Evolutionary Transportation Planning Model: Structure and Application

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An evolutionary transportation planning model wherein the demand in a given year depends on the demand of the previous year is described. The model redistributes a fraction of the work trips each year associated with the relocation of a household or taking a new job, whereas changes in distribution associated with growth (or decline) are considered. This hybrid-evolutionary model is compared with an equilibrium model, wherein supply and demand are solved simultaneously. The reasons for preferring the evolutionary method to the equilibrium approach are several: (*a*) the ability to more easily use observed data and thereby limit modeling to changes in behavior, (*b*) additional realism in the concept of the model, (*c*) the provision of a framework for extension to integration with land use models, and (*d*) the additional information available to policy makers.

Traditionally, transportation planning models are used to forecast levels of traffic or transit ridership at a given point in time. Best practice in travel forecasting, the equilibrium approach, attempts to simultaneously (or iteratively) solve for travel demand given a congested network and to estimate network congestion given the travel demand. However, at no point in time is the demand/supply system actually in perfect equilibrium. Individuals and firms continuously enter and leave the system. Changes in system performance, such as the travel times between places, lead to further changes in user behavior, such as choice of route, mode, departure time, sequence of trips, or destination. Some of these behavioral changes are made readily with only a short lag. The disruptive nature and high transaction costs of others, such as switching jobs or moving to a new residence, mean they are undertaken rarely.

This paper presents and tests an alternative approach to travel demand modeling, which explicitly considers changes over time in work trip distribution as a result of household relocation and job switching. The behavioral theory underlying this model is not the perfect network equilibrium of Wardrop or the supply/demand equilibrium described by Boyce et al. (*1*). Rather, it is comparable to Simon's idea of bounded rationality, where the costs of changing behavior need to be considered as well as the possible suboptimality of that behavior (*2*). Thus, supply and demand are not in perfect equilibrium because the costs of moving and switching jobs are high. Traffic assignment may not be in perfect equilibrium because individuals do not have perfect information about the dynamically changing travel times between places.

The approach presented here is therefore more analogous to an evolutionary model than an equilibrium model. The dichotomy and connection between the two have long been recognized (*3*). In a strictly evolutionary model, decisions are updated continuously (or in more practical terms on some time slice such as a day-to-day basis), with some time lag between obtaining information and executing a change in behavior. Moreover, the time lag for response may vary on the basis of the type of decision and the characteristics of the individual making the decision. In this paper's hybrid-evolutionary model, day-to-day decisions are still treated as though they are in equilibrium, but long-term decisions are lagged. In this case, only a fraction of work trips are redistributed every year, with congested travel times on the basis of the previous year's results serving as the source of impedance. In addition, trips from new homes and jobs are also distributed on the basis of those times. One key question is, To what extent do different travel patterns emerge from the evolutionary modeling approach compared with an equilibrium approach?

In addition to being more realistic, one advantage to the evolutionary approach is the ability to start with observed data such as the Journey to Work census data or a trip table synthesized from traffic counts and an old trip table. The evolutionary approach (in this paper, a synthesized trip table is used as a seed) can begin with all of the information inherent in these data rather than just the impedance curves derived from them and evolve incrementally from observed conditions rather than be modeled in totality. This approach is expected to be better than simply applying zone-to-zone adjustment factors at the end of the equilibrium modeling process to correct demand for under- or overestimation because it reduces the amount of error introduced by modeling.

The evolutionary approach should also have significant advantages for future application to land use forecasting and combined transportation–land use forecasts. Although the transportation model is a largely negative feedback loop—more demand creates more congestion, which leads to less demand—the land use model is in some respects a positive feedback loop: more development increases accessibility, which leads to more development. At the extremes, positive feedback leads to the densities found in Manhattan or Hong Kong. The integration of positive and negative feedback results in a complex model that is more sensitive to historical patterns and initial conditions than a simpler equilibrium-seeking negative feedback loop. However, the model presented in this paper considers land use changes as exogenous for two reasons: (*a*) the lack of resources to calibrate a land use model to the necessary accuracy, and (*b*) the lack of support for computer modeling of land use. Planners in the Washington, D.C., area prefer a hand-crafted approach using Delphi methods for forecasting land use.

Further, many policy decisions, such as the programming of capital facilities, are made by analysis of a single equilibrium point in time. An evolutionary model can measure the transportation system over multiple time slices and give a more accurate reflection of benefits and costs.

The largest drawback to the evolutionary approach is the additional computational time required to implement the system as opposed to a one-shot equilibrium solution. If the results are not sufficiently different, or the additional information is not useful, the benefit may not be worth the additional computer resources and

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complexity. A second consideration is the requirement for additional information. In an evolutionary model, the different time lags in decision making must be determined. In this case, how frequently do individuals relocate? Here, a fixed value of 22.5 percent of individuals is taken to change jobs, houses, or both every year, a figure derived from the 1991 Montgomery County Travel Survey (*4*), but future research should model the value endogenously on the basis of socioeconomic, demographic, and transportation accessibility variables for a given area or trip interchange.

Next in this paper is a discussion of model structure, which includes frameworks for modeling travel demand, a model of relocation behavior, and flowcharts of the hybrid-evolutionary and equilibrium models. This discussion is followed by a description of the model components used in this application. The model inputs of land use, demographics, and networks are presented. A comparison of the convergence properties of the two models is shown. A section comparing the results of the two models is provided. The conclusion discusses some of the questions raised by the evolutionary model.

MODEL STRUCTURE

The model structure is presented in this section. First is a look at modeling frameworks, considering equilibrium and evolution as two poles with two interim combinations of the methods, depending on the decision time horizon evaluated. Next is a presentation of how relocation is incorporated into the model system mechanically. Finally a comparison of flowcharts of the two tested models—hybrid evolutionary and equilibrium—is presented.

Travel Demand Modeling Frameworks

Several approaches can be taken in testing the concept of a dynamic demand model. Each approach is a variation on the spectrum between a lagged model, in which decisions are not simultaneously made by all commuters, and an equilibrium model. In the aggregate models tested here, it is assumed that there are two time frames for travel decisions: day-to-day and year-to-year. Day-to-day decisions include route choice, mode choice, departure time choice, and nonwork trip destination choice. Year-to-year decisions include relocation or work trip (re)distribution (for a fraction of commuters), automobile ownership, and trip (re)generation. These decisions are not entirely separable, so endogenous year-to-year decisions (location/work trip distribution) reflect changes in the day-to-day conditions. In addition, the following system variables vary annually; network, land use, demographics. Although there is a continuum of decision making in reality, this approach is taken for the sake of simplicity.

