Transportation Modeling for Energy and Environment: U.S. Experience and Relevance to the Developing World

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Recent developments in travel demand modeling and their potential for application in the developing world are examined, with a specific focus on energy, air pollution, and land use impacts. Practices in North America, where transportation and air quality modeling were pioneered, are emphasized, and potential in the developing world, where North American paradigms were often applied and where current trends suggest that future urban transport costs will be large, are explored.

For the developing world, the need for transport system improvements is intense, perhaps nowhere more than in the rapidly growing urban areas. Even though they already allocate from 15 to 25 percent of annual spending on urban transportation, developing countries, estimates suggest, must increase their abilities to supply and manage urban infrastructure by 75 percent simply to maintain the current, often unacceptable conditions (*1*). The challenges of accommodating demand for transport in the developing world are compounded by rapid growth in motor vehicle fleets and its associated effects on congestion, energy, environment, equity, and safety. Estimates project that the motor vehicle fleet in the developing world will increase by 220 percent between 1988 and 2000 (*2*). Already, developing world cities face dire congestion problems; in Bangkok, estimates suggest that $15 billion in transport investments over 15 years will speed up snarled traffic conditions by a mere 1 km/hr (*3*). Transportation oil consumption is also rising rapidly, often outstripping growth in gross domestic product (*4*) and straining the capital reserves of oil-importing countries and reducing export earnings for oil exporters. The environmental implications are all too well known, the most notable being air pollution. In some of the world's most polluted cities, transportation is responsible for between 70 and 86 percent of total airborne pollutants (*5*). Safety concerns in the developing world also are growing, as road accident deaths are commonly the second largest cause of death for economically active age groups (*6*).

Facing these large and growing problems, developing countries require innovative urban transport solutions as well as analysis tools—or models—that can measure the broad-ranging impacts of those solutions. Unfortunately, it remains unclear what role traditional transport models can play in addressing the unique challenges facing cities in today's developing countries. Transportation models essentially were developed in the post–World War II United States, an environment of seemingly unlimited financial and natural resources. These models were designed to analyze the need for new highway facilities. Today, however, urban transportation models must effectively analyze a wide variety of transport measures—from alternative land use development to promotion of nonmotorized transport modes. In addition, models must be able to measure energy and air pollution impacts of different transport options and strategies.

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MODELING IN NORTH AMERICA

Travel Demand Models

The urban transportation planning process follows a straightforward methodology evolved over four decades of development and refinement. The process was made possible by the advent of computers, which enabled the translation of theoretical constructs into practical application and analysis. Travel modeling was pioneered in the United States as the federal government attempted to establish a uniform method of priority ranking road investment decisions (*7*). In the standardized process, which came to be known as the urban transportation modeling system (UTMS) or the urban transportation planning process, travel demand is derived from the daily activities of individuals and businesses. The goal of the process is to find the amount, type, and location of travel in the designated study area. The process has a number of requirements that basically are universal (*8*):

1. Gather the data at the lowest possible level of aggregation;
2. Develop (or use other sources of) future projections for population, income, fuel price, transit fares, and so on;
3. Develop a model that accurately forecasts travel behavior; and
4. Apply the models to produce travel forecasts.

Most conventional travel forecasting models include some common elements. First, the primary inputs into the model are land use data (sometimes itself derived from a model) on housing and employment distributions, which are typically not sensitive to changes in the transport system. From this land activity distribution, the travel demand forecast is derived, in a "four-step" method, sequentially estimating

1. *Trip generation*, describing the number of trips originating and ending in each zone;
2. *Trip distribution*, mapping the number of trips between each origin-destination (O-D) pair;
3. *Mode split*, dividing the total number of O-D flows into modes (automobile or transit); and

4. *Assignment,* assigning the automobile O-D flows and transit O-D flows to specific paths in their respective networks.

The conventional four-step travel demand modeling process will produce travel times, speeds, costs, distances, volumes, and volume/capacity ratios (which represent traffic density) by mode. These results are available for individual network links and for O-D pairs. This basic data can then be used to derive information such as total vehicle distances traveled or transit ridership by line (*9*).

