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REGIONAL MANAGEMENT OF AUTOMOTIVE EMISSIONS: The Effectiveness of Alternate Policies for Los Angeles

Office of Air, Land, and Water Use
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REGIONAL MANAGEMENT OF AUTOMOTIVE EMISSIONS: THE EFFECTIVENESS OF ALTERNATIVE POLICIES FOR LOS ANGELES

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ABSTRACT

This study has two objectives: first, to develop procedures to evaluate policies for controlling automobile emissions; and second, to use these procedures to evaluate specific pollution control strategies for Los Angeles.

The first objective is achieved by developing a relatively quick and reliable method for estimating the cost effectiveness of travel related policies. The methods used include application of a behavioral demand model for automobile travel by mode, purpose and destination, and a model which predicts the size of the auto stock and its age distribution. These models are used to compute the costs to society and individual travelers of various policies, and to compute the emission reduction effects of various policies.

In applying these procedures to Los Angeles, the following specific strategies were evaluated:

- increased gas taxes;
- taxes on vehicle emissions per mile based on odometer readings and emissions tests;
- nonresidential parking surcharges;
- extensions of route miles by conventional bus;
- annual taxes based on vehicle model, make and year.

The report's findings indicate that implementation of these policies could significantly decrease pollution. Emission taxes and gasoline taxes are particularly effective strategies; parking taxes are a less effective but still viable policy. Tax-induced decreases in pollution are reinforced by improvements in conventional bus service.

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1. SUMMARY

Among the most important policy issues in controlling mobile source air pollution is determining whether a system of incentives to decrease auto travel is preferable to direct regulation of auto use. Most plans for meeting federal air quality guidelines have emphasized regulation -- for example, rationing gasoline, restricting parking availability, placing quotas on numbers of auto trips, and making retrofitting devices mandatory. More recently, attention has been given to the effectiveness of taxes on auto use and of transit improvements which, when implemented, allow more individual freedom of choice in travel behavior, while rewarding those choices which lead to pollution abatement.

The study reported here had the following two objectives: first, to develop procedures for evaluating policies which create incentives for controlling automotive air pollution; second, to use these procedures to evaluate a number of specific pollution control strategies for Los Angeles.

The first goal was achieved by developing a relatively quick and reliable method for estimating the cost-effectiveness of auto disincentives and transit improvements in changing travel and auto ownership patterns to meet air quality goals. The methods used in this study are based on the application of behavioral demand models to existing urban transportation data bases.

To achieve the second goal, policy evaluations were performed by comparing the cost-effectiveness of various pollution control strategies. The findings indicate that incentive measures can cause major decreases in pollution. Emission taxes and gasoline taxes are particularly effective strategies; parking taxes are a less effective but still viable policy. Tax-induced decreases in pollution are reinforced by improvements in conventional bus service.

In the remainder of this section, we provide additional detail on the policy findings and outline the policy evaluation methodology.

POLICY INSTRUMENTS

There are a large number of potential automobile pollution control strategies, and a full evaluation of all of them is beyond the scope of most regional planning agencies. A small group of pollution control strategies was selected for in-depth analysis on the basis of an *a priori* determination of their probable cost-effectiveness. The necessity for this selection of policy instruments motivated an investigation of the normative aspects of pollution and its control.

Automobile pollution should be viewed as an external social cost of the technology and individual behavior which cause it. An individual car owner has no incentive to control his emissions because his contribution is a small percentage of the whole; thus the individual does not pay the costs borne by others as a consequence of his actions and there is no noticeable effect caused by his sacrifice. Some form of institutional action or adjustment is called for when the problem becomes a social burden. An optimal form of control would be for motorists to pay the marginal social cost of their pollution constrained by other factors such as distributional justice or political feasibility. If it was known what benefits society as a whole receives from air pollution abatement, an optimal level of air pollution would occur when the marginal social cost of pollution abatement equaled the marginal social benefit derived from that decrease in air pollution. A tax could be set at a level which would induce motorists to reduce their contributions to air pollution by driving less, buying cleaner cars, retrofitting, or other methods. The level of emissions that resulted would be the level at which the cost of reducing emissions by one more unit equaled the benefit gained by that reduction.

However, due to the inadequacy of conventional policy evaluation tools, and possibly because of the difficulty in measuring the various social damages caused by air pollution, attempts to improve air quality have focused on regulation of technology and behavior rather than the imposition of incentives for pollution abatement. Nonetheless, the notion of applying disincentives rather than regulations to auto travel as abatement policy is appealing on the grounds of social welfare and personal freedom. Typically, travelers will be better off and scarce resources (including clean air) will be allocated more efficiently when tripmakers have more choice in travel options. Thus, taxation policies and transit improvements designed to meet ambient air quality constraints are generally preferable to direct regulation.

These considerations indicated that the following policies were worthy of in-depth evaluation:

- increased gasoline taxes;
- taxes on vehicle emissions per mile estimated from periodic odometer readings and emissions tests;
- nonresidential parking surcharges;

- extension of route miles by conventional bus to replace auto trips foregone as a result of pollution policies;
- annual taxes based on vehicle model, make and year.

The effects of these policies in reducing emissions are measured in terms of the following:

- reductions in vehicle miles traveled (VMT's) in personal autos;
- reductions in number of auto trips (cold starts);
- reductions in auto fleet size;
- changes in the age distribution of cars;
- incentives to retrofit.

For the purpose of exposition, the effects of the policies can be divided into two types: effects on travel behavior and effects on the auto stock. These are discussed in the following two sections. A third section compares the cost-effectiveness of the various strategies. Taken as a whole, these sections summarize the policy evaluation findings of the study. The models and data developed and used in the study are briefly described at the end of this chapter.

EFFECTS OF POLICIES ON TRAVEL BEHAVIOR

The effects of pollution control strategies on travel behavior are simulated using the disaggregate travel demand model. The travel-related policies under consideration include: a tax on the variable costs per mile of autos related to either gasoline consumption or vehicle emissions; a surcharge on all non-residential parking; and an extension of route miles of conventional bus service.* The demand

*An attachment at the end of this chapter presents the actual levels for the various taxes.

model predicts travel behavior for work trips and, separately, for shopping trips. After the effects of the policies have been simulated for these trip purposes, the trip and VMT reductions are extrapolated to include all trip purposes. The base year for the forecasted effects is 1974; that is, the travel demand models were used to predict travel behavior in 1974 in the absence of any of the proposed pollution control policies. For each tax strategy, four levels of tax were simulated and their effects on VMT's and auto trips estimated in terms of the percentage change from the 1974 base forecast. The effect of additional bus service combined with a selected number of auto disincentives was also simulated.

The simulated effects of the pollution control strategies are presented in Table 1. A detailed account of these effects on travel behavior, broken down by trip purpose and mode of travel, is given in Chapter 3. All strategies reduce auto travel significantly, though there are variations in efficacy.

The gasoline and emissions taxes are more effective in reducing VMT's than parking taxes when compared on a cost per trip basis. The reasons for this are as follows: (1) taxes which increase variable costs per mile have a greater effect on long trips than do parking taxes, thereby inducing more carpools and diversions to bus for those trips which contribute most to VMT's (see the attachment); (2) parking taxes can be avoided by driver serve passenger (chauffeured) auto trips which increase the auto mileage associated with individual trips.

The addition of bus service to serve auto tripmakers when a tax is imposed substantially increases mode diversion and further reduces VMT's. This effect is especially

Table 1. ESTIMATED EFFECTS OF POLLUTION CONTROL STRATEGIES ON VMT'S AND AUTO TRIPS

Gas or emissions tax: variable cost per mile increase[a]	% Change in VMT's	% Change in auto trips	Total VMT's, millions per weekday[b]
25%	- 7.40%	- 5.45%	57.940
50	-13.96	-10.50	53.835
75	-19.58	-15.27	50.319
100	-24.13	-20.39	47.472
Parking tax: parking cost increase[a]			
$0.25	- 5.04%	- 7.66%	59.416
0.50	- 9.58	-14.46	56.576
0.75	-13.07	-19.16	54.392
1.00	-15.43	-21.33	52.915
Transit system improvements with variable cost per mile increase[a]			
25%	-20.21%	-16.43%	49.925
100	-35.77	-29.83	40.189

[a]Table 5 in the attachment converts taxes into absolute and percentage terms for average trip lengths. Table 6 in the attachment also converts variable cost per mile increases into equivalent taxes on gasoline and emissions.

[b]Based on an estimated total of 62.570 million VMT's per average weekday in 1974 for the Los Angeles Air Quality Control Region.

prominent for long trips where transit has a substantial cost advantage over auto travel after the imposition of taxes which increase auto variable costs per mile, such as gasoline or emission taxes.

EFFECT OF TAX STRATEGIES ON AUTO STOCK

Several emission tax strategies were simulated to determine their effects on the size of the auto stock, the age distribution of cars, and the incentive for motorists to retrofit. The design of such taxes is rather complex and will not be described here (see Chapter 4), except to note that they are higher for older cars.

The effects of two emission tax levels representing a high and low range are summarized in Table 2. It can be seen that the auto stock would decline in size as a result of the tax. More importantly, from the standpoint of reducing pollution, the scrappage rate of older cars increases substantially.

The impact of emissions taxes on the age distribution of cars is cumulative over time. This can be seen from the example given in Table 3 where the effect of the imposition of a tax in 1975 is traced through to 1976. The accelerated scrappage of older cars in response to the tax would have a significant impact on the average emissions of the auto fleet.

Emissions taxes which are also based on mileage (odometer readings) provide incentives to retrofit. The results presented in Chapter 4 indicate that voluntary retrofitting would become widespread at emission tax rates on the order of 50 percent of the average auto variable cost per mile. In 1974 this tax rate would have been about $0.03 per mile.

Table 2. EFFECTS ON AUTO STOCK OF ANNUAL EMISSIONS TAX ON ALL POLLUTANTS: LOS ANGELES AND ORANGE COUNTIES

Indicator	Base case	Low tax[a]	High tax[b]
Total auto stock (in vehicles)	4,240,053	4,149,052	3,971,173
New car sales (in vehicles)	403,896	373,260	346,866
Used car price, average	$1272	$908	$574
Aggregate scrappage rate	0.0779	0.1015	0.1508
Average present value of tax, all cars	----	$392	$784

Model year	Base case scrappage rate	Low tax[a]		High tax[b]	
		Annual tax	Scrappage rate	Annual tax	Scrappage rate
1975	0.0013	$ 56	0.0013	$113	0.0017
1974	0.0028	62	0.0028	125	0.0037
1973	0.0058	68	0.0059	135	0.0079
1972	0.0120	81	0.0125	162	0.0171
1971	0.0239	105	0.0268	211	0.0378
1970	0.0449	122	0.0557	245	0.0814
1967-1969	0.1132	158	0.1783	317	0.2808
pre-1967	0.1898	176	0.4398	350	0.6290

[a] Low tax equals $7/gm HC + $1/gm CO + $8/gm NOx.

[b] High tax equals $14/gm HC + $2/gm CO + $16/gm NOx.

Table 3. EXAMPLE OF EFFECTS OF TAX SCENARIOS ON AGE DISTRIBUTION OF AUTOS OVER TIME

Model year	1975 age distribution (assumed)	1976 age distribution		
		No tax	Low tax	High tax
1976 (assumed)	---	0.10	0.10	0.10
1973-1975	0.30	0.29	0.32	0.35
1970-1972	0.25	0.24	0.26	0.28
1967-1969	0.20	0.17	0.17	0.16
pre-1967	0.25	0.20	0.15	0.11
Change in auto stock	---	+2%	-5%	-13%

COST-EFFECTIVENESS OF TRAVEL-RELATED POLICIES

In order to compare policies, it is useful to quantify their cost-effectiveness. This procedure normalizes the various pollution control strategies in terms of their policy objectives. Two cost-effectiveness measures were computed. The first uses costs to individual households, while the second uses resource (or social) costs. The common base for these costs is the degree of VMT reduction. This, of course, is only a proxy for the variable of most interest -- the decrease in emissions. The cost per VMT foregone is nonetheless useful as a method for comparing policies because VMT's are strongly correlated with emissions.

The costs of the policies to individuals include two components: first, the increased money costs associated with travel; second, the opportunity cost associated with travel foregone by the auto driver alone mode. The first type of cost is simply the sum of the taxes paid as a result of the policy. The second type of cost requires more elaboration.

As the cost of travel increases for auto driver alone trips, the number of such trips declines owing to people choosing alternative modes and destinations which were formerly less desirable. Sometimes the change in modes results in longer commute times and lower costs, as in the cases of individuals switching to carpools or transit for long trips. Some individuals will choose these alternatives at relatively low increases in automobile travel costs, reflecting relatively little discomfort in making the switch; others require a high auto disincentive, indicating that the opportunity cost of foregoing auto drive alone modes is relatively great. Calculation of these costs requires estimation of the changes in consumer surplus (which is, using some simplifying assumptions, the change in the area under the travel demand curve).

The resource costs, that is, the costs of resources which have alternative uses for society, must be calculated differently. Briefly, the resource costs include the opportunity costs to households plus the costs of administering the tax policy. These social costs do not include the taxes paid by individuals because such transactions reflect transfer payments rather than utilization of resources.

The results of computing individual and resource cost-effectiveness of policies is presented in Table 4. Several conclusions emerge from these calculations:

1. Parking taxes are considerably less cost-effective than other policies because they induce driver serve passenger trips and, compared to per-mile charges, the longer the trip, the less their relative cost to the tripmaker.
2. Tax collections from individuals are considerably higher than resource costs, indicating that the taxes can be used for administering the programs (including the test facilities for an emissions tax) with enough remaining to help alleviate adverse income distribution effects; note that these tax schemes will be regressive unless a redistribution program is incorporated.
3. Because the cost-effectiveness in terms of VMT's differs only slightly between a gas tax and an emissions tax near the high range of taxes (around $0.05 per mile), the cost-effectiveness for actual reduction of emissions may be significantly greater for emissions taxes, because it will cost relatively more to drive higher-polluting vehicles, and we can predict these vehicles will be used relatively less frequently.
4. The resource costs per unit of pollution reduction are greater with improved bus service, but the cost to

Table 4. COST TO INDIVIDUALS AND RESOURCE COST PER VMT REDUCED

Policy	Cost to individual per mile reduction	Resource cost per mile reduction
Gas tax:		
Variable cost per mile increase		
25%	$0.1852	$0.0063
50	0.1886	0.0123
75	0.1935	0.0177
100	0.2612	0.0217
Emissions tax:		
Variable cost per mile increase		
25%	$0.1852	$0.0216
50	0.1886	0.0205
75	0.1935	0.0235
100	0.2012	0.0264
Parking tax:		
Parking cost increase		
$0.25	$0.4033	$0.0199
0.50	0.3922	0.0377
0.75	0.3921	0.0535
1.00	0.3985	0.0675
Transit system improvements with gas tax:		
Variable cost per mile increase		
50%	$0.1208	$0.0229
100	0.1149	0.0292
Transit system improvements with emissions tax:		
Variable cost per mile increase		
50%	$0.1208	$0.0285
100	0.1149	0.0324

individuals is less due to increased mode diversions. Moreover, it appears that the tax revenues would be more than adequate for covering the cost of additional bus service.

MODELS AND DATA

The procedures used to evaluate the various policies included the application of a series of behavioral models to existing transportation planning data. Figure 1 indicates the role of models in policy analysis. As can be seen, policy instruments are quantified in terms of model inputs. Model relationships are exercised to determine variables (model outputs) which are used in the cost-effectiveness computations. The models and data are briefly defined below.

Travel Demand

The demand models used in the study are estimates of individual probabilities of making specific travel-related choices. The theoretical and statistical development of these models, termed disaggregate demand models, is treated in other studies.* The models predict the following choices:

- whether bus or auto will be used for work trips;
- whether bus or auto will be used for shopping trips;
- which destination will be chosen for shopping trips.

To apply these models, they were generalized in the following ways:+

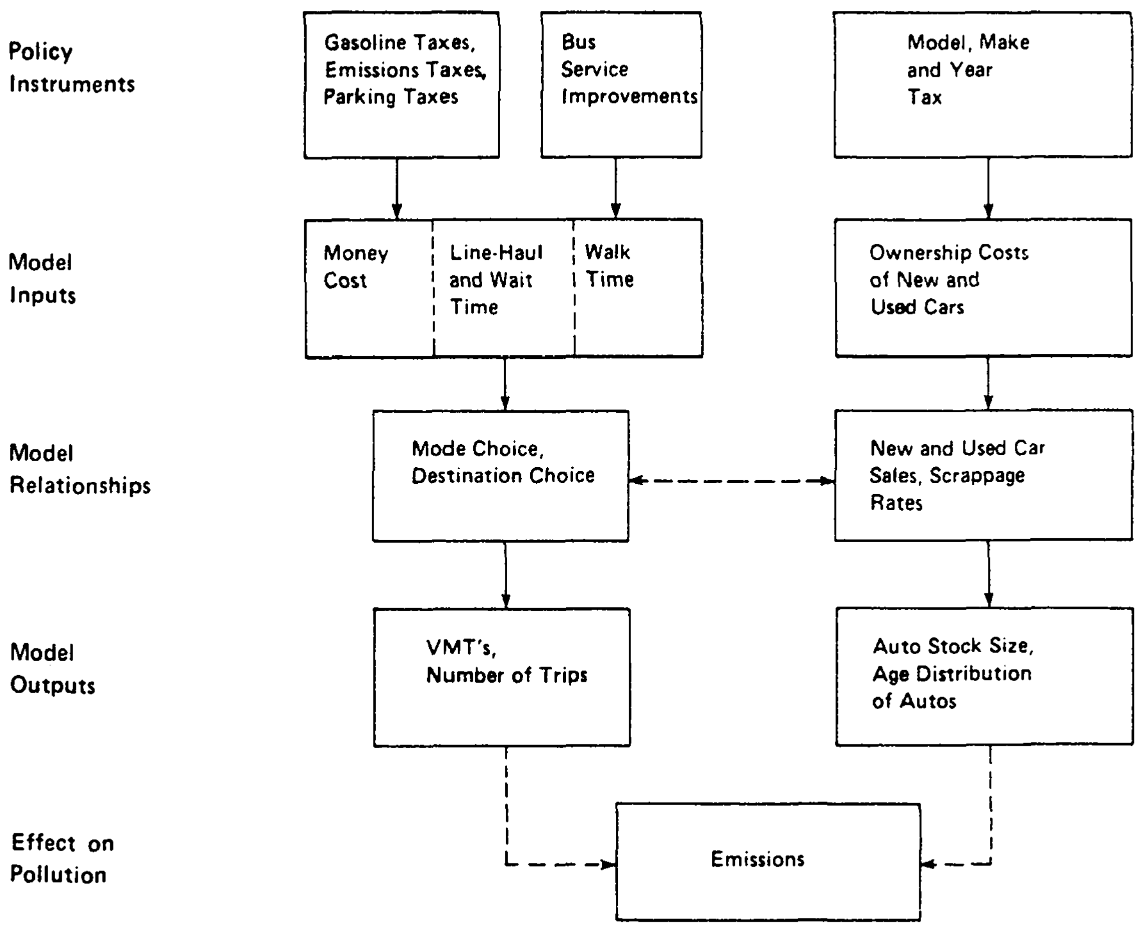
- other mode choices were added, including walking and a variety of shared auto rides;
- the model was adjusted for application to sketch plan zones;

*The particular model used in this report is developed in: Domencich, Thomas A. and Daniel McFadden. *Urban Travel Demand*. Amsterdam, North-Holland, 1975. 215 p.

+The travel demand models are developed for application in Appendix A.

Figure 1

FRAMEWORK FOR ANALYZING POLICY EFFECTS



- the model application results were expanded to include trip purposes other than work and shopping.

Travel demand by mode is forecast as a function of trip costs, trip time and socioeconomic variables. Policy instruments affect travel demand, and consequently VMT's and auto trips, by causing changes in the relative trip costs and times of various modes and destinations.

Auto Stock

The model used to estimate the effects of policy on auto ownership is a multi-equation system which predicts new car sales, scrappage, total auto stock, and the age distribution of cars. Emission control policies affect the auto stock size and age distribution by changing the cost of owning cars of different vintages.*

Cost of Improved Transit

To determine the costs of additional bus service, an econometric bus cost model was estimated. This model is linked to a bus network with an algorithm which computes bus hours, bus miles, and number of vehicles for each level of service. These variables are the inputs into the cost model.+

Data

The data used for analysis of pollution control strategies were derived from a number of sources. Principal among these is a household survey of trips performed by the Los Angeles Regional Transportation Study (LARTS). The trip records of a 24 hour period are tabulated in a trip table at the sketch plan zone level of aggregation. The travel

*The auto stock adjustment model is developed in Appendix B.
+The bus cost models are developed in Appendix C.

data from the survey were enriched with socioeconomic data from the 1970 Census and with a bus network developed from maps and schedules. Auto stock effects of policies were analyzed with auto registration data from a private service. The area covered by the data includes Los Angeles County south of the San Gabriel mountains and Orange County. This area corresponds approximately to the Los Angeles Air Quality Control region.*

CONCLUSIONS

The approach to aggregate urban transportation policy evaluation developed in this study holds considerable promise for planners who must make quick analyses of a wide range of travel-related policy options. The predictive capability of the methods and models was checked at several stages of their development and found to be relatively accurate. The resources and time necessary for using the approach are small by conventional urban transportation planning standards.

