Integrating Feedback into Transportation Planning Model: Structure and Application

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A new structure for the transportation planning model that includes feedback among demand, assignment, and traffic control is presented. New methods, combined with a renewed interest in transportation planning models prompted by the Clean Air Act of 1990 and the Intermodal Surface Transportation Efficiency Act of 1991, warrant reconsideration of the traditional four-step transportation planning model. An algorithm for feedback that results in consistent travel times as input to travel demand and output from route assignment is presented. The model, including six stages of Trip Generation, Destination Choice, Mode Choice, Departure Time Choice, Route Assignment, and Intersection Control, is briefly outlined. This is followed by an application comparing a base year 1990 application with a forecast year of 2010. The 2010 forecast is solved both with and without feedback for comparison purposes. Incorporation of feedback gives significantly different results than does the standard model.

Conventionally applied transportation planning models conforming to the Urban Transportation Modeling System (UTMS) have four sequential steps of trip generation, trip distribution, mode choice, and route assignment (*1*). Available evidence suggests that UTMS is not a behavioral representation of trip making. Foremost, when the four-step model is strictly applied, there is no feedback between the travel time on the network and the estimation of demand. It is widely understood that if congestion is significant, it will affect the individual's decision to make the trip, choice of destination, mode, and departure time. Moreover, this model structure does not account for the impact of signal control on route choice and travel demand. For many trips, delay at intersections is as significant as vehicle running time, and a prolonged delay may motivate a change in route. Not incorporating elastic demand or responsive intersection control in the theoretical framework will cause an incorrect representation of network flow (*2*).

Over the past 20 years, methods have been developed to model the feedback among assignment, demand, and intersection control. Recently, some literature has proposed combining demand, assignment, and intersection control into a single modeling framework (*2,3*). This paper reviews the theory and develops a procedure with feedback among assignment, demand, and intersection control. The procedure is applied to the Baltimore-Washington metropolitan region. The results suggest that introducing feedback between congested travel times and demand and between link flows and intersection control provides a more realistic representation of travel patterns and traffic flows. The procedure is especially relevant in the context of long-term forecasting where the possible interrelationship between travel demand and emerging metropolitan structure is less understood.

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RESEARCH

It has long been recognized that travel demand is influenced by network supply. The example of a new bridge opening where none was before, inducing additional traffic, has been noted for centuries. Much research has gone into developing methods for allowing the forecasting system to directly account for this phenomenon. Evans published her doctoral dissertation on a mathematically rigorous combination of the gravity distribution model with the equilibrium assignment model (*4*). The earliest citation of this integration is the work of Irwin and Von Cube, as related by Florian et al., who comment on the work of Evans:

> The work of Evans resembles somewhat the algorithms developed by Irwin and Von Cube [*Bulletin 347: Capacity Restraint in Multi-Travel Mode Assignment Programs*, HRB, 1962] for a transportation study of Toronto, Canada. Their work allows for feedback between congested assignment and trip distribution, although they apply sequential procedures. Starting from an initial solution of the distribution problem, the interzonal trips are assigned to the initial shortest routes. For successive iterations, new shortest routes are computed, and their lengths are used as access times for input the distribution model. The new interzonal flows are then assigned in some proportion to the routes already found. The procedure is stopped when the interzonal times for successive iteration are quasi-equal. (*5*)

Florian et al. proposed a somewhat different method for solving the combined distribution assignment, applying the Frank-Wolfe algorithm directly. Boyce et al. provide an excellent summary of the research to date on network equilibrium problems, including the assignment with elastic demand (*6*).

Signal-setting policies generally assume that route choices are unaffected by the signal settings chosen (*7*). The reverse is also held true, signal settings are unaffected by the routes chosen. This presumption of independence results in a lag in change to signal policies, which reaffirm themselves in more static traffic patterns. The assumption of complete independence is not supported by available evidence. Common experience suggests that signal policies that provide faster travel on arterials than side streets help to induce drivers to use the favored roads. Moreover, considering the relationship will be even more critical in projecting traffic trends. Over time, signal policies do respond to changes in travel demand.