A transportation model requires a large volume of data for calibration and validation. Typically, these data come from surveys designed specifically for estimating travel demand and the nature of that demand. The most common form of survey is the O-D survey, normally conducted by interviewing people, representing sample demographic segments, within a given travel area. The survey can help determine specific travel patterns in the study area, whether that be a single neighborhood, a subdivision, a commercial development, or an entire metropolitan area (*10*). Means of conducting such surveys vary from direct interviews, phone interviews, mail surveys, or some combination. Other information needs that also are necessary to transportation modeling and complementary to O-D surveys are traffic counts, cordon counts, vehicle occupancy counts, and transit inventories. In the United States, a study of metropolitan area travel surveys revealed that different urban areas varied greatly in the extent and frequency of surveys; they include household surveys conducted on a 10-year cycle, 15-year (or more) cycle, a continuous cycle, and not currently conducting surveys (*11*).

Transportation Emissions Modeling and Air Quality

Outputs from the travel demand modeling process can be used as inputs into a mobile source emissions model to generate estimates of aggregate motor vehicle emissions in an urban area. These emissions estimates can, in turn, be input into a dispersion model, which attempts to predict ambient air quality by simulating pollutants' interaction within a given meteorological and topographical situation in order to estimate future ambient air quality levels under different possible transportation (as well as other emissions source) scenarios (*12*). Ambient air quality levels represent the actual pollution concentration in an urban area's air shed and are crucial for determining emissions impacts on human populations, vegetation, and buildings.

In many of the world's cities that suffer from poor air quality, such as Los Angeles; Mexico City; São Paulo, Brazil; Manila, the Philippines; road transport accounts for between 70 and 86 percent of all pollutant emissions (*5*). To model transportation emissions accurately, and thereby determine impacts on air quality, these emissions should be disaggregated into their components. Motor vehicle emissions can be categorized as exhaust emissions (direct from tailpipe during operation), evaporative emissions (due to fuel evaporating from engine or ambient air temperature), and running loss emissions (evaporative emissions during vehicle operation) (*13*). The rate at which motor vehicles emit pollutants depends on a variety of factors, including vehicle type, age, and maintenance level; driving habits; and ambient air temperature.

A mobile source emissions model is used to determine transport contribution to ambient air pollution. California first developed a mobile source emissions model, EMFAC, to predict emissions factors (emissions per distance traveled) at a given average speed for different vehicle types. In this way, the data from travel forecasting models, combined with vehicle inventories, could be used to project future transport emissions. The Environmental Protection Agency soon developed a similar model, MOBILE. Both models have been refined continually as knowledge of emissions characteristics evolved and vehicle technologies and fuels changed. The current versions of the two models are MOBILE5 and EMFAC7F. Since both models produce factors based on average speed, they can be classified as average speed models (*9*).

Although the assumptions and algorithms underlying the two models differ, both EMFAC and MOBILE require similar data inputs and produce similar outputs based on average speed. In the case of the widely used MOBILE model, the vehicle fleet is categorized into seven types: light-duty gasoline vehicles, light-duty gasoline trucks, heavy-duty gasoline vehicles, light-duty diesel vehicles, light-duty diesel trucks, heavy-duty diesel trucks, and motorcycles (*13*). Inputs necessary to determine actual emissions factors include ambient air temperature, vehicle tampering levels, gasoline volatility class (which influences rate of evaporative emissions), vehicle age distribution, inspection maintenance parameters, emissions control technologies, air conditioner use, vehicle load factors, and altitude (*13*). Such data typically require detailed data bases from local departments of transportation. Fleet characteristic data combined with data from the travel forecasting model on the number, length, and average speed of trips that occur in an urban area and the proportion of cold versus hot starts enable average speed models to estimate vehicle emissions (*9*).

Energy Modeling

Road transportation accounts for approximately 72 percent of total global transport energy consumption (*14*) and at least 14 percent of global fossil fuel carbon dioxide emissions (*15*). As global road vehicle fleets and distances traveled continue increasing rapidly, road transportation will most likely become a larger relative consumer of global energy. Because the sector depends on petroleum as its primary energy source, growing energy consumption in road transport is of concern for a number of reasons, including (*a*) increasing risks of oil price shocks as global demand increases; (*b*) growing threats to many nations' balances of payments because of imported oil products; and (*c*) growing contributions to global greenhouse gas emissions.