As for the policies themselves, all were found to be valid strategies for pollution control, though they vary in cost effectiveness. As a general rule, the more direct a disincentive the more effective it will be. If one desires to reduce emissions, then those taxes imposed to abate pollution are of most use when they relate as directly as possible to the actions and technology which cause emissions. In the instant case, emissions and gasoline taxes are more effective than parking taxes because the former tax pollution more directly than the latter.

In the longer run, emissions taxes become the more powerful instrument. Though costlier to implement than gas taxes, they cause changes in the age distribution of cars

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*Data issues are described in detail in Appendix D.

and induce retrofitting, thus causing a significant decline in emissions from the auto fleet. Also, as emissions decrease, the taxes themselves decline. They are self-regulating in ways that gasoline taxes, parking taxes and bus improvements are not. It is especially pertinent to note that high capital transit improvements, such as fixed rail systems, would be a costly solution to the pollution problem compared to either low capital bus improvements or changes in auto technology induced by emissions taxes.

Several nonquantifiable factors also need to be considered in order to fully evaluate the various policies. For example, the incidence of the tax policies is, in all likelihood, regressive; some strategies for redistributing the income lost in taxes should probably be considered. Also, if a combination of strategies is used (such as taxes and bus line extensions) then there should probably be joint planning and phased implementation to ensure that sufficient bus capacity will exist when taxes are imposed. Finally, permanent changes in the transportation network will have long-range effects on land use, and these should be examined in advance to determine whether they conform to existing land use plans and preferences. Most of the policies considered here would tend to cause more clustered development.

Future research should probably focus on alternative low capital system strategies rather than methodology development. Promising policy options include wide area transit using integrated paratransit feeder and express bus line-haul, and improved traffic management. However, little is now known about the effectiveness of these strategies, and it will be some time before they can be thoroughly evaluated. In the meantime, policies such as those considered in this report may be the best short-term solutions to mobile source pollution problems in urban areas.

ATTACHMENT TO CHAPTER 1

TAX LEVELS

Four tax levels were simulated for each policy. For emissions and gasoline taxes, the four levels represented percentage increases in auto variable costs per mile. Parking charges, which are currently insignificant for most trips in Los Angeles, were increased in absolute amounts. In order to compare these sets of scenarios with each other, Table 5 presents the average absolute and percentage cost increase for work and shopping round trips. This table allows comparison and conversion between percentage and absolute terms of reference for the tax policies. It can be seen that the average cost per trip incurred by an increase in variable costs per mile is much greater for work trips than for shopping trips. Conversely, equal increases in parking charges will affect shopping trips more than work trips on a percentage basis.

It is likely that an emissions tax will not be placed on any single pollutant but will instead be based on a formula which includes all of the emissions. Therefore, it is worth noting that any weighted average of the emissions tax rates in Table 6 is equivalent to the increased variable cost per mile. For example, emissions taxes based on the formula of 50 percent from CO (carbon monoxide), 25 percent from HC (hydrocarbons), and 25 percent from NOx (nitrous oxides) at a combined rate of a 50 percent increase in the variable cost per mile would have the following three components:

0.50 x 0.0873 = 0.0437¢/gm of CO;

0.25 x 0.7936 = 0.1984¢/gm of HC;

0.25 x 0.8390 = 0.2098¢/gm of NOx.

Table 5. ESTIMATE OF EFFECT OF POLICIES ON AVERAGE PERCENT AND ABSOLUTE COST INCREASES OF AVERAGE 1974 ROUND TRIP

Policy	Work trip[a]	Shopping trip[b]
Variable cost per mile increase:	$ Increase	$ Increase
25%	$0.20	$0.07
50	0.40	0.13
75	0.60	0.20
100	0.80	0.27
Parking cost increase:	% Increase	% Increase
$0.25	31%	94%
0.50	62	187
0.75	94	281
1.00	125	374

[a]Based on an average work round trip length of 14.04 miles.

[b]Based on an average shopping round trip length of 4.68 miles.

Table 6. GASOLINE AND EMISSIONS TAXES ASSOCIATED WITH EACH LEVEL OF INCREASED VARIABLE COSTS PER MILE

Variable cost per mile increase	Gasoline tax increase[a]		Emissions tax[b]		
	%	$/gal	CO, ¢/gm	HC, ¢/gm	NOx, ¢/gm
25%	35%	$0.19	0.0436¢	0.3968¢	0.4195¢
50	71	0.39	0.0873	0.7936	0.8390
75	106	0.59	0.1309	1.1904	1.2585
100	141	0.78	0.1746	1.5872	1.6780

[a] Based on a pump price of 55¢/gallon, including federal tax = 4¢/gallon and California state tax = 7¢/gallon.

[b] Based on the following expected 1975 average emission rates per auto for Los Angeles:

Carbon monoxide:	32.7100 gm/mile
Hydrocarbons:	3.5476 gm/mile
Nitrous Oxide:	3.4029 gm/mile

Expected average emission rates are derived by weighing emission rates per model year by age distribution of cars.

2. POLICY ANALYSIS FRAMEWORK AND INSTRUMENTS

This chapter is divided into two main sections. The first section introduces the conceptual framework which will be applied in analyzing the effects and costs of alternative auto pollution control strategies. The second section describes the policy instruments for controlling automobile pollution which will be evaluated in this study.

POLICY ANALYSIS FRAMEWORK

Because it is assumed that individuals are not charged for the social costs of pollution under current practice, the policies are designed to raise the costs of pollution production. The policies are effective to the extent that they alter the incentives of those actions which cause pollution or its abatement.

The first part of this section shows how the short-run policy effects on auto travel are analyzable with the use of a behavioral model of travel demand. The second part outlines an approach for determining the effects of emission control strategies on the composition of the stock of automobiles.

Travel Behavior

The short-run response to the policies considered in this report is limited to changes in personal travel behavior; longer-run effects include adjustments in the stock of automobiles and the regional pattern of land use. Personal travel decisions -- mode choice, destination of trips and frequency of travel -- are the result of equilibrium between household travel demand and the performance of the system. As policy instruments affect system performance, new equilibrium travel patterns are formed. We explain this process below and introduce the concept of travel demand which will be used in the analysis of policy effects and costs.

Travel Demand -- The theory of travel demand has been developed in its essentials for some time and is becoming more widely utilized by transportation planners and other policy analysts. Because more complete treatments exist elsewhere,[1] we will only sketch the fundamentals here.

The first step in analyzing travel behavior is defining trips in a way amenable for analysis. For our purposes we will consider a trip to be a round trip from an origin to a destination by a specific mode. We will consider separately trips which have different purposes (work, shopping, etc.). Typically, we will only be considering single-purpose trips made by households; thus, the origin of a trip will be the residence of the tripmaker and the destination will be a land use which reflects trip purpose (employment center, retail outlet, etc.).

The quantity of travel by a household depends on the costs, speeds, comfort and other performance characteristics of the available means of travel, as well as on the relative attractiveness of alternative destinations and the characteristics of travelers. Thus demand is treated as a function of several variables where the number of trips demanded is dependent on a comparison by each traveler of the expected benefits to him of the contemplated trips and the costs and inconveniences of making them. A demand model is a set of functions which indicate the demand for the various alternatives available to a household. The full range of choices includes decisions on whether and how often to make a trip, the time of day, destination, mode and route. For our purposes, we will mostly be concerned with those relationships which describe mode choice, destination choice and frequency of trip per unit of time.

In making these choices it is assumed -- and evidence contained in transportation studies verifies this assumption -- that individuals make time and cost comparisons in a consistent and empirically deducible pattern. In selecting the mode of transportation, for example, where a traveler can use either transit or auto, he appears to evaluate the trade-off between travel time and cost in a consistent manner. Similarly, the choice of where to travel is systematically influenced by a comparison of the relative travel times and costs of the available alternative destinations. Finally, the number of trips made by a household or individual for a given purpose is influenced by the cost and inconvenience of travel.

System Performance -- *The short-run notion of the performance* of a system refers to the relationship between the generalized costs of travel and the volume of travel. Some components of the generalized cost, such as transit fares and fuel costs, do not vary significantly with the level of use but rather are determined exogenously. However, as a general rule, the greater the volume of traffic on any mode and origin-destination pair, the more time-consuming and inconvenient the individual trip. This volume-performance relationship is determined by the physical characteristics of transportation facilities, the way in which they are controlled, and the exogenously determined prices which affect the costs of a trip.

The interaction of demand and system performance determines the equilibrium number of trips that will be taken and the generalized cost or level of service associated with these trips. Exogenous changes in the system, such as those caused by policy instruments, can be evaluated by comparing the system equilibria before and after the changes.

Analysis of Policy Effects

Building on the analytical concepts presented above, it is possible to measure the short-run effects of various pollution control strategies on automobile trips and VMT's. To do so, the analyst must be able to determine both how the policy will change the system performance and the consequent effect on travel demand.

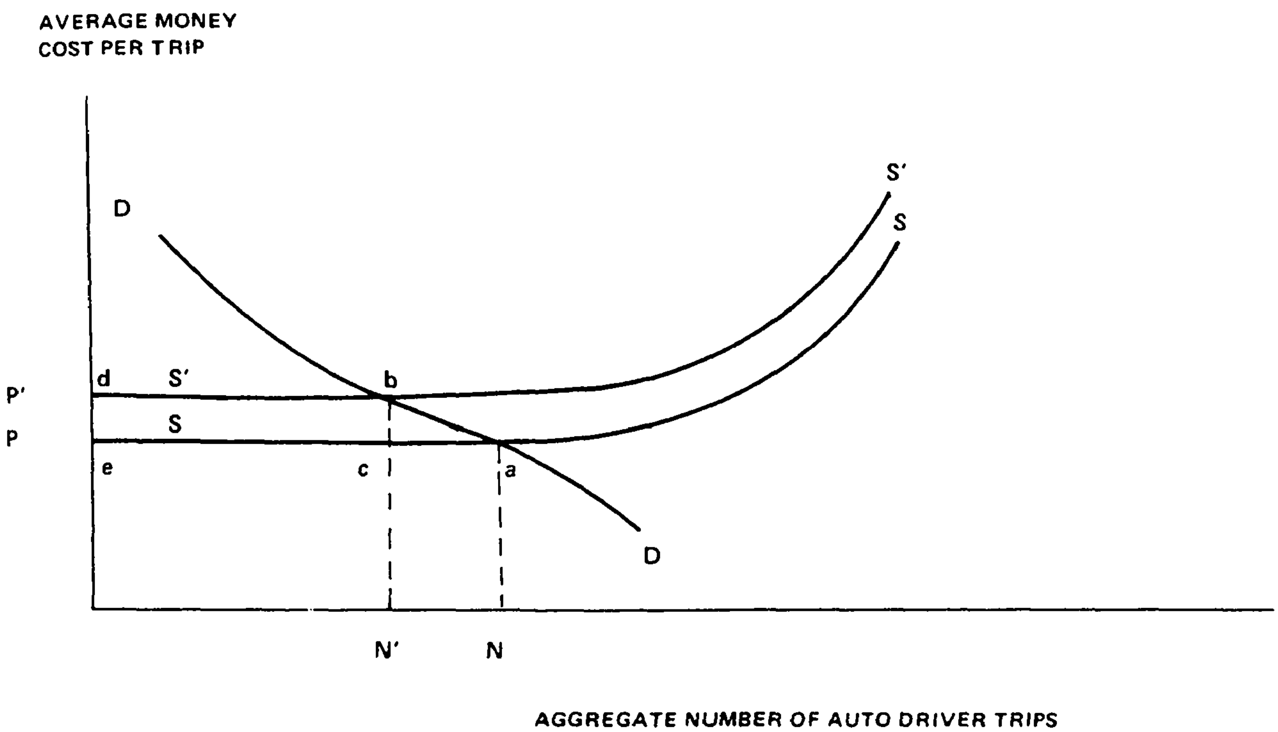
Analysis of Policy Costs -- The policies considered in this report, excluding transit service improvements, increase the money costs of travel to the individual. Thus, the cost of the policy to individuals includes the increased money costs of trips made after the cost increase. Because the cost increase is usually equal to the tax per trip, the cost to individuals includes all taxes paid as a result of the policy.

As the cost of travel increases for, say, auto driver alone, the number of such journeys declines due to people choosing alternative modes and destinations which were formerly less desirable. The cost to individuals for making these less desirable choices is not determined by the new taxes alone. Sometimes the change in mode results in longer commute times and lower costs as in the case of individuals switching to carpooling or transit for long trips. Some individuals will choose these alternatives at relatively low increases in automobile travel costs, reflecting minor discomfort in making the switch; others would change modes only at much higher increases, indicating that the cost of forgoing auto drive alone modes is relatively great.

Figure 2 illustrates how equilibria between demand and system performance are used to approximate the costs of policies to individuals. The demand function is represented by the curve DD; the system performance relationship before a policy instrument is applied is represented by SS. The initial equilibrium occurs at price per trip P and with a

Figure 2

COSTS OF POLICIES TO INDIVIDUALS



volume of traffic equal to N. A policy increasing the cost of travel, such as a tax on gasoline or parking, shifts the system performance curve upward to S'S'. At the new average cost per trip, P', the equilibrium number of trips has declined to N'.

Under reasonable assumptions, the area of the hypothetical triangle connecting points a, b and c gives a reasonable estimate of the aggregate opportunity policy which shifts the money cost of travel from P to P'. This cost would be added to the area formed by the rectangle with corners b, c, d and e (the total increased cost of trips by single motorists making trips after the policy) to estimate the total cost of the policy.

The above discussion covers only the increased costs to households of a system change. The resource costs, that is, the costs of resources which have alternative uses for society, must be calculated differently. Briefly, these costs include the opportunity costs to households, plus the incremental transportation system costs, plus the costs of administering the tax policy. It should be noted that there are also nonmonetary benefits to transit riders when transit system performance is upgraded. Except to acknowledge that such benefits should be included in both the calculation of individual and resouıce costs, we do not attempt to estimate or monetize these benefits.

Individual Cost = Change in Money Cost (taxes)
+ Opportunity Cost

Social Cost = Opportunity Cost to Individuals
+ Change in System Costs
+ Administrative Costs

The actual calculations of policy costs are performed in Chapter 5.

Probability Choice Models -- The demand models used in this study use estimates of individual probabilities of specific travel related choices. The theoretical development of individual techniques is presented in another study to which the interested reader is referred.[2] In this section we place the model in the context of the demand framework presented above.

The estimated relationships which form the basis of the models are ratios of the probabilities of selection for two alternatives to a given choice. Equation 1 gives the general form of these estimates:

$$\ln \frac{P_i}{P_j} = \beta(X_i - X_j) \qquad (1)$$

where P_i = probability of an individual choosing alternative i;
P_j = probability of an individual choosing alternative j;
X_i = vector of attributes, including costs and attractiveness of alternative i;
X_j = vector of attributes, including costs and attractiveness of alternative j;
β = estimated vector of coefficients.

If there exist a number of alternative choices, say n, then the several estimates of pairwise probability ratios of the form of Equation 1 can be transformed to get an estimate of the probability itself by means of the following formula:

$$P_i = \frac{1}{\sum_{k=1}^{n} \frac{P_k}{P_i}} = \frac{1}{\sum_{k=1}^{n} e^{\beta(X_k - X_i)}} \qquad (2)$$

Equation 2 is a generalized logit function.

In analyzing individual travel choices it is useful to separate the decisions involved into the following sequence:*

1. Whether to make a trip;
2. Given a trip is to be made, where the destination will be;
3. Given a trip will be made and the destination is known, what mode will be taken.

Using this artifice, the probability that an individual will make a trip to a given destination by a given mode can be viewed as the product of three conditional probabilities:

$$P_{ijm} = P(t|i) \cdot P(j|t,i) \cdot P(m|t,i,j) \quad (3)$$

where P_{ijm} = probability of an individual at location i making a trip to j by mode m for a given purpose over a specified unit of time, such as a 24-hour period;

$P(t|i)$ = probability that an individual at location i will make a trip for a given purpose over a specified unit of time, such as a 24-hour period;

$P(j|t,i)$ = probability that an individual at location i will make a trip to location j, given that a trip will be made for a given purpose;

$P(m|t,i,j)$ = probability that an individual at location i will make a trip by mode m to location j, given that a trip to location j will be made for a given purpose.

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*See Ben-Akiva, Moshe. *Structure of Passenger Demand Models.* Ph.D. thesis, Massachusetts Institute of Technology, 1973, for a discussion of this issue.

In order to estimate the demand for travel from a zone, the above probability choice functions are summed across all individuals, or households, in the zone of location i. (With most urban transportation data bases, this exercise is not really possible. However, the model can still be applied to zonal aggregates after certain adjustments to replicate the effect of summing the probabilities of individual choice across all households in a zone.)

The demand model used in this study is developed in more detail in Appendix A. It contains estimates of the probabilities of mode choice for work trips and estimates of the probabilities of mode choice, destination choice and frequency of trips for shopping trips. Chapter 3 gives the results of applying these estimates to determine the effects of pollution control strategies on VMT's and number of trips. Chapter 5 uses these models for calculating individual and social costs of the policies.

Auto Stock Adjustments

The policies considered in this report will affect the relative costs of owning and operating cars of different vintages. As a consequence of these policies, the number of automobiles owned will be fewer, causing less auto travel, and the median age of the auto stock will be decreased, so that the emissions per car will on average be less. This section presents the theoretical foundations for the models which will be used in estimating these effects.

Auto Stock Dynamics -- The stock of cars in a region changes from year to year as new cars are purchased, old cars are scrapped, and households migrate with their personally owned autos. These flows to and from the previous period's auto stock determine the fleet size at a given subsequent time. The process is depicted in the identity:

$$T_t = T_{t-1} + N_t - J_t + I_t \quad (4)$$

where T_t = stock of cars at the end of period t in a given region;

T_{t-1} = stock of cars at the end of the period previous to t (or, at the beginning of period t) in a given region;

N_t = total new car purchases during the period t in a given region;

J_t = total cars scrapped (junked and abandoned) during the period t in a given region;

I_t = net inflow or outflow of cars owing to household relocation into or out of the given region during period t.

In analyzing the effect of pollution control strategies on the stock of cars, it is useful to isolate the impacts these policies will have on those components of auto stock which change the fleet size from year to year. Such an approach entails considering new car sales and used car scrappage separately; it is presumed that the effect of the pollution control strategies on net migration of households is negligible.

New Car Sales -- The purchase of new cars in a region is largely the result of the interaction of demand by households and supply by auto manufacturers. Empirical evidence suggests that there is a substantial amount of regularity in the sensitivity of consumers to new car prices.* Equation 5 presents a stylized demand function for new cars:

$$N_t = f_1(PN_t, KN_t) \quad (5)$$

*For a review of research to date, see Dewees, D. N. *Economics and Public Policy: The Automobile Pollution Case.* Cambridge, MIT Press, 1974.

where N_t = new car sales at time t in a given region;

PN_t = price index of new cars at time t in a given region;

KN_t = other factors relating to households and substitute products of new cars (e.g., level of income and availability of transit) which affect new car sales.

We have purposely isolated price in this equation because it mediates the impacts of increased ownership and operating costs on new car purchases. Other variables, amalgamated into the term KN_t, can be ignored in analyzing the effects of policies considered in this study.

If Equation 5 accurately represents the demand for new cars, then an increase in the ownership costs which is not related to any increased consumer benefits would change new car sales according to the following relationship:

$$N_t = f_1(PN_t + \Delta CN_t, KN_t) \tag{6}$$

where ΔCN_t = the cost of increased ownership of a new car during year t for a given region where the increased cost is not related to increased consumer utility.

The effect of increased ownership costs is identical to the effect of an equivalent price increase. Most policies will increase auto ownership costs on a yearly basis, as in an annual tax; the increase in ownership costs at the time of new car purchase decisions will be the discounted present value of these costs over the lifetime of the car. This proposition obtains even if the household does not plan to own the car over its operating life. As will be shown below, the resale value of the car declines by an amount approximately equal to the capitalized increase in cost of ownership over its remaining life.

The effect of a policy to increase car ownership costs will be to lower demand at the equilibrium price, but it will not cause a change in the long-run equilibrium price. The result will be fewer new auto sales.

The actual quantitative assumptions about the new car demand function are given in Appendix B where a technical description of the entire auto stock adjustment model is presented. The results of pollution control strategies on new car sales are presented in Chapter 4.

Used Car Scrappage -- Automobiles tend to exit from the fleet of cars when their costs of repair and reconditioning are greater than the price of existing, operative vehicles. Used car dealers, and households to a lesser extent, consign such cars to wreckers or scrap dealers. Other factors which affect scrappage are the rate of turnover of cars in the market and the age of the auto stock. Higher turnover gives dealers more cars on which to make scrap vs. resell decisions. The older the existing stock of cars, the more expensive are the costs of keeping the cars operative.*

Pollution control strategies will have an effect on scrappage by their impact on used car prices. As the costs of owning a used car increase, the price of used cars will decline (in a manner described in more detail below). Lower market-clearing prices for used cars provide less incentive for used car dealers to make costly repair and reconditioning efforts in order to market the vehicles. The result is a decrease in the stock of used cars.

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*For a somewhat more extended discussion, see Walker, Franklin V. Determinants of Auto Scrappage. *Review of Economics and Statistics*. 503-506, November 1968.