To overcome these problems, several attempts have been made to combine an assignment algorithm with intersection control. These have generally been developed to improve traffic operations, and the perspective is that of the engineer rather than the planner. They offer one path that may be taken for combining as assignment with intersection control.

The naive method for estimating such flows can be termed an "iterative optimization assignment algorithm," as proposed by Allsop. Such a method alternates between network optimization of signal settings using software such as TRANSYT and a full equilibrium assignment. A recursive implementation of this model has been documented (*8*).

A more rigorous models has been developed by Tan et al., called the hybrid optimization model (*9*). This research has noted theoretical problems with iterative optimization models, including the non-necessity of convergence and the possible convergence to nonoptimal signal settings. Alternative mathematical formulations, including treating green time as a flow to be optimized, have been proposed by Smith (*10–15*), Smith and Ghali (*16*), and Van Vuren et al. (*17*).

The application of this research to real-world problems has been slow in coming due to lack of resources to gather data or implement a system and lack of computing facilities. The most likely reason, however, is either lack of knowledge of the methods by practitioners or the lack of recognition of its importance. This issue is important because of the added significance given to transportation planning methods with the 1990 Clean Air Act and the 1991 Intermodal Surface Transportation Efficiency Act.

This paper uses data from the Baltimore-Washington metropolitan region to evaluate the relative advantages of building feedback among assignment, travel demand, and intersection control. These advantages can be best understood by answering such questions as:

- What is the likely future impact of changes in urban structure on travel demand?
- How will individuals alter travel behavior in response to increased congestion?
- Given the ever-present economic, environment, and political constraints to providing additional network capacity, what is the likely impact on travel behavior 20 years from today?

In the Application of Model section, sensitivity tests are performed comparing conditions in the base year (1990) with forecast land use and anticipated networks 20 years hence (2010).

MODEL REGION

The model, which is called TRAVEL/2, is applied to the Baltimore-Washington metropolitan area, with a focus on Montgomery County, Maryland. The full region, which is home to more than 6 million people, two central cities, and numerous suburban activity centers, is divided into 651 traffic zones for analysis. Thirteen of the zones serve as external stations to the region incorporating parts of four states, with access to the region from southern Pennsylvania; eastern West Virginia; central Virginia; and eastern, western, and southern Maryland. Most of the traffic zones (292), however, are located in Montgomery County. The zone structure is derived from zones defined by the Baltimore Regional Council of Governments, the Metropolitan Washington Council of Governments, and the Montgomery County Planning Department (MCPD) for their transportation planning models.

In 1990, 750,000 persons were living in 280,000 households and employed at more than 410,000 jobs in Montgomery County, Maryland. Located to the northwest of Washington, D.C., Montgomery County has grown from being a bedroom suburb into a major employment center. Changing lifestyles and commuting patterns, as well as job and population growth, have had a great impact on the transportation system in Montgomery County (as elsewhere in the country), resulting in increased congestion on the road network. These forces led the county to adopt an Adequate Public Facilities Ordinance in 1973. Determining the adequacy of public facilities, with the consequence of permitting or postponing land development, is the prime reason for developing this transportation planning model. Other uses, including project planning analysis, also involve application of the model (*18*).

DATA

The data used within the TRAVEL/2 model are determined by what information is both available for the present and can be forecasted. Some desirable data types, such as income, are not being used because of difficulties in forecasting them and availability issues.

The primary data set is land use accounted for as housing units and employment by type. Housing units are classified as single or multiple family, while employment is divided into office, retail, industrial, or other. The land-use numbers that are used in this analysis were developed from the ROUND IV cooperative forecast of the Metropolitan Washington Council of Governments and the ROUND III cooperative forecast of the Baltimore Regional Council of Governments (*19,20*). Other demographic data, such as the age structure of the population and the household size distribution, were obtained from the same sources.