Further it is assumed that year-to-year decisions are lagged and are based on information from the previous year but that day-to-day decisions are essentially in equilibrium between demand and supply.

The models are as follows:

- Model 1. Equilibrium: equilibrium for day-to-day and year-to-year decisions;
- Model 2. Hybrid: equilibrium for day-to-day, evolution for year-to-year decisions;
- Model 3. Evolutionary: evolution for day-to-day and year-to-year decisions; and
- Model 4. Alternative hybrid: evolution for day-to-day, equilibrium for year-to-year decisions.

Because of computational intensity (3,652 days for 10 years, requiring a demand update on each day), Model 3 is not pursued here. In addition, Model 3 would need to account for variations in demand because of day- of the week and month of the year. Model 4, an alternative hybrid model, would use dynamic assignment, scheduling, and departure time, perhaps with responsive intersection control, to come up with information used in long-term decisions, which would be assumed to be in equilibrium, and is the opposite of Model 2. In all of the Model 2 runs here, the yearly decisions (trip generation, work trip distribution, and automobile ownership) are computed as lagged decisions.

Relocation

For an evolutionary analysis, a new model component is required. This concerns the decision to relocate: both moving one's home or switching jobs is a relocation decision. Here, the terms relocate and redistribute are considered synonymous, the difference in terms resulting from alternative perspectives: individuals choose to relocate while social planners redistribute individuals (match their home and workplace) in their demand models. The nature of this model is that the number of trips at time t depends on the trip pattern at time $t - 1$ plus any change forecast to happen. This is an inertial, state-dependent approach; a work trip does not change from year to year unless some outside force (a redistribution/relocation decision) causes it to change. On a much longer time scale, long-term location (and hence trip frequency/destination choice) decisions can be seen as analogous to trip chaining, where decisions are history dependent. Kitamura has shown for trip chaining that the use of lagged dependent variables is a plausible and statistically valid specification (*5*). Clearly, empirical and statistical issues will need to be further investigated for relocation choice to determine the best specification in terms of predictive value while avoiding serial correlation problems.

This model needs to rematch a fraction of all workers and jobs into work trips for each time slice (in this case, each year). Further study is necessary to understand whether these recently redistributed trips are of longer, shorter, or the same duration as average trips after controlling for the number of opportunities and competing job seekers. This question is analogous to the difference between marginal and average costs in economics. In this application, the work trip distribution impedance curves were estimated from a survey sample of the entire population (not only those who recently moved).

The following equations are used:

$$T_{ij}^{y} = (1 - R_{ij}) \times T_{ij}^{y-1} + MN_{ij}^{y} \tag{1}$$

where

T_{ij}^{y} = trips from i to j in year = y,
MN_{ij}^{y} = switched job/house and new trips (subject to redistribution),
M_i^y = trips from i in year y which switched from year = $y - 1$,
M_j^y = trips to j in year y which switched from year = $y - 1$,
N_i^y = trips from i caused by growth (not present in year = $y - 1$),
N_j^y = trips to j caused by growth (not present in year = $y - 1$), and
R_{ij} = relocation function for interchange $i - j$ (= 0.225 in this application)

subject to

$$T_i^y = \sum_{j=1}^{J} T_{ij}^y \quad (2)$$

$$T_j^y = \sum_{i=1}^{I} T_{ij}^y \quad (3)$$

$$M_i^y = R_{ij} T_{ij}^{y-1} \quad (4)$$

$$M_j^y = R_{ij} T_{ij}^{y-1} \quad (5)$$

For work trip distribution, a two-dimensional balancing procedure is used. For this, the rows (origins) and columns (destinations) are balanced. The total of origins (O_i^y) balanced here is

$$O_i^y = N_i^y + M_i^y \quad (6)$$

and the destinations (D_j^y) is

$$D_j^y = N_j^y + M_j^y \quad (7)$$

which after balancing, produces the trip table MN_{ij}^y, which is added to the fraction of trips unchanged from the previous year to obtain the final peak-period work trip table.

The following table shows the logic of whether an individual would be redistributed:

		Change Work Location	
		Yes	*No*
Change	*Yes*	Redistribute	Redistribute
Home	*No*	Redistribute	Do not redistribute

Flow Charts

Figures 1 and 2 show the flow chart of the equilibrium and hybrid-evolutionary models, respectively. The endogenous components are identified with rectangles; the exogenous updates to land use and networks are shown with curved corners.

To summarize, exogenous changes over time in the model include updates to the transportation network through the addition of links, updates of the age distribution, and household size distribution by geographical area developed from a separate demographics model and updates of the land use activity (housing units and employment by type) from regional transportation forecasts. These are discussed in detail later. Collectively, these inputs are treated exogenously because, in the short term, there is little interaction between them and travel demand. The longer the timeframe, the more that can reasonably be internalized.

Endogenous changes within this model include updates to travel times on the network, the number of work trips generated, and consequently the interchange of work trips between zones, and in a more complete extension of the proposed model, the relocation decision. Travel demand is not limited to just trips generated, but considers all of the choices in the travel demand process. Therefore, a shift in mode, route, or time-of-day is a change in demand for a facility or route just as an increase or decrease in the number of trips generated is a change in demand for the transportation system as a whole.

MODEL COMPONENTS

The model components (trip generation, trip distribution, mode choice, departure time choice, route choice, and intersection control) used here are the same as those estimated for the Travel/2 model (*6*). Briefly, these are described as follows.

Trip Generation

The person-trip generation model is in two parts (*7*): for the home end of trips, a cross-classification model based on age, household size, and dwelling unit type; for the nonhome end, generation is

