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Measuring the Effects of Urban Transportation Policies on the Environment

A Survey of Models

Alan J. Krupnick

Air pollution from urban travel is influenced by travel demand — by its distribution among modes, by congestion levels, and by the characteristics of vehicles and fuels. How well do existing models evaluate the effect of different policies, especially on welfare and on air pollution?

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Mandating emission control devices in new cars is only one of the most obvious steps to address the problem of vehicle emissions. Others range from taxes on gasoline and parking to incentives to scrap old cars or move businesses out of the cities.

There are models to simulate the "engineering" implications when changes are made to the vehicle fleet (such as the U.S. Environmental Protection Agency's "MOBILE 4"), but other models are needed to capture individual behavior, for two reasons. First, behavior — for example, using certain vehicles — affects emissions, and thereby the effect of policies on pollution. Second, behavioral relations determine how much consumer welfare is affected by different policies — through other channels than the effect on air pollution.

Krupnick reviews existing models of urban transport and evaluates their ability to simulate the effects of different policies on emissions and on other variables relevant to welfare. He finds that:

• Little modeling work is done on developing countries, but some stylized facts (the greater importance of nonmotorized modes, of mopeds, of old vehicles, and of work-related trips, greater growth in urbanization, and greater growth in the urban vehicle stock) allow us to assess how well models from developed countries apply in industrial countries.

• Models vary greatly in complexity. The central question for users is whether they want detailed coverage of the spatial nature of pollution and congestion. The most comprehensive and detailed models also require the most data.

Krupnick proposes eclectic use of several models, since a model incorporating long-term responses, shorter-term responses, and emission consequences is not easily tractable.

Krupnick acknowledges the many complex links between policies (on the one hand) and welfare and air pollution (on the other), but says that research can often be narrowed according to available policy instruments, data availability, and the implications considered relevant. Often, simple models can improve the basis for policy evaluation, particularly when there are limited data and resources for research.

Measuring the Effects of Urban Transportation Policies on the Environment

A Survey of Models

by
Alan J. Krupnick, PhD

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I. WHAT IS THE PROBLEM?

Population and output have been increasing rapidly in the primary cities of developing countries, such as Mexico City, Calcutta and Lima. In addition, the number of large cities is growing. There were 35 cities with population over 4 million in 1980, but by the year 2000, there will be 66, and by the year 2025, 135 (WHO, 1988). This growth has brought with it dramatic increases in vehicle ownership and vehicle-kilometers traveled. In Indonesia, the vehicle fleet tripled from 1970 to 1981, in Brazil it more than doubled, in Nigeria it increased 5 times. Nearly all of this growth has taken place in cities. For instance, from 1970 to 1980, the number of vehicles grew at an annual rate of 7.9% in Bangkok, 10% in Buenos Aires, 17% in Cairo, 5.6% in Calcutta, and 7.2% in Lima (World Bank, 1986). Using more recent data, in Mexico City, there were 1.1 million cars in 1975, with 2.6 million by 1989 (Faiz, et al, 1990). Vehicles per capita generally increased as well.

Of six developing countries reporting vehicle-kilometers-traveled (VKT) in 1977 and 1987, all experienced increases in VKT, ranging from 23% to 250% (UN, 1989a). Bus and truck traffic have also increased. Consider the modal split for San Paulo. In 1990, public transport made up 61.5% of total motorized trips, up from 58% in 1970. This slow rate of increase in share occurred along with very large increases in trips -- from 5.2 million person trips per day in 1970 to nearly 15 million in 1990 (Barat, 1990).[1]

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1. This exceeds San Paulo's high rate of population growth. Note also that San Paulo built a metro and significantly upgraded suburban rail during this period.

Overall, some 600 million trips per day were made by buses in cities in developing countries in 1980; this is expected to double by 2000 (UN, 1989b).

These increases in vehicle fleet size and use have inevitably led to increases in pollution emissions and worsening air quality. Where diesel bus use is high, this source would contribute significantly to particulate, nitrogen dioxide and sulfur dioxide emissions. Gasoline-burning automobiles probably contribute most of the carbon monoxide (CO) pollution, and a significant share of the volatile organic compounds (VOCs)[2] and nitrogen oxides (NO_x), pollutants of concern in their own right and as precursors to ambient ozone. One can be reasonably sure of the importance of autos and gasoline burning trucks to the CO emissions inventory because there are virtually no other sources of CO. Gasoline vehicles emit about the same amount of NOx per mile as diesel vehicles (except in China, most buses and trucks burn diesel fuel), much higher levels of VOCs, but far less particulates (PM) and sulfur oxides (SOx).

Considering actual estimates of emissions by transportation type, in Mexico City in 1987, transportation contributed 89% of the non-methane hydrocarbons (61% from cars, 14% from taxis, and most of the rest from trucks), 64% of the NOx (42% from cars and taxis, 22% from trucks and buses), and 97% of the CO (because trucks contributed 31% of the CO, it appears that substantial numbers of trucks burn gasoline). It is also

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2. These pollutants are also called hydrocarbons, and a large fraction of these, the non-methane hydrocarbons (NMHCs) are of primary concern as precursors to ozone.

reported that transportation has a very low share of PM (9%) and SOx (2%), with trucks responsible for most of these emissions (Eskeland, 1991).[3]

In developing countries with leaded fuel, gasoline vehicles would also produce much of the urban lead emissions and emissions of benzene and 1,3 butadiene. Lead emissions are primarily caused by burning fuel with a lead additive to enhance octane. Few developing countries have taken steps to phase out lead in gasoline (Mexico is an important exception), although nearly all developed countries have taken or are taking actions to do this (UN, 1989b). Diesels would emit polycyclic aromatic hydrocarbons (PAH) (USEPA, 1990).

In many of the large cities in developing countries, concentrations of the conventional air pollutants far exceed U.S. ambient standards and WHO guidelines, and respiratory disease rates are on the rise (Bumgarner and Speizer, 1991) amidst a fall in the incidence of the traditional waterborne diseases (Martines, Phillips, and Feachem, 1991).

There are a broad range of policy initiatives that might be taken to address these worsening problems. The entry point for the policy could include fuel manufacturers, vehilcle manufacturers, vehicle purchase decisions, or vehicle use decisions. The policies include a variety of command and control approaches as well as a similar variety of economic incentive approaches. Each have different private and public costs, different effects on congestion and pollution, and, ultimately, different net welfare effects.

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3. Given that these these pollutants are emitted by diesel engines, these percentages should be viewed with caution and, in any event, exposures to pollutants from trucks and buses are far higher than to the same pollutants emitted by power plants and industrial sources of PM and SOx. In addition, the fraction of particulates that are small and that therefore can travel further in the lung is generally higher for diesel.

Despite the large body of literature addressing transportation behavior and mobile source pollution, on the one hand, and the design of mobile source pollution control policies, on the other, it is unclear to what extent models exist that discriminate among the myriad approaches to reducing urban mobile source pollution, i.e., in the sense of allowing for the assessment of the net welfare effects of alternative policies.

A. OBJECTIVE AND APPROACH

The objective of this paper is to assess alternative approaches to modeling urban transport demand and mobile source pollution for their ability to address the welfare effects of alternative air pollution control policies. As both congestion and pollution are assumed to affect welfare, the capability of the models to translate changes in both congestion and emissions into welfare terms must be assessed. As pollution control policies may affect congestion, transportation demand management policies may affect emissions, and reduced congestion may reduce emissions of at least some pollutants (even with VKTs constant), the ability of the models to address both pollution control and demand management policies needs to be assessed. Revenue and equity issues are also to be considered.

The approach is first to narrow the scope of the analysis, in terms of transport types, modes, emissions, and modeling literature. The next section addresses modeling objectives, the instruments that the model must consider, and the nature of the linkage between instruments and targets. The following section contains the review of the modeling literature. It begins with stylized facts about transportation and pollution in developing countries and their implications for modeling; then an "ideal" model is derived that fully takes into account these facts. Eight models are then reviewed, followed by a discussion that considers some additional, simplified models that might be applicable to the issues of concern. Finally, a set of conclusions are offered on modeling strategies.

B. SCOPE

In this section the appropriate scope for the modeling effort is addressed, including the transport types, modes, and emissions and the relevant modeling literature.

Our concern is with passenger transportation demand in urban areas of developing countries, not with commercial and freight transport demand. This limitation is reflected in the literature, as the modeling of transportation behavior is nearly always bifurcated into commercial and passenger travel decisions. All private modal choices are considered, including walking, bikes, motorcycles, autos (and occupancy), buses, jitneys, mass transit, and minibuses. The models to be considered are only those addressing the demand for transport; the supply of transport (roads, buses, signaling, etc.) is treated in a rudimentary manner, although subject to manipulation in sensitivity analysis using the demand models.

All pollutants from vehicles are considered. These include: sulfur dioxide (SO_2), particulates, volatile organic compounds (VOCs), nitrogen dioxide (NO_2), carbon dioxide (and small quantities of other greenhouse gases), and carbon monoxide (CO)). The volatile organics and NO_2 are precursors to ambient ozone (O_3). Some VOCs are carcinogenic, such as benzene; some particulates are also carcinogenic, such as benzo(a)pyrene and other polycyclic aromatic hydrocarbons (PAH). Significant quantities of lead are also present as an additive to leaded gasoline.

The literature reviewed is, with a few exceptions, limited to the U.S. experience. Given the insignificance of bicycle and motorcycle use (as well as jitneys and minibuses) in commuting in the U.S., these modes[4] will be underrepresented in the discussion below (see Rao and Sharma (1990) for a discussion on the role of non-motorized travel in developing countries).

II. APPROACHES TO A SOLUTION

A. CRITERIA TO EVALUATE POLICY OPTIONS

Economists traditionally divide policy criteria into two types: efficiency and equity. The efficiency criteria, which are far more elaborated, are of two types: net benefits and cost-effectiveness. The net benefits criterion involves estimating the maximum amount gainers from a policy would be willing to pay to obtain the policy benefits minus the minimum amount of compensation required to make the losers indifferent. Policies producing the largest net benefits are preferred. Applying this criterion requires conduct of a cost-benefit analysis.

These costs and benefits may be pecuniary or non-pecuniary. In the context of policies affecting congestion and pollution, the pecuniary costs (or benefits) are expressed as changes in annualized private vehicle costs (fixed plus operating), fares, fees (if any), tolls, and parking charges. Transactions and administrative costs are important cost elements associated with policies that are pecuniary in principle but rarely measured. Non-pecuniary costs (or benefits) include changes in: time and inconvenience, anxiety over unreliability of various transport modes, loss or gain of transport options, work and productivity effects, health effects

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4. Walking will also be underrepresented as the U.S. models generally ignore this mode.

(including pain and suffering and changes in one's risk of premature death), and other environmental effects. The costs of a policy are traditionally measured as changes in expenditures rather than as changes in willingness-to-pay (or willingness to be compensated), which is, theoretically, the more appropriate measure. Costs are also usually measured in partial equilibrium, rather than general equilibrium terms. The more flexible losers are, in the sense of having many options open to them to cushion the effects of the policy, the lower would be their welfare losses.

As use of the net benefit criterion involves the controversial and difficult step of valuing health and other environmental damages, the use of the cost-effectiveness criterion is often preferred. In general, this criterion involves estimating the change in costs associated with a policy and dividing this estimate by some measure of changes in physical effects caused by the policy. The classic transportation/pollution example is cost-effectiveness of emissions standards on vehicles, estimated by taking the increase in vehicle costs over its lifetime divided by the reduction in its lifetime emissions.

The use of this criterion has two major drawbacks. First, it has no normative significance by itself. To know whether a policy is cost-effective it must be compared to some benchmark: the cost-effectiveness of something else or to an estimate of how much these improvements are worth. Second, and more important, when the policy acts on more than one physical effect (e.g., two types of pollutants or two health effects), these effects must be combined into a common measure associated with benefits. Cost-benefit analysis is superior to cost-effectiveness analysis in this regard as the aggregation is performed using the money numeraire. Other means of aggregation exist in specialized instances. However, in general, there are no non-monetary means of aggregating the diverse environmental and health effects of mobile source pollution.

To estimate cost-effectiveness in the context of a policy reducing mobile source emissions and congestion, one would need estimates of the emissions control costs minus the reduction in congestion costs to place in the numerator, leaving the denominator for estimates of the changes in emissions of the pollutant of most interest. In the U.S., this pollutant would be ozone, caused by the precursor emissions VOCs and NOx. In this case, changes in VOCs and NOx could be aggregated using a measure of "ozone forming potential" or using a model of ozone formation to obtain an ozone-effectiveness measure for the denominator. For developing countries, this approach to aggregating over pollutants, while a great step forward over current practice, would probably be overly simplistic because of the importance of lead, particulates, and sulfur dioxide emitted by diesel buses, scooters, and, for lead only, autos.

Other criteria of importance in this analysis are effects of a policy on net public revenues and on poor households. The former is obtained by netting public expenditures associated with the policy against any changes in revenues related to the policy, such as those from gasoline taxes, bus fares, and rail transit fares. Very poor households may not own a vehicle (certainly not in a developing country) and therefore a policy directed only to raising the costs of owning or operating a vehicle is unlikely to be regressive, unless perhaps if public transport fares also rise. Indeed, it is easy to envision progressive policies, such as registration fees tied to the value of vehicles or even a gas tax, which would be tied, of course, to miles driven per year. Indeed, policies to improve the environment in urban areas may disproportionately benefit the poor if they live predominately inside or downwind of major cities. For estimating effects on poor households, one needs household level survey data with income levels, transportation budget shares, and residence location relative to pollution concentrations.

B. DEFINING INSTRUMENTS

The possible policy options for reducing mobile source pollution (and congestion) are nearly limitless because, as noted above, there are so many "entry points" for affecting emissions: the vehicle characteristics supplied, the vehicles demanded, the fuel characteristics supplied, the maintenance of the vehicle and its emissions control system, and the choice of mode, trip length, timing and location, residential location, and employment location.

To organize the set of instruments that a model should be able to consider, we use a modified version of a taxonomy from Eskeland and Jimenez (1991). This taxonomy classifies policies by their type (economic incentive versus command and control),[5] by the control variables (whether prices, quantities, or technologies are being controlled), and by directness of control (either direct, say by a fee on emissions, or indirect, say by a gasoline tax that reduces emissions by reducing driving). Our taxonomy adds one more distinction -- if the policy is direct, whether it directly influences emissions or congestion. The entry point for the policy is obvious from the description of the instrument.