Mode choice data elements, which were held constant throughout this study, were developed by MCPD. These elements included transit fare matrices; parking costs; mode availability variables, such as household automobile ownership and the percentage of houses and jobs within walking distance of transit; and quality of access variables, including the ratio of sidewalk to street miles and employment density.

MCPD developed automobile networks and definitions of turning lanes for inside Montgomery County as well as transit networks for the region. Automobile networks outside Montgomery County were developed by the appropriate Councils of Government. The networks used in transportation analysis in the region included 16,000 links and more than 5,000 nodes. Network detail is approximately uniform throughout the region. Intersection analysis is conducted only for intersections with signals within Montgomery County. Some 380 signalized intersections are coded and optimized in the implementation of the TRAVEL/2 model, a discussion of which follows. Nonsignalized intersections are treated conventionally in the model. Because intersection analysis is performed only within Montgomery County, a separate set of volume delay functions are used inside and outside the county. These model rates and their development are fully discussed in *The TRAVEL/2 Model:*

Technical Documentation (*21*). The data sources are discussed in *The TRAVEL/2 Model & Transportation Information System User's Guide* (*22*).

MODEL STRUCTURE

The TRAVEL/2 model structure differs from the conventional model in several ways. Figure 1 shows a flowchart of this model structure, which can be compared with the conventional transportation planning model shown in Figure 2. The algorithm to execute assignment with intersection control and elastic demand is shown in Figure 3. The TRAVEL/2 model is set up for internal feedback so that when an elastic-demand assignment is performed, the travel times input to the demand become identical to those output from the assignment when the model converges to a solution. This model also contains responsive intersection control, which in the conventional model is implicitly static and nonresponsive. Further, the model explicitly contains a stage where departure time choice is considered as a function of congestion variables.

MODEL COMPONENTS

Numerous equations, functions, and mathematical relationships comprise the TRAVEL/2 model. Specifying them all is beyond the scope of this section, as noted before. They are provided in the Round IV Cooperative Forecast for the Baltimore area (*21*). However, the basic variables and structures are discussed below.

Trip Generation

Trip generation has several components. Trip rates at the home end are estimated from a cross-classification model,

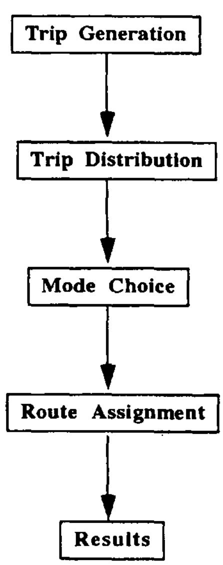

FIGURE 1 Conventional transportation planning model.

where the rate applied is a function of dwelling type, household size, and age of the trip maker. There are two dwelling types: single and multiple family. There are five household sizes, ranging from 1 to 5 or more persons (5 categories). The age of the trip maker is the percentage of persons in each 5-year age cohort from 0 to 85+ (18 categories). At the work end, trip rates are a function of employment by type, namely office, retail, and other employees. At the nonhome, nonwork end, trips are a function of retail employment and population. Trip rates have been estimated for seven purposes, including specific chained work to home trips.

Trip Distribution

Trip distribution as applied uses the doubly constrained gravity model structure. Impedance functions have been estimated for each trip purpose. Impedance is defined as a function of congested automobile travel time. The authors worked separately to improve this model to use a composite multimodal impedance function. The following equation is used:

$$t_{ij} = k_{ij} p_i \frac{(q_j f_{ij})}{\sum_{i=1}^{I} (q_j f_{ij})}$$

where

t_{ij} = number of trips from origin i to destination j,
p_i = number of trips produced at origin i,
q_j = number of trips attracted to destination j (total trip origins = total trip destinations), and
k_{ij} = socioeconomic adjustment factor for zone interchange i to j = 1.

The friction factor is as follows:

$$f_{ij} = \exp(-bC_{ij})$$

where b is deterrence coefficient and C_{ij} is peak-hour travel time between origin i and destination j.

