with the objective of this project. More recently, Nemeth and Mekemson *(13)* derived a model for predicting left-turn saturation flows using NETSIM *(14)* simulated data rather than field data. This has been referred to by some as the Ohio State model. Finally, the 1985 *Highway Capacity Manual* (HCM) *(15)* has models for estimating saturation flows for unprotected left turns at signalized intersections and for give-way traffic at unsignalized intersections.

The various models have included a variety of factors on which the maximum left-turn flow rate (or capacity) depends (e.g., opposing flow, signal timing, number of opposing lanes, and opposing approach speed). All of the aforementioned left-turn models assume that no left turns occur while there is an opposing queue, and once the queue dissipates the opposing arrivals are randomly distributed. Both of these assumptions are certainly reasonable. The assumption of random arrivals is valid for isolated control when the maximum flow rate is calculated as a scalar value applied to the entire effective green phase. However, in TRANSYT the opposing flow rate is known and is the *OUT* pattern on the opposing link.

These models are, however, not directly applicable to the desired application in TRANSYT-7F. Several of these models were calibrated for left turns at unsignalized intersections, which clearly does not apply to the objective for use in TRANSYT-7F. Others were calibrated to estimate an average left-turn flow rate over a period of time, namely a cycle, including turns during or following the change period.

The latter apply only in the case of deterministic models that, for example, simply apply a saturation flow rate in such calculations as the degree of saturation on V/C ratio,

$$V/C = \frac{vC}{Sg_e} \tag{2}$$

where

V/C = volume to capacity ratio;
v = volume of the left turn movement (vph);
C = cycle length in seconds;
S = saturation flow rate in vehicles per hour of green; and
g_e = effective green in seconds.

In TRANSYT-7F a microscopic flow rate function is needed, which estimates the periodic maximum left-turn flow rate as a function of the periodic opposing flow rate. This varies with time in the cycle as noted earlier.

A general form of the model, based on earlier research, may nonetheless apply as follows:

$$MFR = f(Q, T, N, u) \tag{3}$$

where

MFR = periodic maximum flow rate of opposed, permitted traffic, in vph as a function of the succeeding variables;
Q = the periodic opposing flow rate (vph);
T = the critical gap;
N = the number of opposing lanes; and
u = the opposing traffic speed.

Field Calibration Study

To determine the best form of the model, a field study was designed by the TRC and conducted by FHWA. In order to obtain data that were consistent with the way the model would be implemented in TRANSYT, it was important to use a microscopic gap acceptance study.

Data Collection and Reduction

The study and programs were developed by White *(16)* as a graduate research study. The field data were collected in the Washington, D.C., and surrounding area by FHWA's Office of Traffic Operations, Systems and Software Support Branch.

The field data were collected on a portable (notebook) computer. The specific data included the traffic signal timing (from the start of the green phase to the end of the yellow) and traffic flows. Entries were made specifically for each permitted movement and for each vehicle in the opposing streams. Permitted movements were entered only if they had been stopped and queued. The last vehicle in a queue was identified differently because this vehicle, and any ahead of it that accepted the same gap, had to be ignored. The reason for this is that the gap may not have been critical.

The completed data were uploaded to an IBM PC or compatible computer for processing. The data were reduced to perform the following:

1. Identify headways that were accepted by legitimate permitted vehicles,
2. Group the headways into one (or more) second classes and calculate the average flow rate within each class, and
3. Calculate the maximum flow rate of permitted movements for each class.

The processed data are then ready for analysis.

Experimental Design

The final step in the process is to analyze the *MFR* and opposing volume pairs through regression analysis to determine the final model. The Statistical Analysis System (SAS) *(17)* was used for the analysis.

The experimental plan included examination of the following separate opposed movement types:

- Left turns, permitted plus protected;
- Left turns, permitted only; and
- Arterial left turns, unsignalized.

The independent variables were as follows:

- Opposing flow, a continuous distribution measured during the studies;
- Opposing speeds, less than 40 mph and greater than or equal to 40 mph; and
- One or two (or more) opposing lanes.

Some of the discrete cells of this 3 × 2 × 2 matrix were not applicable and others were deemed unimportant for the purposes of this study. The complete experimental design matrix is given in Table 1, with the sample sizes shown in the cells. In Table 1, a sample is nominally a 2-hr study at one intersection. (Note: several RTOR sites were studied as well, but it was decided to use a model similar to that in TRANSYT-8 for RTOR operation and stop controlled approaches. These are not discussed further in this paper.) A total of approximately 27,000 gaps were included in the 27 samples.

The objective is to determine the best model, or set of models, to predict maximum flow rates for the various types of permitted movements as a function of opposing flow rate and as few other variables as possible.