5. An economic incentive policy is defined as one that prices addition emissions or kilometers traveled, either through taxes, subsidies, or tradable permits. Command and control policies may be considered everything else, including, in this case, public sector policies to increase road capacity or buy more buses.

Many instruments have more than one entry point. For instance, a gasoline tax may influence the number of vehicles owned, location decisions, and trip frequency, length, and mode.

The use of the direct/indirect policy distinction is important for classifying instruments affecting emissions from transport. Without technology to measure emissions from a tailpipe directly, all emissions control instruments are indirect, but some use proxies for emissions (such as an inspection and maintenance program that may measure (however crudely) emissions from a standing vehicle (not grams per mile traveled)). These types of instruments would be labeled direct, as would auto emissions standards. Other instruments, such as a gas tax, do not attempt to influence emissions directly and require no measurements of emissions for enforcement. However, this type of policy instrument affects emissions indirectly. Indirect policies have advantages and disadvantages over direct policies. While an indirect policy may be less efficient than a policy operating directly on a target variable, such as vehicle emissions, it may have other advantages, such as lower administrative and enforcement costs. For instance, the gasoline tax is easy to administer. However, as pointed out by Davis, Grusly, and Sioshansi (1989), given that all vehicles must meet the identical emissions standards (on a per mile basis), a fuel efficient vehicle would pay a much lower tax than a gas guzzler while producing the same amount of emissions, making the implied tax per unit emissions much lower for the fuel efficient vehicle. In addition, a gas tax is not sensitive to the timing or location of driving. Thus, it may not be very effective at reducing emissions during congested conditions or reducing the cold start emissions tied to trip frequency.

Indeed, attempts to levy fees on any specific fuel, vehicle, or vehicle characteristic (such as fuel economy or carbon content) as a means of reducing emissions could have unintended consequences, if not carefully thought out. For instance, while a fuel efficiency standard may induce manufacturers to improve fuel economy, it may have little effect on emissions (or energy use, for that matter) as the lower price of driving induces people to drive more. Taxes on gasoline but not other fuels that could be used to power alternative fueled vehicles, for instance, may may not provide the appropriate incentives to develop and market the fuels that have the lowest social cost (private cost plus external cost). Having said all this, however, careful use of indirect instruments may offer the best option when monitoring of emissions is costly.

Some further explanation of the congestion\pollution distinction may also be helpful. Because of the link between vehicle speed and emissions (see below), congestion and emissions tend to be joint products. Thus, many policies for reducing congestion can also be viewed as emissions reduction policies. These include HOV lanes, toll roads, gasoline taxes, and congestion tolls. Yet some emissions reduction policies would have only minor affects on congestion (such as emissions standards), and vice-versa. Area access limitation policies are particularly interesting in this regard. Not only may they act to reduce trips and congestion, but even if trips are simply redistributed they may have the effect of reducing population exposures to pollution on net because population densities are higher in the center city.

Table 1 provides this taxonomy and a broad, but only illustrative set of policy instruments. Policies affecting transportation congestion and pollution have been overwhelmingly of the regulatory (command and control) variety, and operating primarily on the quantity of emissions and congestion: including direct policies on emissions, such as tailpipe standards, direct policies on congestion, such as HOV lanes, indirect policies on emissions, such as banning lead from fuel and indirect policies on congestion, such as road building and housing density restrictions. The incentive policies that have been tried have been applied to the price variable, but has been motivated mostly by the need to raise revenues (such as parking and vehicle registration fees, and gasoline taxes), even though they also cause changes that affect emissions and driving habits. Recently, interest has grown in congestion tolls, in hefty increases in the gasoline tax, and in a variety of quantity-based incentive instruments for emissions control. Interest on assessing emissions fees directly has been confined to schemes that base the fee on miles driven and emissions inspection results, a proxy for emissions emitted by the vehicle in operation.

Instruments to affect pollution have been primarily applied to new vehicles. In the U.S., these vehicles face fuel efficiency standards, emissions standards, and a variety of technology requirements. Because of the costs associated with these standards on new cars, holding on to one's older car has become more attractive. The U.S. fleet has aged to the point where the emissions from older (pre-1981) cars (which are generally more polluting, particularly pre-1971 models) are thought to be the major source of urban emissions, even though older vehicles are driven far less than newer ones. Inspection and maintenance programs, which have questionable effectiveness as structured, are the only instrument addressing older vehicle emissions.[6]

C. LINKING INSTRUMENTS TO TARGETS

This section examines the linkages between individual urban transportation decisions, congestion, and pollution and identifies those that are most important (at least in the U.S.). These relationships aid in the evaluation and estimation of emissions by the fleet. More importantly, they allow for comparison of efficiency of alternative policy instruments by making emissions (and congestion) explicitly a function of fleet size, age, road network characteristics, travel patterns, and other factors, most of which can be influenced by policy instruments. In short, this section provides background information on technical and behavioral relationships that are necessary to link any particular instrument to the target it is supposed to affect.

C.1. Emissions

The discussion begins with consideration of the USEPA's MOBILE4 model because it embodies much of what is known about the transport-pollution link. Although it is the most advanced and complete emissions forecasting model available (California has a similar model), it has several significant limitations: it ignores emissions of lead, particulates, and $SO2$,[7] and it uses estimates for the average vehicle driving cycle rather

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6. For instance, the oldest vehicles are exempted and strict limits are in effect on the ceiling for mandated repair costs. Thus, many vehicles violating emissions standards avoid any corrective actions. See, for instance, Stedman (1989) on the share of old cars in overall emissions.

7. Lead and particulate emissions can be estimated fairly easily using data on fuel quantity and quality.

than preserving information about the distribution of emissions over components of the cycle (acceleration, deceleration, etc.), information very useful in the design of vehicle targeting strategies. It has also been criticized recently (Stedman, 1989) for significantly underestimating HC and CO emissions, on average. Indeed, efforts at EPA and other agencies are now underway to improve forecasting of emissions from vehicles. Most parties in the debate agree that MOBILE4 does a good job predicting emissions of pre-catalytic vehicles.[8] As these dominate in urban areas of developing countries, the recent criticisms of MOBILE4's accuracy may not be particularly important at present.

MOBILE4 estimates hydrocarbon emissions (VOCs, HC, NMHC), as well as NOx and CO emissions on a per mile basis from gasoline autos and trucks, diesel autos and trucks, and motorcycles. Motorcycles do not appear to be differentiated by four stroke and two stroke engines, although their emissions factors would be very different. Buses are ignored and alternate-fueled vehicles have not as yet been incorporated. It provides emissions by vehicle age class (including pre-emissions control vehicle classes). Emissions of HC and NMHC are estimated from exhaust, evaporative, running loss, and refueling activities, considering the reid vapor pressure (RVP) of the fuel, average ambient temperature, and altitude. CO and NOX emissions from exhausts are estimated by temperature and altitude. Exhaust emissions are produced for cold start, hot start, stabilized, and idle operation. Data on trips per day and miles per day are incorporated in the model and vary by vehicle age. Speed correction

8. Very recent results from a vehicle scrappage program run by Unocal Corporation challenge this agreement. Of 74 pre-1971 vehicles tested, tailpipe HC emissions averaged 16 g/mi versus MOBILE4's top estimate of uncontrolled emissions of 9 g/mi. Some of the vehicles tested by Unocal emitted over 50 g/mi.

factors are incorporated for each pollutant, and extensive information is included about the effect on emissions of mandatory inspection and maintenance procedures and tampering.effects.

The importance of trips versus age, model year, fuel quality (volatility measured as Reid Vapor Pressure), and speed can be examined by using relationships adapted from EPA's MOBILE4 model (Shih, 1990). Short of presenting the mathematical relationships, which are difficult to extract from MOBILE4, table 2 provides a "feel" for these relationships by presenting estimated emissions changes arising from some particularly relevant scenarios. The scenarios are based on improving fuel quality (lowering RVP), substituting newer for older models, substituting a zero-mile versions of a model year for an aged version, increasing driving speeds, and eliminating trips by chaining or by car pooling. The focus is on hydrocarbons from autos, but information is also provided for NOx emissions from autos and HC emissions from motorcycles.

From this information, the most significant reductions in HC emissions (but not NOx emissions) are found in fleet turnover, particularly in replacing uncontrolled vehicles with those produced in the late 70's. These reductions are not necessarily the cheapest, of course. Actually, up until 1975 (with emissions standards calling for about a 60% reduction in HC from uncontrolled levels for vehicles with 50,000 miles on them), the standards were met by engine modifications. These were very cheap. Afterwards, up until the 1980 standards, a fairly primitive catalyst was used, which also was fairly inexpensive. However, to meet the 1980+ standards, a three-way catalyst was needed, which has been shown to be cost-ineffective relative to other control options available (Crandall, et al., 1986). From this, it follows that our current modeling effort should focus on uncontrolled vehicles, and vehicles without catalysts, versus all other vehicles. For countries without unleaded fuel, new vehicles are probably being produced or imported with engine modifications to reduce emissions but without catalysts. In this case, substantial reductions in emissions from pre-controlled levels may be already realized.

The foregoing also shows that cold start emissions are quite important, representing 50% of HC exhaust emissions for a 5-mile trip and 40% for a 10-mile trip. Thus, chaining two trips together reduces HCs significantly through the elimination of a cold start, even with total miles driven kept constant. Increases in average vehicle speed appear to be of lesser importance to emissions reductions (but, of course, cost-effectiveness is the ultimate test of importance),[9] although expressing speeds in average terms ignores how the car is being driven, i.e., at a steady speed or with much stopping and starting. The latter are likely to produce much higher emissions than the former, as both acceleration and deceleration tax the emissions control system.

Speed effects when considering ozone concentrations are unclear, as NOX tends to increase with speed while HC decreases. The relationships between (i) emissions and speed and (ii) emissions and volatility are virtually identical across model years and for vehicles of different ages. Thus, these interaction effects can be ignored.

Because of the relatively large proportion of diesel vehicles in developing countries, it is important to compare diesel emissions to those of gasoline vehicles, although no definitive conclusions can be reached. This cannot be done comprehensively using MOBILE4. Table 3 provides data

9. Note now, as we do later, that large benefits in time savings are to be had from increasing speeds.

from one source (USEPA, 1990) (which may not match well with data from MOBILE4) for average U.S. tailpipe emissions coefficients for heavy-duty (HDD) and light duty diesel trucks (LDD) and for passenger and light-duty gasoline vehicles with and without catalytic converters.

The most comparable figures are between gasoline vehicles with catalytic converters and LDD. Emissions per mile traveled varies significantly by whether gasoline or diesel fuel is being burned. Of the conventional pollutants, sulfur oxides are over five times larger and total particulates are 30 times higher for the LDDs, with sulfates about six times larger (mostly in the form of sulfuric acid), while CO, NO_x, and HC (a slightly broader measure of hydrocarbons than VCCs) are substantially lower. Lead emissions are zero for diesel vehicles.

The comparison for particulates is even more unfavorable for diesel than it looks, since nearly all of the diesel particulates are very fine (and therefore can penetrate deeply into the lung)[10] and some carcinogens such as benzo(a)pyrene, are also far more heavily represented in diesel emissions than in gasoline emissions.

HC emissions are even larger for gasoline vehicles than is apparent from the table. Gasoline vehicles have substantial evaporative (and running loss) emissions, in addition to the tailpipe emissions estimates on the table. EPA (1989) estimates that current model gasoline vehicles generate only 41 percent of their total VOCs from the tailpipe, the rest coming from evaporative (16 percent), refueling (11 percent), and running

10. According to another source (WHO, 1988), diesel engines generate ten times more respirable particulates than gasoline engines per kilometer traveled; even allowing for this, diesel buses are less polluting than gasoline passenger vehicles per person-trip (Rallis, 1988).

loss (31 percent) emissions. Also, gasoline vehicles emit three times the amount of benzene, which is also carcinogenic.[11]

The net effect on emissions of modal shifts is of major interest. Any comparison between autos burning gasoline and diesel buses should be normalized by passenger miles traveled. If there is excess capacity, shifting passengers from autos to buses may have little or no effect on bus emissions, while reducing auto emissions, making the emissions benefit unambiguous. If, as is more likely to be the case in developing countries, the existing bus system is at full capacity, we can assume that any major shifts in demand from autos to buses would require additional buses or extension of the peak travel period.

Assuming, for simplicity, that bus emissions are the same as those for heavy-duty diesel in table 3, an average of 20 passengers per mile on a bus and 1 person per mile in an auto would equate NOx emissions per passenger mile between a bus and a late model auto. For SO2, the breakeven point is 23 passengers, and for particulates, 160. In the U.S., where transit buses carry only an average of 10 people per mile (S. Davis et al, 1989, p. 2-23), and auto loads average 1.7 per mile, a bus would need to carry 34 people to create equivalent emissions on a passenger miles traveled (PMT) basis. Data for Mexico, where capacity utilization is much larger for both public and private transport modes (Eskeland, 1991), show that, at least for NOx, combi and microbus emissions per passenger mile are far lower than for autos and taxis: 0.42 g/pass km versus 1.11 g/pass km.

Finally, as scooters and other non-four-wheeled vehicles are so much more prevalent in some developing countries (particularly in Asia),

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11. On the other hand, the diesel HC emissions tend to have a somewhat greater ozone-forming potential than those from burning gasoline.

emissions from scooters are considered. Two-stroke engines can produce high levels of pollution in spite of their fuel economy. Faiz et al. (1990) finds that scooters generate 22 times the amount of VOCs per mile as automobiles.

2. Beyond Emissions.

The preceding section makes it clear that estimates of vehicular emissions are available and may be appended to transportation models without much trouble. Yet, if one is interested in estimating the cost-effectiveness (let alone welfare effects) of alternative policy instruments, it may not be enough to estimate changes in emissions. Different policies may have the same effect on the total emissions of a pollutant but have very different effects on pollution concentrations, on population exposures, on health effects, and on benefits. These differences could arise because of differences in the timing or location of emissions, for instance. In addition, if the mix of emissions changes differs across policy instruments, the mix of health effects may also differ, as may the benefits associated with one policy instrument versus another. How important is it to pay attention to these distinctions?

One generalization about this problem is: it depends on the pollutant being affected. Ambient ozone, formed from HC and NOx emissions in the presence of sunlight, is the least spatially-differentiated pollutant but one with strong time-dependence and significant non-linearities associated with baseline pollution and meteorological conditions. That is, for most cities it is probably acceptable to ignore where within the urban area the emissions changes are occurring, but one should not ignore when and under what baseline conditions. The usual assumption made is that baseline conditions are "worst-case," i.e., conditions on days when the highest ozone levels are observed. In the unlikely event that changes in precursor emissions occurred at night, effects on ozone could probably be ignored. To say more about temporal considerations requires considering which temporal measures are the most important determinants of health effects. Even if one does not intend to predict such effects, the analysis will be more informative if the concentration measures used accord with the measures thought to be most closely linked to health effects.