Within an urban area, transportation energy consumption depends on three primary factors:

1. Vehicle design, including engine technology, transmission, weight, and aerodynamics;
2. Travel conditions, including vehicle speed, stops and starts, road conditions, and driver behavior; and
3. Weather conditions (to a lesser extent).

Ideally, a fuel consumption model should be able to reflect changes in vehicle fuel consumption characteristics and in travel characteristics to estimate current and future urban transport consumption accurately in different scenarios.

The simplest and most commonly applied method of modeling urban transport energy consumption operates in a manner similar to the average speed emissions models discussed earlier. Such models take average vehicle fuel efficiencies (which can be broken down into different vehicle classes, such as those differentiated previously) for a given average speed and, using outputs from the travel

forecasting model for number and length of journeys (which should at least be broken down by vehicle type according to the relative proportion of each vehicle type to total urban fleet), can give rough macrolevel estimates of urban transport energy consumption.

Land Use–Transportation Modeling

Land use is of concern to transportation both because land use data is a necessary input for travel forecasting models and because of the intimate relationship between land use patterns and travel behavior. Not only does land use determine trip generation rates, but land use patterns and urban form influence average trip distance and modal split. At the same time, land uses and trip generations are affected, over time, by changes in transport supply.

In most cases, land use data are input into travel forecasting models as exogenous variables, typically drawn from a group of potential land use scenarios. Although this technique is adequate for showing what transport system requirements a specific land use will dictate, its inability to project the impacts that transport system performance will then have on land use presents a serious shortcoming to travel forecasting.

In recent years, increasing attention in North America has been placed on the land use–transportation link, partly because of environmental impact concerns, as typified in the United States by the recent study *Making the Land Use/Transportation/Air Quality Connection* (LUTRAQ). The LUTRAQ study was designed as a national demonstration to "develop methodologies for creating and evaluating alternative land use patterns and design standards that will: reduce dependence on automotive travel; increase mobility for all segments of society; minimize negative environmental impacts, particularly those on air quality; reduce energy consumption; and foster a strong sense of community character" (*16*). In its preliminary survey, the LUTRAQ study found that land use forecasting procedures in most metropolitan areas in the United States have not changed significantly in the past 20 years (*16*). The study found only two urban areas have fully implemented the tools available to predict the ways in which transportation system performance influences land uses and vice versa, and points out that even these two systems have serious deficiencies.

The LUTRAQ documentation provides a good overview of the operating characteristics of mainstream integrated land use transport models judged available for use in the United States, dividing them into two operational groups, ITLUP and MEPLAN (*16*). Most of these models have two distinct subsystems: a land use subsystem, which when given the level of accessibility provided by the transport system, can divide out available space between different types of land use (residential, commercial, and industrial), and a transportation subsystem, which when given the land use patterns and the transportation network can determine the transport system operation and the level of accessibility of a particular travel zone. The resulting accessibilities for each zone can then be used as a new input into the land use subsystem. The timing of the interactions between the two subsystems is uncertain. However, the most common approach used assumes that the transportation subsystem stabilizes within the current period given the land uses. Over time, land uses evolve and are influenced by the past performance of the transportation subsystem.

MODELING IN DEVELOPING WORLD

Travel Demand Modeling

Several middle-income developing countries engage in travel forecasting modeling (i.e., Thailand, Mexico, Chile, and Brazil), but the vast majority of developing cities have almost no indigenous modeling capability. Of 31 major transportation studies (which include modeling efforts) carried out in developing world cities between 1955 and 1984, only one—the 1972 Delhi and Madras study—was completed by a local organization (*17*). Many have criticized these efforts as "hit and run" jobs, making little effort to survey the local circumstances or engage in technology transfer and capacity building. Some have even accused the U.S. Department of Transportation of being slow in transferring more recent portions of the UTMS to the developing world (*17*).