The scrappage relationship, in a functional form implied by the above considerations, is as follows:

$$J_t = f_2(PU_t, CR_t, R_t, T_{t-1}, A_{t-1}) \tag{7}$$

where J_t = total cars scrapped during the period t for a given region;

PU_t = price index of used cars in period t for a given region;

CR_t = cost index of repairing and reconditioning used cars in period t for a given region;

R_t = rate of turnover of the auto stock during period t for a given region;

T_{t-1} = the stock of cars at the end of the previous period -- the beginning of period t -- for a given region;

A_{t-1} = the age distribution of cars at the beginning of period t for a given region.

The price of used cars is determined by the interaction between demand and available stock. The latter is in turn affected by the scrappage rate. Thus there is a multi-equation system which adjusts used car demand and stock so as to reach equilibrium. We consider first the demand relationship.

As with new cars, the household demand for used cars is considered to be sensitive to the existing market prices for used cars. Thus, a general demand function for used cars would be of the form:

$$U_t = f_3(PU_t, KU_t) \tag{8}$$

where U_t = number of used cars demanded in period t for a given region;

PU_t = price of used cars in period t for a given region;

KU_t = other factors relating to households and substitute products (e.g., level of income and availability of transit) which affect used car sales.

Used car supply is a concept quite different from the supply of new cars, or most other manufactured products. The supply of used cars is the total stock of cars in any given region. Except for scrappage, it is a fixed amount. Though, obviously, all used cars are not sold, it can be presumed that the market-clearing price of used cars represents their market value. Households most often decide to keep their car rather than take the opportunity to sell it to someone else at the market-clearing price. Referring back to Equation 8, we see that equilibrium occurs when:

$$U_t = T_{t-1} \qquad (9)$$

By substituting Equation 9 into Equation 8 and solving for price, price determination in the used car market can be seen to be a function of the used car stock and the other factors in demand:

$$PU_t = f_4(T_{t-1}, KU_t) \qquad (10)$$

We are now in a position to illustrate how the system will adjust to the increase in ownership costs of used cars caused by the imposition of pollution control strategies.

As in the case of new car demand, the added costs of used cars will cause a downward shift in the demand. In equation form, the process is determined by adding the increased costs to price in Equation 8 to yield:

$$U_t = f_3(PU_t + \Delta CU_t, KU_t) \qquad (11)$$

where ΔCU_t = capitalized increase in ownership costs of used cars in period t for a given region, where the increased cost is not related to increased consumer utility.

The new market-clearing price is PU_t^*; it can be computed using the following formula derived from from Equation 10:

$$PU_t^* = f_4(T_{t-1}, KU_t) - \Delta CU_t \qquad (12)$$

The lower price would in turn cause the scrappage rate to increase and, consequently, the stock of used cars would dwindle. This would shift the supply of used cars and cause a corresponding increase in the market-clearing price of used cars. The process would continue until a new equilibrium is established for the price of used cars, the scrappage rate, and the stock of used cars.

The system of equations used to simulate the above process is developed in Appendix B of this report. There, an econometric estimate of Equation 7 is presented together with the assumptions used to determine Equation 8. The results of applying this model to the actual policies considered in this study are given in Chapter 4.

POLICY INSTRUMENTS

This section presents the *a priori* case for, and problems with, each policy alternative along with the nature and incidence of costs. Also, in each case, a brief review of the literature is included so that the results of this study can be checked for consistency against previous research efforts.

Public action to control air pollution is necessary because an individual owner of an emission source has no incentive to reduce its emissions since its contribution is a small percentage of the whole. The individual does not pay the costs borne by others as a consequence of his actions, and there is no noticeable effect from his sacrifice. Some form of institutional action or adjustment is called for when the problem becomes a social burden. An optimal form of control would be for polluters, in this case motorists, to pay the marginal social cost of their pollution. If knowledge existed about the benefits that society as a whole receives from air pollution abatement, an optimal level of air pollution would occur when the marginal social cost of pollution abatement equaled the marginal social benefit derived from that level of air pollution.

Again assuming such knowledge existed, a tax could be set at a level which would induce motorists to reduce their contributions to air pollution by driving less, buying cleaner cars, retrofitting, or other methods. The level of emissions that resulted would be the level at which the cost of reducing emissions by one more unit equaled the benefit gained by that reduction.

The major problem with applying an optimal policy is that the benefits of pollution abatement are ill-defined and, to date, largely indeterminate. Because the notion of social damages caused by air pollution is quite ambiguous, the theoretical approach of equating marginal social cost with marginal social benefit does not provide, in and of itself, an operational guideline to policy development. Typically, the desired level of air quality is given in the political decision-making process in a manner which is beyond the scope of this study. For our purposes, the benefits of air pollution abatement are given; that is, the level of air quality is an absolute constraint which is met by specific individual and social costs. The purpose of this research effort is to inform the political decision-making process of the costs of various air quality constraints.

Many of the policy recommendations to date have focused on regulation of technology and behavior rather than the imposition of incentives for pollution abatement. Regulatory proposals have included such things as gas rationing, parking prohibitions, and restrictions on residential location and place of employment. Aside from the not inconsiderable disruption and administrative costs of such an approach, direct regulations such as these do not cause individuals to pay for their pollution. Thus, even in the absence of exact knowledge about the social costs of pollution, regulations as a solution to the pollution problem are *prima facie* less satisfactory alternatives than a system of taxes and incentives which allows scope for voluntary individual decisions on whether to act so as to pollute while paying the social penalty involved.

The policy instruments considered in this report include the following:

- parking tax
- gasoline tax
- emissions tax
- transit system improvements

These are each covered in detail in separate sections.

The effects of these policies are to decrease the following factors which contribute to air pollution:

- vehicle miles traveled (VMT's)
- trips (the number of cold starts)
- the emission rate of the stock of automobiles

These factors are further influenced by policy effects which alter the following:

- size of the auto stock
- age distribution of automobiles
- the extent of retrofitting

Vehicle miles traveled in a region is the most important contributor to mobile source air pollution. However, it has been demonstrated that a significant portion of total emissions (depending upon the pollutant under consideration) does not vary with mileage, but simply depends upon whether a car was started while the engine was cold.[3] The number of cold starts is assumed to be proportional to the number of trips taken.

In order to consider policies designed to reduce auto emissions, it is also necessary to know about the rate of emissions from the auto stock in some detail. The rate of production of a particular pollutant for a given vehicle at a given moment depends upon the rate of emission of the vehicle at low mileage, the amount of use the vehicle has had, and its state of repair with respect to functional elements which affect emissions. Two vehicles which have identical emission rates coming off the assembly line may have different rates after much use if one receives better maintenance than the other. Two vehicles which have received identical maintenance may have significantly different rates depending on their original low mileage (or optimal) rates. Since increasingly strict emission controls have been mandatory on new vehicles for some years now, especially in California, low mileage emission rates generally vary with the model year of the vehicle, although there is usually a high variance within each model year.[4] Also, it is possible to derive average amounts of use and average maintenance for each model year, with which one may calculate deterioration rates.[5]

The primary factor which affects the current level of emissions per mile from a given stock of cars is the age distribution of the fleet. This is due to the large differences in emissions between precontrolled and controlled vehicles. It is estimated that in 1975, precontrolled vehicles will account for about one-quarter of the vehicles on the road, both nationally and in California. However, as these vehicles emit pollutants at 5 to 100 times the rate of controlled vehicles, their contribution to the total pollution problem is greatly out of proportion to their numbers.[6] Finally, the policies under consideration may affect the emission rate from the stock of cars by inducing maintenance and retrofitting, causing older autos to decrease their deterioration rates as well as their initial rate of emissions.

In the remainder of this section, we shall discuss the policy instruments evaluated in the study.

Parking Tax

There are many possible designs of parking taxes, including those which vary by time of day and localized conditions. However, as will be shown below, some parking tax strategies are clearly preferable to others in satisfying the objectives of decreasing automobile miles traveled and trips in the region as a whole.

A Priori Analysis of the Effects of a Parking Tax -- A parking tax must be defined in terms of spatial coverage and land use before it can be analyzed. Most experience with parking taxes has focused on the effects of increased restrictions on parking in the central business district or even smaller areas. The problem with a parking tax of this nature is fairly obvious -- it fails to deter a significant number of trips in the region. This is especially true in Los Angeles, where the central business district has relatively minor importance. (Less than 5 percent of the total regional employment is in the Los Angeles central business district, and an even smaller percentage of shopping trips have their destination in the CBD.) Thus, the parking tax leaves most trips unaffected, as there are enough alternative destinations to the CBD to prevent substantial deterrence to auto trips as a whole.

Similarly, a parking tax designed to raise the cost of travel for a particular trip purpose, such as shopping, would generally be difficult to administer and enforce. As long as there are cheaper alternative parking places available, then auto trips for any purpose would use these alternatives unless the effort at monitoring the trip makers was highly developed, which would be prohibitively expensive.

Thus, a parking tax over the region as a whole and for all trip purposes presents itself as the most reasonable scenario. The parking tax may be varied, however, by time of day or climatic condition depending on when diversion of auto trips would have the most benefit in abating air pollution. Even this policy can present administrative difficulties, owing to the difficulty of distinguishing between residential parking and other parking.

The imposition of a blanket charge on all nonresidential parking increases the out-of-pocket expenses for auto trips when the vehicle is parked at the trip destination. The percentage increase in the cost of short trips (in money terms) is much higher than the percentage increase in the cost of long trips. Hence, this tax applies unequally by length of trip.

Counteracting this effect is the tendency for a parking tax to induce chauffeured trips in instances where the trip previously had been made by a driver alone. For relatively short trips there is an incentive for members of the same household to ferry trip makers in order to avoid the parking surcharge at the trip destination. Each trip of this nature results in twice the vehicle miles traveled when compared to a trip made by a driver alone. It also substantially increases the amount of time spent in travel because of the increased efforts made by a driver serving a passenger.

A priori, due to increased incidence in chauffeured trips, it is likely that the number of VMT's reduced by a parking tax will be less than the amount reduced by an equivalent increase in the variable cost per mile for auto travel. Also, as is discussed later, other tax strategies which increase the variable cost per mile of auto modes will have a greater effect on VMT's as opposed to number of trips.

It can also be assumed that a parking tax will have some effect on the fleet size for the region. The increase in auto operating costs will provide an incentive for households to have fewer cars. However, it will not necessarily cause the age distribution of automobiles to be lower, nor will it cause the emission rates from the stock of cars to be less. The parking tax provides no incentive for households to buy automobiles which are less polluting per mile of travel. Indeed, if the new car sales are more sensitive to ownership cost changes than used car sales, then the median age of the existing stock of autos may in fact increase from what it otherwise would have been, thereby having counterproductive effects on the average emission rate.

The long-run effects of a parking tax are somewhat difficult to assess but are probably not very significant. Some change in employment trip frequency may be seen and, if the tax varies by hour, the work day may be adjusted in some cases so that work trips would occur when the tax was at lower levels. Though shopping trips can be expected to decline, total retail sales would be reduced only negligibly as a direct result of lower discretionary income owing to the tax; the adjustment which one would expect is that households would buy more at each shopping stop and frequent those stores which are within walking distance or easy access by transit. Thus, there may be some redistribution of retail land use as shopping centers and small local retail outlets become more attractive. Of course, if the parking tax was applied to particular locations, then retail sales would move from areas where the parking tax was highest. Parking taxes on other trip purposes would cause similar adjustments.

Review of Other Research -- Several cities have instituted parking taxes whose effects have been recorded to a limited extent. Kulash has compiled a number of calculations of the elasticity of demand for auto trips with respect to auto parking price. His results are summarized in Table 7. For a number of reasons these elasticities are almost certainly too high. In every case where the effects of a parking tax have been analyzed, the tax was limited to a relatively small locality, usually within the central business district. Hence, the tax affected only a small percentage of the trips in a region, so any elasticity would have to be applied to the percentage of non-through trips in the area under consideration in order to uncover the regional impacts. Kulash theorizes that this could be done by considering an area about four times the size of the typical central business district, since it would have a low percentage of through trips. However, this approach would certainly be invalid for the Los Angeles region because it has virtually no strong core. Other reasons why the elasticities are improperly calculated include:

Table 7. ELASTICITIES OF NUMBER OF TRIPS WITH RESPECT TO AUTO PARKING PRICE

City	Auto driver	Auto passenger	Bus passenger
San Francisco	-.35 to -.43		
L.A. Civic Center[a]	-.29	.26	.47
Washington, D.C.[a]	-.41		.38
Liverpool (survey)	-.3		

[a]Work trips

SOURCE: Kulash, Damian. Parking Taxes for Congestion Relief: A Survey of Related Experience. Urban Institute. Washington, D.C. Working Paper 1212-1. May 1973.

- drivers who switch to being chauffeured to work
- illegal parking
- changes in destination
- drivers switching to taxis
- increased through trips because of people who begin driving as a result of reduced congestion after imposition of a parking tax.

The individual cases are briefly discussed below.

San Francisco -- The elasticity for San Francisco is based on a before and after study of the number of cars parked in off-street facilities with the imposition of a 25 percent parking tax. In addition to all the factors listed above which contaminate these calculations of elasticity, transit services were being improved at the same time, and their effect on traffic was not isolated in the study. The report on the San Francisco episode indicated a consensus opinion that there was little effect on traffic, implying that the elasticity in the range of -.35 to -.43 for parked cars means very little as far as predicting the actual effects on auto trips.[8]

Los Angeles civic center -- The elasticities in this study are based on a cross-sectional mode split calculation for work trips. The elasticity of auto passenger trips with respect to parking price does not indicate whether some chauffeured trips are included or not. The sample utilized has a much higher level of bus service than the region as a whole; as a consequence, the elasticity derived for auto diversion to bus would be too high if it were applied to other destinations in the region. It might be noted that this consideration affects the other elasticities calculated for CBD oriented trips as well.*

Washington, D.C. -- The format of this study was also cross-sectional mode split, with results similar to those for Los Angeles. The original source is not available, but it is apparent from the data which Kulash presents that none of the factors mentioned above have been accounted for in the estimation of the elasticity of demand for auto trips with respect to parking price.[9]

Liverpool -- This study is based on a survey of what people would do in response to some hypothetical situation in which the price of parking changes. A factor called "frustrated demand" is explicitly taken into account. It consists of people who would make trips into (or through) the area under consideration but do not do so because of congestion. To the extent that a parking tax would relieve congestion, these people would start satisfying their "frustrated demand," thus offsetting the effect on the reduction of trips through the area due to an increased parking charge. As in the other cases, the elasticities derived do not indicate what the real effect on auto trips would be if a parking tax were imposed, because of lack of consideration of other factors such as chauffeured trips, etc.[10]

Pittsburgh -- One event reported by Kulash appears to cast considerable doubt upon the elasticities calculated in his report. In Pittsburgh during August 1972, a rather drastic reduction in the availability of offstreet parking occurred when 23,600 of 25,400 spaces were shut down by a strike.

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*See Grominga, C. L., and W. E. Francis. The Effects of the Subsidization of Employee Parking on Human Behavior. Course Paper, University of Southern California. May 1969.

The effect on shopping was limited, as retail sales were down only 6 to 8 percent, but entertainment trips were estimated to have declined by 70 percent. As to work trips, auto volume was off 24 percent in the morning rush hour, while bus ridership increased 12 percent. While these are not insignificant results, a tax with effect equal to the Pittsburgh strike would be enormous, and Kulash's conclusion is that short-run economic incentives have a "limited range of impact" on auto trips.

Conclusion -- For the reasons already mentioned, little of a precise nature can be said about the effects of a parking tax. The research to date has simply not determined the true elasticity of vehicle miles traveled and auto driver trips with respect to a change in parking charges. However, it is likely that the figures presented above represent the maximum elasticity which one would expect when the effects of a parking tax are simulated in the following chapter. The estimated elasticity should fall within the bounds of .1 and -.3. A positive elasticity would occur if the number of chauffeured trips and extra miles traveled to search for cheaper parking overwhelmed the other effects of the parking tax.

Gasoline Tax

A tax on gasoline sales would result in an increase in the variable costs per mile of a trip and would consequently be expected to induce a reduction in VMT's and, to a lesser extent, in the number of auto trips. The legal and administrative framework for gasoline tax collection has been in existence and functioning for many years. Unlike some of the other policy alternatives considered in this report, implementation of a gasoline tax would not require a large investment in equipment, manpower, or planning. The long-run effects of a gasoline tax are somewhat difficult to determine -- for example, gas mileage among autos may be inversely related to low emissions, implying that increased gasoline taxes might decrease the rate of scrappage of older autos.[11]

A Priori Analysis of the Effects of a Gasoline Tax -- The effect of a gasoline tax on the output of automobile air pollution depends, in the short run, upon the elasticity of auto trips and VMT's with respect to a change in the variable costs per mile of making a trip. Table 8 presents a breakdown of variable costs per mile which indicates that gasoline presently accounts for about 70 percent of the marginal operating costs of an auto for a trip. This assumes a retail price of $0.55 per gallon (including taxes). Thus, a 10 percent tax on the pump price of gasoline ($.055 per gallon) would be equivalent to a 7 percent increase in variable costs per mile. It is important to keep this conversion factor in mind when discussing the effects of a gasoline tax because travel demand models typically utilize variable costs per mile rather than gasoline costs as an argument in the demand function.

Gasoline taxes have the attractive feature of being relatively well-correlated with emissions for any given automobile, since gasoline consumption over a trip cycle is directly proportional to the amount of emissions. However, the rate of gas mileage across automobiles may be inversely correlated with the rate of emissions. Autos with emission controls tend to have decreased mileage. The imposition of a gas tax offers an incentive for households to keep older, more economical, automobiles instead of trading them for newer, cleaner cars.

Table 8. ESTIMATED VARIABLE COSTS PER MILE OF OPERATING AN AUTOMOBILE
(cents/mile)

Item	Cost
Gasoline (excluding taxes)[a]	3.23
Gasoline taxes[b]	0.81
Oil[c]	0.12
Repairs and maintenance[d]	1.15
Replacement of tires[e]	0.40
TOTAL	5.71

[a] Based on price (including taxes of 55¢/gal and 13.6 miles per gallon).
[b] Federal tax = 4¢/gal; California state tax = 7¢/gal.
[c] One gallon of oil per 186 gallons of gasoline.
[d] Includes all common periodic and minor repairs, but excludes major repairs, which is why 1.15 is used instead of 2.15 cited in source.
[e] Covers 7 new regular tires, 4 new snow tires during life of vehicle.

SOURCE: *Statistical Abstract of U.S.*, 1973, p. 550.

NOTE: Based on assumed 10-year average life of auto, and 100,000 miles.

The flexibility of a gasoline tax is relatively limited when compared to, say, a parking tax. It cannot be realistically varied over small locations because of the ability of motorists to buy gasoline at those stations where the tax is lowest. Even for an area of the size covered by the Los Angeles Regional Transportation Study, this will be something of a problem, although not of major proportions. Similarly, a gas tax cannot be varied by time of day, because households can easily arrange to buy gas during that period of the day when it is least expensive. Even day-to-day variations in the gasoline tax would be of little effect if the changes in the gasoline tax could be accurately predicted by households. Seasonal variations are possible, and such an approach may be seriously considered in the case of Los Angeles, where pollution is greatest during late summer and early fall.

As a percentage of the total cost of a trip, a gasoline tax is roughly proportional to the length of the trip. In absolute terms, long trips would incur a greater penalty than short trips. As a general proposition, the higher the cost of an activity, the more elastic its demand, other things being equal. Thus, it can be presumed that a gasoline tax would have greater effects on the longer auto trips; correspondingly, one would expect to see greater impact of a gasoline tax on VMT's as opposed to number of trips.

The long-run effects of a significant increase in the price to households of gasoline would be to redistribute some land uses to take account of the higher costs of travel. One pattern that might emerge from the increased cost of trips is the clustering of higher density residences. Commerce would localize around these centers, which in turn would be located with easier access to employment centers. Employers would be more likely to locate near these high density labor markets.

Review of Previous Research -- There have been two unrelated lines of research which can be reviewed in order to determine what the expected effect of a gasoline tax would be. The first of these is in the realm of travel demand forecasting for planning purposes; the second is the recent body of econometric estimates of the elasticity of demand for gasoline on an aggregate level. We discuss the recent results in each of these types of studies.

Direct demand model of travel -- Aside from the disaggregated demand model of individual choice used in this study, the only other estimated relationships between the variable cost per mile of auto trips and the demand for travel are in what have become known as direct demand models. The most widely applied direct demand model was estimated by CRA on Boston data at the traffic analysis zone level. A full description of the model is presented elsewhere.* The relationships in the model estimate the number of trips by mode between origin and destination pairs for a given purpose. The number of trips so defined are functions of the costs and time of the given mode, the costs and time of alternative modes, the socioeconomic characteristics of the zone, and trip attractiveness of the zone or destination.

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*See any of the following: *A Model of Urban Passenger Travel Demand in the San Francisco Metropolitan Area.* Charles River Associates Incorporated. Cambridge. Prepared for the California Division of Bay Toll Crossings. 1967; Kraft, Gerald, and Thomas A. Domencich. *Free Transit.* A Charles River Associates Incorporated Report. Cambridge, Lexington Books, 1970; Domencich, Thomas A., Gerald Kraft, and Jean-Paul Valette. Estimation of Urban Passenger Travel Behavior: An Economic Demand Model. *Highway Research Board Record.* 238, 1968.

From the model, it is possible to calculate the elasticity of travel demand with respect to an increase in the variable cost per mile of auto trips. These elasticities have been computed at the mean of the Boston data and were approximately -.4 for work trips and -.8 for shopping trips.