One can obtain some idea of these measures by referring to the measures used to express U.S. ambient air quality standards, which are set to protect health with a margin of safety. Staying with ozone, the most important temporal measure is the maximal one-hour average for the day. This measure is used to express the ambient standard and is used by all of the available epidemiological studies linking ozone exposure to acute health effects.[12] Because of this and for other reasons, there are shortcut approaches to linking emissions to concentrations. Dowlatabadi, Krupnick, and Russell (1991) report on a variety of "ozone sensitivities" in the literature, which relate the percentage change in an ozone precursor (either HC or NOX or both) to the percentage change in daily maximum ozone readings. Ozone isopleth diagrams also are available for this purpose. However, the initial fraction of each precursor emitted by mobile sources and baseline ambient HC/NOX ratios must be known to compute the ozone effects and such diagrams are unlikely to be available for cities in developing countries.

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12. There are no studies of chronic effects or of the ozone-mortality link.

CO is the most spatially sensitive emittant. FPA has specialized models for estimating CO concentrations within the vicinity of roadways. There are no dose-response functions available for CO that will provide health endpoints for valuation (although there is a one-hour ambient CO standard).

NOx has little, if any, effect on health in its own right, at least at ambient concentrations in U.S. cities. Its importance is through creating ozone. The same can be said for HC. Although some components of hydrocarbons emitted from vehicles are carcinogenic (such as benzene), risk assessments for these air toxics invariably show trivial effects on health of their elimination, let alone for the small differences in their concentrations that would be examined as part of an assessment of effects of alternative policy instruments.

Particulates are of potentially major concern, as a recent set of studies have shown consistent and significant effects of daily maximum particulate concentrations on mortality within an urban area (Schwartz and Dockery, 1991). As almost all of these studies feature linear dose-response functions, annual average particulate concentrations can be used without hesitation.

Because there are so many industrial sources of particulates, to link changes in mobile source particulate emissions to concentrations requires an emissions inventory and ambient particulate readings; assuming proportionality between reductions in mobile source particulate emissions and particulate concentrations is probably acceptable, with one caveat. Some attention must be paid to particle sizes. Diesel particulate emissions are extremely fine, so a change in these emissions will not necessarily change total particulates proportionally.

For health effects, the diesel emissions, being so fine, penetrate most deeply into the lung and, therefore, are presumably the most dangerous fraction of total particulates (TSP). Yet, the recent mortality studies cited above use TSP not fine particulates as their measure of pollution. In fact, health professionals are not at all in agreement on the particulate agents that are most dangerous to health (indeed, effects of particulates have not even been differentiated from those of SO2).

Unlike ozone, changes in particulate emissions at one location (or transport corridor) will generally have greater affects on the surrounding area and little, if any, effects on other areas. For policies that have differential effects across space, this distinction could be important if exposed populations also differ significantly across space. EPA has programs to model corridor effects of TSP but the standard point source, Gaussian plume models would not apply to mobile sources.

SO2, as a gas, will be less spatially differentiated than particulates but owing to its direct emissions from diesel sources, more spatially differentiated than ozone, which is a product of chemical transformation. In any event, as an SO2 effect has not been clearly differentiated from a particulate effect, it may be acceptable to ignore SO2 emissions (unless a policy of reducing sulfur in fuels in being contemplated) on the grounds of otherwise double-counting health effects, focusing on the particulate effects as capturing all of the particulate-SO2 diesel effects.

Lead, as a particulate, will have spatially differentiated effects if traffic patterns are altered along a specific transportation corridor. But otherwise, one can assume that mobile source lead emissions are ubiquitous.[13] On the basis of health effects, lead is by far the greatest

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13. Evidence of this ubiquitousness is that very tight statistical relationships have been discovered between monthly gasoline sales in a city and blood lead levels in children.

concern, as it strikes children hard (both acute effects and learning disabilities) and there is little uncertainty over the dose-response function.

3. Modeling Congestion

The congestion effects associated with alternative policies is a critical modeling issue for two reasons. First, congestion on roadways is a potentially important cause of the poor air quality of cities. Second, as Krupnick (1991) notes, the vast bulk of benefits from transportation control measures may be found in time savings -- in his example for the U.S., the ratio of the value of travel time savings to a "high" estimate of the value of health improvements (through reductions in ambient ozone) is over 20 to 1. Therefore, in this section, congestion modeling and the linkage to emissions is examined in some depth. It should be noted that the discussion below is based on a stylized model, ignoring such important "micro" effects as junction delays, acceleration and deceleration while in highly congested conditions, etc. Also, this discussion applies to U.S. cities, where information concerning congestion is reasonably well known. There has been less research on congestion in developing countries.

The fundamental equation of a stream of vehicles is:

$$q = uk,$$

ere q is vehicle flow past a point, in vehicles per hour, u is average vehicle speed (miles/hour), and k is vehicle concentration, in vehicles per mile. Each of these variables vary simultaneously and are interdependent;

at higher speeds the spacing between vehicles increases, which reduces concentration k. The effect on flow in indeterminate, *a priori*.

The underlying relationships are non-linear. As suggested above, concentration falls at a decreasing rate with speed. Flow thus increases initially with increasing speed but, depending on the safety regime assumed, may reach a maximum and then fall with still higher speeds. These two relationships imply that flow first rises and then falls with increasing concentration.

The u-q relationship is typically stressed and is portrayed in figure 1 which relates vehicles per lane per hour to speed on a four-lane expressway with a design speed of 60 mph. At a volume of 1600 vehicles, average speed is 15 mph, for a concentration of 107 vehicles per mile. With 600 fewer vehicles per lane per hour, speeds could increase to 50 mph, with a concentration of 20 vehicles per mile.

Models without congestion effects simply assume an average speed and volume of vehicles or estimate speed from traffic volumes relative to road capacity. All models where congestion is endogenous contain versions of the above fundamental relationship, albeit much more sophisticated.

In the absence of a real world example, Krupnick (1991) offers an example of the time savings for a very simple fabricated scenario: eliminating 600 of 1600 trips per hour from a five-mile freeway section through, say, a car pooling program. Based on figure 1, each remaining vehicle would be saved 14 minutes of driving time over the five mile section. Valuing this time at $1.00 per occupant[14] and counting occupants

14. This may be appropriate for developing countries, but is extremely conservative for the U.S., where studies show auto on-vehicle commuting time is valued at 178% of the wage rate, or $4.15 per occupant for this example (Winston, 1985).

doubling in car pools, results in benefits of $2.67 per vehicle trip eliminated. We will return to this example to examine the environmental link.

This environmental link may be modeled using information from MOBILE4, which provides equations relating vehicle speed to emissions, by model year. A graph of some of these equations for HC emissions of autos is reproduced as figure 2, which provides speed correction factors to MOBILE4, based on a factor of 1.0 for the average vehicle speed of 19.6 mph. These factors are multiplied by the estimates of emissions per mile, which are calibrated to a 50,000 mile vehicle traveling at 19.6 mph. Note that the functions are highly non-linear in the 10 to 30 mph range and that model year has little effect on these relationships. (The same is true of earlier model years). Also note that MOBILE4 omits any estimates for emissions when accelerating or decelerating since it is based on average speeds.[15]

Returning to the above example, assuming all vehicles are 1981+ with 50,000 miles on them, the increased speed of the 1,000 vehicles remaining over the 5-mile stretch of freeway "saves" 3.35 kg of HC in total. Valuing the health benefits at a very generous $10,000 per ton HC reduced (five times higher than the "high" estimates for such benefits in Krupnick and Portney, 1991),[16] results in benefits per trip eliminated of only $0.06.

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15. Faiz et al (1990), p. 46, provides comparisons of emissions (in ppm per volume) while cruising, accelerating and decelerating. Emissions while cruising are far lower (for hydrocarbons, 1000 ppm while cruising versus 1,600 ppm while accelerating and 10,000 ppm while decelerating).

16. These estimates should be lower in a developing country than a developed one because of the expected lower WTP for health reductions in the former. At the same time, the reduction in health impacts for a given reduction in air pollution may be larger.

Thus, total congestion-related benefits (not counting the emissions reductions from the 600 trips eliminated) are $37 from the emissions reduction and $1,600 from time savings. Adding $180 to the emissions reduction benefits from the 600 fewer cars driving (10 miles) to work, we find a ratio of congestion reduction benefits to emissions reductions benefits of 1,600/217 = 7 to 1.

III. MODELING THE TRANSPORT-POLLUTION LINK: LESSONS FROM THE LITERATURE

In this section, stylized facts about urban areas of developing countries are presented to aid in simplification of the modeling task and to highlight components of models that must be present if the transport-pollution link is to be reasonably modeled in a developing country setting. Next, as a useful modeling benchmark, an ideal, probably unattainable, model is sketched out -- one that meets the modeling objectives stated above, provides "levers" for modeling all the policy instruments of interest, covers all the important technical and behavioral relationships and comports with the stylized facts. Finally, the models in the literature are analyzed for how close they come to the ideal model.

A. STYLIZED FACTS AND MODELING IMPLICATIONS

There are several stylized facts appropriate to urban areas of developing countries that would influence the way in which an ideal model of the individual transportation-pollution link would be constructed. Some of them are:

(i) The areas with high levels of air pollution are all growing rapidly. This means that the ideal model should incorporate residential location decisions and make them dependent on air pollution concentrations (say by permitting housing prices to vary with air pollution). It also suggests that land use controls and infrastructure policies be considered as policy variables. If residential location is endogenous then the feedback of transportation emissions and congestion on the location decision might usefully be represented in such a model.

(ii) Public transit systems in developing countries are at much higher capacity utilization and have larger market shares than in the U.S. Thus, if policies are put into place to discourage use of other modes and/or encourage use of buses they need to be linked to policies for expanding the fleet. The menu of potentially cost-effective policies to consider should, therefore, include: increasing bus fares (to improve maintenance and the financial stability of fleet owners and operators) and privatization.

(iii) Programs to inspect and maintain emissions control systems are generally non-existent in developing countries. As relatively low-cost procedures (such as tune-ups) can reduce emissions significantly, such programs should be highlighted on the menu of cost-effective policies.[17]

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(iv) If the research in Jaipur is any guide (see Deaton, 1987), work/student trips are a very large percentage of total trips and few people take more than one round trip per day. This has important practical implications for applying U.S. models to developing countries, as these models generally incorporate non-work trip equations specified in great detail. This is a promising area for simplification.

(v) Vehicle and fuel quality (diesel) is low, with most vehicles without catalytic converters (which would be poisoned by leaded gasoline in any event). Incentives to raise fuel quality and to produce lower-emitting vehicles may be as or more efficient than direct transportation incentives.

(vi) Very low income developing countries face trade-ups primarily from walking or bicycles to motorized forms of transport, such as scooters and buses. These modal choices are unrepresented in conventional models. Policies encouraging a slowdown in mode switching from scooters to autos present particularly interesting tradeoffs between pollution and congestion, as the scooters are so small (which aids in keeping congestion down), yet are so polluting.

(vii) Basic highway investments are lacking, such as traffic signals and integrated timed systems, that would speed flow, lowering congestion and emissions. An ideal model would permit assessment of the effect on traffic speeds of these investments to be estimated.

(viii) The major reason for caring about vehicle age is the embodied technology for emissions control in each model year not the relationship between age and emissions, for a given model year. As

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17. U.S inspection and maintenance programs are considered by some to be fairly cost-ineffective; but these programs are applied to a fairly clean fleet. When applied to a fleet with more obvious and lower cost problems, such a program may, perhaps be more effective.

very large, cost-effective reductions in emissions are likely by substituting newer non-catalytic vehicles for older ones, the vehicle purchase decision is an important one to model if medium term to long-term welfare comparisons are desired. It is also important because vehicle ownership is so income elastic at current ownership rates. The aging of vehicles can perhaps be ignored, basing emissions estimates on some estimate of average cumulative mileage per vehicle.

(ix) One could assume that no household owns more than one vehicle, eliminating this complicated modeling component. However, occupancy rates of the vehicles that are owned are probably higher than in developed countries, suggesting that an ideal model would address occupancy.

(x) The growing share of gasoline vehicles in urban emissions and the large current share contributed by diesel vehicles means that attention must be paid to both the ozone precursors emitted primarily by autos and the emissions from diesel vehicles, primarily particulates and NOx.

B. AN "IDEAL" MODEL OF TRANSPORTATION DEMAND

"Ideal" is defined in the sense of permitting one to examine the widest array of policy approaches unconstrained by data limitations. The ideal passenger transportation-externality model is one permitting the estimation of the net welfare change associated with policies affecting transport demand and other types of behavior with implications for emissions (and congestion). The model would be applicable to urban areas and, within an area, be spatially and temporally detailed, as appropriate.[18]

Space would be represented in enough detail to capture the general equilibrium effects on traffic of spatially localized policies, such as establishment of HOV lanes and downtown access restrictions. This generally means that some representation of a road network with origins and destination is needed, although there are numerous approaches to short-circuit this costly process.

18. Of course, more than one model could be combined or run to address all of these issues. The construct of a single "ideal" model is adopted for simplicity in exposition only.

The model would consider decisions ranging from those made in the long-run to those made in the very short run: residential/work location, vehicle purchase/ownership (new versus used,'vehicle characteristics, but in general not number of vehicles per household), occupancy, and mode choice (bus, auto, shared auto, scooter, rail, walk, bicycle, combinations). Trip choice could in general be eliminated, if one is willing to focus on commuting. Otherwise, trip choices could be elaborated upon (number per period, purpose (commuting, social, etc), timing, and destination (embodies trip length)). In general and in the shortest run, given location and vehicle ownership, mode and trip choices are made simultaneously. Over a longer period, the vehicle ownership decision may be considered as simultaneous with mode and trip choice. Over an even longer period, residential and work location, and even hours worked (which may usefully be considered as fixed in the short run) may be considered choice variables at the individual level.

For consistency with individual behavior and investigation of distributional effects, the model would be disaggregated to households or persons and incorporate econometrically estimated parameters. To account for urban growth, the model would be dynamic and incorporate demographic changes. Discrete choice models, as the most advanced and realistic models of individual behavior, would be used to capture modal choice, ownership decisions, and any other appropriate (non-continuous) decisions.