Mode Choice

Mode choice is estimated as a multinomial logit model for seven modes and two primary purposes (work and nonwork). The factors determining the utilities of mode choice are travel time, mode availability, the quality of the access trip, and cost. The actual relationships in the model use the variables relative time and relative cost, which are the ratio of the time, or cost, of a mode divided by the time, or cost, of making the same trip by driving alone in the base year 1989. The 1989 automobile time and automobile cost serve as a constant base on which to normalize the model relationships. The higher the "relative time," the less attractive the mode, which is true for both automobile and nonautomobile modes. For the base year, the automobile relative time and relative cost equal 1:

$$P(m_{ij}|M_{ij}) = \frac{\exp(U_m)}{\sum_{m=1}^{M} \exp(U_m)}$$

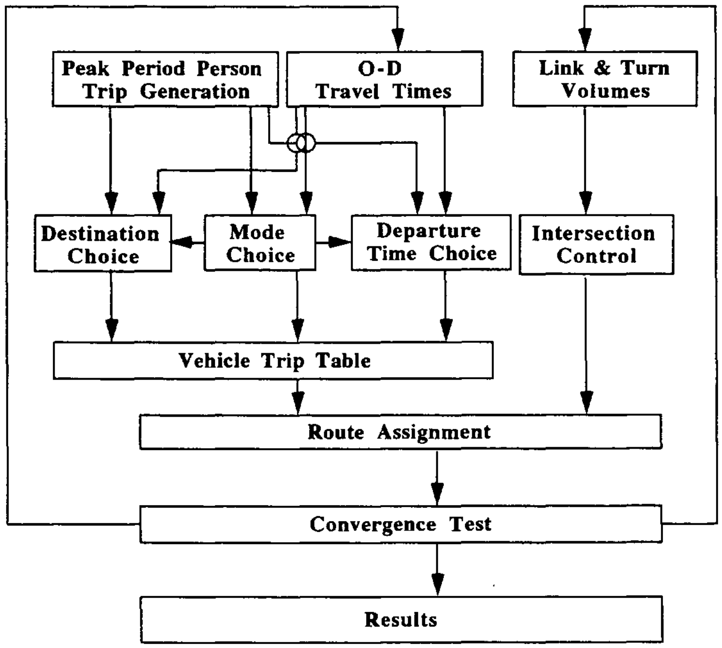

FIGURE 2 Transportation planning model with feedback.

where

U_m = utility function for choice m,
m = the (mode) choice under question, and
M = the set of (mode) choices possible.

Departure Time Choice

Departure time choice is specified by a binomial logit model, with the choice being travel in the peak hour or in the shoulder hours of the peak period. The peak period is defined as 3:30 to 6:30 p.m., the peak hour is from 4:30 to 5:30 p.m. Parameters were estimated for work and nonwork purposes. The primary components of the utilities are the network variables of congested and freeflow travel times and distance.

Step 0: Initialization

- Set intersection delay = 0 , link travel time = freeflow, demand=0

Step 1: Equilibrium Assignment Program

- Perform one iteration of the assignment problem with
  intersection delay , link travel time , O-D demand as specified
- Let the solution of the assignment optimization problem be
  link flows, link travel time, intersection flows, O-D impedance

Step 2: Stopping Criterion

- If closing criteria are greater than the prespecified amount
  and the number of iterations is less than the maximum
  prespecified number Then go to Step 3, Else stop

Step 3: Control Optimization Problem

- Perform the signal optimization problem utilizing intersection flows
- Compute intersection delay from signal timings and turn flows

Step 4: Demand Reestimation

- Recompute O-D demand from O-D impedance; GOTO Step 1.

FIGURE 3 Algorithm for assignment with intersection control and elastic demand.

Route Choice

The automobile assignment is solved by the static user equilibrium method. The variables are freeflow travel time, volume, and capacity, which are used to estimate congested travel time. The general form of the equation was developed by Levinson (*23*) and is a modified form of the standard Bureau of Public Roads form, with an additional term to represent delay at volumes less than capacity. Link functions have to be developed considering intersection control. Although the conventional model implicitly incorporates delay from intersection in link freeflow speeds and capacity, this model raises link capacity and freeflow speed on arterials from what would otherwise be expected to avoid double counting the additional time penalty at intersections.