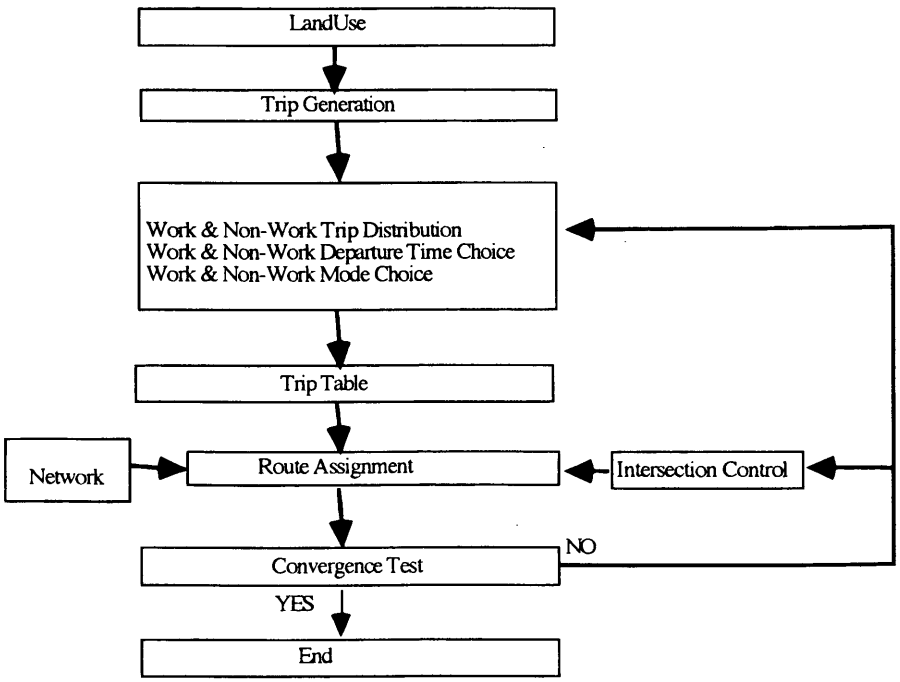

FIGURE 1 Flow chart equilibrium model.

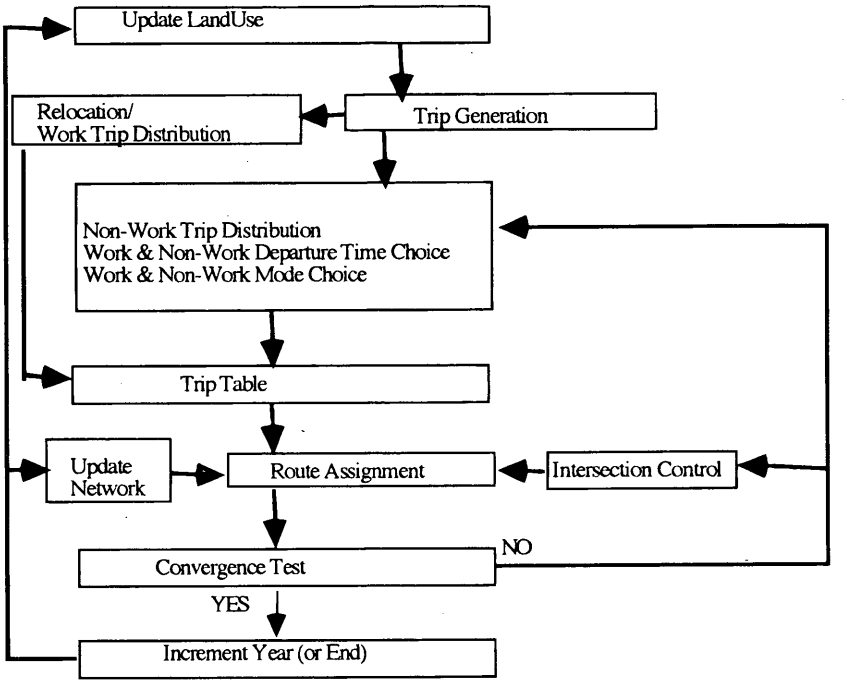

FIGURE 2 Flow chart hybrid evolutionary model.

based on the number of employees (office, retail, industrial, other). The purposes used in the model are work to home, work to other (to home), home to other, other to home, other to other (and home to work. Trip generation is computed for the afternoon peak period (3:30 to 6:30 p.m.). In the hybrid model discussed in this paper, both work to home and work to other (to home) purposes are considered "work trips"; the other purposes are considered "nonwork." Because this is a person-trip model, mode choice is estimated for both work and nonwork trips and all modes (including nonmotorized). Future research should derive trip generation from an activity approach considering activity frequency, duration, and scheduling.

Destination Choice

A multimodal trip distribution model is used in this model (*8*). A composite impedance calculated as the weighted average of the mode-specific impedances is computed, using mode shares as the weight. In the hybrid model, for nonwork trips, destination choice is computed in equilibrium with route assignment and intersection control. For all relocated and new work trips, the final travel times from the previous year are used to compute the trip distribution in the subsequent year. Other trips are carried from the previous year. Detailed information on the estimation of the initial (seed) trip table is available from the author and was not included for reasons of space.

Departure Time Choice

Departure time choice determines the proportion of peak-period vehicle trips that occur in the peak hour. It is a binomial logit model with two choices: peak hour and not peak hour. The factor that is used to determine probability of peak hour is the ratio of congested to free-flow time on a zone-interchange basis. This component is solved in equilibrium with route assignment and intersection control for both work and nonwork trips.

Mode Choice

In this application of the model, mode choice is held fixed at 1990 levels. Earlier tests of the model found little differentiation of mode choice because of the changes in network and land use between 1990 and 2000 when policies are kept fixed. In theory, this component could be solved in equilibrium with route assignment and intersection control. However, to reduce computational time and possible sources of minor variation, the zone-to-zone mode shares were therefore kept constant. Future research should consider a simultaneous approach to mode and departure time choice, and possibly destination choice, at least for nonwork activities, although various questions about the relative timing of these components would need to be resolved.

Route Choice and Intersection Control

A single-class user equilibrium assignment model provided by the EMME/2 software is used in this application (*9*). This model considers both link delay and turn delay. The inputs to turn delay (cycle length, green time per phase) are computed with an external program each iteration of the automobile assignment, and the results are fed back into the turn penalty function (*6*).

EXOGENOUS MODEL INPUTS

Two key sets of exogenous data are used in the model: land use and demographic changes by zone, and modifications in the highway and transit networks. These are described as follows.

Land Use and Demographics

The land use assumptions in this application are derived from the Round IV forecasts of the Metropolitan Washington Council of Governments and the Round IV forecast of the Baltimore Regional Council of Governments (*10,11*). In 1990, for Montgomery County, Maryland, the focus of this study, there were 280,000 housing units and 460,000 jobs, which is expected to increase by the year 2000 to 320,000 housing units and 580,000 jobs (Figure 3). These forecasts are based in large part on approved but unbuilt development (typically a 6- to 12-year inventory) and by the queue of developers who are applying for development approval. Future land use forecasts will incorporate estimates of transportation accessibility explicitly, and perhaps eventually the forecasting will be integrated. However, as noted earlier, resistance to combined transportation/land use forecasting in the Washington area is at least as political as technical. Demographic inputs (age distribution by area, average household size) are updated each year on the basis of results from an exogenous demographic forecasting process independent of any transportation variables.