Some care must be taken in interpreting these figures. They were estimated when the price of gasoline was much less than currently obtains -- both in absolute terms and in terms of the percentage of variable costs per mile. Also, the model may be subject to a long-run bias owing in part to its having been estimated on cross-sectional data. That is, the elasticities presented may be higher than would have been obtained if purely short-run behavior had been isolated. As the model now stands, there is some reason to believe that it contains some aspects of locational behavior on the part of households and the employers or retailers as well as the effects of the costs of travel on automobile trips alone. If the bias is indeed significant, then it is likely that the elasticities presented above are relatively accurate when applied to VMT's over the long run, but may be spurious if applied to number of trips.

The two problems cited above -- relatively low operating costs at the time of estimation and the long-run bias in the estimates themselves -- have effects in different directions if the model is to be used to give *a priori* estimates of the effects of a gasoline tax in Los Angeles today. It is not known to what extent these will cancel each other in interpreting the elasticities. However, taking the numbers as they are given, gasoline costs accounted for 70 percent of the variable cost in the Boston data, and consequently, the model would predict that a 10 percent tax on gasoline at current costs to the customer would entail a 2.8 percent decline in work travel and a 5.6 percent decline in shopping travel.

Econometric estimates of the demand elasticity for gasoline -- Largely as a result of the oil embargo in the fall of 1973, there have been a number of attempts to estimate the demand for gasoline. Usually these models are estimated on a time series or pooled time series/cross-section of data aggregated to fairly large geographic units such as states or nations. Because of errors in variables owing to the aggregation of data to these levels, and the problem of multi-collinearity among independent variables in the demand function over time, most of the results must be approached with a high degree of caution. It is remarkable that most of the estimates have clustered around -.2 as the elasticity of demand for gasoline in the United States.

Even if this figure is accurate, there are two important caveats before it is applied to the conditions current in Los Angeles households. First, the sample periods have always been pre-oil embargo; therefore, the price of gasoline was lower relative to other goods and services, and we may presume that the elasticity of demand was correspondingly less. Recently, an attempt was made to measure the elasticity of demand for gasoline in Europe, where the prices are significantly higher than those which exist in the United States.* Secondly, a significant portion of gasoline is consumed by non-household trip makers. Gasoline consumed in this way, usually for freight transportation, is a factor input into other goods or services. To the extent that gasoline is a relatively small portion of the total cost for a given good or service, it can be presumed that the elasticity of demand for gas used in these trips is less than the household elasticity of demand for gasoline. All things considered, it can be presumed that -.2 represents a lower region for the household demand elasticity of gasoline.

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*See Charlotte Chamberlain, unpublished report, Transportation System Center, 1970.

Conclusion -- The estimates of gasoline demand give us a lower bound on the expected effect of a gasoline tax on VMT's in Los Angeles. The estimates of travel behavior as a function of variable costs per mile from the direct demand model give us a region in the upper end which we can check for consistency against the disaggregated demand model applied in the next chapter. The shopping trip purpose in the direct demand model was most sensitive to automobile operating costs. If other household-based non-work trips were assumed to be as sensitive to costs of travel as shopping trips, then this would give an approximate high end to the range one would expect for the elasticity. In the Los Angeles region, 25 percent of all trips were of the home-based journey-to-work type; weighting the total number of trips taken by an elasticity of -.4 for work trips and -.8 for all other trips gives a total elasticity of -.7 for all auto travel with respect to the variable costs per mile. This in turn implies a price elasticity of gasoline of about -.5. In summary, we would expect to see the elasticity of VMT's with respect to a change in the price of gasoline to be on the order of -.2 to -.5.

Emissions Tax

There are a relatively large number of proposals for basing a tax on motorists which is proportional to the amount of pollution produced in their travel. A tax or charge of this nature is based upon an estimate of the emissions of a particular automobile over a given period of time. Theoretically, an emissions tax should correspond most closely to the actual marginal social cost of pollution of any of the policy alternatives considered in this report. The effects of such a tax would be to increase the costs of owning and operating vehicles in proportion to the pollution potential of the vehicle, thus making dirtier cars more expensive relative to cleaner ones. This should cause the age distribution of vehicles in use to shift more rapidly away from older, pre-controlled autos, as people would prefer vehicles with low initial emission rates and deterioration factors. A tax based upon the actual emissions per trip would cause increases in the variable costs per mile of the vehicle in much the same way as a gasoline tax. This could induce a decrease in VMT's and number of trips, and, through the incentive to perform maintenance and retrofit older autos, cause a decrease in deterioration rates and initial emission rates.

A Priori Analysis of the Effects of an Emissions Tax -- The various proposals for emissions taxes can be initially screened by judging *a priori* their effectiveness in meeting their pollution abatement goals. The objective of reducing automobile emissions through a tax would be achieved by inducing motorists to take measures to reduce the contribution of their vehicles to air pollution. These measures include the following:

1) driving less;
2) purchasing cleaner cars;
3) retrofitting older cars;
4) performing maintenance; and
5) using a less polluting fuel.

Bearing in mind that an emissions tax should induce motorists to take one or more of these steps, the following proposals are considered:

1) Tax on the sale of new vehicles. This is a one-time tax levied when the automobile is purchased, and graduated relative to the projected lifetime emissions of the vehicle (or to some parameter of the vehicle which is correlated with the emissions rate).[12]

2) Annual tax on vehicle based on the projected lifetime emissions. This tax would be collected annually on all registered automobiles and would vary according to model, make and year (MMY) based on tests on a sample of vehicles which estimate the projected lifetime emissions rate.[13]

3) Annual tax based on actual emissions. In this proposal, each auto would be inspected annually to determine its mileage and emissions rate (MER) for the year.[14]

4) Monthly tax based on actual emissions. This proposal differs from number three only in that the tax is collected monthly, based on average emissions either for the whole year or for that month and on actual miles driven during the month.[15]

Of the above proposals, we find that the first and fourth are either redundant or counter-productive. The first proposal, a tax on the sale of new vehicles, would penalize car owners for purchasing the newer and hence less polluting automobiles. Such an approach may, in the long run, reduce pollution after most currently owned automobiles have been scrapped, but the interim result would surely be to recondition and maintain the precontrolled automobiles much longer than would have otherwise been the case. The fourth proposal, an MER tax paid monthly rather than annually, is based on the somewhat dubious proposition that a monthly charge is more visible than an annual payment and would prove to be a greater incentive to retrofit and reduce trips than an annual payment equal to 12 monthly installments. We find no evidence to support this supposed behavior; indeed, there is as strong an argument in the other direction -- namely, that an annual charge will be so large relative to 12 roughly equal payments that it will be more visible. For these reasons, we will further consider only the MMY and MER taxes, both on an annual basis.

In order to implement either of these proposals, certain steps would have to be taken. For the MMY tax, proposal two, the necessary steps include:

1) Derivation of reliable estimates of average projected lifetime emissions for the models, makes and years of automobiles owned. A first approximation of emission rates can be made by testing the sample of vehicles as they come off the assembly line. More precise estimates are gained by actually conducting tests in the field of vehicles after specified time periods in order to gain information about deterioration rates in on-the-road use. Field tests should also be made for determining the effectiveness of retrofit devices on precontrolled cars.

2) Provision for collection of the tax through some state agency, most probably the automobile registration agency.

The principal requirements for the implementation of an MER tax, proposal three, would be the following:

1) An efficient, easy to administer, reliable emissions test capable of implementation on a massive scale.

2) The facilities, equipment, and trained personnel necessary to administer the test.[16]

3) A relatively inexpensive, tamper-proof odometer capable of installation on older cars and part of standard equipment on new cars.

4) Provision for collection of the tax at the time of registration or at the time of testing.

We consider later the results of research into whether either of these proposals is administratively feasible. At this time, it appears that emissions tests on a massive scale and the monitoring of mileage on the same scale would be the primary barriers to the imposition of an MER tax. It is thus worth noting that many states have annual inspections of registered vehicles for nominal fees, typically at service stations designated for the purpose. The scale of such an enterprise is therefore not as much an issue as the cost of technology for administering the tests and the organization of a relatively fool-proof tax collection system.

The effectiveness of each tax on controlling pollution is similar in the long run but divergent in the short run. The MER tax would have many of the same effects as a gasoline tax because both affect auto variable costs per mile: diversion of auto trips to other modes, a stronger impact on VMT's than on trips, and a reduction in discretionary travel, particularly that to distant destinations. An effect which would be different from those caused by the gasoline tax, however, would be for multi-car families to utilize their less polluting vehicles more intensively; it will be recalled that a gasoline tax may have the altèrnative effect of causing older, precontrolled vehicles, those with better gas mileage rates, to be used more than would have otherwise have been the case. To the extent that an MER tax increases the variable cost per mile the same amount as a hypothetical gasoline tax, it would have similar effects on driving behavior overall, even though there would be differential impacts according to the age of the car. If either an MMY or MER tax provided an incentive for retrofitting, then this form of pollution abatement would increase as the taxes themselves increased.

The auto stock would be smaller owing to the imposition of either tax because of the effective increase in ownership costs. Moreover, because the tax would be higher relative to the value of older cars, the median age of the auto stock would decline, since scrappage rates relative to new car purchases would increase.

Similar to the other proposals considered above, the emissions taxes would make transportation more expensive and would cause a realignment of land use. One would expect to see, in the long run, a greater clustering of housing, employment centers and commerce serving households.

Review of the Literature -- The effectiveness of any emissions tax will be determined to a large extent by its administrative and technical feasibility (i.e., can the knowledge and resources needed for implementation on a large scale be channeled into the project at a reasonable cost). A related problem is the degree of certainty with which average emissions (and mileage) for classes of vehicles can be estimated. One study, which attempted to predict mileage and emissions from vehicle and engine characteristics, came to the pessimistic conclusion that an "indirect" tax, such as that considered in proposal two, is not feasible because the variation among supposedly identical vehicles is too high.[17] Furthermore, since very little is known about the deterioration rates of emissions control devices under varying road maintenance conditions, this introduces more uncertainty into average emissions calculations.[18] Stated in a positive way, the conclusion from these results is that continual testing of samples of vehicles is necessary in order to give accurate figures for relative taxes among vehicles if the MMY option is instituted.

On the other hand, there is considerable disagreement as to whether an emissions tax of the type in proposal three, an MER tax, is technically and financially feasible. Extensive field experience may be required before it is possible to decide whether an inexpensive, relatively tamper-proof odometer is practical. To measure emissions, a large scale inspection system is now feasible, according to d'Arge and Northrup;[19] Bellomo and Dewees have reached different conclusions ("the technology for measuring emissions quickly and cheaply does not yet exist").[20] One possible basis for the difference in opinions is that both d'Arge and Northrup were considering the specific case of California, while Bellomo and Dewees were basing their conclusions on considerations of a national policy.

A cost function with which to measure the cost effectiveness of different types of emission test systems was developed by the Northrup Corporation in their study of the possibility of implementing a mandatory inspection system in California. Using what is known as the key mode test in state-operated inspection stations, they estimated that inspection cost per vehicle would be $1.05, with an initial investment of $19,830,000. These costs are, of course, considerably dated insofar as secular inflation has caused them to increase since the study was completed in 1971.

There has been virtually no work done on what the effects of an MER tax would be. It can be assumed, however, that traveler reaction to an MER tax would be similar to the effects of a gasoline tax. Both taxes increase the variable costs per mile of an auto trip. Therefore, from our discussion of the effects of a gasoline tax, we can conclude that the elasticity of automobile trips (measured in terms of VMT's and/or actual trips) would be between -.25 and -.7 when the tax is measured in terms of a percentage of the variable costs per mile.

In analyzing the effects of a tax on emissions, it is useful to make a comparison to the effectiveness of a policy requiring cars to meet a mandatory standard. In a 1971 study for California, it was estimated that for standards causing a 50 percent rejection rate, an inspection system would bring about an initial reduction on the order of 25 percent in carbon monoxide and hydrocarbon exhaust emissions; these reductions would decline as implementation was delayed because of the change in the age distribution of automobiles.[21]

In a somewhat less rigorous study, it was estimated that an initial reduction of 10 percent to 25 percent in aggregate emissions for a given state or region would be the upper bound that could be expected, given a 20 percent to 40 percent rejection rate. It was emphasized that the 10 percent figure was more likely than the 25 percent figure, and that these estimates did not take into account deterioration of emission control systems over time.[22]

Little quantitative work has been done on estimating motorist reaction other than travel response in order to determine the appropriate annual level for a tax. One California study concludes that a charge of $200 or more per "pollution unit" would begin to induce motorists to take measures to reduce pollution; a "pollution unit" is defined as the total emissions from a non-controlled auto driven 10,000 miles per year.[23] Moreover, if the charge is based on an average emissions measure rather than a measure of the emission of each individual auto, the incentive to perform maintenance, or possibly even retrofit, is lost, and the charge would probably have to be higher in order to induce purchase of newer, cleaner cars.

In summary, most research on the effects that an MER or MMY tax would have on changes in the auto stock, including retrofitting, maintenance, and adjustments in the age distribution, are highly speculative and qualitative. Much of the commentary must be put in the perspective of the proportion of ownership or operating costs which would be due to the taxes under consideration. For example, an annual tax rate of $200 is equivalent to 17 percent of the total average ownership cost of $1,200 per year. However, taxes of the MER type of sufficient quantity to induce retrofitting would be closer to $100 a year for most vehicles; such taxes would increase the variable cost per mile of a trip from 2 percent to 40 percent, depending upon the particular pollutant being controlled and the age of the automobile. Chapter 5 gives rough, quantitative estimates of the effects of these tax strategies on retrofitting and changes in the age distribution of the regional fleet.

Transit Improvements

For the purposes of this study, transit improvements are a passive response to the other policies. As pollution control taxes on auto travel increase costs to motorists, it is expected that transit improvements will become a more effective substitute for the auto. Such an approach to analyzing the impacts of changes in transit somewhat constrains the number of potential transit service improvements. In particular, we will consider only the effects of an addition to transit which substitutes trips which would otherwise not be made.

Even this constraint allows for a wide variety of types of transit service improvements. Some of the options include rail rapid transit, express bus, conventional bus, dial-a-ride, etc., to name only those for which technology presently exists. Within each type there are further issues of route structure, frequency of service, and other options for network design. In order to further screen the potential service improvements, we need to consider which appear to be most cost-effective on *a priori* grounds.

Of the several types of transit service improvements which are technologically feasible, we need only be concerned with those which can be implemented relatively quickly and do not have high initial capital costs. The reason for applying these criteria is that the benefits of auto trip diversion are themselves a relatively short-run phenomenon; as new cars with increasingly strict controls are introduced into the fleet, the emissions from cars will decline toward acceptable levels. The result of this consideration is to rule out rail rapid transit, since it typically takes a decade to implement and requires many more decades to recover the initial capital costs.

The remaining options include express bus service, dial-a-ride and conventional bus. In Los Angeles, conventional bus and express bus merge into the same category unless express bus is considered to be only those systems where bus operations are put on separate right-of-ways. However, separate grade right-of-way is also a high capital cost improvement, though not as expensive as rapid rail. Separate right-of-way of existing freeways would improve service somewhat during rush hours, but a cursory look at the existing bus network indicates that the most important components of trip times are access time to the bus and schedule delay. For these reasons, express bus is not examined in this report though it is recognized that such systems should be evaluated in order to determine their cost-effectiveness (see Chapter 6 for a discussion of future research needs).

Given that access time and schedule delay are the most important considerations in designing service improvements, one would expect that dial-a-ride transit (DRT) systems may be an effective candidate for transit policy. However, little is known at this time about the service characteristics of a DRT system of the size necessary to serve the Los Angeles area. Most of those currently in operation are on modest scales with limited area coverage. Though conceptually the demand relationships used in this report can be utilized to forecast the patronage for DRT under assumptions about the level of service, the equilibrium system performance of a DRT network cannot be determined. As a consequence, neither the equilibrium travel nor the costs for the service can be estimated without more research into the existing systems in order to infer system performance. Again, additional research in this area would be valuable (see Chapter 6).

The above mentioned gaps in the state of knowledge on DRT, in conjunction with the considerations on express buses, suggest that the relevant system improvement to focus on is changes in the conventional bus network. This is still an ambiguous task, however. One approach is route extension; another is adding buses to existing routes.

To compare the efficacy of these two methods, it is useful to determine whether bus patronage is more sensitive to walk time or to ride line-haul time. The major research on this topic includes the previously mentioned Charles River Associates estimate of direct demand models for urban travel.[24] The results of this model show that the elasticity of transit trips with respect to an increase in access time (walking) is over -.7; the elasticity of transit trips with respect to an increase in line-haul time (riding) including schedule delay is about -.4. The calculations of the cross-elasticities on auto trips with respect to increases in access time and line-haul time for transit also demonstrate that travel behavior is more sensitive to access time. The results indicate that decreasing access time by extending route miles is more effective in drawing passengers to buses than increasing frequency of service on existing routes.

In order to determine *a priori* the effects of increased route coverage, we have to be highly speculative because the evidence is sparse. However, the following calculations will help give some idea of the expected effect on VMT's and auto trips. Consider the elasticity of auto trips with respect to an increase in variable costs per mile to be -.20 (the lower bound presented above). Then a 50 percent tax on auto variable costs per mile would decrease auto trips by 10 percent. Further assume that the current mode split in Los Angeles is 70 percent auto and 6 percent transit, with the remaining 24 percent being auto passengers and walking. If the transit network is to increase in order to substitute for auto trips foregone, it would need to about double its capacity in route miles, thereby about halving the average access time throughout Los Angeles. Using the average cross-elasticity of transit access time on auto work and shopping trip demand from the CRA direct demand model (.149), this would decrease further auto trips by 8 percent. Thus, the cumulative effect on auto trips of the increased variable cost per mile and the assumed improvements in transit would be a decline of 18 percent. The cumulative elasticity in terms of the increased variable costs per mile would be -.36. This is admittedly a rough estimate and there is consequently some error associated with our *a priori* expectations of the effects of transit system improvements on auto trips.

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3. EFFECTS OF POLICIES ON TRAVEL BEHAVIOR

This chapter presents the estimated effects of pollution control policies on VMT's and auto trips. The models for predicting these effects are developed in Appendix A (Travel Demand). Also included in this chapter are the effects of the policies on mode split. The uncertainty associated with the models and their applications is discussed in order to determine the robustness of the predicted results. Each of the policies under consideration imposes costs to individuals and society which must be considered. Using the results of the predicted effects in this chapter and Chapter 4, the cost-effectiveness of the various policies is estimated in Chapter 5.

The effects of pollution control strategies on travel behavior were simulated using the demand model developed in Appendix A. Chapter 2 covered the conceptual framework of the model and the types of pollution control policies to be analyzed, along with their *a priori* expected effects. The travel-related policies under consideration include:

- a tax on the variable costs per mile of autos related to either gasoline or vehicle emissions;
- a surcharge on nonresidential parking;
- improvements in the conventional bus system which substitutes for auto trips.

The demand model predicts travel behavior separately for work trips and shopping trips. The results of these simulations are extrapolated to include all trip purposes.

The base year for the forecasted effects is 1974. The travel demand models were used to predict travel behavior in 1974 in the absence of any of the proposed pollution control policies. The model itself was calibrated and tested on 1967 data for Los Angeles and Orange Counties; thus some changes in the level of service variables were necessary in order to forecast 1974 travel behavior. Discussion with transportation officials in the Los Angeles region revealed that the only significant changes in overall system level of service between 1967 and 1974 have been the increased variable costs per mile of auto travel and a decrease in transit fares. As noted in Table 8, the 1974 variable cost per mile is $.0571 compared to $.0300 in 1967. The new fare policy, introduced in the spring of 1974, is a flat fare of $.25 for a one-way transit trip with a $.05 charge for transfers. These prices replace the 1967 fares which were based on distance traveled. The above changes in trip costs were substituted into the travel demand model to predict the base case 1974 travel behavior. (The base case estimates of mode split are presented in Tables 13 and 14 for work and shopping trips.)

Other changes in the intervening years affect the number of trips in the zonal interchanges for the samples being analyzed. Most notably, land use changes would cause adjustments in trip generation and distribution. However, the model is applied to determine the percentage change in trips and VMT's rather than the absolute level of change. These percentages can then be applied to the regionwide totals of 1974 trips and VMT's to determine the absolute level of effect of the policies. Thus, it is appropriate to use zonal interchanges as samples of observations even though the number of trips within any interchange is not the same in 1974 as it was in 1967.

It should also be noted that the travel demand model was estimated on Pittsburgh data from 1967.* Though the model is behavioral, there are regional peculiarities in the form of excluded variables which may bias its application to Los Angeles. Chief among these would be climatic conditions which would have the effect of making access time more onerous in Pittsburgh than in Los Angeles. However, during the process of estimating the model, it was found that weather-related variables were not statistically significant in explaining travel behavior.+ Moreover, the model does not appear to underpredict 1967 Los Angeles transit patronage, as would be the case if a significant bias was present (see Appendix A).

More serious is the problem of applying 1967 estimates to 1974 conditions, especially in the face of increases in household income which have occurred over that time. Though income is not an independent variable in the demand models, it probably has an effect on the relative weight travelers put on costs as compared to time. In order to determine the significance of this potential bias, the average 1970 income (from census data) for households in the Los Angeles sample was calculated and compared to the average household income in the Pittsburgh sample used for model estimation. For the Los Angeles sample, average household income was $7939 per year; for the Pittsburgh sample, average 1967 income was $8800 per year. Even allowing for inflationary increases in income since 1970, the Los Angeles sample will not have income levels greatly different from those obtained by households included in the Pittsburgh estimation sample. Thus, it can be presumed that the model's implied relative trade-offs between travel cost and time will be reasonably accurate.