The equation for link travel times is as follows:

$$Tc = Tf\left[1 + A\exp\left(\frac{Q}{\mathrm{CAP}}\right) + B\left(\frac{Q}{\mathrm{CAP}}\right)^{c}\right]$$

where

Tc = congested travel time,
Tf = freeflow travel time,
Q = flow (veh/hr),
CAP = capacity (veh/hr), and
A,B,c = calibration parameters.

Intersection Control

The output of the intersection control model is the average delay for a turning movement. The delay model is the Hurdle model (*24*), and cycle time and green time is estimated using methodologies suggested by Webster (*25*). Lane adjustment factors and lane utilization factors are adopted from Chapter 9 of the *Highway Capacity Manual* (*26*). The green time is assigned to equalize the volume/saturation flow on the critical approaches.

The equations for congested travel times at intersections are as follows:

$$d = \mathrm{CYC}\,\frac{\left(1 - \dfrac{g}{\mathrm{CYC}}\right)}{2} + T\,\frac{\left(\dfrac{Q}{\mathrm{CAP}} - 1\right)}{2}$$

$$\mathrm{CYC} = \frac{(1.5L + 5)}{\left(1.0 - \displaystyle\sum_{p=1}^{4} \frac{Q}{\mathrm{SAT}}\right)}$$

where

d = average delay,
CYC = cycle length,
T = length of congested time period,
g = green phase length,
L = lost time per cycle,
Q = volume (flow) on movement in vehicles per T,
CAP = capacity on movement [(g/CYC) * SAT],
SAT = saturation flow rate (1,800 veh/hr of green), and
p = phase.

APPLICATION OF MODEL

This section discusses several sensitivity tests that were performed using the TRAVEL/2 model. The model is tested by running the model for two different time periods: a 1990 base year and a 2010 forecast year. Various results are compared for the two time frames to demonstrate how feedback affects results for a typical application.

The data sensitivity tests here compare 1990 and 2010 land use and demographics on 1990 and 2010 automobile and transit networks. Summaries of some key data (for Montgomery County) are presented in the following table:

Data Input	*1990 (thousands)*	*2010 (thousands)*
Housing units	280	340
Jobs	415	650
Road capacity	3,210	4,190

Mode choice was not iterated within the feedback process and therefore is not discussed. The mode choice in these runs was solved previously using congested times for both the base 1990 and future 2010 scenarios. The formulation of the mode choice model, including non-automobile times, costs, and trip quality variables, makes it both relatively insensitive to changes in travel times and computationally intensive.

Trip Generation

As noted earlier, for the home end of trips, generation is determined with a cross-classification model, while a regression model is used for the nonhome end of trips (*21*). In Montgomery County, for the base year 1990, Figure 4 suggests that 27 percent of all afternoon work-to-home trips originating in Montgomery County have stops, and 29 percent of those trips destined for the county are linked. Estimates of the forecast year 2010 are similar, with 28 percent of those trips being linked.

The normalization procedure results in the total number of work to other (linked) destinations, which is equal to the number of other-to-home (linked) origins at the traffic zone level. Regionally, the number of trip origins equals the number of trip destinations for each purpose.

Given that these trips are significant in trip generation, they can be expected to affect distribution. Chained trips are distributed as if they are two trips: work-to-other (linked) trip and other-to-home (linked) trip. Both of these trip purposes have different, and shorter, trip length distributions than work-to-home trips.

Trip generation for nonwork trips is also important. These trips grow significantly over the period with changing land use and demographics. A 21 percent increase is found in nonwork trips, which compares with a similar 18 percent increase in households.

Departure Time Choice

The TRAVEL/2 model includes an explicit model of departure time choice as a function of congestion. Given a 3-hr peak period with a fixed number of trips, the peak hour would have no less than 33 percent of all peak period travel. Work trips, however, exceed that fraction as they are less elastic in departure time choice than nonwork trips. Nonwork trips also tend to peak in the third hour of the afternoon peak period, and work trips (and traffic overall) peak in the second hour. However, because of the greater length of work trips, more than one-third of all peak period travel occurs in the peak travel hour.