In recent years, trends suggest movement toward greater technical capability in southern countries, especially those countries with rapidly growing economies. For example, in Chile, a partnership between the government, major universities, and consultants developed an urban transport model for use in Chilean cities, specifically the capital, Santiago. In the early 1980s, researchers there determined that the current models available on the commercial market would not effectively address the realities of the transportation system in Santiago, namely, a very congested system and a system in which public transportation satisfied the overwhelming majority of urban trips. Without an adequate commercially available model, the government decided to develop its own model. Known as ESTRAUS, the model uses a simultaneous supply-demand equilibrium equation that solves the two stages of demand (trip distribution and modal split) and supply (network assignment) at the same time instead of the two steps normally required (*18*). In this way, the model ensures that the costs used to estimate travel demand are the same as the costs used in assigning that demand to the transport network, providing internal consistency.

Despite the trend toward more in-country capacity, a large knowledge gap still remains in most of the developing world. History has shown that most cities of southern countries do not start effective modeling until they have reached middle-income status (around $4,000 per capita). Unfortunately, by then the problems of automobile proliferation, air pollution, and large bills for imported oil already exist.

In the developing world, information on the extent and cost of O-D surveys is difficult to obtain, but obviously it is available only in areas where some type of travel modeling has been attempted or considered. In Chile, for example, as part of the development of the ESTRAUS model, relatively comprehensive O-D surveys were conducted. When ESTRAUS was developed in the mid-1980s, it was calibrated with limited data available at the time. In 1991 a thorough O-D survey was conducted, covering a total of 33,000 households (3.3 percent of city households) at a cost of nearly $1.3 million (U.S.). The time necessary to design the O-D survey and collect, process, and validate the data was 18 months. After the 1991 O-D survey was finished, recalibrating the model took approximately 12 months.

Transportation Emissions and Energy Modeling

Attempts to replicate U.S.-style transportation air quality modeling in the developing world introduces complexities due to diverse

vehicle fleets, rapid and unpredictable fleet growth rates, and unavailable or inaccurate basic data (i.e., vehicle miles traveled per year and vehicle emissions factors). Nevertheless, studies of various degrees of technical sophistication exist. In Bangkok, Thailand, for example, in 1990 researchers and consultants at the Thailand Development and Research Institute developed a transportation model to help project the growth of travel, energy use, and emissions as well as to evaluate various policy options. The travel data base and projections were drawn, with slight modification, from a study completed in 1990 by the Japan International Cooperation Agency (*19*). Emissions were calculated for all modes of transport, except rail and ferry services, using emissions factors from MOBILE4, EMFAC7, and other models (*19*). Nationally available data were used for calculating energy consumption factors. With these data, the research team developed a spreadsheet model that estimated emissions and energy use for 19 travel zones according to different estimated average travel speeds. Running the model under different future scenarios showed that only a combination of technical improvements to vehicles *and* area road pricing with improved mass transit would improve Bangkok's air quality (although carbon monoxide emissions would continue to increase) (*19*).

Other, more rudimentary attempts at modeling urban transportation and energy use include studies by the International Institute for Energy Conservation of three Asian cities (*20–22*). In these studies, linear extrapolations of current trends in urban growth, motorization rates, trip making, modal use, and trip lengths were combined with estimated emissions and energy consumption factors to project emissions and energy use under different scenarios. The World Bank–conducted Metropolitan Environmental Improvement Program has been examining air quality improvement possibilities, including transportation, in four Asian cities: Bombay, India; Jakarta, Indonesia; Katmandu, Nepal; and Manila, the Philippines. Unfortunately, the available literature does not highlight specific methodologies used (*23*). Other known studies include a European-backed effort to model the air quality of Tehran, Iran, using the European Union's CORINAIR model.