Networks

A dynamic model requires that changes to the transportation network be coded to the year of change. Here the model transportation networks come from the Montgomery County Planning Department (for Montgomery County), the Metropolitan Washington Council of Governments (for the rest of metropolitan Washington) and the Baltimore Regional Council of Governments (for metropolitan Baltimore). The future network within Montgomery County has coded changes in link capacities (number of lanes) as well as additional links to the year of opening. Outside Montgomery County, the change in networks occurs for the base year and 1995. Thus, the capacity outside Montgomery County from 1990 to 1995 and from 1996 to 2000 is fixed.

MODEL CONVERGENCE

Figures 4 and 5 show convergence results for the two models, both in the year 2000 time horizon summarizing the entire model region. The results for the equilibrium model represents the value of the objective function on each iteration in the year 2000. The results for the hybrid-evolution model reflect the decisions decided in equilibrium (nonwork trip distribution, time-of-day choice, and route choice) also in the year 2000 for each iteration. In the evolutionary model, there is no convergence from year to year (as discussed in the next section on results). Figure 4 shows the total vehicles on the network, which for both runs converges to about 1 million vehicles by the 30th iteration. The equilibrium model has somewhat more vehicles than the hybrid-evolution model, although more research will be necessary to say whether this is inherent in the model structure or just an artifact of the particular data set. It should be noted that the hybrid-evolutionary model converges more quickly than the equilibrium model, probably because one major component, work trip distribution, is fixed before the model is run for a given year. By the 10th iteration the hybrid model has a demand that is substantially identical to the 30th iteration; however it takes 15 iterations for the same to be true of the equilibrium model.

Figure 5 shows the convergence of the objective function (absolute gap) for the two models. The gap is an estimate provided by the EMME/2 software of the difference between the current assignment and a perfect equilibrium assignment in which all routes used for a given origin-destination (O-D) pair would have the same

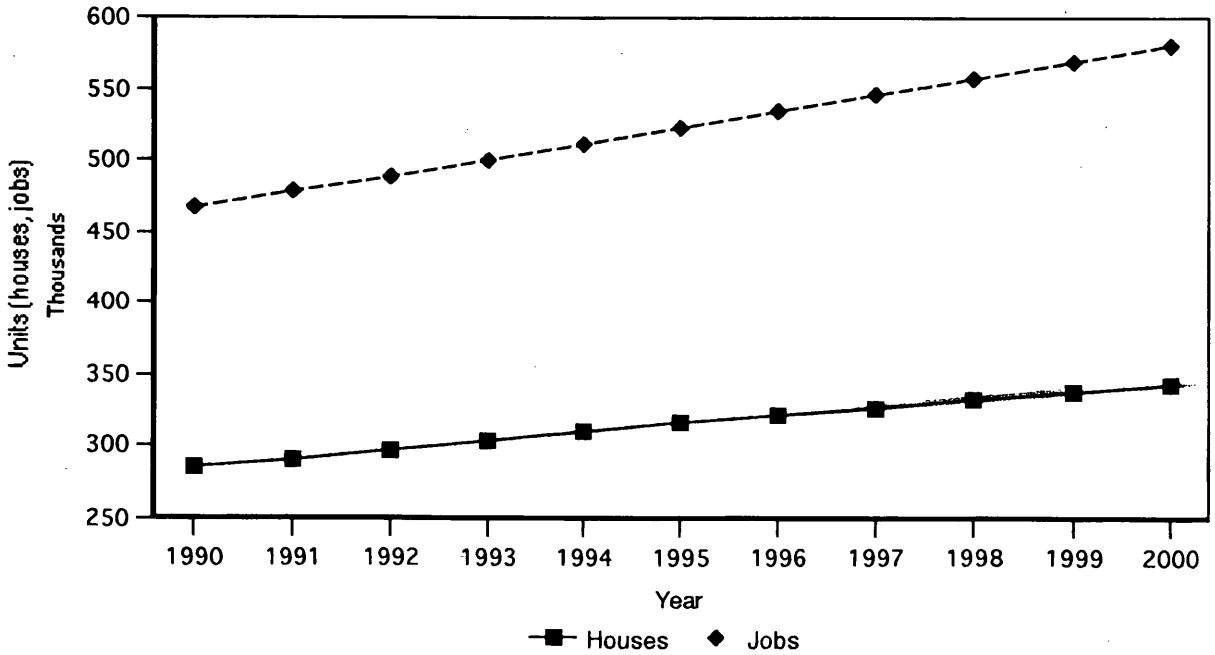

FIGURE 3 Land use activity, Montgomery County, 1990–2000.

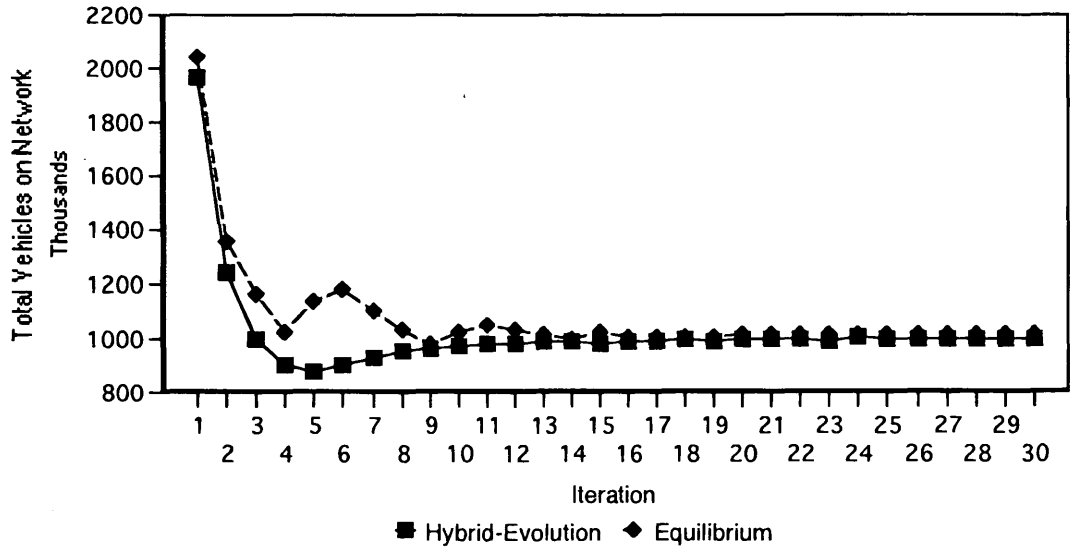

FIGURE 4 Convergence of models: total vehicles on network, 2000.