By assuming contant factors over time instead of incorporating a congestion-based departure time choice model, the result would be 6 percent more work and 10 percent more nonwork trips on the road network in the forecast year. This quantity of trips is certainly significant, particularly considering the desire to use the model in a relativistic fashion, comparing a future forecast with a base year estimate.

Destination Choice

Application of the model suggests that congestion in 2010 will be worse than the base year. Without feedback, 2010 would

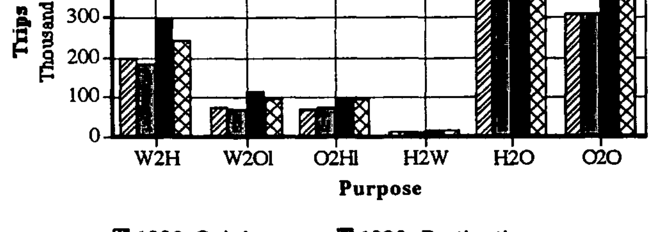

FIGURE 4 Trip generation.

appear to be an unmitigated disaster, with feedback, 2010 is worse than the present, but likely not intolerable. Although trip length declines in response to both land use changes and traffic congestion, trip time increases, and thus the amount of delay as perceived by the traveler increases. The forecast showed a larger increase in jobs than housing, so the county would have to import more workers in the morning from outside and send more home in the afternoon, hence the increased travel time for trips originating in the county (generally work trips end in the afternoon peak). All of this assumes no major change in travel behavior. This is shown in Table 1.

Table 2 gives a summarized trip table of trips to and from Montgomery County, Maryland, from adjoining jurisdictions. The number of trips grows on every trip interchange with Montgomery County as an origin, except for the Montgomery County to Fairfax County, Virginia, pair. The number of trips destined for Montgomery County increases overall, but declines from Fairfax, Howard, and Frederick counties as Montgomery County jobs capture resident workers and export fewer to other counties. Montgomery County and Fairfax County jurisdictions are joined by a single facility, the American Legion Bridge, for which no capacity increase was tested between the base and forecast year. With the addition of jobs in both counties relative to others, both jurisdictions serve as magnets but do not send as many workers to the other.

The "no feedback" example uses input 1990 peak-hour travel times and 2010 land-use patterns to estimate trip distribution. This is computationally equivalent to assuming that trip distribution is a function of trip length or of base year congested travel time in that the additional congestion between the forecast year (2010) and the base year (1990) does not affect travel times. The largest difference between the "feedback" and "no feedback" examples is in the change in the number of trips between Montgomery County and Fairfax County, which is nearly double.

TABLE 1 Transportation System Attributes

	1990 Feedback	2010 Feedback	2010 No Feedback
Average Trip Time (minutes)			
Origins	16.8	20.1	31.3
Destinations	16.7	16.8	22.2
Average Trip Length (miles)			
Origins	9.4	8.7	9.5
Destinations	8.9	7.4	7.6
Average Trip Speed (MPH)			
Origins	33	26	18
Destinations	32	26	20
Ratio of Congested to Freeflow Time			
Origins	1.3	1.6	2.4
Destinations	1.3	1.5	2.0

note: all trip purposes, peak hour trips, Montgomery County trip ends

TABLE 2 Comparison of Jurisdictional Flows

	1990 Feedback	2010 Feedback	2010 No Feedback
Work Trips Originating in Montgomery County			
Destination			
Washington D.C.	25941	28827	28413
Montgomery Co. MD	159109	243075	230086
Prince George's Co. MD	25980	37137	37058
Fairfax Co. VA	18976	15362	28620
Frederick Co. MD	12593	33635	36320
Howard Co. MD	6153	15134	16781
Work Trips Destined For Montgomery County			
Origin			
Washington D.C.	34783	37588	41806
Montgomery Co. MD	159109	243075	230086
Prince George's Co. MD	19924	25208	24093
Fairfax Co. VA	13622	12501	12456
Frederick Co. MD	1495	690	2238
Howard Co. MD	6519	4866	5127