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*See Chapter 2 for a brief discussion of the model.

+See Domencich and McFadden. *op, cit.* Chapter 7. However, day to day response to weather may not capture all the travel effects due to climate.

VMT AND TRIP REDUCTIONS WITH THE CURRENT TRANSIT SYSTEM: WORK AND SHOP TRIPS

The specific policies considered in this section are the increases in automobile variable costs per mile caused by an emissions or gasoline tax and the increase in automobile out-of-pocket expenses caused by a parking surcharge. For each type of policy, four levels of tax were simulated, and their effects on VMT's and auto trips were estimated in terms of the percentage change from the 1974 base forecast.

Specific Tax Levels

For emissions and gasoline taxes, the four levels represented increases in auto variable costs per mile of 25 percent, 50 percent, 75 percent and 100 percent. Parking charges, which are currently insignificant for most trips in Los Angeles, were increased in absolute amounts of $.25, $.50, $.75 and $1.00 per trip in the simulations. Table 9 presents the average absolute and percentage cost increases for work and shopping round trips. This table allows comparison and conversion between percentage and absolute terms of reference for the tax policies. It can be seen that the additional cost per trip caused by a given percentage increase in variable costs per mile is much greater for work trips than for shopping trips. Conversely, increases in parking charges will affect shopping trips more than work trips on a percentage basis.

The percentage increases in auto variable costs per mile are converted to gasoline tax increases and emissions taxes in Table 10. For example, a 50 percent increase in the variable cost per mile for autos is equivalent to the following:

- an increase in the pump price of gas of $0.39 per gallon, or about 71 percent;

Table 9. ESTIMATE OF AVERAGE PERCENT AND ABSOLUTE COST INCREASES OF AVERAGE 1974 ROUND TRIP INCURRED BY POLICY SCENARIOS

Policy	Work trip, $ increase[a]	Shopping trip, $ increase[b]
Variable cost per mile increase:		
25%	$0.20	$0.07
50%	0.40	0.13
75%	0.60	0.20
100%	0.80	0.27

Policy	Work trip, % increase[a]	Shopping trip, % increase[b]
Parking cost increase:		
$0.25	31%	94%
0.50	62	187
0.75	94	281
1.00	125	374

[a]Based on average work round trip length of 14.04 miles.

[b]Based on average shopping round trip length of 4.68 miles.

Table 10. GASOLINE AND EMISSIONS TAXES ASSOCIATED WITH EACH LEVEL OF INCREASED VARIABLE COSTS PER MILE

Variable cost per mile increase:	Gasoline tax[a] increase %	Gasoline tax[a] increase $/gal	Emissions tax[b] ¢/gm CO	Emissions tax[b] ¢/gm HC	Emissions tax[b] ¢/gm NOx
25%	35%	$0.19	0.0436¢	0.3968¢	0.4195¢
50	71	0.39	0.0873	0.7936	0.8390
75	106	0.58	0.1309	1.1904	1.2585
100	141	0.78	0.1746	1.5872	1.6780

[a]Based on a pump price of 55¢/gallon; including federal tax = 4¢/gallon and California state tax = 7¢/gallon.

[b]Based on the following expected 1975 average emission rates per auto for Los Angeles:

Carbon monoxide: 32.7100 gm/mile
Hydrocarbons: 3.5976 gm/mile
Nitrous Oxide: 3.4029 gm/mile

Expected average emission rates are derived by weighing emission rates per model year by age distribution of cars (see Table 22) and expected mileage per model year (see Table 22).

- a tax on carbon monoxide emissions equivalent to .0873 cents per gram per mile;
- a tax on hydrocarbon emissions equivalent to .7936 cents per gram per mile;
- a tax on nitrous oxide emissions equivalent to .8390 cents per gram per mile.

It is likely that an emissions tax will not be placed on any single pollutant but will instead be based on a formula which includes all of the above emissions. Therefore, it is worth noting that any weighted average of the emissions tax rates in Table 10 is equivalent to the increased variable cost per mile. For example, emissions taxes based on the formula of 50 percent from CO, 25 percent from HC and 25 percent from NO_x at a combined rate of a 50 percent increase in the variable cost per mile would have the following three components:

$$.50 \times .0873 = .0437¢/gm \text{ of } CO$$
$$.25 \times .7936 = .1984¢/gm \text{ of } HC$$
$$.25 \times .8390 = .2098¢/gm \text{ of } NO_x$$

Model Predictions

The effects of the tax policies are summarized in Tables 11 and 12. The implied elasticity of work trip VMT's with respect to auto variable cost per mile is -.38; the implied elasticity of shopping trip VMT's per auto variable cost per mile is -.17. The former figure is well within the bounds implied by previous travel demand studies (see Chapter 2). The shopping trip elasticity is rather low, but it can be explained by the tendency for shopping trips to be relatively short (4.68 miles per round trip) and to offer comparatively few transit options in the Los Angeles area, assuming no change in tripmaking frequency. (This assumption is relaxed at the end of the chapter.) The implied elasticity for

Table 11. EFFECTS OF TAXES ON WORK TRIPS

Gas or emissions tax:	% Change in VMT's	% Change in auto trips
Variable cost per mile increase:[a]		
25%	-10.073%	- 7.226%
50	-19.154	-13.709
75	-27.547	-19.341
100	-35.303	-24.442
Parking tax:	**% Change in VMT's**	**% Change in auto trips**
Parking cost increase:[a]		
$0.25	- 3.496%	- 5.845%
0.50	- 7.099	-11.583
0.75	-10.618	-17.109
1.00	-14.000	-21.998

[a]Table 9 converts taxes into absolute and percentage terms for average length trips. Table 10 converts variable cost per mile increases into equivalent taxes on gasoline and emissions.

Table 12. EFFECTS OF TAXES ON SHOPPING TRIPS

Gas or emissions tax:	% Change in VMT's	% Change in auto trips
Variable cost per mile increase:[a]		
25%	- 4.541%	- 4.498%
50	- 8.726	- 8.749
75	-12.477	-12.939
100	-15.872	-17.006
Parking tax:	**% Change in VMT's**	**% Change in auto trips**
Parking cost increase:[a]		
$0.25	- 6.686%	- 8.626%
0.50	-12.319	-15.958
0.75	-15.938	-20.209
1.00	-17.215	-21.010

[a]Table 9 converts taxes into absolute and percentage terms for average length trips. Table 10 converts variable cost per mile increases into equivalent taxes on gasoline and emissions.

gasoline for work trips is -.27; for shopping trips, -.12. Again, these results are within acceptable bounds, especially considering the relatively low level of alternative transit service.

As expected, the effects of a parking tax on VMT's were significantly less than an equal increase in average trip costs caused by a gasoline or emissions tax. For example, extrapolating from the results for the work trip, a parking surcharge of $.80 would cause an 11.29 percent decline in VMT's; yet an equal increase in variable costs per mile (100 percent increase on average, from Table 9) causes a 35.30 percent decline in VMT's. A similar calculation for shopping trips shows that a parking surcharge of $.27 causes a VMT decline of 7.14 percent; a comparable increase in variable costs per mile would induce a 15.87 percent decline in VMT's.

A more detailed breakdown of the effects of the pollution control strategies is presented in Tables 13 and 14. From the mode split changes it can be seen that the parking charge significantly increases the number of driver serve passenger trips, which consequently boosts VMT's, since each such trip doubles the number of miles per trip which would have been the case for a driver serving himself.

Predicted Changes in Travel Patterns

The model simulates over zonal interchanges and, as a consequence, there is information additional to the above tables about the effects of policies on travel behavior. This detail on travel patterns helps one to understand how the model works in giving predicted effects. Most of the issues presented briefly below are discussed at greater length in Appendix A.

Effects of Policy by Distance of Trip -- The model indicates that long distance auto trips are the most sensitive to variable cost per mile increases whereas short distance

Table 13. MODE SPLIT ESTIMATES ON WORK TRIPS

For Gas or Emissions Tax:					
		Variable cost per mile increase:			
Mode	Base - 1974	25%	50%	75%	100%
Auto	72.984%	69.343%	65.313%	61.233%	57.456%
Transit	7.903	10.787	14.216	18.086	22.204
Passenger	16.613	17.924	18.684	18.816	18.314
Driver serve passenger	1.452	0.730	0.325	0.162	0.081
Walking	1.048	1.216	1.462	1.703	1.945

For Parking Tax:					
		Parking cost increase:			
Mode	Base - 1974	$0.25	$0.50	$0.75	$1.00
Auto	72.984%	66.295%	59.184%	52.006%	45.117%
Transit	7.903	10.518	13.265	15.972	18.622
Passenger	16.613	19.602	22.528	25.309	27.782
Driver serve passenger	1.452	2.151	3.061	4.090	5.224
Walking	1.048	1.434	1.962	2.623	3.255

Table 14. MODE SPLIT ESTIMATES ON SHOPPING TRIPS

For Gas or Emissions Tax:					
		Variable cost per mile increase:			
Mode	Base - 1974	25%	50%	75%	100%
Auto	67.505%	65.240%	62.709%	60.155%	57.542%
Transit	3.923	4.966	6.129	7.342	8.638
Passenger	27.719	29.238	30.776	32.246	33.648
Driver serve passenger	0.853	0.556	0.386	0.257	0.172

For Parking Tax:					
		Parking cost increase:			
Mode	Base - 1974	$0.25	$0.50	$0.75	$1.00
Auto	67.505%	59.129%	50.187%	41.667%	34.123%
Transit	3.923	6.551	9.571	12.601	15.522
Passenger	27.719	32.545	36.954	40.244	42.101
Driver serve passenger	0.853	1.775	3.288	5.488	8.254

trips are the most sensitive to parking tax increases. The incentive to take a bus or share auto costs through a carpool is greater the larger the total cost of the trip; thus, if costs increase with distance, incentives for mode diversion also increase with distance. On the other hand, parking taxes are a higher percentage of total trip cost for shorter trips. Thus they penalize short trips more than long trips. The effect is that for taxes of equivalent average size, parking taxes will have less impact on VMT's because they have less impact on longer trips. This effect is reinforced by the driver serve passenger option. This mode is virtually never chosen in long trips because of the inconvenience for the driver who must make a round trip twice a day. However, it is a viable alternative for short trips and is therefore especially attractive as a way to avoid high parking charges. If one increased variable costs per mile, however, the driver serve passenger mode is penalized because it doubles the additional cost of a trip compared to auto drive alone.

Effects of Destination Changes -- The model allows for changes in destination patterns as a result of travel cost increases. Because the average length of a shopping trip is relatively short in Los Angeles, this did not prove to be a major effect. Most of the change in VMT's in the shopping trips came about as a result of mode diversions from auto drive alone. This is partially a result of using sketch plan zone data which places an effective minimum (of about two miles on average) on the round trip distance of shopping as the average distance of an intrazonal trip. More refined data may have somewhat increased the elasticity of VMT's owing to destination changes. Long trips are the most susceptible to destination changes but there were relatively few in the Los Angeles sample.

Effects of Transit Availability -- The higher the level of service of transit (shorter access time, shorter line-haul time and fewer transfers) the greater the effect of auto disincentives. Stated another way, the elasticity of auto travel demand is higher the better the level of service of the alternate modes. Thus, the policies have their greatest impact on those origin/destination combinations which are best served by transit. This result is partially confirmed in the next section.

VMT AND TRIP EFFECTS WITH IMPROVED TRANSIT SYSTEM: WORK AND SHOPPING TRIPS

This section considers the effects of increasing conventional bus operations in order to provide alternative service as a substitute for policy induced decreases in auto trip travel. Model predictions showed that if a particular number of bus routes was increased in a zonal interchange when 100 or more auto trips had been diverted without improved bus service, then the combined effect of a tax on variable costs per mile and improved bus service would be an insignificant change in number of trips -- the net effect of the strategy was an intermodal shift from auto driver to bus passenger. Thus the bus service provides an adequate alternative for those wishing to avoid the tax penalties.

The assumed bus service improvements were all extensions of route miles rather than higher frequencies on existing routes. The number of bus routes added depended on the total decline in automobile trips, a decline due to increased taxes in the absence of changes in the bus network. Generally, for every decline of 100 auto work trips within a zonal interchange, a new direct bus route with 2.67 loadings (or scheduled buses -- round trip) was instituted at peak hours; in addition, for every decline of 100 auto shopping trips within a zonal interchange, a new direct bus route with four loadings (round trip) was instituted. (A more complete discussion of the assumed network changes is presented in Appendix C.)

This rule for assigning bus capacity is motivated by a need to accommodate diverted motorists rather than an attempt to optimize transit investments. Placing new bus routes where the most auto drivers are affected automatically increases the level of service on the highest density routes. However, as the above discussion indicated, these are also likely to be the routes where the best service exists before the improvement. An alternative strategy which locates additional bus service where there was less impact on auto travel but a large number of auto trips may be more effective in reducing VMT's.

Tables 15 and 16 present the effects on VMT's and trips due to the combined auto variable cost per mile increase and improved bus service. (The combination parking tax and bus service improvements scenario was not simulated. One reason for not examining this set of scenarios is that gasoline and emission taxes are the dominant policy on cost-effectiveness, as the previous section has shown. Another reason is that similar conclusions about the incremental cost-effectiveness of providing substitute bus service would seem to apply in either case.) As can be seen from the tables, the net effect of these policies is a less than 1 percent change in auto plus transit trips. The percentage changes are with respect to the 1974 base case projections with no new taxes and no changes in bus service.

It can also be seen from comparing Tables 15 and 16 to Tables 11 and 12 that the effectiveness of gasoline and emissions taxes in reducing VMT's is enhanced by providing increased opportunity for travel by bus. This is especially pronounced for shopping trips, where the percentage reduction

Table 15. EFFECT ON WORK TRIPS OF GAS OR EMISSION TAX COMBINED WITH TRANSIT IMPROVEMENTS

Variable cost per mile increase	% Change in VMT's	% Change in auto driver alone trips	% Change in transit trips	% Change in auto and transit trips
50%	-24.497%	-16.796%	+147.959%	-0.698%
100	-43.038	-28.177	+268.367	+0.798

Table 16. EFFECT ON SHOPPING TRIPS OF GAS OR EMISSION TAX COMBINED WITH TRANSIT IMPROVEMENTS

Variable cost per mile increase	% Change in VMT's	% Change in auto driver alone trips	% Change in transit trips	% Change in auto and transit trips
50%	-15.636%	-16.235%	+270.652%	-0.478%
100	-28.810	-30.701	+521.739	-0.358

in VMT's is nearly doubled. These results are somewhat expected, since the additional bus routes offer significantly reduced access time (and some reduced line-haul time, usually owing to direct service being substituted for transfers), and this is a particularly elastic component in mode choice models. Note that the additional bus service did not typically have a large impact on wait time and that the assumed fares were the same as currently obtain in Los Angeles.

Tables 17 and 18 show the mode split estimates which result from the combined strategies. (The 1974 base estimates were presented in Tables 14 and 15.) It can be seen that the mode split under the assumed scenarios more closely replicates the experience of older, CBD oriented cities which have a more highly developed transit system.

The aggregate elasticity for work trip VMT's with respect to a change in both auto variable costs per mile and improved transit is -.4304. The similar elasticity for shopping trips is -.3004. The implied price elasticities for gasoline are -.3251 for work trips and -.2123 for shopping trips. All of these results satisfy *a priori* expectations and indicate that in situations with higher levels of transit service, VMT's are more sensitive to auto penalties.

THE AGGREGATE SHORT-RUN TRAVEL EFFECTS

This section gives the results of extrapolating the above simulations to include all trip purposes. Using 1974 adjustment factors to trip purpose categories,* work trips presently account for about 24 percent of total Los Angeles region trips and shopping trips for about 17 percent. The remaining trip purposes have been allocated to either the

*These were given to CRA by Jerry Bennett of Caltrans, District 07 (LARTS District).

Table 17. MODE SPLIT ESTIMATES WITH TRANSIT IMPROVEMENTS FOR WORK TRIPS

Policy alternative	Share of auto	Share of transit	Share of passenger	Share of driver serve passenger	Share walk
Bus improvements and auto operating cost increase:					
50%	61.319%	19.788%	17.427%	0.326%	1.140%
100	52.888	29.374	16.111	0.801	1.546

Table 18. MODE SPLIT ESTIMATES WITH TRANSIT IMPROVEMENTS FOR SHOPPING TRIPS

Policy alternative	Share of auto	Share of transit	Share of passenger	Share of driver serve passenger
Bus improvements and auto operating cost increase:				
50%	56.886%	14.629%	28.185%	0.300%
100	47.122	24.570	28.179	0.129

work trip elasticities or the shopping trip elasticities depending on which category was deemed most appropriate.

Table 19 presents the estimated trip purpose shares for the Los Angeles region in 1974. Trip purposes of similar attributes in terms of average trip length and of significant destination choice have been grouped together. Using these criteria, it can be seen that about 35 percent of total trips are most closely associated with the attributes of work trips, and the remaining 65 percent can be assumed to be associated with shopping trip attributes. When the trip purpose shares are weighted by the average length of trip, the relative contribution to VMT's from each of the major categories is roughly equal.

To determine the aggregate effects of the pollution control strategies on auto trips and VMT's, weighted averages were applied to the simulation results on work and shopping trips. These weights depend on the relative shares by purpose of region-wide auto trips or VMT's, whichever is appropriate, in each of the two major categories. The weights are changed at each tax level for simulations at the next tax level to reflect the change in relative trips or VMT's caused by the policy.

The area covered by the sample of work and shopping trips includes Orange County and Los Angeles County south of the mountains. This area corresponds roughly to the Los Angeles Air Quality Control region. However, it does not correspond to the original and existing Los Angeles Regional Transportation Study (LARTS) area, which is the source of all aggregate data for the region. LARTS includes all of Los Angeles County, Orange County and parts of Ventura, San Bernardino and Riverside Counties. It is estimated that the Air Quality Control region contains about 65 percent of all

Table 19. ESTIMATED 1974 TRIP PURPOSE SHARES

Purpose	Total trip shares	VMT share
Home-work	20.93%	30.02%
Work-other	3.35	4.80
Work-work	6.23	8.94
Home-education	4.23	4.55
Subtotal share ("work")	34.74%	48.31%
Home-shop	16.71%	7.57%
Home-social, entertainment, recreation	14.49	18.25
Home-other	14.64	10.57
Other-other	17.07	12.32
Home-home	2.36	2.97
Subtotal share ("shop")	65.27%	51.68%

LARTS VMT's (it will be seen that our estimate is considerably less). The 1974 estimate of weekday VMT's for the entire LARTS region is in the 160 to 170 million range.*

It is, in general, difficult to get a consistent estimate of total trips and VMT's for the auto trips which take place solely within Los Angeles and Orange Counties. CRA arrived at the figure of 62.570 million miles per weekday using the following approach: first, we received from the Southern California Rapid Transit District (SCRTD) an estimate of total round trip bus riders per weekday for Los Angeles and Orange Counties (412.5 thousand); using this, we computed total household trips by all modes and for all purposes by dividing the number of bus trips by the estimated 1974 base case bus share. (The mode split estimate for transit was checked with SCRTD planners and found to be consistent with their own estimates.)

$$\frac{\text{number of bus trips}}{\text{total trips}} = \text{base case bus share}$$

$$\text{total trips} = \frac{\text{number of bus trips}}{\text{base case bus share}}$$

Total auto trips were determined from the estimated 1974 base case mode split for auto trips (5.479 million round trips). The aggregate number of trips was multiplied by the average auto round trip length (estimated by CRA to be 11.420 miles) to get the daily total VMT's of 62.570 million.

It should be noted that this estimate is significantly less than would be expected from the Caltrans estimate of total VMT's for the LARTS region. Obviously, significantly

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*Gerry Bennett of Caltrans District 07 supplied CRA with much of this information. It should be noted that the estimates on VMT's are preliminary.

fewer trips are covered by examining only Orange and Los Angeles Counties. Also, our estimates do not consider VMT's associated with vehicles other than household-owned passenger cars and pickup trucks. It is somewhat disturbing that CRA uses an estimate of average trip length that is significantly lower than that used by Caltrans. For example, data from the 1967 Household Survey show that the average work round trip was about 14.5 miles; the 1974 CRA base case estimate is about 14 miles. LARTS and Caltrans tend to use 18 miles as the average work round trip distance from 1967 through 1974.

Table 20 represents a summary of the estimated region-wide effects of the pollution control strategies. The following conclusions emerge from the estimates:

- the elasticity of VMT's with respect to increases in the variable costs per mile is -.27 with the current transit system and -.38 when combined with the assumed improved transit system;
- the implied elasticity on the price of gasoline is -.19 with the present transit system and -.27 when combined with the assumed improved system;
- the elasticity of VMT's with respect to increased trip costs due to a parking tax is -.12 with the current transit system.

UNCERTAINTY OF THE RESULTS

Though the approach to estimating the effects of pollution control strategies on travel behavior represents a considerable advance in the state of the art, there are several sources of potential error which should be noted. Some sources of error lead to greater randomness in the predictions; others may bias the results in a particular direction. We briefly discuss each potential source of error and its effects on the estimated results.