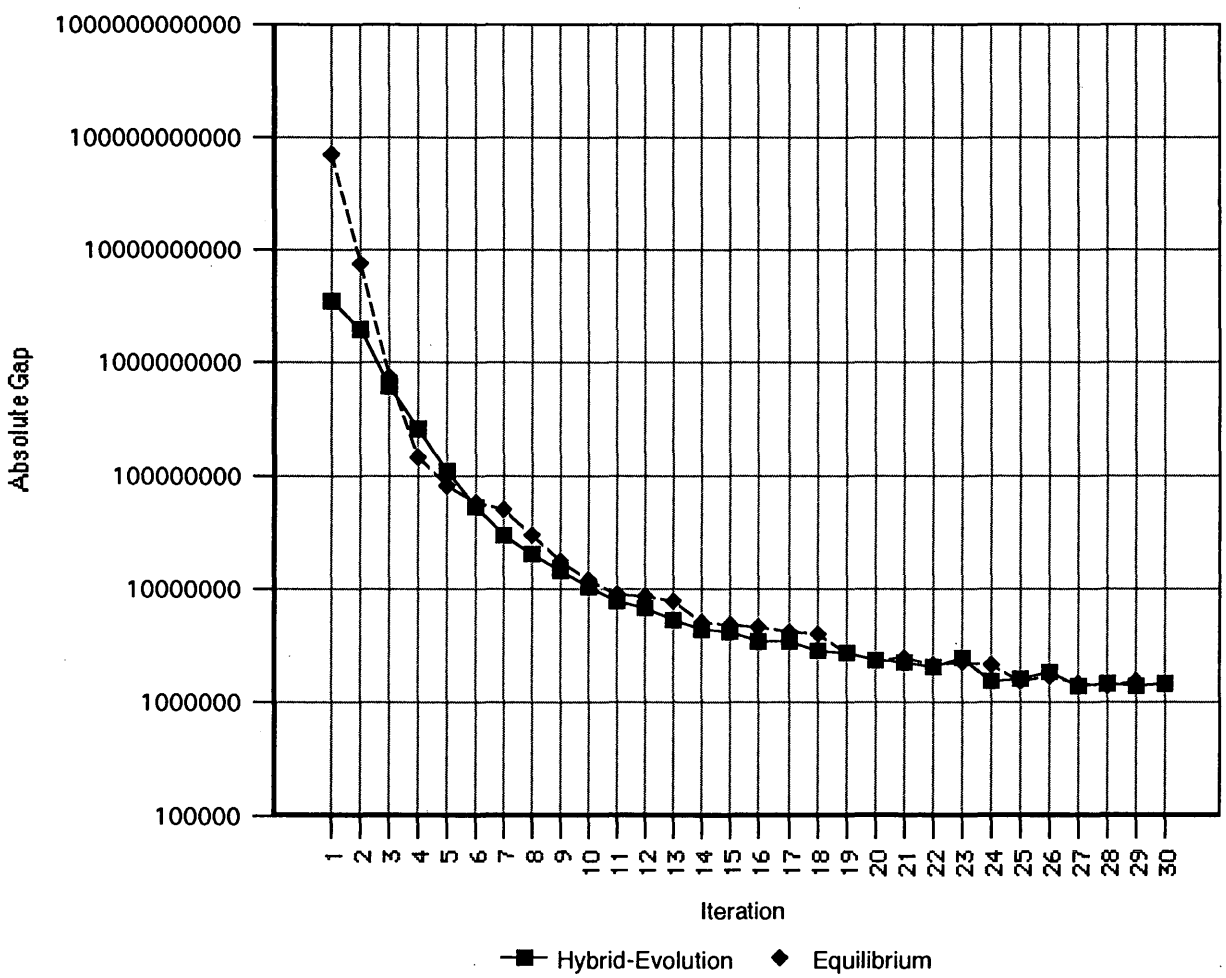

FIGURE 5 Convergence of models: absolute gap, 2000.

length (*9*). The value is tending to level out at about 1 million by the 25th iteration.

Thus, for any given time slice (1 year), the hybrid-evolutionary model reaches an equilibrium, although over time the equilibrium point moves. This particular structure, which is largely composed of convergent negative feedback loops is unlikely to have the potential for chaos, cascades, or catastrophes. However, depending on the rate of change of exogenous variables such as the network description or amount of development, the equilibrium point should move more or less smoothly.

RESULTS

Some summary figures are provided for the various models to compare their results. Figure 6 shows the peak hour vehicle trips (the same result as in Figure 4) for each year, again for the entire model region. The number of trips increases in the hybrid model, but is less than that in the equilibrium model. The large uptick in 1995 is caused by the increased network capacity, which was coded to come on line during the year (recall that outside Montgomery County, capacity from 1990 to 1994 is the same as it is from 1995 to 2000.) This clearly emphasizes the need for time coding of networks if this approach is to be used.

Figure 7 shows the vehicle miles traveled (VMT) within Montgomery County for the two models. Again the hybrid model is somewhat less traveled than the equilibrium model. VMT shows a sharp increase from 1990 to 1991. In that year I-270 was widened from 6 to 12 lanes through much of the county, which resulted in increased demand. Otherwise the growth is fairly smooth.

Figure 8 displays the average work trip time (in minutes), length (in kilometers), and speed (in kilometers per hour) for Montgomery County work trip origins (because this is the afternoon, origins are Montgomery County workers going home). All three values are stable across the decade, indicating that the feedback process is maintaining these attributes. In fact, speed improves over this period while travel time decreases slightly, indicating appropriate capacity increases and shifting travel patterns from suburb to suburb trips, which have higher average speeds. The difference of means tests performed over the 10 years, comparing the mean traffic zone time and speed (comparing 1990 and 2000 results f or the model) shows that the results for the year 2000 are statistically different from those in 1990 for the hybrid-evolutionary model for time and speed but the same for length. For the equilibrium model, the time, speed, and length did not show a statistical difference.