Land Use Modeling

According to Darbéra (*24*), a Lowry-type (*25*) land use model was used in the French-conducted transport planning study of Santiago, Chile, in the late 1960s—one of the earliest, if not first, computer-based modeling studies in a developing country city. Conducted largely to plan the French construction of the Santiago metro, the modeling and subsequent transportation plan had interesting effects on Santiago's transportation system and planning efforts. Six metro lines were laid out in the plan, two of which are currently operating (a third line is under construction). Line 2 of the Santiago metro has been criticized widely, at least by Chilean planners, as unjustifiable, largely because it never fulfilled the anticipated land use impacts that would have increased ridership to projected levels. Today, Line 2 continues to operate below capacity. The Lowry-type model used in the original French study was not used again in Santiago (*24*). The mixed impacts of the metro in Santiago on land use resulted in a general disenchantment with land use modeling among planners in Chile because, as some believe, the current state of land use–transport models is not sophisticated enough to handle the complex relationship between the two and simply because of the rapid, unrestrained growth of cites in typical developing countries.

At least two of the integrated land use transportation models have been applied to cities in developing countries. MEPLAN was applied in São Paulo, Brazil, where the forecasts produced by the model were validated by surveys over a 5-year interval (*16*). The TRANUS model, developed by a Venezuelan firm, has been used in Venezuela to evaluate urban land use planning on the island of Curaçao and the city of La Victoria, to conduct regional land use planning for a motorway and railway, and to study urban transportation planning in the city of Caracas (*16*).

SHORTCOMINGS OF CURRENT MODELING TECHNIQUES AND POSSIBLE SOLUTIONS

Travel Demand Models

In recent years federal legislation in the United States regarding both air pollution (the Clean Air Act Amendments of 1990) and transportation investment (the Intermodal Surface Transportation Efficiency Act of 1991, or ISTEA) has spurred increased scrutiny and criticism of travel demand modeling and its relation to air quality modeling. In general, criticisms of the traditional approach to travel forecasting focus on three primary areas: the underlying theories behind the models, the data used in the models, and the way in which the models are used (*12*). Detailed technical criticisms of the models are available in a growing collection of literature (*8,9,12,26,27*).

Criticisms of Models

Model Size A fundamental problem of travel demand modeling is the typically large, regional nature of the models used. These models were designed to predict the volume of traffic on major arterials. Smaller streets and localized traffic are most often not represented, thereby overlooking the significant congestion, energy, and emissions impacts of traffic situations on those facilities. Including all network features—high-occupancy vehicle (HOV) facilities, local streets, bicycle and pedestrian facilities, microscale information on intersections, and so on—would be greatly facilitated by a move to geographic information systems (GIS) (*28*).

Time of Day The models typically are designed for examining peak-period (a.m. peak) and sometimes off-peak travel, but they are not very sensitive to time-of-day variations. Time-of-day modeling is important to measure congestion impacts of time-shifting transport measures (peak-period pricing or flexible work schedules) and because air quality is very sensitive to time of day (because of evaporative emissions and photochemical smog formation). Measures to overcome this shortcoming include incorporation of time-of-day modeling possibly through developing time-of-day trip tables after trip generation or adding a fifth time-of-day submodel (*26*).

Travel Speeds Conventional models typically cannot provide average trip speed (not to be confused with link speeds), and even link speeds typically are not validated (*26*). Accurate speeds are critical for estimating emissions and accounting for the effects of congestion on transport, such as modal shifts (*26*).

Automobile Ownership Automobile ownership typically is either an exogenous input to the modeling system or modeled in very simplistic ways, ignoring the role played by gender, age, land use, and transit access (*8*). The process should explicitly incorporate models that relate automobile ownership to such variables (*8*).

Transit and HOV The four-step models typically cannot offer decent representations of measures that attempt to change vehicle occupancy levels (*9*); although most models can measure the impacts of HOV facilities, they need to include more detailed information (such as urban form and density) that might affect transit use.

Model Feedback Loops and Internal Consistency The typical four-step approach occurs in a sequential process—for example, outputs from one stage serve as inputs into the next. But final model outputs themselves, such as travel speeds, directly affect earlier stages of the process, such as land use development, trip generation, and modal split. Model iteration, whereby travel speeds are recycled back into the earlier stages of the process and models are rerun, can help make the models internally consistent so that travel speed outputs from assignment are the same as those used in earlier steps. Iteration has been shown to change future travel and emissions projections significantly (*29*) but may still produce inaccurate results, particularly when congestion is especially high. Another method for addressing internal consistency is through direct demand modeling, which is based on the premise that the decision to travel occurs simultaneously with the selection of destination and mode choice (*7*). Direct demand modeling simultaneously solves the distribution, modal split, and assignment stages in one equation (*30*).