Table 20. ESTIMATED EFFECTS OF POLLUTION CONTROL STRATEGIES ON VMT'S AND AUTO TRIPS

Gas or emissions tax: variable cost per mile increase[a]	% Change in VMT's	% Change in auto trips	Total VMT's, millions per weekday[b]
25%	- 7.40%	- 5.45%	57.940
50	-13.96	-10.50	53.835
75	-19.58	-15.27	50.319
100	-24.13	-20.39	47.472
Parking tax: parking cost increase[a]			
$0.25	- 5.04%	- 7.66%	59.416
0.50	- 9.58	-14.46	56.576
0.75	-13.07	-19.18	54.392
1.00	-15.43	-21.33	52.915
Transit system improvements with variable cost per mile increase[a]			
25%	-20.21%	-16.43%	49.925
100	-35.77	-29.83	40.189

[a]Table 9 converts taxes into absolute and percentage terms for average trip lengths. Table 10 converts variable cost per mile increases into equivalent taxes on gasoline and emissions.

[b]Based on an estimated total of 62.570 million VMT's per average weekday in 1974 for the Los Angeles Air Quality Control Region.

Model Structure and Estimates

As discussed elsewhere,[1] the disaggregated demand model has strong theoretical foundations as a representation of travel choice behavior. The structure and specification of the model are relatively sound.

Unfortunately, estimation techniques for the model do not allow easy interpretation of most commonly used test statistics. However, some information about the confidence one may have in the estimates is available, including the following:

- The parameter estimates in all relationships are generally significant within a 2.5 percent level of confidence using a one-tailed t-test.
- A sensitivity test of parameter estimates by estimating alternative specifications indicates that the mode choice models are quite robust.
- The predictive ability of each relationship is relatively good when applied to individual households in the estimation sample, although no easily interpretable test statistic for this characteristic of a probability choice model has been devised.
- The parameter estimates were consistent with *a priori* expectations and other studies of travel demand and value of time.

The predictive ability of the model has been validated in this study with one important exception: the frequency of shopping trips relationship is overly sensitive to the cost of travel.* For this reason, the choice of whether to make a shopping trip during a 24 hour period was not

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*See Appendix A of this report.

simulated under the alternative policies. The effects of this omission on the estimates are discussed in more detail in a later section.

Data

Underlying errors in the data will affect estimation results in two broad categories: errors in observation and sampling error. These are each discussed in turn.

Errors in observation -- The data are discussed in detail in Appendix D. The primary source of data for this project has been the 1967 LARTS Household Survey. The survey itself can be presumed to have yielded reasonably accurate observations of the variables included in the model simulations, and considerable effort has gone into augmenting this source with other data on interzonal distances, transit level of service and socioeconomic characteristics of zones. It can be concluded that these efforts have been rewarded with minimal errors in the data.

Sampling error -- Although only a fraction of the total zonal interchanges were simulated, the samples are representative of the regional population. Aggregate mode shares from the samples were very close to those obtained from the regionwide survey.

Model Application

For this study, the area of model application gives rise to the most serious sources of error. Six potential problems are discussed below.

Generalizability -- As mentioned before, the model parameters were estimated on 1967 Pittsburgh data, and it is possible that this would make its estimates inapplicable to a different region for a different year. However, the behavioral nature of the model implies interregional generalizability. The major influence of time on the model structure -- secular increases in the value of time owing to rising money income -- has been previously discussed. It was concluded that this is not a major factor in biasing the results.

Application beyond the range of observations for estimates -- As a general rule, forecasts employing estimated equations become more uncertain as the values of independent variables used in the forecast exceed the range of independent variables used in estimating the model. The auto variable cost per mile is the only variable for which values in the simulations substantially exceeded the values found in the Pittsburgh data set. The policies themselves are most responsible for this problem insofar as one of their primary impacts is to increase significantly the variable cost per mile for automobile trips. In this regard, the use of *a priori* information helps to validate the predictions of the model.

Application to other modes -- The model was originally estimated on only two modes, auto drive alone and transit, but is here applied to several others including carpooling, driver serve passenger and walk. Some uncertainty may be attached to the estimates which are obtained for the other modes.

Aggregation to zonal levels -- Some adjustments in applying the model were necessary for it to be an appropriate tool for prediction with zonal data rather than data on individual households. The results of these adjustments, as documented in Appendix A, add some error to the simulated effects, but the forecasts are well within reasonable bounds of accuracy. This issue is of some importance because the effects of the policies in reducing VMT's partially depend upon diversions from auto drive alone to carpooling. Also, part of the reason parking taxes are found to be less effective (at the same average cost per trip) compared to other strategies, lies in the inducement to chauffeured trips. The decisionmaking process for these other modes is more complex than that represented by the rather *ad hoc* adjustments to the basic model performed in Appendix A. However, accurate models of carpool behavior do not exist at this time -- nor do the data exist to estimate such models. More importantly, the relative ranking among policies is probably not affected by errors in the estimated mode shares of carpool, walk and driver serve passenger as long as the direction of predicted effect is correct. In this regard, the model performs approximately as one would expect traveler behavior to change in response to auto trip cost increases. Thus, though there may be some error in the elasticity estimates, the ranking of policies remains sound.

Application to other trip purposes -- The ability of the unadjusted work or shopping trip model to predict mode split for other purposes is discussed briefly in Appendix A. The general conclusion is that uncertainty is added to the projected policy effects for aggregate travel, but it is difficult to tell whether these projections are biased. Again, one must rely on *a priori* reasoning in making a judgment about the confidence with which aggregate projected VMT's and auto trips can be used.

Frequency of trips -- It was assumed that the aggregate number of trips remains constant, although mode and destination choices may change as the cost of auto travel increases. Even if such an assumption is appropriate when analyzing the short-run behavior of non-discretionary travel (work and education related trips), it is not necessarily plausible for some other trip purposes. To put quantitative bounds on the underestimation which may occur because of this assumption, the following exercise was performed:

- Home-shop, home-social/entertainment/recreation, and home-other were all determined to be trip purposes for which the frequency of travel may decline owing to an increase in auto trip costs.
- Their contribution to regionwide VMT's was calculated from Table 19 to be about 40 percent.
- It was assumed that the effort to cut back on VMT's by taking fewer trips was equivalent to the effects of choosing other modes and closer destinations; that is, the elasticity of VMT's with respect to variable costs per mile is the same for changes in trip frequency as it is for changes in the combination of destination choice and mode choice. This assumption has the effect of, for example, doubling the elasticity of shopping trips with respect to a policy scenario.
- The effect on aggregate changes in VMT's was calculated using the 1974 base case weights and elasticities from Table 20; the change in VMT's implied by these assumptions was a decrease of approximately 25 percent in the changes predicted in Table 20.

The above computations place a reasonable lower bound on the predicted effects of the previous section.

CONCLUSIONS

Though no confidence intervals have been explicitly calculated, an upper bound on the predicted changes in VMT's and auto trips has been implied by making a strong assumption about the effects of trip frequency choice on discretionary trips. This upper bound augments the conclusions about short-run travel response to pollution control policies in the following ways:

- The elasticity of VMT's with respect to increases in the variable costs per mile is -.27 (with a bound of -.34) with the current transit system and -.38 (with a bound of -.48) when combined with an improved transit system.
- The implied elasticity on the price of gasoline is -.19 (with a bound of -.24) with the current transit system and -.27 (with a bound of -.34) when combined with an improved transit system.
- For equivalent incremental costs per average trip, the gasoline and emissions taxes are over two times more effective than parking taxes in reducing VMT's, a conclusion unaffected by the frequency of travel.

Subject to the qualifications discussed in this chapter, these results are confirmed by *a priori* expectations and can be considered to be reasonably reliable.

List of References, Chapter 3

[1]Domencich and McFadden. *op. cit.*; McFadden, Daniel. Conditional Logit Analysis of Qualitative Choice Behavior. In: *Frontiers of Econometrics*, Zarembka, Paul (ed.). New York, Academia Press, 1974.

4. EFFECTS OF POLICIES ON THE AUTO STOCK

This chapter presents the estimated effects of pollution control policies on age distribution of cars and size of auto stock. Appendix B (Auto Stock Adjustment) develops models for predicting these effects. This chapter also discusses estimates of policy effects on retrofitting. The confidence to be placed in predicted results is examined. Chapter 5 uses the results presented below in determining the cost-effectiveness of various policies.

The effects of emissions taxes on the size and age distribution of automobiles was determined by simulating the model presented in Appendix B. This chapter considers two separate forms of emissions taxes, both of which have been discussed in Chapter 2: first, we present the effects of an annual tax based on the estimated average emission rate per mile for automobiles of specific models, makes and years (MMY tax); next we describe the impacts of a tax which is based on the estimated amount of emissions as a result of the car's emission rate and miles driven (MER tax). Among the impacts considered for the MER tax is the incentive for car owners to retrofit with emissions control devices.

EFFECTS OF A MODEL, MAKE AND YEAR TAX

The age distribution of cars affects the aggregate emission rate from the total stock of cars in that a fleet with a higher proportion of old cars will have, on average, greater pollution rates per vehicle. The age distribution of cars is determined by the scrappage rate of cars of different vintages and the proportion of the auto stock which is made up of new cars. This section gives estimates of the effects of various MMY taxes on scrappage rates by age of car and on new car sales.

Table 21 gives the base case estimates for the characteristics of the 1975 auto stock in the Los Angeles area. These estimates were produced by simulating the model described in Appendix B with assumptions, also discussed in Appendix B, about the average price of new cars (assumed to be $3,850) and the average price of used cars. Scrappage rates by age are calculated by using Equation 53.

Although only Los Angeles and Orange Counties are represented, they account for 86 percent of the autos owned in all five counties which have part of their area in the LARTS region. These autos undoubtedly account for an even higher percentage of the pollution in the Los Angeles region. It can also be assumed that the characteristics of the auto stock in Los Angeles and Orange Counties are reasonably similar to those in relevant areas not covered by the data.

The characteristics of automobiles by age are further described in Table 22. It shows that although there are significant numbers of higher polluting cars in the fleet, their contribution to vehicle miles traveled is much less than their numbers would otherwise indicate. Pre-1970 cars, largely uncontrolled, were grouped into two categories because they have similar emissions rates within the categories. The decline in emission rates since 1970 has been fairly continuous for all pollutants. Also to be noted is that each dollar of an annual tax puts a greater burden in absolute terms on newer cars because their longer life expectancy increases the present discounted value of the annual

Table 21. BASE CASE ESTIMATES OF 1975 AUTO STOCK CHARACTERISTICS FOR LOS ANGELES AND ORANGE COUNTIES

Total auto stock (in vehicles)	4,240,053
New car sales (in vehicles)	403,896
Used car price, average	$1,272
Aggregate scrappage rate	0.07786

Model year	Scrappage rate by age of auto
1975	0.0013
1974	0.0028
1973	0.0058
1972	0.0120
1971	0.0239
1970	0.0449
1967-1969	0.1132
pre-1967	0.1898

Table 22. ESTIMATES OF 1975 MID-YEAR AUTO STOCK CHARACTERISTICS BY AGE OF CAR: LOS ANGELES AND ORANGE COUNTIES

Model year	Proportion of total[a]	Average mileage per vehicle[b]	Proportion of total VMT's
1975	0.0781	15,000	0.1585
1974	0.1018	13,000	0.1696
1973	0.1031	11,000	0.1228
1972	0.0972	9,600	0.1083
1971	0.0818	8,400	0.1071
1970	0.0808	7,600	0.0815
1969-1967	0.2030	4,900	0.1395
pre-1967	0.2552	3,700	0.1116

Model year	Discounted present cost of $1 annual tax[c]	Emission rates (gm/mi)[d]		
		CO	HC	NOx
1975	$5.6502	19	2.70	2.30
1974	5.3282	22	2.83	2.55
1973	4.9676	25	2.97	2.71
1972	4.5638	26	3.05	4.20
1971	4.1114	48	3.35	4.23
1970	3.6048	52	4.21	5.10
1969-1967	2.6136	72	5.62	6.14
pre-1967	2.4018	83	8.66	4.21

Table continues on following page.

Table 22. ESTIMATES OF 1975 MID-YEAR AUTO STOCK CHARACTERISTICS BY AGE OF CAR: LOS ANGELES AND ORANGE COUNTIES (Continued)

[a]Based on estimates from model simulation, including scrappage rate by age of car, starting with July 1, 1973 data on Los Angeles and Orange counties from Polk Statistics, National Vehicle Registration Service. See Appendix B for auto stock model and assumptions.

[b]Source: Lees, *et al.* *Smog: A Report to the People.* Pasadena, California Institute of Technology, 1972. Table 18, p. 128.

[c]Based on assumption of 12 percent discount rate of interest. Also, cars are assumed to have a 10-year life span, except that all cars are considered to have at least three years of life remaining.

[d]Pre-1970 rates are actual rates, measured by California State Air Resources Board, cited in: Downing. *Benefit/Cost Analysis of Air Pollution Control Devices for Used Cars.* University of California, Riverside, September 1970. pp. 3-9.; or predicted rates based on data in *Compilation of Air Pollutant Emissions Factors.* Environmental Protection Agency. Report #AP-42. February 1972. pp. 3.1.1-6 through 3.1.2-9.; the higher of either is presented. Other years are based upon predictions in *Compilation of Air Pollutant Emissions Factors, op. cit.*

tax stream; however, older cars have the greater burden when the present discounted value of the tax is viewed as a proportion of the market value of the car.

It is important to note that in the long run nearly all of the higher polluting cars will exit from the fleet even in the absence of an emissions tax. National standards on new cars will cause older autos to be replaced by lower polluting vehicles as age takes its toll on the existing stock. Thus, the effects of emissions taxes must be viewed as providing only interim benefits in terms of lowering the average emission rate per vehicle. Also, a separate effect of an emissions tax -- a reduction in new car additions to the auto stock -- may only have short-run impact if currently proposed national standards for future automobiles are maintained. The projected emission rates from cars in the late seventies implies that any but the most massive emissions tax on current cars would be negligible on future cars. Thus, the reduction in travel induced by less car ownership would be transitory. (This report does not consider the feedback effects of automobile ownership on travel demand, though such an analysis is conceptually possible.)

As a consequence of these effects, the model simulations in this section must be interpreted as providing interim benefits only. In particular, the questions asked were:

- whether an MMY tax will significantly increase the rate at which older cars are scrapped;
- whether an MMY tax will lead to a short-run decrease in the size of the auto stock.

The results of the model simulations are presented in Tables 23 through 26. Tables 23 through 25 focus on taxes based on particular pollutants: CO, HC, and NO_x. Table 26 shows the effects of a combination tax on all three pollutants for both a high and a low level of taxation.

Table 23. AUTO STOCK EFFECTS OF ANNUAL TAX ON CARBON MONOXIDE: LOS ANGELES AND ORANGE COUNTIES

Variable	$1/gm	$2/gm
Total auto stock (in vehicles)	4,207,293	4,165,515
New car sales (in vehicles)	392,974	382,627
Used car price, average	$1,118	$969
Aggregate scrappage rate	0.0863	0.0971
Average present value of tax, all cars	$163	$326

Model year	$1/gm Annual tax	$1/gm Discounted present value of cost	$1/gm Scrappage rate	$2/gm Annual tax	$2/gm Discounted present value of cost	$2/gm Scrappage rate
1975	$19	$107	0.0013	$ 38	$214	0.0013
1974	22	117	0.0027	44	234	0.0027
1973	25	124	0.0057	50	248	0.0057
1972	26	119	0.0120	52	237	0.0120
1971	48	197	0.0248	96	395	0.0260
1970	52	187	0.0487	104	375	0.0528
1967-1969	70	183	0.1400	140	366	0.1678
pre-1967	81	195	0.2732	162	389	0.3581

Table 24. AUTO STOCK EFFECTS OF ANNUAL TAX ON HYDROCARBONS: LOS ANGELES AND ORANGE COUNTIES

Variables	$7/gm	$14/gm
Total auto stock (in vehicles)	4,219,864	4,195,762
New car sales (in vehicles)	392,974	382,627
Used car price, average	$1,164	$1,057
Aggregate scrappage rate	0.0830	0.0892
Average present value of tax, all cars	$114	$228

	$7/gm			$14/gm		
Model year	Annual tax	Discounted present value of cost	Scrappage rate	Annual tax	Discounted present value of cost	Scrappage rate
1975	$19	$107	0.0013	$ 38	$214	0.0012
1974	20	106	0.0027	40	211	0.0027
1973	21	103	0.0057	42	207	0.0057
1972	21	97	0.0119	43	195	0.0119
1971	23	96	0.0241	47	192	0.0244
1970	29	106	0.0465	59	212	0.0486
1967-1969	39	103	0.1269	79	206	0.1419
pre-1967	61	146	0.2507	121	291	0.3136

Table 25. AUTO STOCK EFFECTS OF ANNUAL TAX ON NITROGEN OXIDE: LOS ANGELES AND ORANGE COUNTIES

Variables	$8/gm	$16/gm
Total auto stock (in vehicles)	4,219,462	4.194,910
New car sales (in vehicles)	393,272	282,194
Used car price, average	$1,163	$1,056
Aggregate scrappage rate	0.0831	0.0895
Average present value of tax, all cars	$115	$230

Model year	$8/gm			$16/gm		
	Annual tax	Discounted present value of cost	Scrappage rate	Annual tax	Discounted present value of cost	Scrappage rate
1975	$18	$104	0.0013	$37	$208	0.0013
1974	20	109	0.0027	41	217	0.0027
1973	22	108	0.0057	43	215	0.0057
1972	34	153	0.0120	67	307	0.0121
1971	34	139	0.0243	68	278	0.0251
1970	41	147	0.0476	82	294	0.0509
1967-1969	49	128	0.1309	98	257	0.1503
pre-1967	34	81	0.2217	67	162	0.2562

Table 26. AUTO STOCK EFFECTS OF
ANNUAL EMISSIONS TAX ON ALL POLLUTANTS:
LOS ANGELES AND ORANGE COUNTIES

Variables	Low tax[a]	High tax[b]
Total auto stock (in vehicles)	4,149,052	3,971,173
New car sales (in vehicles)	373,260	346,866
Used car price, average	$908	$574
Aggregate scrappage rate	0.1015	0.1508
Average present value of tax, all cars	$392	$784

	Low tax			High tax		
Model year	Annual tax	Discounted present value of cost	Scrappage rate	Annual tax	Discounted present value of cost	Scrappage rate
1975	$ 56	$316	0.0013	$113	$633	0.0017
1974	62	330	0.0028	125	661	0.0037
1973	68	338	0.0059	135	676	0.0079
1972	81	370	0.0125	162	739	0.0171
1971	105	432	0.0268	211	863	0.0378
1970	122	440	0.0557	245	880	0.0814
1967-1969	158	413	0.1783	317	826	0.2808
pre-1967	176	423	0.4398	350	845	0.6290

[a]Low tax equals $7/gm HC + $1/gm CO + $8/gm NOx.

[b]High tax equals $14/gm HC + $2/gm CO + $16/gm NOx.

Generally, the taxes have a large impact on the scrappage of older cars and on used car prices. Over time, this effect could be expected to speed considerably the exit of older cars from the fleet. For taxes on the order of those presented in Table 26, the result over time will also be a decline in the auto stock.

To give an example of the effects the taxes in Table 26 may have, the scrappage rates were applied in an exercise presented in Table 27. This exercise is based on the fall 1975 age distribution of automobiles; the percentages given in the four age categories approximate the results that would be predicted by the model in Appendix B for Los Angeles and Orange Counties. It is further assumed that 1976 auto sales are 10 percent of the auto stock in all tax scenarios. The scrappage rates from Tables 21 and 26 are then applied to determine the resulting age distribution of cars.

Generalizing from Table 27, it can be seen that the effect of age alone on redistribution of the auto stock is significant and that the emissions taxes would further deplete the stock of older cars. Moreover, the taxes would cause a decline in the auto stock: the present discounted value of the "low" tax is about 25 percent of the market value of the weighted average of new and used cars and causes a net change -- 7 percent in the auto stock on a one to two year period. The change incurred by the higher tax is roughly proportional.

EFFECTS OF A MILEAGE-EMISSIONS RATE TAX

There are a number of potential reactions to an MER tax, including: higher scrappage rates for older autos; fewer VMT's and trips by auto; switching trips to the lower polluting auto in multicar households; retrofitting presently owned cars with pollution control devices or tuning cars more often to lower the measured emission rates. Because

Table 27. EXAMPLE OF EFFECTS OF TAX SCENARIOS ON AGE DISTRIBUTION OF AUTOS OVER TIME

Model year	1975 age distribution (assumed)	1976 age distribution		
		No tax	Low tax	High tax
1976 (assumed)	---	0.10	0.10	0.10
1973-1975	0.30	0.29	0.32	0.35
1970-1972	0.25	0.24	0.26	0.28
1967-1969	0.20	0.17	0.17	0.16
pre-1967	0.25	0.20	0.15	0.11
Change in auto stock	---	+2%	-5%	-13%

of the multiplicity of responses, it is not possible to determine with any precision what the impact of an MER tax on the age distribution of autos would be; nor could much meaning be attached to a change in the age distribution as it relates to aggregate emissions because of the incentive to retrofit and switch trips among cars in multicar households. Nonetheless, this section does present some computations which are indicative of the effects of an MER tax.

Ownership Costs

A tax divided equally, on average, over emissions per mile of CO, HC and NO_x is briefly analyzed in this section. The tax is equivalent to, again on average, a 25 percent increase in the variable costs per mile. Table 28 shows how the tax would be distributed across age categories of automobiles. Though the average annual MER tax per car would be roughly equivalent to the average annual low MMY tax considered in Table 26, it would be distributed across age categories quite differently. An MER tax affects the auto age distribution significantly less than an MMY tax. The reason is that older cars are driven much less than newer cars; hence, the annual tax charges on older cars are less for the MER tax relative to the MMY tax.