The ideal model would also interact with a commercial transportation model and an infrastructure supply model. The former is needed to estimate effects on commercial traffic with respect to various pollution control policies and to tote up the net welfare effects to business from resulting changes in congestion. In addition, changes in truck traffic affect welfare of those using private and public transport through effects on congestion.

The ideal model would also captuse the revenue effects of any policy and track welfare effects falling on the poor. Projecting revenue effects from changes in gasoline purchases and fares is easy using most conventional transport demand models. Effects on the poor require that the most important links between instruments and low income households (such as expenditures on transportation and labor market effects) be modeled.

An important elaboration is the feedback effect of emissions (and ultimately, health effects) on location choice. The ideal model would capture this feedback.

In addition, the model would not only incorporate an emissions component distinguishing emissions by auto versus bus (diesel except in China), model year, speed, whether there is an inspection and maintenance program or not, etc., but would incorporate all the linkages from emissions to the valuation of health and other effects related to those emissions. As location and timing of emissions as well as the type of emissions affect the size of injury and avoidance behavior, and the former factors are affected differentially by policies, the model would have a high degree of spatial and temporal resolution, at least for some pollutants. HC, NOx, particulates, lead, and CO emissions (with possibly SO2 for some policy instruments) would be included.

C. MODELS IN THE LITERATURE

In this section, eight models are reviewed in detail, for their ability to meet the objectives of this project (i.e., predicting the welfare effects of alternative pollution control and transportation control policies (section

I.A), permit various policy instruments to be modeled (section II.B.) and link these instruments to targets (section II.C.). Their empirical tractability is also assessed. In addition, some additional simplified transportation models are reviewed as a group because these types of models may be of particular use in inexpensively discriminating between alternative policy instruments.

These models are by no means the only models in the literature. Rather, an attempt was made to obtain a set of models that together cover the full range of temporal choices and spatial detail. Consistent with the earlier discussion, these choices may be arrayed temporally, from the very short-run decision of whether to take a trip, through the medium term decision about whether to own a vehicle, to the long run decision about where to live and work. Spatial detail ranges from a full representation of a particular city's network of streets and expressways, through very simplified networks of several nodes and links, to models that present space in abstract terms of simply ignore the spatial dimension. The models also include those with individuals as a unit of measurement and those based on aggregates.

These considerations result in four different types of models:

(i) models focusing on the residential/work location decision of individuals with commuting cost or time as an argument and with an abstract but mathematically tractable network (McConnell and Strazheim (1982), Kim (1979)). The monocentric model can examine policies that alter the variable cost but not the frequency or location of commuting. The polycentric models (Kim, 1979) can do the latter but the only examples of this do not include congestion. They do not and probably cannot examine the ownership decision and do not consider modal choice. They can consider congestion tolls but not vehicle restraint schemes.

(ii) models focusing on vehicle make/model/VMT choice at the national level (Train, 1990), with location given and no network (Deaton, 1987) or network exogenously obtained (Cameron, 1991) and used in simplified form. In principle these models can consider all relevant policies except those directly influencing location choices, although none are designed to be this complete. These models can be individually of group-based.

(iii) "classic" transportation models, usually engineering/gravity based, that take location choice and network as given but are very detailed spatially (Ingram, 1975). These provide the most micro-level policy guidance but at a price of major complexity and data requirements. These models can address the set of instruments conventionally examined by urban transportation planners, but can't examine all instruments because they take car ownership and location decisions as given. These models can be individually or grouped-based.

(iv) aggregate models of, say, fuel demand that abstract from space or from any particular urban area (Wheaton (1982), Wharton (1977)).

Table 4 summarizes key characteristics of these models: whether they produce estimates of welfare change, whether a breadth of instruments and targets are considered, the choices modeled, the model's tractability, and how it deals with space, congestion, and emissions.

Wheaton (1982). This model represents a class of studies estimating reduced-form fuel demand elasticities using cross-section, time-series, or pooled data on regions of a country or on many countries. Wheaton's model rises above some of the others in this class because he introduces more structure into his equations, in particular, estimating three related equations (for fleet fuel efficiency, vehicles per capita, and VMTs (as a function of fuel efficiency and vehicles per capita)) which yield an estimate of gasoline demand for passenger vehicles.

His gasoline demand expression can be decomposed into its three components by using the relationship:

Fuel demanded per person = vehicles per person * VMTs * 1/mpg.

Taking logs and denoting income by y and gasoline price by p, the above equation can be expressed in elasticity form:

$$\varepsilon_{\text{fuel, y or p}} = \varepsilon_{\text{vehicles}} + \varepsilon_{\text{VMTs}} - \varepsilon_{\text{mpg}}.$$

Wheaton estimates these elasticities (both income and gas price elasticities) for a 25 country sample and a 42 country sample, the latter containing a number of developing countries.

The results of the model may not be useful or reliable because they rely on old (1972) data. As the data requirements are fairly modest, however, the paper could be updated fairly easily. Explanatory variables used in the regressions include, in addition to the dependent variables, the percentage of the population in urban areas, the size of the country, the prices of gasoline and autos, and per capita income. Obtaining data on fleet efficiency and auto prices was somewhat complicated and the procedures employed questionable; better ones could surely be devised.

The models in this class do not estimate welfare effects of alternative policies, but they could be used for that purpose, as could any model that provided demand functions for a commodity. However, it permits only a limited set of the "broad" policy instruments to be modeled, linking these instruments to some targets of interest. For instance, the effects on fuel demand of gasoline taxes, policies affecting vehicle prices, and even policies affecting income can be modeled. Policies affecting modal choice and congestion are beyond the reach of this model, particularly where the entire country is a unit of observation. This general approach to modeling is useful as a first-cut in explaining fuel demand (and from there, emissions), and could be a useful source of data to include in a more elaborate model. In this regard, versions of this approach applied cross-sectionally to cities with more recent data would be the most helpful.[19] If new modeling were to be undertaken, more thought would need to be given to the set of explanatory variables and to the interrelationships assumed between endogenous variables. Perhaps exogenous variables for price and availability of public transport options could be used to make modal choice implicit.

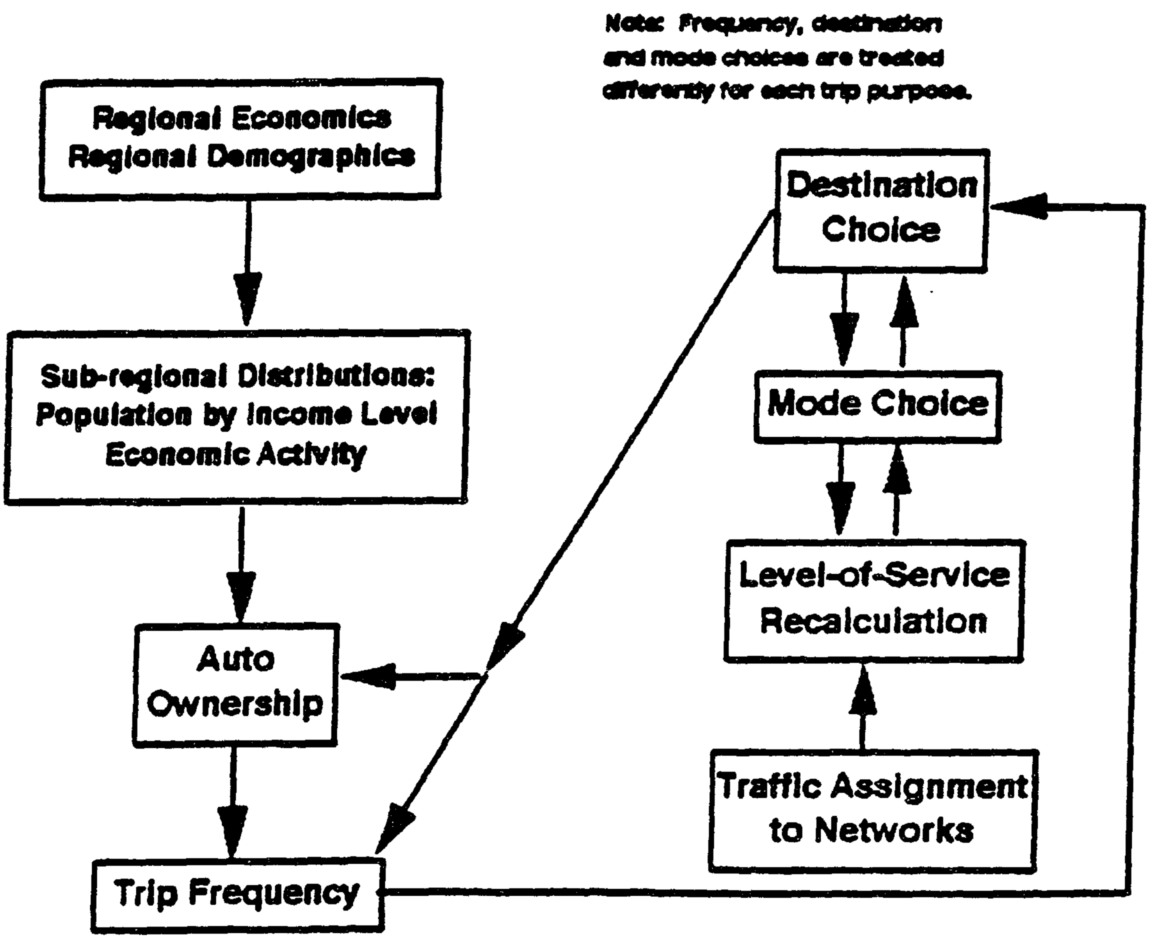
Wharton (1977). This model represents a class of models that focus on predicting the demand for autos by applying econometric techniques to aggregate, rather than individual, data. Some of these models are based on a model of individual demand consistent with consumer choice theory; some are not. They may focus on the auto ownership decision only, or on the type of vehicles as well, but not on vehicle use. They apply time series analysis on a national or regional basis. Emissions characteristics are not incorporated.

The most complete of these models is by Wharton (1977). Not only does it estimate new vehicle demand by type but it also estimates the number of used vehicles owned. This focus permits a crude analysis of changes in the age distribution of the vehicle fleet in response to policy or to technology changes in vehicles. It simplifies the vehicle choice problem by including only a term for cost-per-mile by vehicle type (which embodies fuel economy, purchase price, and maintenance expense) but omits non-price vehicle characteristics. As price and non-price characteristics can be correlated (i.e., fuel efficiency and size), this is a significant limitation, in general, biasing demand estimates.

As seen for the Wheaton-type models above, the Wharton-type models could be used to estimate welfare effects associated with a very limited set of

19. Time series analysis is unlikely to provide sufficient variation in variables to obtain useful estimates, even with perfect data.

FIGURE 4. TRIPS Structure and Information Flows



policies: those affecting vehicle ownership. Beyond this, they can be used as a source of data and modeling strategies for the component of a more comprehensive model. Regarding the ownership decisions, the model contains a wide range of explanatory variables for examining the effects of policies. The cost-per-mile variable allows modeling of how policy-induced changes in costs affect the structure of vehicle ownership but does not permit discrimination of the effect of different policies on this structure. For instance, by not discriminating between fixed and variable costs of vehicle ownership, the effects of a gas tax and a vehicle registration fee equivalent to it in annualized terms (given baseline VMTs) cannot be distinguished. The "number of commuters" variable, income, and percent urbanized population can be used to help track vehicle fleet changes as a city grows. Changes in occupancy rates (ride-sharing) could perhaps be modeled through the commuter variable. The new-old car distinction would allow the age/model year effects on emissions to be estimated with respect to any policy change acceptable by the model.[20]

Train (1990) (CARS Model). The Wharton-type model is dominated in theoretical sophistication and breadth of choices by the disaggregate models of auto demand. These models are all based on models of consumer choice, estimating demand from household data. They may explain how many vehicles are owned per person or household, and the type of vehicle to own or purchase (makes and models, new and used). Train's review of these studies reveals

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20. A few models (not reviewed here) may be classified as aggregate vehicle demand models based on individual utility functions (CRA, 1980). These models focus only on new vehicle decisions, which is of limited usefulness in a developing country context) and, while they incorporate non-price characteristics, they ignore socio-economic variables.

that vehicle price, fuel efficiency (operating cost), size, and age affect purchase and holdings decisions. Socioeconomic variables of importance include: number of persons per household, age, and income. As a class, these models generally ignore the effect of miles traveled on vehicle purchase or holding decisions, and more important, ignore the reverse causation, introducing simultaneous equation bias when the VMT variable is treated exogenously and misspecification error when this variable is ignored. Winston and Mannering (1984) estimate a model with VMTs endogenous, but do not permit persons to own no vehicles, a serious limitation for an analysis of developing countries.[21]

Train's own model, which was applied to data collected in 1978 from a U.S. national sample of over 1,000 households, addresses all of the above objections and represents an econometric state-of-the-art approach to estimating choices of auto ownership, type, auto VMTs, and fuel demand. However, it ignores modal choice, hardly acknowledging the presence of a non-auto option, except in the use of a "number of transit trips" variable to help explain vehicle ownership decisions. Appended to this model is a component for disaggregating VMTs into work/non-work and intercity/intracity VMTs, although it is non-utility-based with no feedbacks to other choices.

The theoretical model is specified with the conditional indirect utilitv function for a household:

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21. Some modelers focus on only a small piece of the problem. For instance, Berkovec (1985) is one of the few papers to focus on the vehicle scrappage decision. He regressed data on scrappage for 13 vehicle against variables for current market value (excluded vehicle characteristics were used as instrumental variables for price), model year and make dummies, and several other variables to estimate this equation. The theoretical model is based on an individual's decision, weighing the repair cost against the value of the vehicle in use or sold (less scrap value).

$$V = f(Y, p, x),$$

where V is the number of vehicles by class and vintage, make and model, Y is income, p is the cost-per-mile differentiated by the above elements, and x is a vector of other variables affecting utility, which may be differentiated by the above elements. For estimation purposes, utility is assumed to be additively separable, although the cost term is exponentiated. An expression for the demand for VMT is derived as:

$$VMT = \frac{\partial V/\partial p}{\partial V/\partial Y} = g(Y,p,x).$$

Vehicle ownership choices are made to maximize conditional indirect utility, where the probability that the household chooses a vehicle number n*, of class/vintage c* and make/model m* is:

$$P_{n^* c^* m^*} = \text{Prob}(V_{n^* c^* m^*} > V_{ncm})$$

Figure 3 shows a flow-chart of the model; choices of households on number of vehicles to own (including zero), their class and vintage, and VMTs (by class and vintage) are made simultaneously. In the estimating equations, unlike Wharton, the cost variable is represented in both the vehicle ownership equations and the VMT equations by variables for vehicle purchase price and operating costs.