Model Calibration To match model predictions with observed system performance, *K*-factors are used to correct for any differences. Although the use of *K*-factors will help achieve a "fit" between the current system and the model, it may not allow for accurate predictions of the future. The use of *K*-factors should be explicitly recognized, minimized, and quantitatively related to land use and socioeconomic factors (*27*).

Land Uses Attempts at feeding transportation modeling outputs into a transport-sensitive land use model still occur only in a handful of U.S. metropolitan areas. Because of the intimate relationship between transportation and land use, transportation model outputs should, at least, feed into a transport-sensitive land use model.

Nonmotorized Transportation Most models are based on vehicle trips, not person trips, virtually ignoring the role of nonmotorized modes of transport. The large-scale nature of the models also reduces the possibility of modeling the microscale nonmotorized transportation (NMT) network. Because of the lack of information on NMT facilities, amenities, and networks, changes in these cannot be accounted for in modal choice models (*26*). To overcome these shortcomings, trip generation should always be based on person trips, not vehicle trips (*27*). In addition, models should use zones small enough to capture short NMT trips and should include variables that represent NMT accessibility in trip generation, distribution, and mode choice (*27,31*). In Portland, Oregon, the modeling process incorporates a "pre–mode choice" model, which splits modes among walk/bike versus motorized modes. The pre–mode choice model uses the pedestrian environmental factor, which attempts to assess the model's travel zones for NMT-friendliness according to topography, street characteristics, and sidewalks (*32*). After generation, however, the nonmotorized trips are not distributed.

Data Availability and Collection

Relative to the amount of money and effort spent in constructing transportation infrastructure, the costs of data collection are low; still survey data are often neglected in planning because policy makers do not understand their importance to strong technical analysis (*8*). Failure to collect adequate data, however, will result in modeling and transport analysis efforts that will be, at best, subpar. Many urban areas in the United States use survey data that are close to 30 years old (*11*), which cannot accurately measure important demographic changes. Important considerations for data collection include the following:

- Costs have dropped because of technological advances (*8*),
- Surveys should focus on activities instead of trips (*27*),
- Survey data can have useful applications beyond travel forecasting (*8*), and
- A longitudinal panel survey approach (where a series of surveys are conducted with the same group of respondents) can improve data content and flexibility (*8*).

All data collection efforts should include information on walk and bike trips, including facilities inventory, NMT volume survey, speed and travel time survey, household survey, operators' survey, road accident inventory, inventory of costs and fares, an inventory of traffic regulations, and an outer cordon survey (*33*).

Emissions and Energy Models

One crucial shortcoming to both emissions and energy modeling for transportation stems from the fact that the models draw their inputs directly from the travel demand models, so any inaccuracies coming from the four-step model will be transferred into emissions and energy estimates. In that regard, addressing many of the model shortcomings identified here will help improve the accuracy of energy/emissions work. In addition, there are particular aspects of the four-step model that, although they do not necessarily affect the accuracy of the travel forecasting process, have important implications for air quality modeling. For example, the typical 10- to 20-year time frames that transportation planners use require that air quality analysts interpolate shorter-term conditions with often inaccurate results (*12*). Air quality analysis also requires information on the mix of vehicle types using the system, the proportion and time distribution of cold engine starts (which affect emissions levels), and seasonal variation (because different seasons produce different air quality effects)—all of which the typical travel model cannot produce (*28*).

The current generation of emissions factors models themselves also have limitations, in part because they estimate vehicle emis-

sions on the basis of average speeds, whereas actual vehicle emissions depend more heavily on actual driving patterns (stops and starts, accelerations and decelerations). Both EMFAC and MOBILE historically have underpredicted emissions; however, further research is necessary to determine the extent to which the underprediction of motor vehicle emissions on a regional scale is due to the transportation models from which they get their input data or the emissions factors within EMFAC and MOBILE (*34*).