The reduced field data for the cases with three or more samples were initially analyzed using SAS with the following model formulations:

$$\text{Polynomial:} \quad MFR = A + BQ + CQ^2 + DQ^3 \qquad (4)$$

$$\text{Exponential:} \quad MFR = A \exp[(-B(Q^{**}C)] \qquad (5)$$

where

MFR = maximum flow rate of left turns in vehicles per hour, as before;
Q = opposing flow rate in vehicles per hour, also, as before; and
A,B,C,D = model coefficients.

The data were fit using a nonlinear regression procedure in SAS. During the best fit regression analysis, the individual samples were weighted by the actual number of gaps making up the data point. Thus, gap classes with relatively many individual observations had more influence in the model than classes with few individual samples.

Although both model forms produced similar results, the exponential form has several clear advantages over the polynomial form:

1. In the higher opposing flow range the exponential models behave more realistically. The polynomial models either went negative or began increasing after reaching a minimum value.
2. The negative exponential goodness of fits were better.

Model Selection

Based on the reasonableness of the exponential models, it was concluded that the model selected for implementation in TRANSYT-7F would be as follows:

TABLE 1 EXPERIMENTAL DESIGN MATRIX

	One Lane, < 40 mph		Two or More Lanes, < 40 mph		One Lane, ≥ 40 mph		Two or More Lanes, ≥ 40 mph	
Condition	Data Code	N	Data Code	N	Data Code	N	Data Code	N
Permitted only	PO11	3	PO12	3	PO21	1	PO22	3
Protected plus permitted	PP11	4	PP12	3	PP21	1	PP22	3
Unsignalized	US11	0	US12	3	US21	0	US22	3

NOTE: 40 mph = 64 km/hr.

$$MFR = \begin{cases} S, \text{ if protected} \\ A \exp[-B(Q^{**}C)], \text{ if permitted} \end{cases} \tag{6}$$

where S is the saturation flow rate (vphg) for protected left turns and the rest were defined previously.

As just noted, it was desirable to combine models for different conditions among the total of eight for which data were available. The model parameters were compared using a Z-test. It was found that only the unsignalized models were suitable for combining. Several other models were statistically significant, but there was no rational reason for combining them. Therefore it was concluded that a total of seven sets of model coefficients should be implemented in TRANSYT-7F (see Table 2).

TABLE 2 INDEPENDENT REGRESSION MODELS

	Model Coefficients			
Data Set	A	B	C	R^2
PO11	1217	3.14E-3	1.00	0.86
PO12	1463	1.28E-4	1.47	0.88
PO22	1650	1.79E-3	1.09	0.89
PP11	1524	2.83E-4	1.38	0.92
PP12	1640	2.03E-4	1.36	0.93
PP22	1483	2.61E-4	1.37	0.80
US12	1443	5.01E-4	1.27	0.89
US22	1390	1.25E-3	1.14	0.74
US[a]	1404	9.36E-4	1.18	0.86

NOTE: Model: $MFR = A \exp(-BV^{**}C)$.

[a] Combination of US12 and US22.

Treatment of Vacant Cells

Table 1 has a total of 12 cells, but, as stated previously, adequate data were obtained for only 8 of the cells. Assignments for the cells with insufficient data were made as follows:

1. For the two permitted and permitted plus protected cells with inadequate data for single lane and high speed, the single-lane low-speed model was selected.
2. For the vacant unsignalized cells, the calibrated model for permitted-only, single-lane condition was adopted because there was close comparison of the unsignalized, two-lane model with its corresponding permitted-only model.

MODEL IMPLEMENTATION

Having selected a model for gap acceptance, it was necessary to install it in the TRANSYT-7F program. In fact, the TRC had already accomplished much of this as part of a graduate research project *(18)*.

In addition, the treatment of "sneakers," which was not a subject of the field validation, was implemented in the model. The significant issues involved are user input data and model operations.

Input Data

From the preceding model formulation, it is clear that the following specific inputs are required by the permitted model, including the source of the data:

1. Saturation flow rate (vphg) for protected periods—this is an existing input.
2. Maximum flow rate (vph) of permitted movements to fix the upper limit of the model—a new input.
3. Link flows (vph) and speeds—existing inputs.
4. Opposed or opposing link, including what percentage of the opposing links' flows apply—new inputs.
5. "Sneakers" (vehicles per cycle)—a new input.

Thus, the required new inputs, which can all be accommodated on existing cards, are

1. Identification of permitted links and of which phases they are permitted in, and
2. Identification of the opposing links and the percentage of traffic applicable (the default will be 100 percent).

Other optional inputs are

1. The secondary maximum flow rate that will be the upper limit of the model. The defaults are the A coefficients given in Table 2; and
2. Number of "sneakers" per cycle. No sneakers will be assumed as the default.