The multinomial logit model is used for the ownership choices. The vehicle ownership decisions are found to depend on number of workers per household and income. A variable for number of transit trips per capita in area of residence negatively affects the probability of owning one or two vehicles.

The class/vintage choice for one and, separately, two vehicle households is significantly affected by purchase price and vehicle age. Operating cost is marginally significant. From the results, a lower income (<$12,000/year) household is willing to pay up to $844 in the purchase price for a one cent per mile reduction in operating cost. This figure is far less than the present discounted savings in operating costs.

VMTs for one and, separately, two-vehicle households are estimated in the log form using instrumental variables. Instruments are applied to a variable for the operating cost of the vehicle it chooses (an endogenous variable). These instruments have much policy significance, and include gas price, number of transit trips in area, and distance to work, among others. Operating cost is the only significant variable for one-vehicle households, with a coefficient of -0.2795, implying that a one-cent increase in operating cost reduces VMTs by 1300 miles per year.[22] For two-vehicle households, operating cost is highly **insignificant**. Income and transit trips are the only significant variables (besides whether the vehicle is the newer of the household's vehicles).

Finally, the division of VMTs in different categories of trips is made with a multinomial logit model. Within a city, gas prices significantly affect non-work, but not work trips. The proportion of household members who work affects work trips. Household size is marginally significant.

This model and its data base are now being up-dated by the USEPA (called the Consumer Automotive Response (CAR) Model) for use in forecasting CO_2

22. If operating costs are $.20/mile and VMTs are 10,000, this implies an elasticity of over 2. This seems very high.

emissions responses to alternative policies and growth scenarios, with plans to append EPA's MOBILE4 model to it.[23]

The most recent application of the model was for the California Energy Commission, where the effect on vehicle demand, gasoline demand, and VMTs was modeled for scenarios involving alternate fuel prices and availability of alternate-fueled vehicles.

This model has never been programmed to calculate utility changes but it surely could be. Its numerous variables used to model ownership and mileage traveled decisions provide many handles for modeling policy instruments. And these instruments would be linked to targets in a sophisticated simultaneous decision model. Yet, for application to a developing country, the sophistication in modeling car ownership choices is not highly valued and the omission of modal choice decisions (which for purposes of this discussion should include occupancy) is a serious disadvantage. Of course, the model also ignores the spatial dimension (travel times and distance, the character of the VMTs (i.e., extent of congested conditions), etc.) and has no emissions estimates as yet.

<u>McConnell and Straszheim (1982).</u> This model represents a class of "monocentric" urban location models that focus on the utility maximizing tradeoffs faced by households in a city between land prices and congestion in their housing location decision. This model is one of a small sub-class of models that adds avoidance of effects of pollution to this choice. To obtain analytically tractable solutions to the location problem, the spatial representation of the city is drastically simplified. These "monocentric "

23. Note that no equations are being re-estimated. The data collection is only to bring parameter values and sample weights into line with current conditions.

models assume all production takes place in the city center, with one auto commuting worker per household. In the McConnell and Straszheim model, which is the most complete treatment of the transportation-environmental linkage that I have seen, both congestion and environmental externalities are addressed simultaneously. They enter into the utility functions, as households maximize utility:

$$U = f(h, a, t, g),$$

i.e., over land, amenities, time spent commuting, and other goods, subject to a budget constraint:

$$y = g + hr(x) + p(x),$$

where r(x) is the price of land at distance x, and p(x) is commuting cost. Amenities are assumed to be inversely related to emissions at the residential location (with no lateral dispersion of emissions). The amenities index is:

$$a(x) = K - (T(x)e(x)/2\Pi x\delta),$$

where e is emissions and T is traffic volume, and δ is emission dispersion (although dispersion is only vertical).

Vehicle speed at x (v(x)) depends on the amount of land devoted to roads and on traffic volume:

$$v(x) = \beta \frac{\phi(x)}{T(x)}^{\gamma}$$

where $\phi(x)$ is the amount of land devoted to roads at x. As emissions are predicted as a function of vehicle speeds and volume using EPA emissions factors (now out of date), and traffic and congestion are highest in the city center, amenities are lowest there. The cost of commuting is inversely related to speed and may be adjusted by changes in gasoline prices and vehicle purchase price, etc. Complicated expressions are derived for the compensating variation welfare measure with respect to changes in pollution and congestion.

The model is used for three types of cities, differing by the parameters assigned to amenities and vertical dispersion. Marginal WTP functions are assumed linear in emissions. Positively sloped rent gradients near the city-center arise if congestion externalities are sufficiently small relative to environmental externalities. The former tends to increase the demand for housing close to the city, pushing up rents (the traditional solution); the latter, owing to the greater density of vehicles as one moves into the center of the city, tends to increase the demand for housing in outlying areas, depressing demands in the center city. The model is also used to examine the welfare effects of congestion tolls (optimal and equal per mile) and alternative mandated changes in engine designs (differing in operating costs and emissions) for two different city types.

This type of model, and this model in particular, can be used to estimate welfare losses associated with alternative types of policies for drastically simplified representations of cities. The simplicity of this model, its inclusion of congestion and emissions as well as their feedback (the latter through health effects) on location choice), and its consistent framework for estimating welfare losses are notable advantages. Because it explicitly considers space, albeit in the simplist way, it can capture the effects on welfare of congestion tolls, parking charges, changes in highway capacity, and other locationally specific policies. However, the household can only choose to change its location of residence in response to policy. There are no modal options, including car pooling, in the model, and no decisions on vehicle ownership. As an analytical rather than an econometric model, the choice of parameters is ad hoc.

Monocentric models are surely a poor representation of modern U.S. cities that have many satellite centers and much reverse and cross-town commuting. They may be much better at characterizing new cities in developing economies (but not large areas, such as Mexico City). The model could easily be updated with new emissions data and illustrates how to set the appropriate parameter values.[24]

Kim (1979). A less drastic simplification of space is provided by the Kim model, representing the class of urban land rent models that attempt to make the spatial representation of the city somewhat more realistic by allowing for polycentricity. Kim does this with a linear programming model of an efficient city. The city is divided into four mirror image quadrants, each divided into squares. The model focuses primarily on goods transport, both within the city and for export, minimizing an objective function with costs of production, costs of commercial and household transportation, and costs of exporting as main components. In spite of the focus on commercial transport and in contrast to the McConnell-Straszheim model, multiple commuting modes are modeled. Households are assumed to make only work trips, however, and there is no congestion in the model.

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24. Several key parameters require information on the benefits of reducing emissions. More and better information is available on this issue than when the McConnell study was written.

The model is a cost-minimizing linear programming (LP) model that can yield estimates of welfare changes if one is willing to equate welfare losses to the sum of time, transportation, construction, and other costs. Instruments that influence capital, land, time, or operating costs of transportation can be modeled, with a direct link to targets. For households, these are housing locations, work places, and travel modes. The model is tractable, but messy; it was applied to two hypothetical cities to examine whether a subway system is economical.

This model provides more flexibility in representing an urban area than the monocentric models; it even allows for satellite cities. However, its focus on the commercial transport problem and lack of attention to household choices with implications for the environment (vehicle ownership, trips, occupancy, congestion, etc.) are serious drawbacks.

Ingram (1975). The Ingram model represents the class of classic transportation models. These models have four major components: trip generation, distribution, modal split, and assignment. The approach begins with the specification of a transportation network (which may mirror an actual road network or be much simplified) connecting zones characterized by population, recreation, and economic activity. The data for each zone are used to obtain total trips generated and attracted to each zone (often using regression models using variables such as income in the zone, car ownership, land value, employment as independent variables). Trips are distributed to particular origins and destinations, generally using gravity models. Modes for the trips are then estimated (sometimes with aggregate discrete choice models).

Aggregate travel demand models may be used to estimate generation, distribution, and modal choice simultaneously. These are of the form:

$$T_{ijk} = f(\text{ population, income, travel time and cost}),$$

where T_{ijk} is trips from origin i to destination j on mode k. These models have been mainly used in an inter-urban context, where zones are large. Timberlake (1988) suggests that this aggregate demand approach is superior to applying the classic transportation model in developing countries, citing a study of the Karthoum-Wad-Medani Corridor in Sudan.

Finally, in the classic model, the trips by mode are assigned to the network, matching travel demand (estimated for the baseline level of service) to network characteristics, such as distance and capacity, as well as public transport availability. Congestion may be included in defining an equilibrium according to the Waldrop principle: "Under equilibrium conditions, traffic arranges itself in congested networks such that no individual trip maker can reduce his path costs by switching routes" (Ortuzar and Willumsen, 1991, p. 254). Congestion results in rerouting, mode switching, or demand reductions according to a cost minimization algorithm, where costs may include travel time, convenience, waiting time, and out-of-pocket costs. Alternative versions of these models seek network equilibrium (within one mode), multi-mode equilibrium, or system-wide equilibrium (including switching time-of-day and destinations for trips).

These models are capable of estimating welfare effects of alternative policies, although they have not been used in this way. They permit a wide variety of policies to be modeled, particularly those affecting short-run decisions on mode choice and route. Vehicle ownership and residential and work locations are taken as given and could affect estimates of trip generation in the first stage. Models featuring feedback to trip generation are needed to endogenize these decisions. The effect of changes in facilities on trip generation also cannot currently be modeled.

The classic transportation model is most explicit about the behavioral and engineering links from instruments to targets within the choice set covered by these models. However, its use for predicting emissions effects and changes for alternative scenarios is still problematical. Emissions, particularly of HC and CO, depend to a great extent on what has been termed "modal vehicle activities," such as acceleration, deceleration, idle, cruising, and engine starts and stops. This type of activity-level detail is not provided by the classic models. With research now underway to identify "modal emissions rates" to match modal activities, the classic model can, in theory, be modified to provide activity-level information for use with the emissions factors.

Concerning tractability, a major effort at applying a sophisticated classic transport model and analyzing its properties is still very expensive and time-consuming, although data requirements are not much more than with simple models. Such a major effort is the Santiago Transportation Study. A VAX 8600 was run over 24 hours to run the full system equilibrium with 260 zones and several modes (Ortuzar and Willumsen, 1991). Models with many fewer nodes and links are available as packages (but without the source code). The best of these is EMME/2 developed by Michael Florian.

Turning now to the Ingram model, being an older model, it does not incorporate many of the innovations in the recent versions of the classic model; it uses a gravity model, for instance, and does not use discrete choice modeling. Nevertheless, this model is reviewed because it was probably one of the first designed to examine the transport-environment link. It contains sets of emissions coefficients (for CO, NOx, SOx, particulates, and HC), algorithms for estimating pollution concentrations over the urban area (now out of date in light of recent developments in ambient ozone modeling, for instance), and a simple means of estimating population exposures. With this information, measures of cost per exposure reduction can be estimated for alternative transportation control policies. This is an important refinement of traditional cost-effectiveness analysis and use of transport model results, as exposures are superior to emissions as a measure of "effectiveness."

The model considers transportation choices over four modes, plus mixes of these, for three types of trips (home-based work, non-home-based work, and home-based non-work trips), over 122 zones in a simplified "spider" network. Explanatory variables are limited and include population, education and income variables by zone, number of cars by zone, travel time and cost by mode and zone, and a variable for level of transit service. In estimating emissions, a distinction is made between cold start and other emissions, the former being assumed to apply to 57% of the number of trips and independent of speed. Emissions are converted to air quality using an area source model (Hanna-Gifford). The effects of the primary pollutants on secondary pollutants, such as ozone, are ignored.

This model is capable of estimating welfare effects associated with alternative policy instruments, treating all individuals as having identical additive and separable utility functions. Welfare effects are provided in terms of annualized capital costs, administrative costs, out-of-pocket costs of travel, and time costs. The zonal nature of this model is problematical because person-level variables (family size, marital status, etc.) cannot be examined for their effect on behavior.

A wide variety of instruments can be modeled. In the paper, Ingram examines the cost-effectiveness of transit extensions, fare reductions, local licensing, traffic bans, parking charges, and reducing speeds in Boston. Links of these instruments to targets are made explicitly and in detail, with the primary targets being exposures to pollution and travel outcomes.

While, this model is unique is its explicit linkage of a traditional transportation model to a model capable of estimating population exposures to various pollutants, it would need wholesale updating to be useful today.

Cameron (1991). In contrast to the Ingram model and other classic transportation models, which operate on a zonal level of aggregation, the model used by Cameron, TRIPS, operates at the household level. This is preferred because the household is the relevant behavioral unit and equations can be estimated based on household choices and explained by household level variables rather than aggregations of population characteristics within a zone (an example of the aggregation problem). Using individual data also permits one to analyze and present results according to personal characteristics, such as income class, rather than only geographic characteristics.

The model itself was created in 1979 for Cambridge Systematics with the basic data drawn from a 1976 survey of 5,000 households in Los Angeles. Trip diaries, socio-demographic, and auto ownership information was taken from each person. As in Ingram, this model incorporates an emissions component (NOx, ROG, CO, CO2) differentiated by vehicle age-class and by activity (cold start, running, evaporative) and related to speed and trip length but, unlike Ingram, lacks a concentration or exposure component.

TRIPS lacks a network, but simulates the effect of congestion on trip and mode-choice by making travel time over any origin-destination-mode a function of corridor volume and incorporating a travel time variable in explaining these choices. Baseline peak and off-peak traffic volumes by corridor are taken from a local large-scale transportation model. The database is supplemented by data on trip time and length by origin-destination-mode.

The components of TRIPS are shown in figure 4. In all, nine demand models are used; each of these have been adapted for use in Los Angeles after they have been applied in other cities. Modal choice and mode-destination choice equations are multinomial logit; trip frequency equations are estimated using a term for expected utility for destination/mode choice. No welfare effects are estimated.

This model embraces a fuller range of choices than the Ingram model, adding number of vehicles owned (0,1,2 or more), a ride-sharing mode to the standard modal choices and trip types. In addition, a fairly unique aspect of this model is that it treats trip destinations (but not origins) as endogenous for work trips, shopping, and social/recreational trips, although the formulations are very simple. For instance, the probability of choosing destination d as the workplace depends on the number of workers in d and in all other zones and a term estimated in the auto ownership equation for the utility of work mode choice to destination zone d, given auto ownership status, and to all other zones.