note: peak period trips, Montgomery County trip ends

Route Assignment and Intersection Control

As might be expected with increased delay on trips, links also have worse levels of service. While, as expected, supersaturated conditions were not found with feedback, without feedback, conditions became very congested. Figure 5 shows the percentage of links at each of the six level-of-service (LOS) classifications for arterials and Figure 6 for freeways. The midpoint of LOS E is defined as a volume-to-capacity ratio of 1, and the other LOS categories were derived from that definition. Link traffic stream capacities were used. Freeways were distinguished from arterials because of dissimilar performance characteristics.

Intersection critical lane volume (CLV) is another performance measure that sheds light on system performance. When there is no capacity placed on intersection, a common practice in transportation models, unreasonable intersection CLVs, can result. In the TRAVEL/2 model, the inflection point of the intersection delay curve is set at 1,800 vehicles per hour of green per lane, and thus simulation of a CLV above this level is less likely. The midpoint of LOS E is set at 1,600 CLVs, and, as with links, the other LOS categories were derived from this. Figure 7 shows CLVs for two points in time, with and without feedback, for 2010. Clearly, when 1990 intersection delays are kept fixed for 2010, the equivalent of assuming no change in intersection delay and assuming that delay as implicit in the link delay, a large number of additional intersections fail as compared with a more reasonable assumption of feedback.

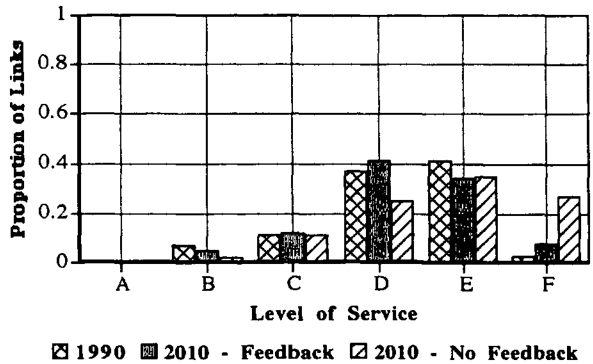

FIGURE 5 Freeway LOS.

COMPUTATIONAL EFFICIENCY

This section reviews the computational efficiency of the system under analysis. The conventional model has four steps that are executed sequentially. Within the distribution computation there is a "balancing" procedure, which guarantees that total origins equal total destinations and minimizes the variance from the gravity matrix representing the observed trip distribution patterns. Within the assignment stage, a number of iterations may be performed to seek convergence of the system subject to user equilibrium.

The TRAVEL/2 model recomputes demand n times, until the input travel times used in the demand components are within the accepted convergence criteria of the output travel times of the assignment. The total number of iterations in the assignment may need to be higher to achieve the same level of convergence than in a conventional model. Intelligent use of previous balancing coefficients in subsequent iterations of the TRAVEL/2 model could reduce distribution computation time, but this has not yet been done by the authors. Similarly, it is important to minimize the number of computations within the iterations to minimize total run time. Socioeconomic computations necessary for destination, mode, or departure time choice have thus been performed before beginning the iterative process.

The total computation time varies depending on initial starting conditions. More congested networks take considerably longer to converge than less congested networks. Because the application has been executed on a multiuser UNIX operating system, efficient CPU utilization depends on other user loads on the system. On the whole, the TRAVEL/2 model takes 5 to 10 times as long to run to a similar level of convergence as a conventional transportation planning model.

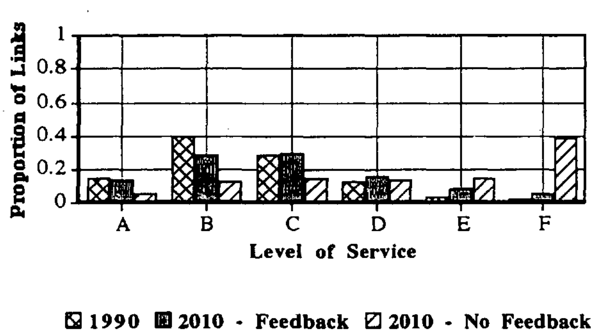

FIGURE 6 Arterial LOS.