Figure 9 shows the proportion of Montgomery County links in each level of service category (LOS A through F). No trend is apparent. In fact, for the year 2000, the percentage of links better than LOS C/D is identical in both the hybrid and equilibrium models. Figure 10 shows the intersection LOS (using the critical lane volume method) for intersections in the county. Again no trend is

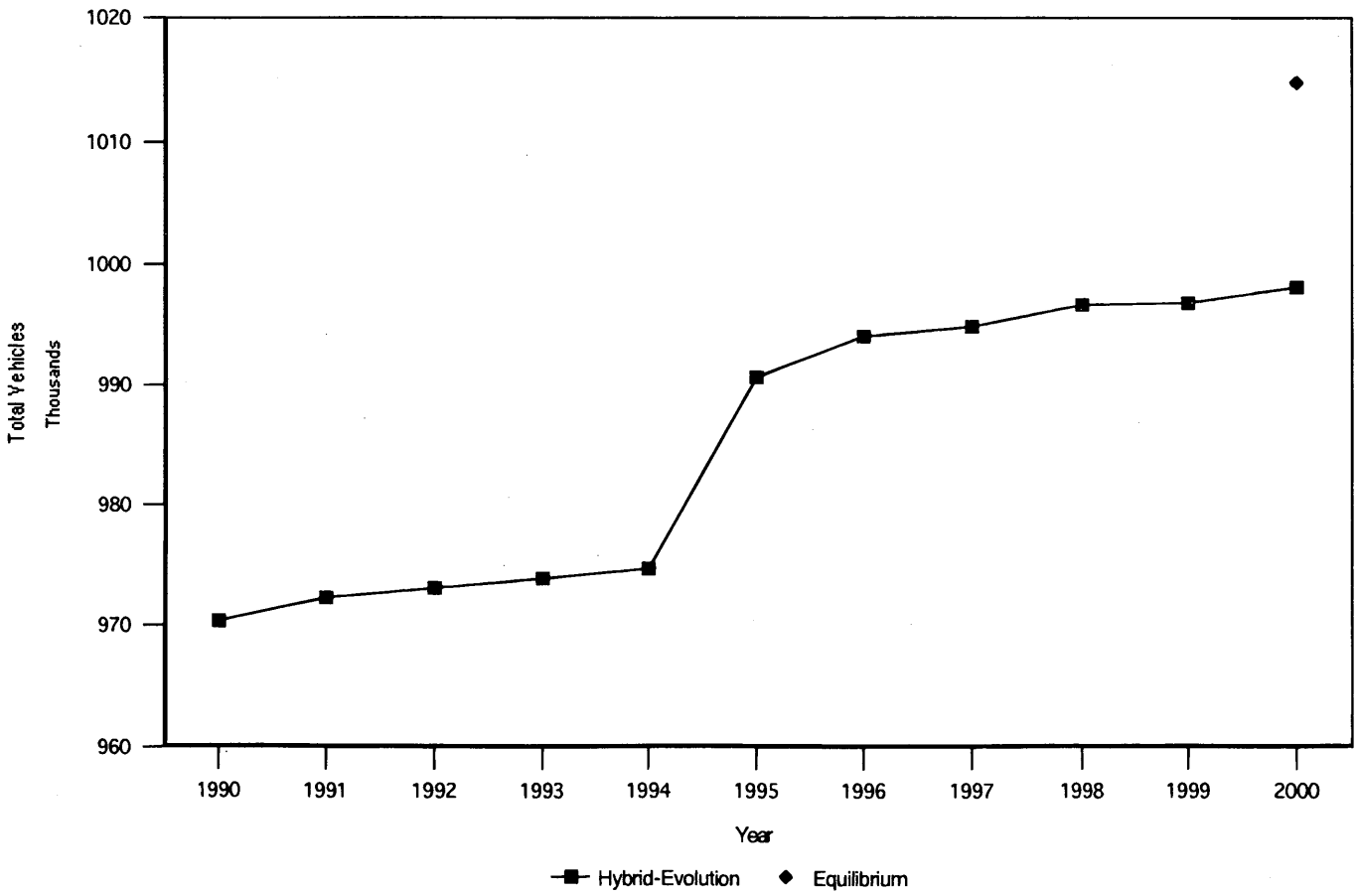

FIGURE 6 Peak-hour vehicle trips by year, entire model region.

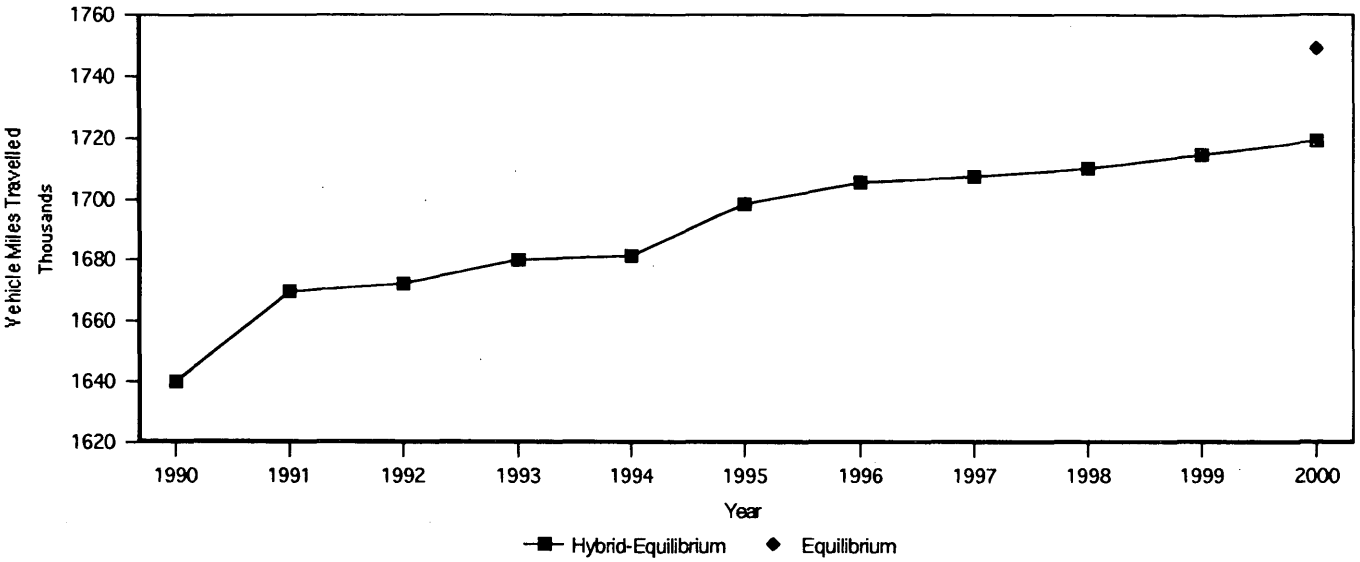

FIGURE 7 Vehicle miles traveled, Montgomery County links.

apparent, and the number of intersections above LOS C/D in both models is the same in the year 2000.