Policies modeled include regionwide congestion pricing at $0.15/mile, a parking charge of $3.00 per day, non-employees parking of a cent per minute, emission-based registration fees calculated by multiplying odometer reading change by a measure of emissions/mile (average of $110 per vehicle), and increased number of transit buses.

This model is capable of estimating welfare effects aggregated across individuals associated with a wide variety of alternative policy instruments. Links of the instruments to targets are made explicitly and in detail, with the primary targets being emissions and travel outcomes. As in the Ingram model (and all other models I know of), emissions are estimated from average, not modal activity, factors. That the model was recently revived and applied to Los Angeles means that it can be used elsewhere, although re-parameterization of the demand models would be needed, and some expansion of the model to accept other mode choices, such as walking and bicycling.

This model is superior to the Ingram model or the classic transportation models for our purposes. First, it models vehicle ownership choices (0,1,2 cars for workers households and non-worker households), while Ingram does not. Nevertheless, the modeling of this choice is not as sophisticated as Train's (some clearly engogenous variables, such as vehicle choice, are treated as exogenous variables in equations explaining other endogenous variables, such as in the mode choice equation). To a certain degree, however, simplicity is a virtue. Detailed choices on the number of cars and their type are perhaps less important in a developing country setting than for a developed country. Second, unlike Ingram, the Cameron approach does not require use of a network model, vastly simplifying the modeling and data tasks, while incorporating the relationships between time, trip making, and congestion in a spatial context. How well the Cameron approach performs remains unclear, as the relevant reports omit validation exercises.

Deaton (1987). This study contains several models of interest to us, particularly because the applications are in a developing country setting. One model, based on information from a travel survey of 800,000 Indian people, explains trips per household by mode at the state rather than the individual level as a function of per capita household expenditure, an urban dummy, and household size. Aggregate analysis was necessary because data at the individual level were unavailable to the researcher. Of much interest to us, Deaton found that trips to work and school are 82.2% of all urban trips; and a sizable fraction of urban trips (34.8%) are on foot, with another 19.0% by bicycle.

Another model, applied to the city of Jaipur, India using a travel survey undertaken in 1983, is much more sophisticated. Deaton estimates directly the relationship between income and demographic variables on the one hand and travel time, distance, and travel expenditures, on the other. A special feature of the model is that the available modes are represented by a continuum represented by speed of travel.

The survey of 6300 households collected data for the previous day on home-based trips, by mode, distance and time per trip; household characteristics, and household expenditures. Unfortunately, no data were collected on fares or other travel costs. Descriptive statistics show that students and workers generate one round trip per day and such trips are about 90% of all trips. This information is the evidence for suggesting that a preferred model may not need equations for estimating non-work trips and number of trips.

The model had similarities with the urban monocentric models in that it focuses on employment trips with choice variables for residential location given distance from the city center and time spent traveling. In addition, however, it includes modal choice, where the speed of travel can be increased at a price. As in the urban monocentric models for cities in developed countries, utility depends partly on distance to work, in the sense that distance is a proxy for amenities, such that greater distance increases utility, cet. par. because housing and leisure are cheaper further from the city center:

$$u = u(d, T-t-h, q)$$

subject to a full cost constraint:

$$q + f(d/t) * d = h * wage + b,$$

where T is total hours, h is work time, d/t is distance to work over travel time (equals speed (v)), q is all other goods, and the f function summarizes all details of ownership decisions, such as running costs, fares, parking, etc. The choice variables are d, t, h, and q.

Solving the model reveals that trip speed increases with the wage and the more rapidly costs increase with speed the slower does speed increase with the wage, i.e., as wages rise, distance becomes cheaper relative to time, so speed rises.

By specifying a particular utility function, Deaton derives demand equations for distance, speed, and travel time as functions of the wage and demographic variables. He estimates an ordered probit model for desired speed compared to actual speed of each mode. This yields predicted modal choice probabilities for given household income levels, number of children, and number of adults. Data on the cost of each mode are missing. The probability of vehicle ownership is then estimated based on income; number of children, adults, workers, students; rooms in house; and length of residence.

This model is capable of yielding welfare measures for comparing the efficiency of alternative policies to reduce emissions, although it, like all the models reviewed here but McConnell and Strazheim, omits feedback effects of emissions (and subsequent effects on health) on behavior. It has a number of handles for modeling the effects of policies on targets, where these targets include residential locations, vehicle ownership, modal choice, speed, and gasoline consumption. It produces complex qualitative results from a very simple structure that accord with expectations. However, congestion externalities could not be estimated with this model.

The model is exceedingly tractable. Indeed, this model is attractive for modeling transportation demand precisely because its ingenious features make maximum use of sparse data. In addition, being developed for application in a developing country, it accords particularly well with our stylized facts.

D. MORE ON SIMPLIFIED MODELS

Simplified models of transport demand include, first, those that do not represent space at all, such as elasticity models, which link various choices together in a formal structure and second, sketch planning models, which have a very simplified representation of space.

1. Elasticity Models.

The elasticity models can be very simplified, e.g., considering the elasticity of trips for one mode or considering the price elasticity of gasoline demand, or decomposing the demand for travel into its components. More complicated elasticity models, called pivot-point modal split models, can address modal choice in a consistent framework. Using an incremental form of the multinomial logit model, one need only know the demand functions, modal shares and the changes in level of service variables (but not baselines). Incremental nested logit models have been developed as well.

As an example:

$$p_k^1 = \frac{p_k^1 \exp(V_k - V_k^o)}{\Sigma p_k^o \exp(V_k - V_k^o)}$$

where p_k^1 is the new proportion of trips using mode k; p_k^o is the original proportion of trips by mode k; and $(V_k - V_k^o)$ is the change in utility of using mode k generated by a change in attributes of mode k.

If the elasticities are replaced by equations derived from a structural model and calibrated with local data, what Ortuzar and Willumsen call a "non-spatial interaction model" is obtained. One such model (Kahn and Willumsen, 1986) has been applied to study car ownership, road construction and maintenance, and gasoline demand in developing countries.

The following identity can prove useful for organizing the use of elasticities (estimated either from individual or aggregate data) to estimate the effect on emissions:

$$P_i = \sum_{t,k} \text{emissions/mile} * \text{miles/gallon} * \text{gallons/trip} *$$

trips/vehicle * vehicles, (1)

where P_i is total emissions of pollutant i. By this formulation, emissions of a pollutant i are summed over t vehicle types (i.e., t = auto-gasoline diesel-bus, gasoline-bus, etc.) and k age classes. The variables in (1) each may be different for each t and k. Emissions per mile is itself dependent on the emissions standards, on actual driving conditions, on characteristics of the fuel being used, and on deterioration of and tampering with emissions control equipment and other components of the vehicle.

To convert emissions per mile (by t and k) into total emissions, estimates of vehicle miles traveled (VMTs) are needed. However, the use of VMT measures obscures complex relationships that have policy implications. Hence, this term is divided into four terms, i.e., all the terms on the right-hand side of identity (2) except "emissions per mile." Miles per gallon depends on the various vehicle characteristics and fuel type (which can be affected by fuel efficiency standards, as well as driving and vehicle condition. Gallons per trip is inserted to highlight the effects of congestion on mileage. Trips per vehicle can be disaggregated further into trips per person multiplied by occupancy rates (persons per vehicle) to take into account the occupancy rates of different types of vehicles and the possibility that such rates can be modified by policy.

With the emissions per mile term, emissions standards on vehicles inspection and maintenance programs, and targeting high emitters can be modeled. The miles per gallon term permits consideration of a gas guzzler tax, congestion tax, gas tax, and use of fuel efficiency standards. The gallons per trip variable permits consideration of residential and work location decisions (where commuting trips are concerned). The trips per vehicle terms permits consideration of parking fees, HOV lanes, changing costs of alternative travel modes. The # of vehicles term can be used to capture vehicle ownership decisions.

Since (1) is log-linear, the elasticity of emissions with respect to any policy variable can be estimated as the sum of the elasticities of each of the main components, plus the sum of multiplicative relationships where cross elasticities are non-zero (Wheaton).

2. Elasticities of Gasoline Demand.

One can make a crude estimate of emissions effects of alternative policies by modeling the effect of the policy on gasoline prices (and/or income) and multiplying the change in demand by the fuel efficiency and the relevant emissions factors (in grams/mile). This procedure would assume that vehicle speed, trips, and other factors would remain unchanged. As increased prices would probably reduce trips, which would raise speeds, and encourage turnover to obtain more fuel efficient vehicles, the resulting estimate of emissions change (at least for HC and CO) could be considered an upper bound.

The literature on gasoline demand elasticities has been summarized by Bohi and Zimmerman (1984). The authors consider reduced form models, both static and dynamic, aggregate and disaggregate; they also consider the Wheaton-type model, which is a structural model of demand, estimated from elasticities for VMT, mpg, and number of vehicles. Summary tables from Bohi and Zimmerman are included as tables 5 and 6. The Dahl (1982) and Wheaton (1982) articles are the only ones reviewed that would contain results suitable for developing countries.

3. Sketch Planning Models.

A final set of approaches are called sketch planning models in the transportation literature. These models are simplifications of network approaches offering some of their advantages without the cost of building or specifying a complex model but with the disadvantages of imprecision from the coarseness of analysis and reliance on the transfer of parameters and relationships from other studies.

One example of these models is UMOT (Unified Mechanism of Travel) (Zahavi, 1979) which produces as output car ownership by income group, aggregate modal choices, average travel time and speed, and total expenditures and travel time. It has been used to address many of the policies we are interested in, although some analysts have found it to be a poor predictor of travel behavior. Canned programs, such as EMME/2 are at the other extreme in terms of spatial detail. These programs follow the standard four step procedure used in the classic transportation model, using default parameters to drive much of the model.

A huge literature has developed on using traffic count data to estimate trip matrices and demand functions. Such data are easy to collect compared to origin-destination data, the latter, according to Ortuzar and Willumsen, having a short shelf life in rapidly developing cities.

Finally, teaching models are available. One model, called GUTS (Willumsen and Ortuzar, 1985), is available on the PC. It has two transport modes operating in a circular-symmetric city and the user appears to have the ability to model many of the policies of interest to us (fares, level of service, parking fees, dedicated bus lanes, licensing schemes, and even highway investment projects). The model produces outputs for volume, speed, modal split, travel time, and expenditures by person-type.

IV. CONCLUSIONS

The objective of this paper is to assess alternative modeling approaches for evaluating the environmental and congestion externalities and private costs associated with alternative policies to reduce emissions or affect individual urban transport decisions. Criteria for this evaluation focuses on the ability of the approach to address efficiency concerns and to be flexible enough to address a broad array of policy instruments and individual choices, but also includes concerns about distributional effects and effects on public revenues. This assessment involved first exploring the properties of various pollutants and their linkage to vehicle use. Then, models in the literature were reviewed in detail.

This review focused on several characteristics of the models (table 4): whether they generate estimates of welfare loss (i.e., the efficiency criterion), their capability to examine a wide range of policy instruments and link them to targets (such as emissions and congestion), the choices they can examine, and their tractability.

Most of the literature reviewed is designed for application in developed countries, some attention was given to developing stylized facts associated with transportation and the urban environment in developing countries and evaluating the ability of the models to address them.

The overall conclusion of this effort is that none of the models reviewed meets all the criteria. This suggests that new models are needed, that different models be used for different purposes or to address different aspects of the problem (taking the loss of consistency as a necessary evil), or that tradeoffs will need to be made if any one existing model is used directly or modified.[25]

Welfare Estimates. Few of the models reviewed explicitly derive compensating variation expressions (i.e., using expenditure functions or indirect utility functions) for changes in policy variables. The monocentric models and the Train model are exceptions. The others either provide expressions for utility based on ad hoc assumptions (e.g., assuming additive and linear utility functions; some studies simply multiply the net change in commuting time by an exogenously determined value of time) or ignore any valuation of policy consequences.[26]

Instruments. Although the instruments actually implemented to control emissions and congestion are quite limited, focusing on command and control approaches and, for emissions, on new vehicles, the models generally permit a wide range of instruments to be addressed. Exceptions are the Wheaton and Wharton models, which were designed to consider more specific policy objectives. For the most part, the more complex models permit one to model the simultaneous application of transportation control measures and emissions control measures, to the extent simply changing emissions

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25. Performing a two-stage analysis -- where first one estimates the cost-effectiveness of an emissions control policy, assuming that transportation behavior is invariant, and then one reevaluates cost-effectiveness after permitting transportation behavior to change and feedback to emissions -- is also an option but outside the scope of this paper, which focuses on models that can simultaneously address the environment and transportation.

26. A reasonably complicated but ad hoc approach is from Ortuzar and Willumsen (1991, p.179) who derive the value of utility change from a linear "observable utility function" that has access time, travel cost as a fraction of income, and number of cars (among other variables) as arguments.

coefficients or the use of emissions tax proxies (such as an increment to the gasoline tax) suffice. None of the models reviewed are designed to model behavior in response to emissions control policies, such as inspection and maintenance programs or emissions fees.

Targets and Choices. The targets considered by the models are quite limited in some cases. Most transportation models ignore emissions, for instance, but are useful, nonetheless, because we can use additional models to infer emissions consequences from the variables they predict. None of the models incorporates all of the choice variables of interest, i.e., residential/work locations, vehicle ownership, modal choice, and choices involving trips or miles traveled. The most complete model in this regard is Cameron's TRIPS model, which considers all but the location decision and is capable of handling a wide variety of instruments and most targets of interest.

Tractability. Unfortunately, flexibility and comprehensiveness in a model often are obtained at the expense of tractability. The models considered here are no exception. For instance, applying TRIPS in a new setting would require a major effort. Perhaps the best compromise between tractability and comprehensiveness is the Deaton model. This model, in recognizing the difficulty of obtaining data in a developing country setting, uses data efficiently to address all choice variables but the trip choice. If, as we argue, one can assume that people in a developing country make no more than one trip per day, this omission may not be a serious drawback. While the model ignores congestion and emissions, the latter is easily added.

An alternative, highly tractable model is that of McConnell and Strazheim. If one can live with an idealized representation of space, this model has many attractive features. The most important, beyond its tractability, is that it is the only model to incorporate congestion and emissions, translate emissions into health damage, and permit the possibility of health damage to influence choices. Its serious drawback is that its only choice variable is residential location.

Space and Congestion. A defining characteristic of these models is their representation of space and congestion. Such a representation is needed not only to estimate external costs associated with congestion, but to relate emissions to "modal activities" (e.g., acceleration, idle) affected by congestion. Space (and congestion) needs to be represented even if a pollutant of concern is regional in scope (such as ozone, in some situations). While, in this case, the location of the precursor emissions would not affect prediction of ozone concentrations, the degree of congestion under which driving occurs would influence such concentrations by affecting the amount of HC and NOx emissions produced per mile.