The user instructions for these new inputs will be included in an update to the *TRANSYT-7F User's Manual (1)* for Release 5 of the program. All previously existing Release 4 data sets will be upward compatible to Release 5 of the program itself.

Model Operations

The major interest in this paper is how the permissive model will be implemented in TRANSYT-7F. There are two parts described separately in the following subsections.

Gap Acceptance Model

This is the model calibrated by the field studies discussed previously. Initially, sneakers are not considered.

In the standard TRANSYT simulation process, links must be simulated in upstream-to-downstream order so that the link-to-link platoon propagation is correct. In the case of permitted operations there is a further requirement that opposing links be simulated before their opposed links so that the *OUT* pattern of the former is known. This adds a serious complication to the order in which the links are simulated. To simplify the problem and to avoid a time-consuming recursive approach, it was decided to first simulate all links in the usual order without applying the gap acceptance model, and then to resimulate the permitted links to obtain better estimates of their delays and stops. It is recognized that this changes the flow patterns of permitted links, and therefore, their effects downstream, but it is assumed that this bias will generally be minimal.

The simulation of a protected plus permitted link will thus initially result in a maximum (*GO*) pattern with two flow levels. The first will be the saturation flow rate (*S*) during the protected phase (the primary *GO* pattern). At the end of the protected phase, the *GO* pattern will drop down to level *A* from the permissive model (see Equation 6). As usual, the *OUT* pattern will be the lesser of the *GO* or the arrival (*IN*) patterns. If the phase order was permitted then protected, the *GO* pattern would reverse to *A* and *S*.

Next the permissive model will be exercised to resimulate the permitted link. During each step of permitted operation, the model will calculate the value of the *MFR* as a function of the opposing link's output, or *OUT* pattern, and the resulting permitted link *OUT* pattern will be the lesser of the calculated *MFR* or its own *IN* pattern. As long as *IN* exceeds the *MFR*, vehicles will queue and contribute to the *OUT* pattern later in the cycle.

Sneakers

The "sneakers" algorithm to be implemented is trivial. It is easy to see that when cleared to go, sneakers will do so at relatively low headways often equivalent to through traffic. Thus, it is not the maximum flow rate at which they discharge that is significant, but how long it takes to do so.

Because the user will have coded the number of "sneakers" in vehicles per cycle, the evaluation is simple. The time to clear sneakers is calculated as follows:

$$t = 3600s/SrN \tag{7}$$

where

t = time to clear sneakers in steps;
s = user-coded number of sneakers per cycle;
S = systemwide saturation flow rate (default is 1700 vphg per lane);
r = seconds per step resolution; and
N = number of left-turn lanes derived from the coded maximum flow rate.

Thus, at the end of normal effective green, if the simulation model detects that there is still a queue on the permitted link, and if the next phase is red, the *OUT* pattern will be continued into an extended period of effective green up to *t* steps at the flow rate *GO* = *S*, as before, or *IN*, depending on whichever is less.

Although this approach does not explicitly consider the effect of "sneakers" on the following phase, the user can model any such effect by delaying the start of effective green on the movements in the following phase if observations indicate this is appropriate.

Example

To illustrate the use of the model, an example is shown in Figures 1 and 2. Shown in Figure 1 is a simulated TRANSYT-7F flow profile diagram for an opposing through movement of 1,000 vph, and Figure 2 is an opposed, protected and permitted left turn. The protected left-turn period is from Step 4 through Step 19. During the permitted phase both movements have the same effective green in this example (Steps 20 through 50), but the permitted left turn is unable to begin discharging until the opposing queue has dissipated at Step 26. Thus, left-turn arrivals between Steps 20 and 26 queue, as indicated by *I* in Figure 2. Note that for Figure 1:

I = arrivals that queue either because the signal is red or the arrival rate exceeds the maximum rate;
O = arrivals on green, which either join the back of an existing queue, if one exists, or depart without delay; and
S = discharge of the queue, generally at the saturation flow rate.

In Figure 2, *I*, *O*, and *S* bear the same definitions as given in Figure 1; however, note the arrivals on green phase during the permitted phase for that queue. The unbroken outline indicates the TRANSYT-7F *GO* pattern for the left-turn link.

Beginning at Step 27 the left turners may begin moving at a rate that may vary from step to step, as a function of the opposing *OUT* pattern. Finally, the effect of "sneakers" (at two per cycle and a 90-sec cycle) is shown in Steps 51 through 53. The complete *GO* pattern for the left turn is drawn over the flow profile.

To illustrate the difference between this microscopic, time series approach and the macroscopic approach of some of the earlier models, the area under the *GO* pattern for the left turn can be integrated and divided by the time duration (Steps 20 through 53), which results in an average maximum left-turn volume of 460 vph. This compares with a value of 470 vph, which would be obtained from Michalopoulos' model *(10)*.