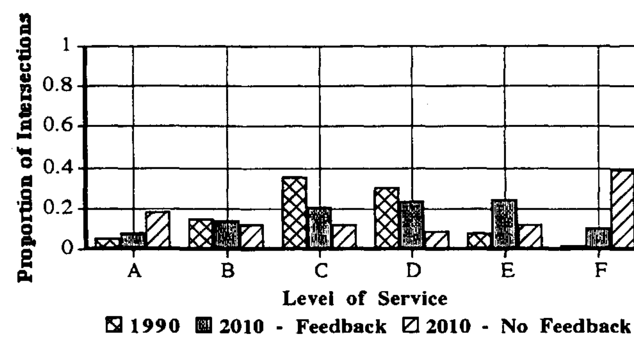

FIGURE 7 Intersection LOS.

CONCLUSIONS

The implementation of route assignment with elastic demand and responsive intersection control was heuristic and is suitable for practical application on a realistic, large-scale network. Several attributes of the model were investigated, including model convergence and sensitivity to data. A comparison of the model with and without feedback was also presented.

While it was not possible to discuss all aspects of the model in this paper, several key findings are worth noting. It is very important that zone systems be as disaggregate as the network description. Highly aggregate zones loading to a single point will oversaturate the network at that point and seriously disrupt signal timings. The authors suggest one zone per link with signal control at its head, or j node, is necessary to accurately model intersections in a signal network.

Another factor to note on intersection control concerns optimization methods. In this application, intersection signals were optimized in isolation. A more rigorous approach would optimize signals on a systemwide basis as with TRANSYT, or on an arterial basis such as MAXBAND. These would certainly produce different results. Another factor to consider is including nonsignal traffic control devices in the model. However, it is expected that little delay comes from these devices, and a highly microscale network would be needed for a reasonable application.

This application shows the sensitivity of transportation demand and traffic patterns to intersection control. Also worth noting are the air quality impacts of stopped delay and running speed. Given current fuel choices by the vehicle fleet and present technologies, valid estimates of air pollution need to be able to determine stopped delay, running speed, and total traffic demand. Incorporating the intersection in the planning model is necessary to properly implement Clean Air Act requirements.

The system is computationally intensive, so shortcuts might be desired. The authors have experimented with the use of heuristic averaging or equilibration procedures, but these processes are still under investigation. These methods could help the system close more rapidly. In addition, tests that perform multiple iterations of the assignment before reestimating demand or recomputing intersection control might converge the system more quickly with little degradation of results, but this awaits further research.

Application of this model produces forecasts that the model developers consider more reasonable than using a simplistic four-step approach. The authors are aware that technological or behavioral change makes all long-term forecasting suspect; however, even for short-term planning, it is necessary to have an idea of what the "best guess" future might be. With feedback, congestion increases with faster growth in land use than network. In the application presented here, travel times increase, primarily in response to an increased job/housing ratio moving the system from a balance where the number of jobs and resident workers in Montgomery County is about equal to a skew toward jobs. Considering the historical stability of travel times for work trips, this may suggest that land-use forecasts are predicting more jobs than transportation accessibility would provide. Incorporation of a land-use allocation model may alleviate this discrepancy. Clearly location choice is in part a function of transportation accessibility. When land-use forecasts are performed independently of transportation analysis, a "no feedback" situation exists, which may over-represent one element of the system at the expense of others.

A second obvious extension of this model is to the network design problem (NDP). The NDP attempts to determine the optimal sequence of increasing transportation supply by comparing different alternatives on a common basis, such as total travel time in the system. The NDP has traditionally assumed static demand. However, with the ability to reasonably forecast changes in demand with respect to congestion, developing rankings of benefits in reduced system travel time given by additional facilities is a promising area of research.

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