The options for addressing space (and congestion) include: (i) ignoring space entirely (Wheaton); (ii) taking space into account implicitly through equations that make speed a function of roadway capacity and VMTs or modal choice (Deaton); (iii) idealizing space (McConnell and Strazheim, Kim); (iv) estimating trip origin-destination matrices from traffic counts (sketch planning models); (v) using traffic volume data as a baseline but permitting trip and modal choices to be affected by travel time, which is dependent on estimated traffic volume by corridor (Cameron); (vi) representing space as a network and solving for equilibrium traffic flow

(Ingram). None of the models models that realistically account for space permit feedbacks to location decisions. The Cameron model is the best compromise between realism of spatial relationships and tractability.

In applying any of these models to an urban area of a developing country, or even in building a new model, information on baseline congestion levels, as well as travel and vehicle demand elasticities will be needed. This type of information is in very short supply.

Emissions. None of the models satisfactorily addresses the issues related to emissions. While McConnell and Strazheim (MS), and Ingram go beyond emissions to estimate concentrations, exposures, and in the former model, health impacts and damages, none deal with the host of pollutants and associated health and other effects. MS use a simplified dispersion model that is clearly wrong and Ingram's models are far out of date. Cameron deals with the most complete set of pollutants, but does not go beyond emissions. Emissions models for developing countries must address lead and sulfur dioxide, as these substances are present in gasoline and diesel fuel, respectively and are of considerable concern for their health effects.

Without addressing health effects, one cannot compare the offsetting health effects of policies influencing modal choices. Increased bus ridership can lead to increases in particulate emissions from diesel buses and decreasing ozone-forming emissions, assuming bus VKTs increase (rather than simply increasing occupancy).

Some representation of trips as an endogenous variable is desirable because of the dominance of cold starts in producing emissions. Yet, only the most complex of the models reviewed here address this choice (Train, Ingram, Cameron).

In any event, if any models are to be applied in a developing country, a reasonably complete emissions inventory will be an essential element in linking policies to reduce mobile source emissions to attainment of ambient standards or even to welfare. As few developing countries have such inventories for their cities, this should be a high priority. Note, however, that even in the U.S., many federal and state policy initiatives for improving urban air pollution are taken based on estimates of emissions effects, without examining effects on ambient air quality.

The paper also concludes that measures resulting in reductions in both congestion and emissions have greater consequences to welfare through time savings than through health improvements. If this conclusion held for a developing country, it would imply that more effort should go into modeling and acting upon the congestion problem than the emissions problem. Whether this conclusion does hold for a developing country is unknown, depending on relative measures of value for reducing health effects and time savings relative to reductions in congestion. While some information on the value of travel time is available, no welfare-theoretic estimates of the value of health improvements (i.e., those based on willingness-to-pay) are available.

Distributional Issues. Only the Cameron and Train models can deal reasonably well with the issues associated with who gains and loses as a result of a particular policy initiative. These models are based on data from individuals; therefore, the effects on individuals can be regrouped according to income class or other defining characteristics. The classic transportation models, in particular, cannot address these issues because they use data at the zonal level.

Match up to Stylized Facts. Considering the stylized facts in section III.A., we find these models coming up short. The idealized spatial models (MS and Kim) and Deaton's model accord well with developing country conditions by making residential location endogenous, assuming one roundtrip per family (or per person) per day, and (in Deaton's case) limiting vehicle ownership options to none or one vehicle per family. None of the models fairly represents the range of modal choices in a developing country and the issues associated with policies to increase ridership of buses and other public transit that are already operating at full capacity.

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Table 1. Taxonomy of Instruments for Reducing Externalities from Vehicles

Instrument Type/Directness	Price	Quantity	Technology
Incentives			
Direct			
Congestion	bus fares, congestion toll parking charges		
Pollution	emissions fee	tradable emissions permit early vehicle retirement	
Indirect	fuel tax registration fee gas guzzler tax		
Command and Control			
Direct			
Congestion		area access limits HOV alternative drive days	CAFE standards fuel composition standards
Pollution		Inspection and Maintenance banning lead mandating RVP decrease emissions standard	Alternate-fuel vehicles conversion/ retrofit
Indirect		zoning	Road building

Table 2. Changes in emissions (g/mile) for selected scenarios using from MOBILE4 emissions information.

Scenario	Reduction in Tailpipe HC emissions (g/mi)	Percent	Baseline (g/mi)
Fuel-based:			
Reduce RVP from 11 (current) to 9	1.07[a]		
Vehicle-based:[b]			
Replace 1967 model with 1979 model:			
@ 100,000 miles	4.2	47	8.9
@ 50,000 "	5.0	63	7.9
@ 0 "	6.0	83	7.2
Replace 1979 model with 1985+ model:			
@ 100,000 miles	3.6	75	4.8
@ 50,000 "	2.3	85	2.7
@ 0 "	0.6	73	0.8
Replace given model year with 100,000 miles with same model year with 0 miles:			
1967	2.0	23	8.7
1979	3.8	78	4.9
1985+	1.05	81	1.3
Driving-based:			
Increase average speed from:			
15 to 20 mph[c]	1.2	29	4.2
20 to 25 mph	0.75	25	3.0
Eliminate a cold start and hot soak by chaining two trips:[d]	0.4	28	1.4
Eliminate a 10 mile trip by car pooling:			
uncongested	1.7	100	
congested	2.6	100	
Motorcycles:			
Replace 1979 motorcycle with 1979 auto:			
@ 50,000 miles	6.75	69	9.75
Replace 1985+ motorcycle with 1985+ auto:			
@ 50,000 miles	3.73	81	4.59

	Reduction in Tailpipe NOx Emissions g/mi	%	Baseline g/mi
Vehicle-based:			
Replace 1967 model with 1979 model:			
@ 100,000 miles	(0.2)	(6)	3.4
@ 0 "	1.4	42	3.3
Replace 1979 model with 1985+ model:			
@ 100,000 miles	2.3	64	3.6
@ 50,000 "	1.9	70	2.7
@ 0 "	1.3	65	2.0

a. All evaporative HC.
b. Driving profile: 20.6% cold start, 27.3% hot start, 52.1% stabilized, at 19.6 mph.
c. For 1979 model with 50,000 miles, spped adjustment factor = 1.4 @ 15 mph.
d. For 1987 model traveling 25.6 mph: 2.89 g/mi exhaust. Eliminate one cold start and hot soak by making one 20 mile trip instead of two 10 mile trips: one 10 mile trip is 8.5 grams cold start, 3 grams (0.6 g/mi) stabilized, 2.5 grams hot soak, or 14 g in total; two trips is 28 grams. One 20 mile trip is 14 grams plus 6 grams (10 miles * 0.6 g/mi) = 20 grams, saving 8 grams, or over the 20 miles trip, 0.4 g/mi.

TABLE 3. Average Tailpipe Emissions (g/mi) (FTP Cycle).

	POLLUTANTS								
				HC		Particulates			
VEHICLE TYPE	CO	NO_x	SO_2 [f]	THC	Benzene	Total	BaP	SO_4 [e]	Pb
Diesel								0.037	
Heavy-Duty	10	28	1.6			3.2[c] (1.4)[d]	54		
Light-Duty	3	1	0.53	0.23[a,b]	0.02	0.6[c] (0.4)[d]	13		
Gasoline								0.006	
No Catalyst	15	4	0.1	5.4[a,b]	0.31	0.1	20		0.020
Catalyst	5	2	0.07	1.8[b]	0.06	0.02	0.4		
U.S. Late Model	8[h]	1.39[g]		.72[g]					
U.S. VEHICLE TAILPIPE EMISSIONS STANDARDS									
Light-Duty Diesel Trucks	10.0	1.2		0.8		0.26			
Light-Duty Gasoline Passenger Vehicles & Trucks	3.4	1.0		0.41		0.6(<1987) 0.2(≥1987)			

a. 1975-82 models.
b. Diesels emit heavier alkanes, which have greater ozone-forming potential.
c. Mostly fine particulates (≤ 1 um).
d. Field experiments in a tunnel.
e. Accounts for nearly 20% of particulate matter mass, mostly as H_2SO_4.
f. Diesel sulfur content of 0.3% (U.S.).
g. EPA (1989c). 50,000 mile in-use.
h. CARB (1989). 50,000 mile in-use.

Source: EPA (1990).

Table 4. Characteristics of Eight Transportation Models.

Model	Welfare Estimate (Y/N)	Instruments (Y/limited)	Instruments to targets (Y/limited)	Tractability (G/F/P)[k]	Choices (L,V,M,T)[l]	Space (Y/N)	Emissions (Y/N)
Wheaton	N[a]	limited	limited	G	b.	N	N[a]
Wharton	N[a]	limited	limited	F	V[c]	N	N
Train	N[a]	Y	Y[d]	F	V,T	N	N
McConnell & Strazheim	Y	Y	limited	G	L	Y (monocentric)	Y[e,f]
Kim	Y	Y	limited	P	L	Y (polycentric)	
Ingram	N	Y	Y	F	M,T	Y (network)	Y[e]
Cameron	Y	Y	Y[g]	F	V,M,T	Y (indirect)[h]	Y
Deaton	Y	Y	Y[d]	G	L,V,M[i]	N[j]	N

a. Could be modified to yield wlefare estimates for very simple utility function.
b. Estimates fuel demand. But approach could be used to model many types of choices.
c. Models new and used car ownership/scrappage decisions.
d. Not congestion
e. Goes beyond emissions to concentrations, and/or exposures, and/or health effects and damages.
f. Incorporates feedback effects of health damages to location decisions.
g. Can address more targets than Ingram.
h. See text.
i. Assumes one trip.
j. See text.
k. Good, Fair, Poor
l. Location, Vehicle ownership, Modal choice, Trip/VMTs

TABLE 5. Gasoline Demand Elasticities

Study (date)	Sample[a]	Price elasticity[b] Short	Price elasticity[b] Long	Income elasticity Short	Income elasticity Long	Regression procedure[c]	Other variables[d]
Reduced-form, static							
Agg., domestic							
Greene (1979)	1966–75; P; US (state)	−0.34		0.36		LSDV	G, auto, truck, D
Berzeg (1982)	1972–76; P; US (state)	−0.17		0.36		GEC	POP
Reduced-form, dynamic							
Agg., domestic							
Kwast (1980)	1963–77; P; US (state)	−0.07	−1.59	0.03	0.76	EC	G, E, POP
Berzeg (1982)	1972–76; P; US (state)	n.s.	n.s.	−0.18	−0.34	OLS	CPI, POP
		−0.15	0.14	0.42	0.40	GEC	CPI, POP
International							
Dahl (1982)	1970–78; P: 41 countries (country)	−0.13	−0.76	0.06	0.35	OLS	Auto
		−0.20	−1.00[e]	0.10[f]	0.50		Auto (low-price countries dropped)
Reduced-form, end-use							
Agg., static							
Reza & Spiro (1979)	1969–76: T; US (US)	−0.21	−0.33	0.60	1.44	GLS	Auto, D, E, MPG pollution, PAutos
Wheaton (1982)	1972; C: 25 countries		−0.74		1.26	OLS	Auto, MPG, T, D, G
Dahl (1979)	1936–41; 1947–72; 1975; T; US (US)	−0.44		not reported		2SLS	PAuto, auto, T, pollution, MPG
Disagg., static							
Archibald & Gillingham (1980)	1972–73; C; metro areas (household, residential)	−0.43		0.29		GLS	Auto, 1-car households
		−0.43		0.56			Auto, multi-car households
Archibald & Gillingham (1981)	1972–73; C; metro areas (household, residential)	−0.77		0.29		OLS	Auto, D, pollution, employ, 1-car households
		−0.22		0.56			Multi-car households
Agg., dynamic							
Paxson (1982)	1975–81; T; US (US)	−0.17		1.20		GLS	Auto, employ (1-year adjust)
		−0.07		0.91			Nonauto, employ (1 year)
		−0.14		0.56			Total (weighted average)

[a–d] See Table 1 notes.
[e] Value of −0.98 reported in text (p. 377) is not consistent with reported lag coefficient (p. 376).
[f] Value of 0.11 reported in text (p. 377) is not consistent with that reported in the text (p. 376).