To go beyond average speed emissions models requires developing more detailed network assignment procedures that can generate something more than average link speed estimates and that are more directly integrated with the emissions calculation process. In general, at least two broad classes of more detailed models can be identified (*9*): (*a*) instantaneous speed models, which attempt to simulate in detail speed-time-distance trajectories of individual vehicles, usually on a second-by-second basis; and (*b*) elemental or semiqueueing models, essentially an "intermediate" or "meso" level of model not requiring the extreme detail of the instantaneous approach.

As with emissions models, alternatives to average speed models basically involve microsimulation instantaneous speed models or mesolevel, elemental models (*9*).

Miller and Hassounah (*9*) suggest that mesolevel models may provide the best compromise between model detail (required for credible estimation of emissions), feasibility of generating data inputs required, and computational intensity for the foreseeable future.

Land Use Models

One of the major problems with the travel forecasting process today is the lack of feedback between transportation infrastructure and system performance on land use development. The almost complete absence of integrated land use transportation models throughout the United States reflects both cynicism about the models themselves and the lack of resources required to successfully implement them. Even ITLUP, which was designed to be a "fifth stage" of the traditional four-stage travel demand forecasting process, requires significant effort to implement.

When used, the typical integrated transport land use forecasting models (i.e., ITLUP and MEPLAN) have shortcomings:

- *Limited variables.* Most models operate under the assumption that the major factor determining residential location is accessibility to the workplace, although workplace access represents only one of many factors affecting residential location, with many other factors often dominating the process (price of housing, neighborhood attributes, and such). In addition, designed with the typical central business district–dominated city in mind, the models do not treat multicentered cities well. These models must explicitly represent the housing market and recognize the role that automobile ownership plays in location choices.
- *Equilibrium.* The models assume an equilibrium state, although urban areas rarely, if ever, can be considered to be in a state of equilibrium.
- *Travel models.* The travel demand components of these modeling systems tend to be fairly conventional and similar to four-stage models and thus carry the shortcomings outlined earlier. Advances in travel demand modeling should be integrated into the land use models.
- *Data requirements.* The calibration requirements and data needs of these models are significant. A move to GIS can help here, by allowing for several layers of data to be maintained in very disaggregate forms and aggregated according to need (*35*).

Problems of Developing Countries

When compared with a typical North American application, modeling in the context of a developing country introduces an extended set of challenges. Indeed, many have criticized the relevance of the UTMS to cities in developing countries, including Peter Watson, a World Bank official, who attempted to view the process from the perspective of the poor, saying (*17*), "Do I walk 12 miles and eat an extra bowl of rice or [do I] take a bus? All these fancy parameters that some transport planners are trying to model are absolutely irrelevant to some people."

Certain shortcomings in the UTMS as discussed here have particular relevance to the developing world:

- *Ignoring NMT travel.* Walking and cycling play a critical travel role in developing country cities. In many Asian cities, for example, NMT modes account for up to 80 percent of vehicle trips (*31*). Nonmotorized modes are also most important to the poorest segments of the population; ignoring their role raises serious equity issues. Even in Asian cities, many models now in use typically ignore NMT (*31*), and researchers consider the development of a transportation network model capable of reflecting NMT modes to be an urgent need (*33*).
- *Internal consistency.* The lack of feedback between model stages can produce very unreliable travel (and emissions) forecasts, especially in the face of congestion, which is typical in many cities of developing countries.
- *Value of time.* Travel cost estimates are based on the value of time, which approaches zero for the very poor. The quantification of time does not address equity for the poorest inhabitants of developing country cities (where the poor can compose 40 percent of the population).
- *Lack of data.* As discussed, data collection is critical, yet time- and resource-consuming. The needs of data collection are complicated further in the developing world, because telephone and mail surveys typically will not reach a representative cross section of the population, again raising important equity issues. House-to-house surveys are often the only possible means of collecting accurate data, and high illiteracy rates in some regions may force verbal surveys.
- *Automobile ownership.* With booming automobile ownership rates, cities in developing countries need to explicitly integrate the effects of growing fleets on urban land use and transportation system evolution.