Though it is difficult to predict the effect of the MER tax on the distribution of VMT's across model years, Table 28 presents the results of an exercise using the elasticity of VMT's with respect to variable costs per mile. This elasticity was computed to be -.27 in Chapter 3. Applying the same elasticity to the percent change in variable cost per mile for each age category yields an estimate of the average reduction in annual mileage as a result of the tax. If VMT's are reapportioned after the tax (see the last column in Table 28), assuming no change in the age distribution of autos, there will be a small shift in the proportion of

Table 28. EFFECTS, BY AGE CATEGORY OF AUTO, OF MER TAX EQUIVALENT TO AVERAGE 25 PERCENT INCREASE IN VARIABLE COSTS PER MILE

Model year	Cents per mile tax[a]	Average annual mileage pre-tax[b]	Annual cost at pre-tax mileage	Proportion of VMT's pre-tax[b]
1973-1975	1.05	13,000	$136	0.45
1970-1972	1.92	8,600	164	0.30
1967-1969	2.65	4,900	129	0.14
pre-1967	2.94	3,700	108	0.11
Model Year	**Percent change in variable cost per mile**	**Average annual mileage post-tax**	**Annual cost at post-tax mileage**	**Proportion of VMT's post-tax**
1973-1975	18.39	12,354	$130	0.47
1970-1972	33.63	7,819	150	0.30
1967-1969	46.41	4,286	114	0.13
pre-1967	51.49	3,186	94	0.10

[a] Based on 0.0145 gm/mi CO, 0.1323 gm/mi HC, and 0.1398 gm/mi NOx.
[b] Table 22.

auto travel away from older to newer cars. These results do not take into account the ability of multicar households to shift trips to those vehicles with lower operating costs per mile. Thus, the actual impact would probably be greater than the estimated shift shown in Table 28.

Retrofitting

Retrofitting is one of the ways a motorist could reduce an MER tax bill. However, the incentive to retrofit only exists if the tax rate is high enough to justify the initial expense (and higher future maintenance costs) of retrofitting. Moreover, retrofit devices vary in effectiveness of control for given components of emissions.*

In order to determine how large an incentive to retrofit is implied by the MER taxes considered in this report, the costs of retrofitting are computed on an average per mile basis for each age of car. It can be assumed that tax rates greatly exceeding this cost provide a strong inducement for retrofitting.

The data on retrofitting costs and effectiveness are scanty or, in the case of recent models of autos, nonexistent. Tables 29 and 30 use what data is available to determine retrofitting cost/effectiveness. These data take account of neither the deterioration rates of retrofit devices nor the effects of regular tuneups. It is assumed that a catalytic reactor is applied to reduce carbon monoxide and

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*For studies of mandatory retrofitting schemes, see: *Evaluating Transportation Controls to Reduce Motor Vehicle Emissions in Major Metropolitan Areas*. Institute of Public Administration. Washington, D.C. Report #APTD-1364. Environmental Protection Agency. November 1972. Chapter One; *The Automobile and the Regulation of Its Impact on the Environment*. Legislative Drafting Research Fund of Columbia University. Draft Report. 1974. Chapter 6; and California Air Resources Board for information on California's mandatory retrofit plan.

Table 29. RETROFIT COSTS FOR CO AND HC WITH CATALYTIC REACTOR

Model year	Emissions reduction in gm/mi[a] CO	HC	Annual costs of retrofit[b] Annualized initial cost	Maintenance	Reduced gas mileage	Total annual cost
1975	15.5	2.34	$18.62	$41.67	$19.00	$79.29
1974	18.5	2.47	18.62	41.67	17.40	77.69
1973	21.5	2.61	20.00	41.67	15.80	77.49
1972	22.5	2.69	21.25	41.67	14.68	77.60
1971	44.5	2.97	23.75	41.67	13.72	79.14
1970	48.6	3.85	27.04	41.67	13.08	81.79
1969	64.0	5.22	31.31	41.67	11.24	84.21
1968	71.0	5.56	37.74	41.67	11.00	90.41
1967	71.0	5.24	48.50	41.67	10.52	100.69
1966	65.0	7.69	48.50	41.67	10.36	100.53
<1966	83.0	8.36	48.50	41.67	9.80	99.97

[a]Pre-1970 listings based on data in: Downing. *Benefit/Cost Analysis of Air Pollution Control Devices for Used Cars*. University of California, Riverside, September 1970. For other years, reductions are assumed to occur to levels equal to an average between highest and lowest levels achieved in pre-1970 autos (from Downing).

[b]Costs of retrofit are derived from estimates in Downing, *op. cit.* For annualizing initial costs, autos are assumed to have a ten-year life span, except that all cars are considered to have at least three years of life remaining; an annual 12 percent discount rate is assumed.

Table continued on following page.

Table 29. RETROFIT COSTS FOR CO AND HC WITH CATALYTIC REACTOR (Continued)

Model year	Per mile cost[c]		Cost of retrofit per gram/mile reduction, ¢/gm/mi	
	Cents/mile	½ ¢/mile attributable to each pollutant	CO	HC
1975	0.53	0.26	0.017	0.115
1974	0.60	0.30	0.016	0.125
1973	0.70	0.35	0.016	0.135
1972	0.81	0.40	0.018	0.145
1971	0.94	0.47	0.010	0.155
1970	1.08	0.54	0.011	0.140
1969	1.59	0.80	0.012	0.150
1968	1.81	0.90	0.012	0.160
1967	2.29	1.10	0.016	0.210
1966	2.39	1.20	0.018	0.160
pre-1966	2.86	1.43	0.017	0.170

[c]Mileage by age of auto given in Table 22. Original source is Lees, *et al.* *Smog: A Report to the People.* Pasadena, California Institute of Technology, 1972. Table 18, p. 128.

Table 30. RETROFIT COST FOR NOx WITH EXHAUST RECYCLE DEVICE

Model Year	Emissions reduction, gm/mi[a] Max	Min	Annual costs of retrofit[b] Annualized initial cost	Maintenance	Total annual cost
1975	0.77	0.22	$ 7.45	$6.00	$13.45
1974	1.02	0.47	7.45	6.00	13.45
1973	1.18	0.63	8.00	6.00	14.00
1972	2.67	2.12	8.50	6.00	14.50
1971	2.70	2.15	9.50	6.00	15.50
1970	3.57	2.30	10.82	6.00	16.82
1969	4.84	4.84	12.53	6.00	18.53
1968	4.25	4.25	15.10	6.00	21.10
1967	3.78	3.78	19.40	6.00	25.40
1966	3.54	3.54	19.40	6.00	25.40
pre-1966	2.47	1.92	19.40	6.00	25.40

[a]Pre-1970 listings based on data in: Downing. *Benefit/Cost Analysis of Air Pollution Control Devices for Used Cars*. University of California, Riverside, September 1970. Maximum reductions occur when levels are achieved equal to the lowest levels occurring in pre-1970 autos (Downing); minimum reductions are to highest levels achieved in pre-1970 autos (Downing).

[b]Retrofit costs estimates derived from data in Downing, *op. cit.* Annualizing procedures are the same as were used in Table 29.

Table continued on following page.

Table 30. RETROFIT COST FOR NOx WITH EXHAUST RECYCLE DEVICE (Continued)

Model year	Retrofit cost per mile, ¢/mi[c]	Cost of retrofit per gram/mile reduction: Maximum effectiveness, ¢/gm/mi	Minimum effectiveness, ¢/gm/mi
1975	0.09	0.12	0.41
1974	0.10	0.10	0.21
1973	0.13	0.11	0.21
1972	0.15	0.06	0.07
1971	0.18	0.07	0.08
1970	0.22	0.06	0.10
1969	0.35	0.07	0.07
1968	0.42	0.10	0.10
1967	0.58	0.15	0.15
1966	0.60	0.17	0.17
pre-1966	0.73	0.30	0.38

[c] Mileage by age of auto given in Table 22. Data are originally from: Lees, *et al. Smog: A Report to the People*. Pasadena, California Institute of Technology, 1972. Table 18, p. 128.

hydrocarbons and that the costs of the reactor can be allocated equally between the control of CO and HC. An exhaust recycle device would be necessary for reducing nitrogen oxide.

The last columns in Tables 29 and 30 give the estimated average cost of retrofitting per gram/mile reduction. Motorists will tend to benefit from retrofitting when the MER tax is greater than this figure. For example, an MER tax which increased auto variable costs per mile by 25 percent and which would provide only a marginal inducement for most car owners to retrofit would be divided equally among the three pollutants as follows: .0145 cents per gm/mi on CO; .1323 cents per gm/mi on HC; .1398 cents per gm/mi on NO_x. However, under a tax rate which had the same proportions among pollutants but was double the rate, making it 50 percent of auto variable operating costs, most motorists would benefit from retrofitting.

It should be noted that these figures are quite approximate. Moreover, within any model year there will be significant variation owing to differing characteristics of various auto models, variation in the personal discount rate on initial expenses for retrofitting, variation in subjective estimates of the remaining years left on an auto, variation in the miles driven by individual car owners, etc. Obviously, not every automobile will be retrofitted even if the average tax reduction is greater than the cost of retrofitting.

These qualifications notwithstanding, it appears that voluntary retrofitting would become widespread at emission tax rates on the order of 50 percent of the current average auto variable costs per mile; this would entail an additional cost of about $0.03 per mile on average. Tax rates per mile on auto travel would be decreased in proportion to the extent of retrofitting, and there would be a feedback effect on auto VMT's and the auto scrappage rates by age of car.

The incremental effects of emissions tax rates on auto travel would decline as more retrofitting occurred. Also, as retrofitting would prevent higher ownership costs due to MER taxes, the impacts of these on the auto stock size would decline at higher rates. As an approximation, retrofitting would probably begin to become an option as taxes were raised to 25 percent of variable costs per mile; the effects of extra taxes beyond 50 percent of variable costs per mile on travel and auto ownership would be quite small.

UNCERTAINTY OF THE RESULTS

As in the estimates of policy effects on travel behavior, we examine the confidence which can be placed in the results obtained in this section. The discussion is divided into two major sections corresponding to the MMY tax and the MER tax.

Effects of an MMY Tax

The estimated impacts of an MMY tax on the auto stock derive from a model of auto stock adjustments. Some of the relationships in the model are econometric estimates while others are assumptions. Each relationship is considered briefly below.

New Car Sales -- The estimates of the effects of annual taxes on new car sales derive from an assumed supply-demand structure. The key assumption is that the price elasticity of demand for new cars is -1. This assumption has been verified by careful econometric studies, but there have been estimates of automobile demand which yielded other measures of the price elasticity. Virtually all estimates fall between -.5 and -1.5.

Used Car Price -- There is less verification for the assumption made here that the elasticity of demand for used cars is -1. The one major study of the demand for cars (by Gregory Chow, *op. cit.*) yields this result.

Aggregate Scrappage Rate -- The equation used in this report is based on an ordinary least squares estimate from national data. Parameter estimates were highly significant; the coefficient of determination (R^2 corrected) was .6346, and the standard error was 11 percent. The equation was further adjusted to be applicable to the Los Angeles area where the scrappage rate due to age alone appears to be less than the national average.

Scrappage Rate by Age of Auto -- The equation for scrappage by age of auto due to age effects alone was estimated by Franklyn Walker on national data. All parameter values were highly significant (1 percent level of confidence with t-tests) and the coefficient of determination (R^2 corrected) was .9994. However, the scrappage rate was adjusted to be applied to Los Angeles, which probably increases the error associated with the equation.

Besides these relationships there several key assumptions which should be noted:

1975 Price of New Cars -- It was assumed that the 1975 price of new cars would be $3,850 on average. In fact, the price of the new models would be very difficult to predict due to the countervailing impacts of inflation and recession.

1975 Price of Used Cars -- It was assumed that the 1975 price of used cars would be $1,272 on average. However, the price of used cars is dependent to some degree on the price of new cars, which is itself largely indeterminate.

Used Car Price by Age of Car -- It was assumed that the price of used cars by age is inversely proportional to the scrappage rate by age. This assumption is somewhat arbitrary, but not unlikely. The reason older cars are scrapped at higher rates is that their value is less when repaired and maintained. Thus, there is a direct relationship between the value by age of auto and its scrappage rate. Of course, the relationship need not be one of direct proportionality as assumed here.

The quality of data also affects the confidence associated with the results. On the whole, data on the auto stock characteristics of cars in Los Angeles and Orange Counties are quite reliable; they are the result of an independent survey made annually by Polk Associates. These data are only available through July 1, 1973; the 1975 auto stock characteristics (Tables 21 and 22) are based on model simulations with 1973 data as inputs. The model as a whole was calibrated on data from Polk statistics over the period July 1, 1969 through July 1, 1973.

Data on recent emission rates and average VMT's per auto year are reasoned predictions which may be open to question. Pre-1970 emission rates are the result of actual samples taken in California.

With two exceptions, the model is applied to values of variables within the ranges of observations which were used for estimation. The exceptions are areas for concern in interpreting the results: first, the current high prices of new cars and the added ownership costs of an MMY tax may strain the assumption that the price elasticity of demand for new cars is -1; second, the aggregate scrappage rates predicted by the model become less certain as they increase past 10 percent of the auto stock. Thus, for example, the estimated effects of the high tax scenario presented in Table 26 should be viewed with less confidence than the estimates based on low taxes.

In general, the sum of the various sources of error indicates that there is significant randomness in the estimated results. However, two important results can be presumed to be reasonably robust:

The Effects of Taxes on the Size of the Auto Stock -- The model itself is relatively reliable in predicting auto stock size because the estimated or assumed relationships predict flows which are small proportions of the total auto stock size. That is, new car sales are generally less than 10 percent of the existing auto stock, and aggregate scrappage is an even smaller proportion. Also, they work in opposite directions, causing the net change to be less than their relative proportions would indicate.

Relative Scrappage Rates by Age of Auto -- The estimated relationship for scrappage owing to age alone gives very good fits to the actual data. Thus, the relative scrappage rates among age categories can be presumed to be reasonably accurate even though the predicted net aggregate scrappage rate is less reliable.

Effects of an MER Tax

As indicated previously, it is difficult to determine the effects of an MER tax on automobile ownership and VMT's by age of car. All that can reasonably be said is that the impact on auto ownership will be less than that of an equivalent MMY tax and that there will be some increase in the proportion of VMT's from newer relative to older cars. Quantitative estimates of these effects were not attempted, except to the extent that Table 27 puts an upper bound on the auto stock effects and Table 28 puts a lower bound on the VMT effects.

This uncertainty is attributable to the estimates of costs and effectiveness of retrofit devices. Though the assumptions are conservative, any single number which purports to describe the effectiveness of retrofitting for a model year is subject to considerable variability for the reasons already cited. Nonetheless, it appears reasonable to conclude that retrofitting would not be widespread at emission tax rates less than 25 percent of auto variable costs per mile, but would become prevalent before taxes reached 50 percent of auto variable costs per mile.

5. POLICY COST-EFFECTIVENESS

Each policy discussed in the previous chapters imposes a cost on individual travelers and a cost on society. As discussed in Chapter 2, these costs will differ because taxes on individuals are transfer payments rather than social costs, whereas transit improvements and program administration impose social costs. These costs are examined in this chapter. The last section of the chapter considers the effects of alternative policies on fuel consumption.

INDIVIDUAL COSTS

Individual costs due to taxes on travel (gasoline, emissions and parking taxes) include both the increased cost of auto trips from the tax and the opportunity cost associated with choosing other alternatives. The opportunity cost includes the value of additional time spent on other modes and the value of choosing less preferable destinations.

Although the theory of computing policy costs is conceptually the same for all policy scenarios (see Chapter 2 for an explanation), there are differences among the policies themselves which require that the costs be calculated in a somewhat different manner. Each type of policy (gas/emissions tax, parking tax, and gas/emissions tax with improved transit service) is considered in a separate section, and the cost-effectiveness of each is compared in a final section.

Cost to Individuals of Gas/Emissions Tax

With a gasoline or emissions tax, the good being taxed is vehicle miles traveled. Thus, the cost of this tax to motorists is that added cost per mile times the miles traveled after the imposition of the tax, plus the opportunity cost associated with fewer VMT's. For each vehicle mile traveled after the tax, the two components of the individual's costs are calculated as follows:

1) cost per vehicle mile driven = tax per mile
2) opportunity cost per vehicle mile driven =

$$\tfrac{1}{2}(\text{tax per mile})\left(\frac{\text{Change in VMT's}}{\text{VMT's after tax}}\right)$$

As described in Chapter 2, this is an approximation of the actual individual cost. In particular, relationship 2) assumes that the demand curve is linear. In the model used to compute changes in VMT's, the demand is nonlinear. However, the potential error of using this approximation is small compared to the estimated costs. It is a common procedure for computing consumer surplus.

The aggregate costs for the region are determined by multiplying each of the above components by the aggregate VMT's after the tax. Table 31 presents the costs of four tax levels, the travel effects of which were presented in Chapter 3. The data on percentage change in VMT's and aggregate VMT's for the area, both as a result of each tax level, are from Table 20. The variable cost per mile before the addition of a gasoline or emissions tax is $0.0571.

Cost to Individuals of Parking Tax

With a parking tax, the good being taxed is the auto trip (except for serve-passenger trips) rather than vehicle miles traveled. The aggregate costs to individuals in the

Table 31. COSTS TO INDIVIDUALS OF GASOLINE OR EMISSIONS TAX

Tax rate: *percentage* of variable costs per mile	Cost per vehicle mile		
	Added cost of trip taken, $/mi	Opportunity cost of vehicle miles not traveled, $/mi	Total, $/mi
25%	$0.0143	$0.0005	$0.0148
50	0.0286	0.0020	0.0306
75	0.0428	0.0043	0.0470
100	0.0571	0.0069	0.0640

Tax rate: percentage of variable costs per mile	Aggregate cost of weekday travel within Los Angeles and Orange Counties		
	Added cost of trips taken, $ thousands	Opportunity cost of vehicle miles not traveled, $ thousands	Total, $ thousands
25%	$ 828.5	$ 29.0	$ 857.5
50	1,539.7	107.7	1,647.4
75	2,153.7	216.4	2,370.1
100	2,710.7	327.6	3,038.3

region is arrived at by multiplying the added cost per trip times the auto trips (exclusive of serve-passenger trips) taken after the imposition of the tax, plus the opportunity cost of trips foregone by this mode. The two cost components are calculated as follows:

1) cost per auto trip made = parking tax
2) opportunity cost per trip =

$$\tfrac{1}{2}(\text{parking tax})\left(\frac{\text{change in number of auto trips}}{\text{number of auto trips after tax}}\right)$$

Again, this is an approximation based on the assumption of a linear demand curve.

Table 32 presents the individual costs associated with a parking tax of various levels. The effects of such a tax on travel were presented in Chapter 3. It is estimated that there were 5.397 million auto trips, other than driver serve passenger, per weekday within Los Angeles and Orange Counties in 1974. This estimate is arrived at by multiplying the share of vehicle trips which are not driver serve passenger (.985) times the estimated total of household vehicle trips. It should be remembered that this figure would include neither travel which crosses into other counties nor truck and bus travel.

The percentage change in aggregate auto trips exclusive of driver serve passenger for all trip purposes is given in Table 33. The percentage changes were calculated the way changes in VMT's and all auto trips were calculated in Chapter 3.

Costs to Individuals of Gas/Emissions Tax with Transit Improvements

The net cost of this scenario has four components:

- the increased cost per mile owing to the tax;
- the opportunity cost associated with VMT's foregone;

Table 32. COSTS TO INDIVIDUALS OF A PARKING TAX

Parking tax: parking cost increase:	Cost per trip		
	Added cost of trip taken, $/trip	Opportunity cost of trips foregone, $/trip	Total, $/trip
$0.25	$0.2500	$0.0130	$0.2630
0.50	0.5000	0.0532	0.5532
0.75	0.7500	0.1184	0.8684
1.00	1.0000	0.2040	1.2040

Parking tax: parking cost increase:	Aggregate cost of weekday travel within Los Angeles and Orange Counties		
	Added cost of trips taken, $ thousands	Opportunity cost of trips foregone, $ thousands	Total, $ thousands
$0.25	$1,209.0	$ 62.9	$1,271.9
0.50	2,124.5	226.0	2,350.5
0.75	2,769.4	437.2	3,206.6
1.00	3,195.5	651.9	3,843.3

Table 33. EFFECTS OF PARKING TAX ON AUTO TRIPS EXCLUSIVE OF DRIVER SERVE PASSENGER TRIPS

Added parking cost	Percentage change from 1974 base
$0.25	-10.39%
0.50	-21.27
0.75	-31.58
1.00	-40.79

- the benefits of improved service to bus patrons who would have taken transit in the absence of any tax on auto travel or transit improvements;
- the benefits to people who become bus patrons solely because of the transit improvements.

Extra computation is also necessary to monetize the benefits of decreased access and line-haul time associated with transit.

The individual costs per vehicle mile traveled in this scenario are the same as those calculated for the case of a gasoline or emissions tax in the absence of transit system improvements (Table 31). The aggregate costs to auto drivers are equal to aggregate VMT's after the imposition of the policies (from Table 20) times the cost per vehicle mile traveled, plus the opportunity costs associated with VMT's foregone.