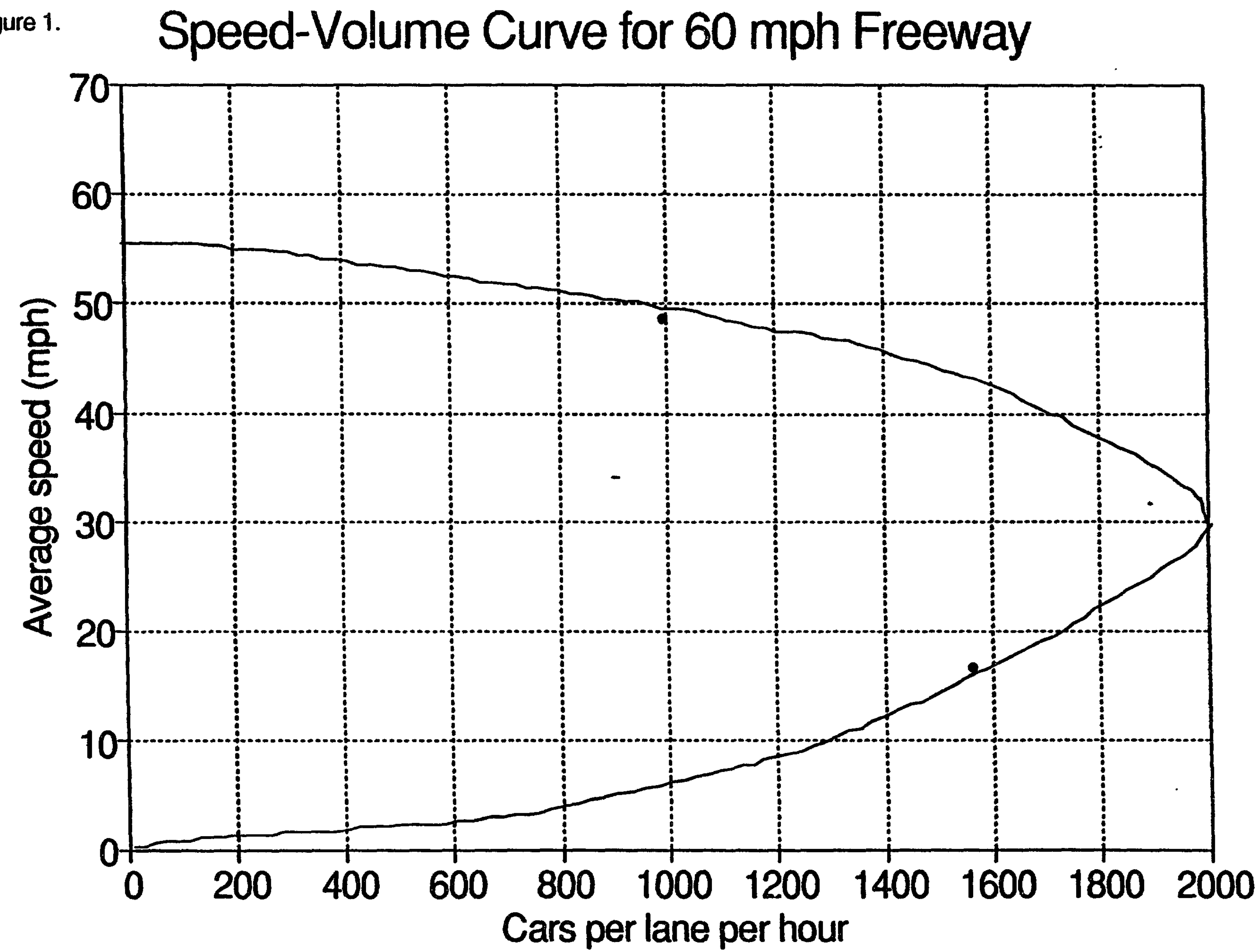
TABLE 6. Decomposition of Gasoline Demand Elasticities

	Short-run gas price elast.			Long-run price elast.			Short-run income elast.			Long-run income elast.		
Study (date)	MILES	STOCK	MPG	MILES	STOCK	MPG	MILES	STOCK	MPG	MILES	STOCK	MPG
Reza & Spiro (1979)	−0.21			−0.20	−0.13		0.60			0.83[a]	0.61	
Wheaton (1982)												
25 countries, nominal				−0.50	n.s.	0.32				0.54	1.38	−0.21
25 countries, deflated				−0.54	n.s.	0.33				0.46	1.89	−0.20
42 countries, nominal				−0.55	n.s.	0.26				0.33	1.43	−0.12
Archibald & Gillingham (1981)												
One car	−0.61		0.16				0.23		−0.06			
Multi-car	−0.16		0.06				0.47		−0.08			
Paxson (1982)												
One year	−0.14						0.56					
Dahl (1979)												
MILES econometrically estimated												
(1936–72 data)	−0.08		0.21									
(1936–74 data)	−0.2[b]		0.08									
MILES not econometrically estimated												
(1936–72 data)	−0.23		0.21									

[a] The figure of 1.44 reported in Reza & Spiro (59), p. 312, is for total miles traveled: this figure is adjusted for the change in the capital stock to obtain a miles-per-automobile figure and for consistency with the other studies.

[b] Assumed from statement in text, p. 430.

Figure 1.



Source: Papacostas (1987), p. 141.

FIGURE 2. Speed Correction Factors
Light duty gasoline powered vehicles
Hydrocarbons
Low altitude

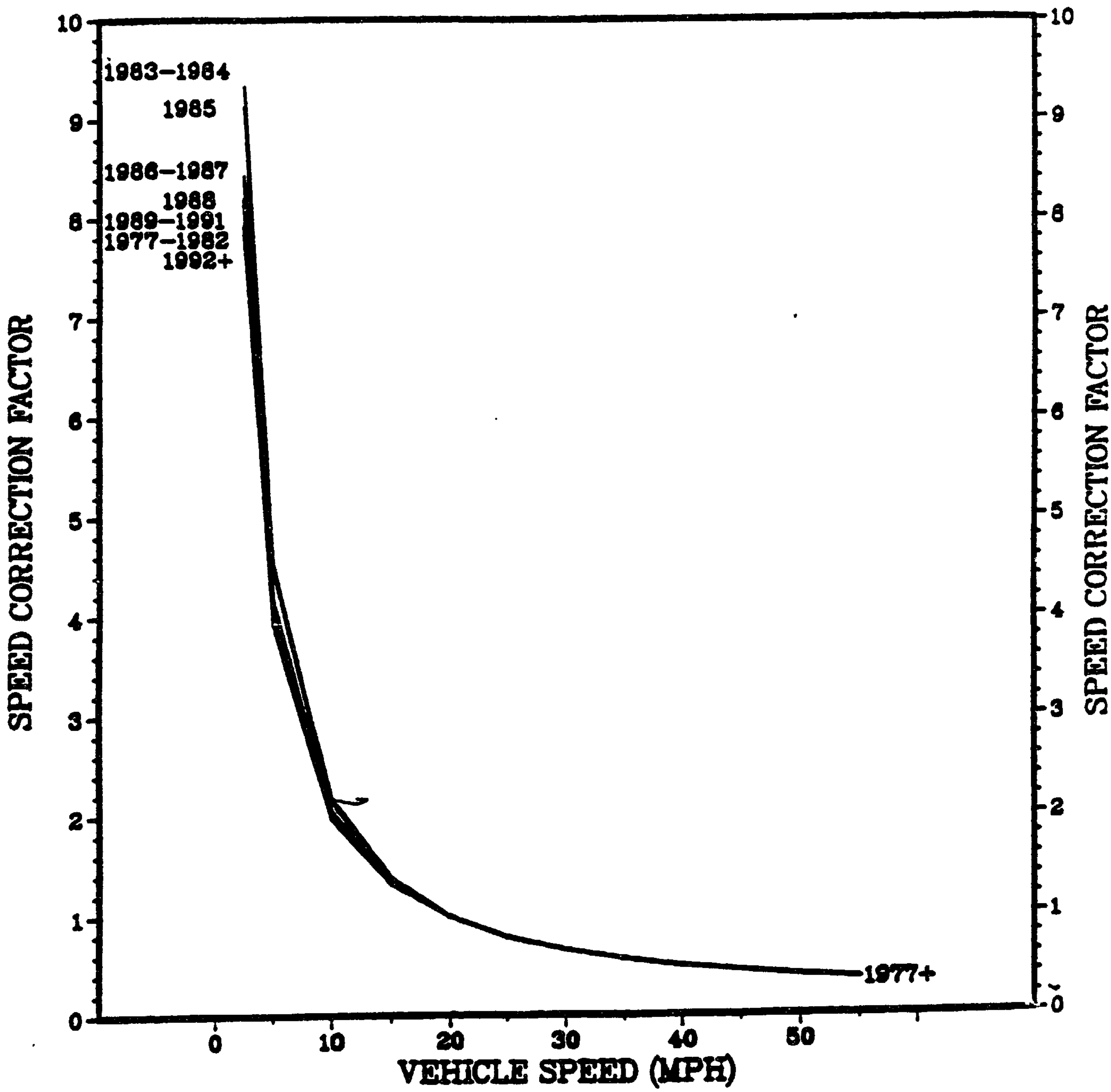


FIGURE 3. Household Vehicle Demand.

Each box represents a separate submodel

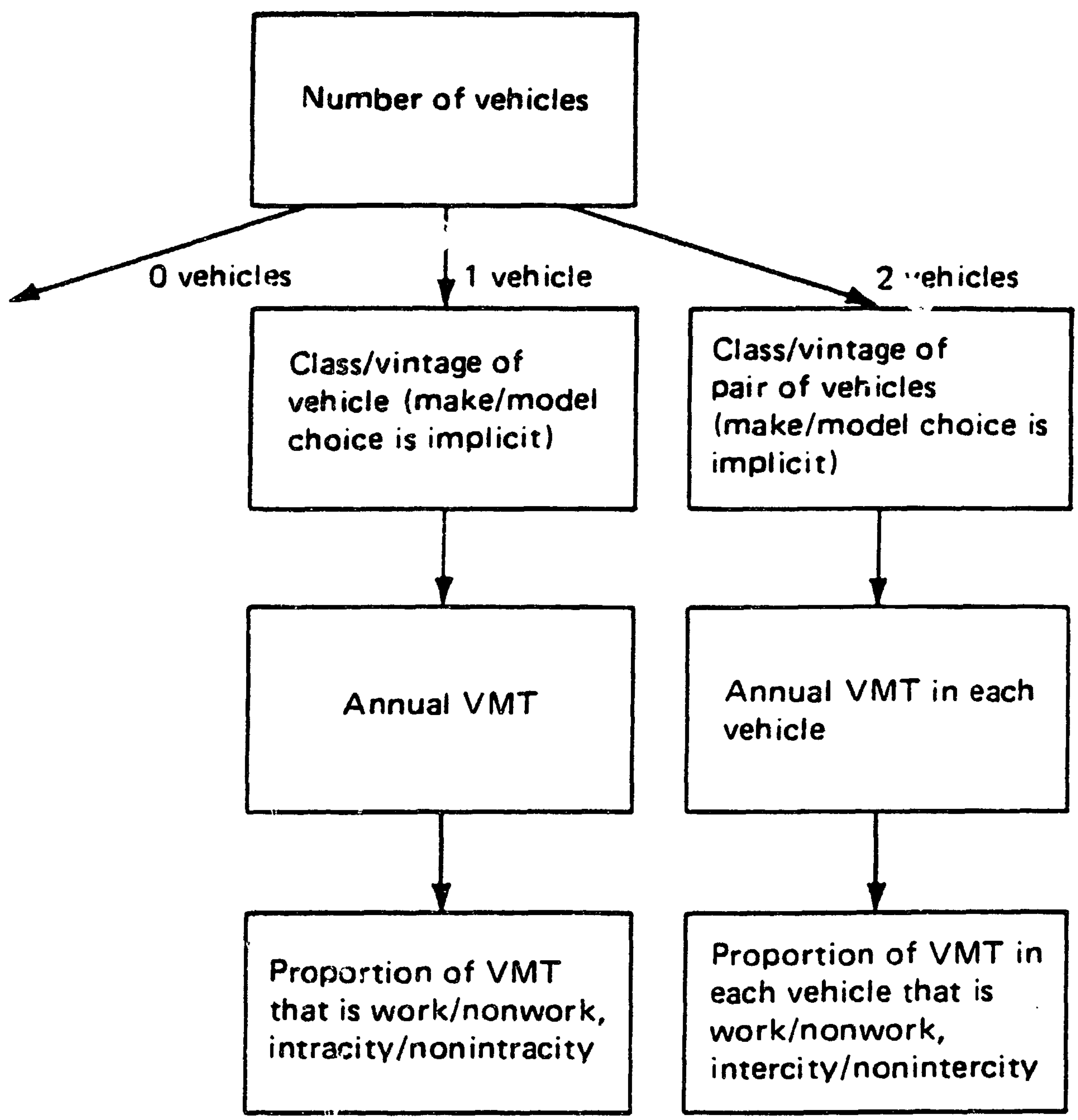
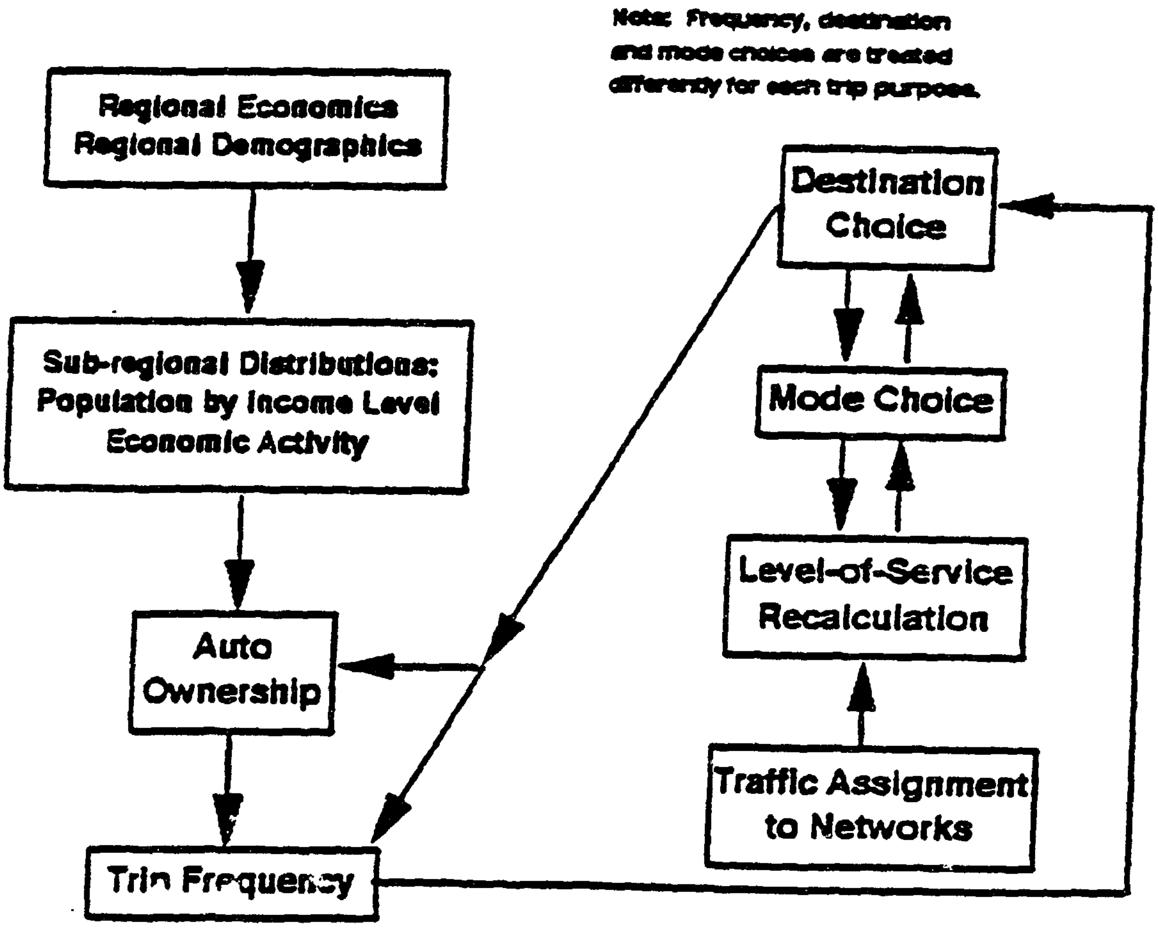


FIGURE 4. TRIPS Structure and Information Flows



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