CONCLUSIONS

This paper discusses some of the implications of introducing dynamic work trip demand into the transportation planning model. As a behavioral assumption for the forecasting of a specific year in the midterm, evolution is conceptually better than equilibrium. The results were similar, but not identical between the two models. The length of the time period under study and the relative change in input data may influence model results.

The question of equilibrium or evolution is important in the context of attempts to construct dynamic models of urban structure and growth or travel demand. Most such large-scale models are now static, or dynamic in only the crudest sense, using 5-year time slices (*12*). However, the structure and function of every city, and the behavior of individuals within that city, depend crucially on their mutual co-evolutionary history. Because cities and human activity

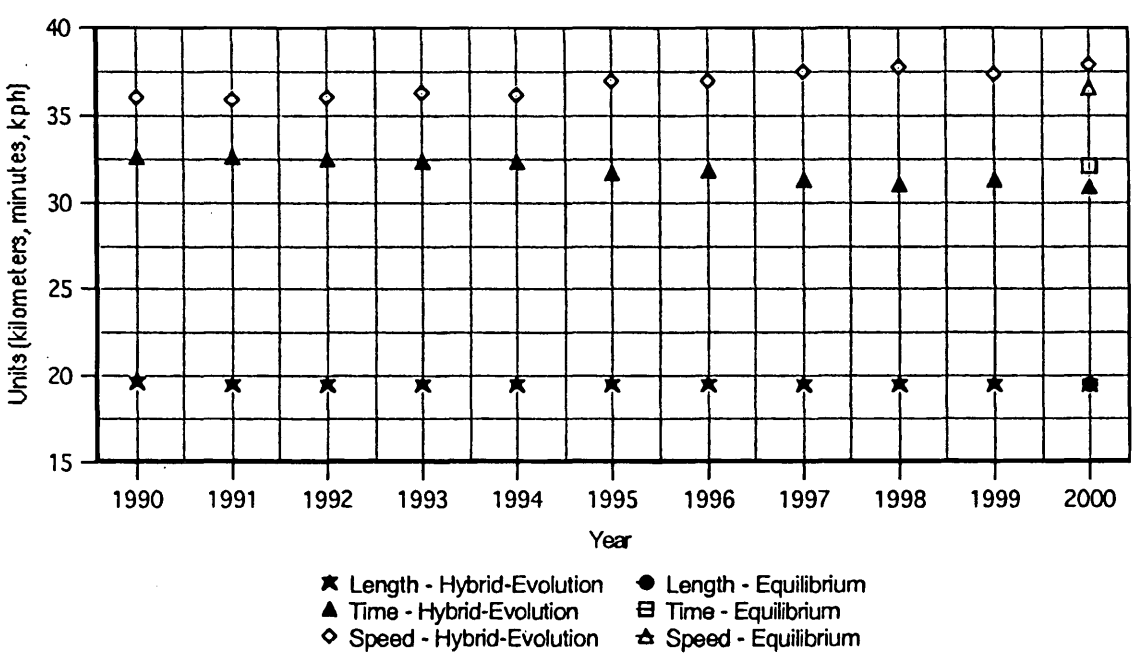

FIGURE 8 Evolutionary transportation planning model: comparison of time, length, and speed, Montgomery County work trip origins.

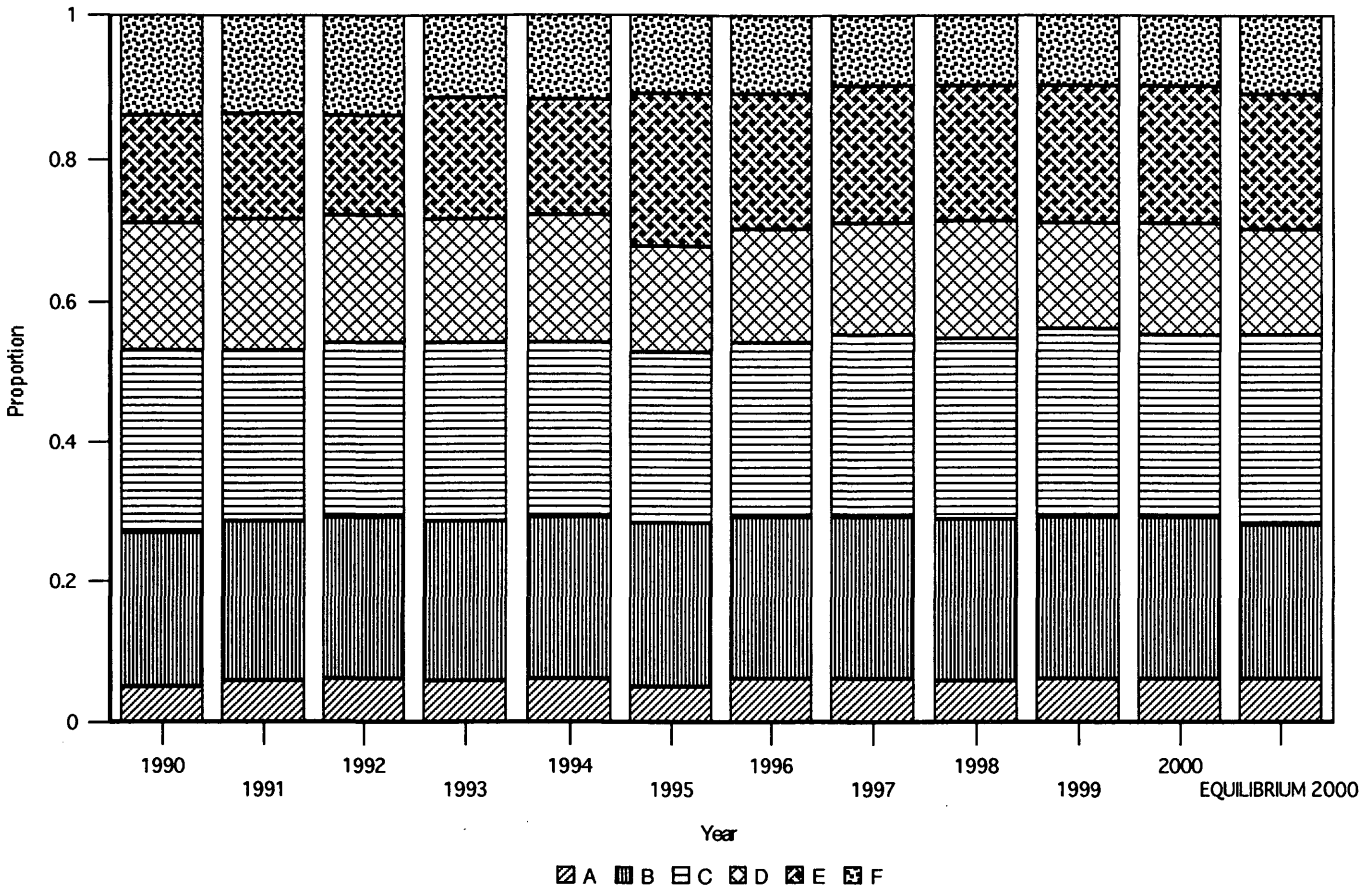

FIGURE 9 Link level of service, Montgomery County.

patterns evolve through time in complex, dynamic "environments," the interactions of urban form and human behavior do not, and should not be expected to, conform to equilibrium conditions. According to Forrester (*13*, p. 121), "The urban system is a complex interlocking network of positive and negative feedback loops. Equilibrium is a condition wherein growth in the positive loops has been arrested."