Emissions and Air Quality Modeling

Again, most of the problems concerning emissions modeling apply to the developing world. In the United States, for example, experience suggests large differences in emissions during vehicle tests and actual on-road performance. In the developing world—with its extremely diverse vehicle fleets, increased problems of vehicle maintenance, lack of proper testing facilities, and the increasing phenomenon of "dumping" of secondhand vehicles from the industrialized world—the challenges are heightened.

The Bangkok work discussed earlier is being updated in an attempt to predict air quality for the Bangkok region in 2000. Using an internal travel forecasting model for 1994, the study divides the city into 118 traffic zones and 4 outside zones and sets up a traffic network consisting of arterial and feeder roads (*36*). Three different year 2000 road scenarios were formulated and base-year trip matrices were calculated from a 1989 study and calibrated against 1994 traffic cordon and screenline counts. Year 2000 trip matrices were calculated and emissions were estimated with MOBILE5 modified for Bangkok. The output of MOBILE was then plugged into the Swedish air pollutant dispersion model AIRVIRO (*36*). The results show that under current plans, air quality in Bangkok will continue to deteriorate, unless additional traffic improvement measures and stricter vehicle emissions and inspection standards are implemented. Although not variables in the study, incentives to discourage automobile use and more effective land use planning are highlighted as having a potentially critical role (*36*).

Land Use Modeling

The conclusions of the Bangkok study show that integrated land use transport models have a potentially important role in developing world urban transportation analysis, especially because of the rapid growth in most of these cities. It appears somewhat appropriate, therefore, that one of the most promising recent efforts in the field comes from the developing world, the Five-Stage Land Use–Transport model (5-LUT), developed in Chile. The 5-LUT is a "unified" model in which transportation and location are determined simultaneously, assuming that the consumer makes consistent location and transport decisions based on maximizing utility (*37,38*). The 5-LUT model comprises two submodels, a land use submodel and a transport submodel. The transport submodel provides the accessibility and attractiveness characteristics that consumers consider to be an attribute of the land site. Accessibility and attractiveness both are based on trip costs derived from a trip distribution model (*38*). The transport attributes help determine the land use market equilibrium, which in turn requires feedback and a further iteration of the transport model (*38*). Reportedly, work is under way to calibrate the 5-LUT model for operation in Santiago in 1995 with ESTRAUS as the transport submodel.

CONCLUSIONS

Travel modeling and necessary improvements, such as incorporation of nonmotorized modes and iteration of model runs, involve significant costs at the local level. In addition, travel modeling innovations, such as advanced equilibrium or direct demand modeling, require local technical skills that even experienced professionals typically lack (*7*). More advanced emissions, energy, and land use modeling also require additional resources and expertise. There is much truth to the suggestion by Gakenheimer and Meyer (*39*) that often "significant indications of transport system performance can be found from simple field observations."

Still, as large infrastructure investments rapidly occur to address transport demands throughout much of the developing world, the need to fully consider the broad impacts of these investments is critical. What will be the long-term energy or air quality impacts of such investments? What role can alternative land use development play or how will land uses be affected? These critical questions suggest that cities in developing countries can benefit significantly from recent developments in urban modeling efforts. Indeed, considerable potential to "leapfrog" technological boundaries and learn from the experiences of other nations exists. Multilateral and bilateral agencies, which account for a major portion of infrastructure investment in developing countries, could aid in this technology transfer by dedicating at least a portion of their investments to developing appropriate models, in-country technical capacity, and the data collection necessary for good modeling.

Recent and ongoing developments in emissions and travel forecasting modeling in the United States suggest that resolution of many of the current shortcomings is possible in the foreseeable future. Unfortunately, wide dissemination and implementation of such advances remain a challenge and the optimal level of modeling detail is unclear. What does seem clear, from the experiences of countries such as Chile, is that the most effective modeling efforts will be those developed by local, in-country expertise. So, as models evolve and move from laboratory to practice, it is important that they be shared with other practitioners in the field and implemented where appropriate, but they must have caveats of both strengths and weaknesses. In the end, modeling must be clearly recognized as simply one tool in a transportation planning process that is ultimately and necessarily political.

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