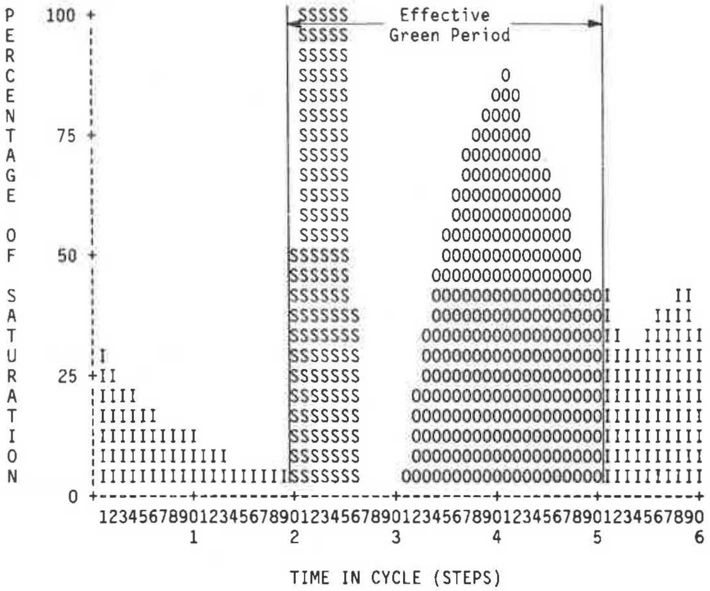
CONCLUSION

The addition of a permissive model that allows explicit modeling of permitted movements and "sneakers" will remove one of the most serious limitations of the TRANSYT-7F model. This enhancement will make the program significantly more useful to practitioners who have a large number of permitted-only or protected plus permitted signal operations. It will particularly be more useful in the latter situation because previously some of the traffic simply had to be ignored.

It must be recognized that the coefficients given in Table 1 were calibrated by field data collected in the Washington, D.C., area. Although the model is probably reasonable for general application, it would be desirable to expand the calibration to other areas. The appropriate discharge rate for sneakers should also be calibrated.

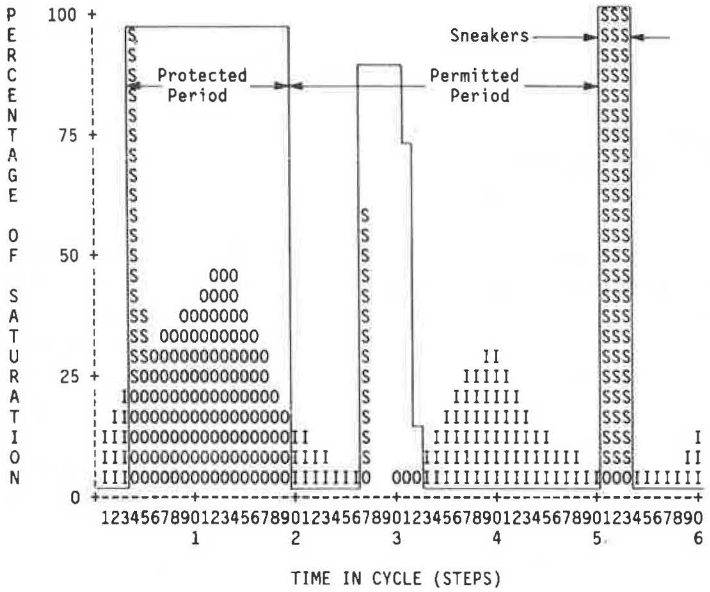
ACKNOWLEDGMENTS

The authors thank the other FHWA employees who conducted the field studies. This important enhancement to TRANSYT-7F



Key: I = arrivals that queue, either because the signal is red or the arrival rate exceeds the maximum rate.
0 = arrivals on green which either join the back of an existing queue, if one exists, or depart without delay otherwise.
S = Discharge of the queue, generally at the saturation flow rate.

FIGURE 1 **Permissive model application to opposing through link.**



Key: I,0,S = as described in Figure 1. Note here the arrivals or green during the permitted phase that queue.
——— = the TRANSYT-7F 'GO' pattern for the left turn link.

FIGURE 2 **Permissive model application to permissive left-turn link.**

would not have been possible without this support. The assistance and advice given by Steven Linda of the University of Florida's Institute of Food and Agricultural Science's Statistics Department are also appreciated.

The enhanced TRANSYT-7F program, which will be referred to as Release 5, will be available in the summer of 1987 from FHWA for mainframe applications and from the Center for Microcomputers in Transportation (McTrans) for microcomputer users.

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