The reasons for preferring the evolutionary method to the equilibrium approach are several: (*a*) the ability to fully incorporate an observed data set such as a vehicle (or transit) trip table synthesized from traffic counts (*14*) (or transit ridership data) and the Journey to Work census data (unlike the use of equations and adjustment factors, all of the information inherent in the observed data can be used, and only the change over time needs to be modeled); (*b*) additional realism in the concept of the model; (*c*) the provision of a framework for extension to integration with land use models; and (*d*) the additional information available to policy makers for decisions such as the sequence of programming and constructing capital facilities, where the benefit depends on the timing of the facility.

This research points out the need to develop realistic behavioral models of switching in all model components. For instance, the Wardrop equilibrium principal states that no route is used between an O-D pair if the travel time is greater than on another route. But this implies perfect information. Once individuals have selected routes, their travel times change from day to day for a variety of factors. At what point does an individual decide to try another route? Under what conditions will this commuter stay with the second route or return to the first? How will advanced traveler information systems play into this? Switching is an issue in departure time choice, activity sequencing, mode choice, and nonwork trip destination selection (e.g., the choice of a grocery store). These and other questions will need to be answered as dynamic evolutionary modeling is implemented.

Some practical issues also emerge. There are not yet enough data to know the long-term temporal stability of this relocation value. What is it a function of? Are distribution curves (and other components) the same at the margins as they are on average? Further research can be aimed at implementing a full day-to-day evolutionary travel/activity demand simulation, with models of switching rather than attempting to predict the behavior of the entire population.

However, in the near term, application of supply/demand equilibrium models of travel demand is still preferable to conventional application with fixed zone-to-zone travel times independent of changes in the transportation network.

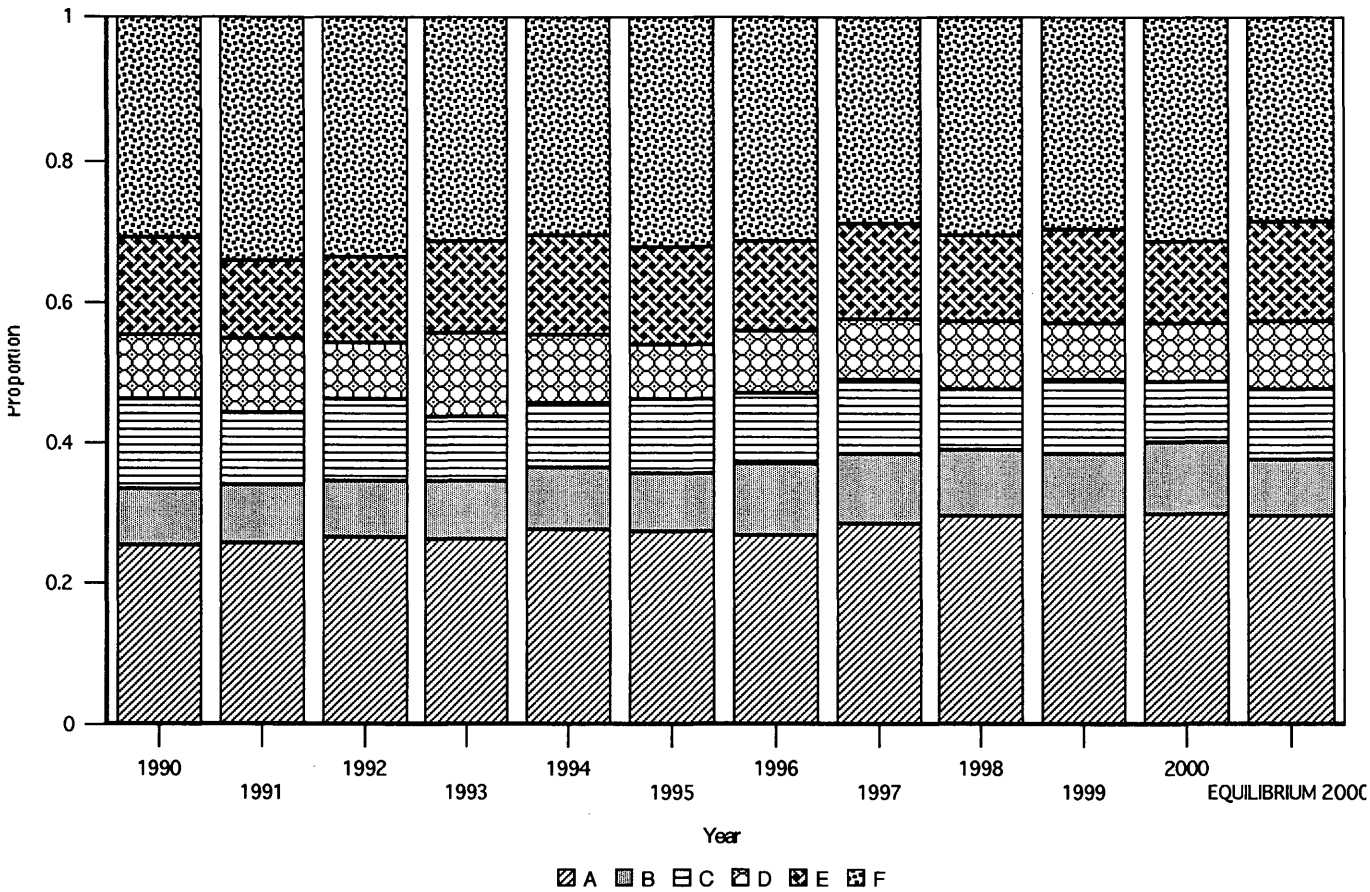

FIGURE 10 Intersection level of service, Montgomery County.

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