It was not possible, given summary information on travel demand, to calculate the benefits of improved transit service to new and continuing riders. Also, it should be noted that the demand estimates assume no changes in fares as a result of the service improvements; thus, resource costs are passed on to individuals only to the extent that they are covered by the existing fare structure. Table 34 presents the results of computations based on the costs to motorists.

Individual Cost-Effectiveness

In order to make a comparison among the policies, the aggregate dollar costs were divided by the aggregate reduction in VMT's. The results of these computations are presented in Table 35. As expected, the parking tax is the least cost-effective method of reducing VMT's. Also, the cost-effectiveness of a gas or emissions tax shows a slight tendency to decrease as the tax is raised.

Table 34. COSTS TO INDIVIDUALS OF A GASOLINE OR EMISSION TAX WITH TRANSIT SYSTEM SERVICE IMPROVEMENTS

Transit system improvements with a tax on variable cost per mile of:	Aggregate cost to auto drivers of a weekday of travel within Los Angeles and Orange Counties		
	Additional costs for trips taken, $ thousands	Opportunity cost of miles not traveled, $ thousands	Total, $ thousands
50%	$1,427.9	$ 99.9	$1,527.8
100	2,294.8	277.3	2,572.1

Table 35. COST TO INDIVIDUALS PER VMT REDUCED
($/mile)

Gas or emissions tax: variable cost per mile increase	Cost per mile reduction
25%	$0.1852
50	0.1886
75	0.1935
100	0.2012
Parking tax: parking cost increase	
$0.25	$0.4033
0.50	0.3922
0.75	0.3921
1.00	0.3985
Transit system improvements with variable cost per mile increase	
50%	$0.1208
100	0.1149

RESOURCE COSTS

The resource costs of the policies include opportunity costs of trips foregone, costs of bus service improvements and costs of administering tax programs. Opportunity costs were calculated in the previous section. In this section bus costs are calculated and administrative costs are discussed. The section concludes with an evaluation of the cost-effectiveness of the policies from the standpoint of resource costs.

Bus Costs

The bus network changes were specified in Chapter 3. Briefly, they consisted of adding new bus routes to zonal interchanges where more than 100 auto trips had been diverted by the policy; for every 300 auto trips diverted a new bus route was designed. For every 75 auto trips diverted in a zonal interchange during peak hours, an additional bus trip (with two loadings) was installed. For off-peak travel, additional bus trips were instituted for every 50 auto trips diverted and a new route was designed for every 200 auto trips diverted. Peak travel was simulated with work trips, and off-peak travel was simulated with shopping trips.

For any policy which induces greater bus ridership, there is the problem of determining whether additional capacity will be necessary in order to serve the added passengers. Thus, though no bus system improvements were specified in some of the auto tax scenarios, it is likely that their effectiveness assumed added capacity in the existing system. Similarly, in the scenario where added bus service is coupled with an auto travel tax, the combination of the two policies yields greater additional transit ridership than the initial increase in capacity.

The additional capacity which may be necessary to meet induced demands is not considered in the calculations which follow. The cost calculations are only based on the assumed network changes specified above. If there is no excess capacity in the existing system, then the costs estimated below may underestimate somewhat the costs associated with additional bus capacity to serve diverted motorists.

The bus costs were calculated as follows:

- The network changes in the samples of zonal interchanges were put into terms of additional annual bus hours, annual bus miles, and buses needed in order to provide the service (see Appendix C); it is assumed that only peak travel entails additional buses and, consequently, off-peak travel uses the additional bus capacity needed for the peak.
- The annual bus hours, annual bus miles, and buses needed for peak travel were expanded to give the values for serving all of Los Angeles and Orange Counties by multiplying the sample values times the total number of trips. The latter is obtained from the sample size in the following way:

$$\text{sample size} = \frac{\text{number of trips sampled}}{\text{total trips}}$$

$$\text{total trips} = \frac{\text{number of trips sampled}}{\text{sample size}}$$

- The annual bus hours and annual bus miles for off-peak travel were expanded to the values for all of Los Angeles and Orange Counties in the same way as for peak hour travel.
- The aggregate annual bus hours, annual bus miles and buses for peak and off-peak travel in Los Angeles and Orange Counties were used in the incremental bus cost function estimated in Appendix C which computes the

additional 1974 annual cost of the improved bus service. (Cost per weekday is determined by dividing annual cost by the weekday factor of 351. This is a factor used by the SCRTD.)

The sample size of peak-hour trips is determined by dividing the number of trips in the CRA sample of work trip zonal interchanges by the total estimated peak-hour trips in Los Angeles and Orange Counties for 1974. Estimated in this way, the peak-hour sample size is 4.55 percent of total peak-hour trips. The off-peak sample size is similarly calculated as 2.47 percent of total off-peak travel. Peak-hour travel is assumed to be work and education-related; off-peak travel includes all other purposes.

Table 36 presents the estimates of bus system changes and resulting costs for Los Angeles and Orange Counties resulting from the above procedures.

Emissions Test

As mentioned in Chapter 2, an emissions tax based on actual annual pollution (an MER tax) requires testing facilities and an administration to oversee the inspection and tax collection system. (It can be presumed that the added administrative expenses of a gasoline tax will be negligible compared to the other costs in this chapter. A parking tax would require some administrative and enforcement expense, but we will not attempt to estimate these in this chapter.) These expenses represent resource costs which should be estimated in order to infer the cost effectiveness of an MER tax.

Because there is no experience with testing facilities of the scale necessary to monitor all cars in the Los Angeles-Orange County area, actual figures on costs are highly speculative. We will start with the 1971 estimates for California (given in Chapter 2) of $1.05 per vehicle

Table 36. COSTS OF BUS SERVICE IMPROVEMENTS FOR TRAVEL WITHIN LOS ANGELES AND ORANGE COUNTIES

Annual Changes in System

Transit system improvements with auto variable cost per mile increase of:	Bus miles per year, thousands	Bus hours per year, thousands	Number of Buses
50%	30,618	2,205	800
100	66,995	4,700	1,774

Costs of Changes

Transit system improvements with auto variable cost per mile increase of:	Annual, $ thousands	Weekday, $ thousands
50%	$ 63,676	$181.4
100	114,681	326.7

inspection cost and an initial start-up cost of $19,830,000.[r] The 1974 cost per vehicle inspection on a smaller scale for Los Angeles-Orange Counties would be about $2.00 per test. Start-up and administrative costs, annualized over the life of the program, can be assumed to add another $2.00 per vehicle per year in the area where the program is applied.

In sum, if two inspections per year are required, the total cost of administering the program would be on the order of $6.00 per vehicle per year. Using the CRA estimate of 4,166,288 vehicles in Los Angeles-Orange Counties in 1974, these assumptions lead to an annual program administration cost of $25 million. Put on comparable weekday terms (dividing by 351) of the other costs in this chapter, the cost is $71 thousand.

Resource Cost-Effectiveness

To compare the policies in terms of social costs, the aggregate resource costs of each were divided by the aggregate reduction in VMT's. Table 37 presents the results of these calculations. Several important caveats must be kept in mind in order to interpret these results appropriately. In particular, the following biases affect the figures given in Table 37:

- In comparing the emissions tax and gas tax costs, VMT's are an inappropriate measure of effectiveness; an emissions tax of equal proportion to a gas tax will cause significantly lower pollution levels because of its greater impact on lowering VMT's of older, higher polluting automobiles (see Chapter 4).
- The parking tax scenario does not include the costs of administering and enforcing a parking tax program.
- The net costs of transit system improvements do not include the benefits to ongoing patrons of improved

Table 37. RESOURCE COST PER VMT REDUCED

Policy	Aggregate resource cost per weekday, $ thousands	Cost per mile reduction
Gas tax: Variable cost per mile increase		
25%	$ 29.0	$0.0063
50	107.7	0.0123
75	216.4	0.0177
100	327.5	0.0217
Emissions tax: Variable cost per mile increase		
25%	$100.2	$0.0216
50	178.9	0.0205
75	287.6	0.0235
100	398.8	0.0264
Parking tax: Parking cost increase		
$0.25	$ 62.9	$0.0199
0.50	226.0	0.0377
0.75	437.2	0.0535
1.00	651.9	0.0675
Transit system improvements with gas tax: Variable cost per mile increase		
50%	$289.1	$0.0229
100	654.3	0.0292
Transit system improvements with emissions tax: Variable cost per mile increase		
50%	$360.3	$0.0285
100	725.5	0.0324

service, nor do they include costs of additional capacity which may be necessary to serve induced demand.

In addition to the above qualifications, there are uncertainties in the estimates owing to the predictions of VMT reductions (see Chapter 3), the approximate nature of the opportunity cost estimates, and the lack of validation of assumed costs for administering an emissions inspection program.

Given these sources of error in the cost-effectiveness computations, it is somewhat difficult to draw definitive conclusions comparing the policies. Nonetheless, it appears that a parking tax is the least preferable policy on grounds of cost-effectiveness. More information is necessary to distinguish among the other policies (see Chapter 6), but it should be noted that the cost of bus service improvements is not inconsiderable -- it adds probably about 50 percent to the cost per VMT reduced when conjoined with other policies.

FUEL CONSUMPTION EFFECTS

This section computes some of the impacts on fuel consumption which can be attributed to the policies. Typically, disincentives to automobile travel can be expected to decrease fuel consumption. Table 38, using U.S average miles per gallon figures, shows how much gasoline can be saved in Los Angeles and Orange Counties as a result of the various tax policies. The table also presents the increased fuel consumption due to the assumed changes in the bus network.

The effect of retrofitting on fuel consumption has two impacts which cause the estimates in Table 38 of fuel savings due to emissions taxes to be misleading:

Table 38. FUEL CONSUMPTION CHANGES AS A RESULT OF THE POLICIES: LOS ANGELES AND ORANGE COUNTIES

Policy	Passenger car gasoline consumption decline weekdays, 10^3 gallons/day[a]	Percent change in VMT's	Bus diesel fuel consumption increase weekdays, 10^3 gallons/day[b]
Gas or emissions tax: Increase in auto variable costs per mile			
25%	338.92	- 7.40%	
50	639.40	-13.96	
75	896.77	-19.58	
100	1105.17	-24.13	
Parking tax: Increase in parking costs			
$0.25	230.87	- 5.04%	
0.50	438.76	- 9.58	
0.75	598.63	-13.07	
1.00	706.75	-15.43	
Transit system improvements with increase in auto variable costs per mile:			
50%	925.61	-20.21%	13.43
100	1638.29	-35.77	29.39

[a]Miles per gallon for passenger cars equals 13.67, from *Statistical Abstract of the United States.* Washington, D.C., Government Printing Office, 1973.

[b]Miles per gallon for buses equals 6.49, from U.S. Department of Transportation. *Characteristics of Urban Transportation Systems.* Washington, D.C., Government Printing Office, March 1974.

- If retrofitting occurs on a massive scale (say, after a 50 percent tax on auto costs per variable mile) then the VMT reduction estimated by the travel demand model will be seriously overstated.
- Retrofitting with catalytic reactors (for CO and HC) causes a decrease in the fuel economy of cars on the order of 3 to 4 percent.

List of References, Chapter 5

[1] *Mandatory Vehicle Inspection and Maintenance, Part A -- A Feasibility Study, Volume I: Summary.* Northrup Corporation, in association with Olson Laboratories. Prepared for State of California Air Resources Board. June 1971.

6. CONCLUSIONS

This chapter reviews the major conclusions from the preceding chapters, discusses other factors in assessing the pollution control strategies, and recommends fruitful areas for future research.

The results of Chapters 3, 4 and 5 suggest the following conclusions:

- In the short run a gasoline or MER tax is more cost-effective in reducing VMT's than a parking tax.
- Taxes based on emission rates of cars (MER and MMY) will have a large impact on the age distribution of cars and some impact on the distribution of VMT's by age of car.
- Emission taxes between \$0.015 and \$0.03 per mile will induce retrofitting.
- Improving transit lowers the individual's travel cost for pollution control but increases the cost to society.
- For individuals, the cost per VMT reduced of all strategies except parking taxes varies from \$.10 to \$.20 per mile; for parking taxes, the costs are around \$.40 per mile, depending on the size of the tax.
- The resource costs per VMT reduced of all strategies except parking taxes varies from \$.015 to \$.035 per mile; for parking taxes, the costs are around \$.05 per mile.

We next turn to a consideration of other issues which are important in determining optimal pollution control strategies.

NONQUANTIFIED FACTORS

We stress that the results of the foregoing analysis of policy effects and costs should be placed in the context of certain factors not quantified in this report to give a balanced evaluation of the alternative strategies.

These factors are the incidence of taxes across income groups, the feasibility and phasing of policies, and the land use impacts of taxes on auto travel. Most of these issues require more research in order to evaluate completely the proposed pollution control strategies. However, the qualitative discussion presented below will help clarify the issues and show the interrelationships among the pollution control strategies and the diverse impacts of transportation system changes.

Incidence of Costs

Most tax schemes either explicitly or implicitly affect income groups differently; the tax proposals reported in this study are no exception. As a general rule, excise taxes on nonluxury consumer goods are regressive -- the poor pay a higher percentage of their income than the rich. This is particularly true when the good bearing the tax has a relatively inelastic price demand, as is the case with auto travel. In the short run, VMT's can be reduced by individuals, but on average this does not recoup their increased total cost of auto travel.

Though low income groups can, and often do, use their cars less, their total cost of auto travel is greater in proportion to their income than is the case for high income groups. Thus, it can be expected that gas, emission and parking taxes will consume a higher proportion of income for low income households.

Taxes which increase with respect to the age of cars, such as emissions rate based taxes, would also tend to be regressive. Higher income families owning more than one car will be able to use the newer, lower-taxed cars more intensively. Low income families will, on average, not have as much freedom of choice because they will not be multicar households and will probably tend to own older models.

To ameliorate the regressive aspects of emissions control taxes, policies can be introduced which either redistribute income through other taxes or give more options to families in their travel decisions. Generally, the former approach is preferable, if it is feasible. However, the ability of local governments to impose income redistribution tax schemes is severely limited. An example of another approach is to improve transit service, perhaps using the ample revenues from emissions control taxes.

Feasibility and Phasing of Policies

There is some question as to whether certain policies are feasible and, when more than one policy is considered in the overall strategy, whether there should be a lag between implementation of various policies. As noted in Chapter 2, there may be considerable technical, enforcement and administrative obstacles to certain strategies. Also, because the effectiveness of the policies in reducing emissions tends to decline as new cars meet stricter standards, there is a need for the policy to be quickly implemented and then dismantled, perhaps gradually, in order to capture short-run benefits without incurring long-run costs.

As noted in Chapter 2, parking taxes should cover all trip purposes and land use categories, except residential, in order to be effective. Otherwise, enforcement is impractical and trips can be made without incurring the tax penalty, thereby leading to less (if any) reduction in VMT's.

Yet such a broadly based tax would be difficult to administer because of the dispersion and number of parking facilities, including the potential for onstreet parking.

Also as noted in Chapter 2, there is some dispute as to whether an emissions tax based on inspections of vehicles is technically feasible. Current experience with safety inspections suggests that the scale of the system is not a problem. The major issue seems to be the existence of relatively low-cost, simple and reliable emissions tests. Some sources claim that such tests now exist, but there is little experience with them in terms of the routine processing of 4 million or more vehicles a year -- the current size of the Los Angeles fleet.

Since improvements in the bus system may be a necessary policy step before the imposition of taxes or other constraints on automobile travel, some attention must be given to the delays entailed in adding to bus system capacity. Owing in part to federal funding procedures, it now takes about a year to obtain conventional buses. A large order could cause considerably more delays. The additions to the fleet contemplated in this report could not, in all probability, be made in less than 18 months. Some improvements in bus service can begin earlier with certain steps, such as mobilizing used buses, as the Southern California Rapid Transit District did recently. Nonetheless, potential bottlenecks in improved transit service would require interfacing among various agencies in order to implement policies in an orderly fashion.

Finally, it is important to realize that the emissions rate from the auto stock decreases over time, and in the relatively near future (such as the early 1980's), it may reach acceptable levels. If this is indeed the case, the policies which might entail low annual costs but high initial costs should be avoided. In particular, transit system improvements with high initial capital expense and with long recovery periods (such as rapid rail) are not cost-effective in this scenario, even though they may bring considerable auto trip diversion. Certain transit improvements may not even be implementable in the time period which is required for pollution abatement benefits to be gained. This is not to say that these transit system changes should not be made, but rather that in their evaluation their pollution control benefits should be discounted heavily.

A similar problem arises with tax policies not directly related to the rate of emissions from automobiles. There would be a strong tendency to keep a gasoline or parking tax for general public revenue purposes even after the pollution control benefits of the tax had declined.

Land Use Effects

Increasing costs of travel, if permanent, may have significant long-run effects on urban form. Unfortunately, there is only limited understanding of the interrelationships between transportation system changes and general urban land use impacts; the small amount of theoretical and empirical literature on the subject is oriented toward cities with strong cores, unlike Los Angeles. Nonetheless, some inferences about location decisions can be made based on the assumption that households and businesses will tend to reduce superfluous travel owing to increased costs of auto trips.

In Los Angeles, work trips are typically longer than trips for other purposes; for example, work trips average about 14 miles, round trip, whereas shopping trips are between four and five miles, round trip, on average. Taxes on miles traveled, such as either a gas or emissions tax, would tend to increase the cost of a work trip relative to a shopping trip. This realignment in the relative costs of travel would cause households and employers to tend to move closer together. Because households have more flexibility in location, the tendency would be for higher density residential development located closer to the many employment centers in the area. Such a migration would accentuate the current trend in Los Angeles toward multifamily dwellings.

Retail centers tend to be as dispersed as households; it is apparent from the data in the 1967 LARTS Household Trip Survey that most families shop within a five-mile radius of their homes. This suggests that there would be some relocation of retail land use if household dwelling patterns change. Because the present land use system in Los Angeles appears to be most beneficial for shopping trips -- these trips tend to be shorter, hence less expensive, than trips for other purposes -- the effects of the taxes on retail location in the absence of any tax-induced residential changes would be slight.

Finally, it should be noted that land use changes will be lessened if households feel that the pollution controls on travel are of relatively short duration. For example, an emissions tax may increase the cost of auto travel for most families for only a few years; after that, the new and cleaner autos available will lower the cost of travel, thereby causing travel patterns to return to those which currently obtain. The locational advantage of dwellings closer to employment centers will consequently decline.

SHORT-TERM RESEARCH RECOMMENDATIONS

In addition to the issues discussed above, there are other areas of study which are potentially important in equipping policy makers with the information necessary to develop motor vehicle pollution control policies.

These studies involve the evaluation of other strategies to control mobile source emissions. We first examine the subjects and then briefly describe issues related to research design.

Additional Strategies

An important area of research involves the evaluation of transportation other than the private automobile. As mentioned above, these additional systems should involve low initial capital outlays and be readily available for implementation.

An integrated feeder and line-haul bus service where the feeder portion is paratransit may have these characteristics. The initial capital cost of a paratransit vehicle is about half that of a conventional bus (the service life is also about half that of conventional buses; see Appendix C) Paratransit tends to be much more costly per passenger mile than a conventional bus largely because of the lower passenger-to-driver ratio. However, the service is also of higher quality, and some of the increased cost can be recovered by charging higher fares for the extra convenience.

Little is known about the characteristics of an integrated feeder and line-haul bus system on the scale necessary to serve and connect all the more densely populated portions of Los Angeles and Orange Counties. Most existing systems are on a demonstration project basis, and thus users view them as a risky future alternative; consequently, the service has had little impact on automobile ownership and other factors which would increase patronage over time.

The line-haul portion of the trip for such a service involves express buses. Such buses may have their own facility (as does the El Monte express run by the SCRTD) and their own right of way on existing freeways, or they may simply compete with autos for freeway space. The first alternative may improve the commuting time of bus passengers because the buses would not be slowed on portions of freeways which are currently congested at peak periods.

An advantage of bus rapid transit is that it requires relatively low initial funding unless stations and separate graded right-of-ways are deemed necessary. An express bus costs less than a conventional bus, though it has a shorter service life (see Appendix C). It also has the benefit of substituting for relatively long auto trips, which would incur the greatest penalty from the imposition of a gas or emissions tax, and offer the greatest potential for reducing VMT's. The express bus would do little for shopping trips or other trips of intermediate to short range distance.

Auto travel controls are another area of potentially useful research. These are measures which would encourage carpools and/or reduced auto travel. There is an intuitive appeal in avoiding severe constraints, such as gas rationing without white markets, because such controls in other markets have tended to result in severe resource misallocation. The effect of national gasoline rationing and regulations in the winter of 1974 is a case in point. Yet it must be admitted that there is very little research on the costs and effects of such controls.

One travel control now in use in Los Angeles is freeway monitoring at certain entry points. To the extent that such a control is used to restrict access to freeways, it raises the costs of auto travel and may reduce VMT's. However, there are potentially counter-productive effects if auto drivers choose to use unlimited access, more circuitous routes in order to attain their destinations.

Policies overtly designed to increase carpooling have not yet received thorough analysis. It appears from previous experience that simply attempting to market carpooling through public awareness campaigns and passenger matching programs has little impact on overall auto occupancy rates. Merely increasing the costs of auto travel through gas or emissions taxes may provide the most effective incentive to carpool.

Research Design

The conceptual approach for evaluating the above strategies is similar to the one used in this report: travel demand and system performance are equilibrated using assumed effects of a policy on system performance variables (see Chapter 2). Under the presumption that an appropriate travel demand model exists, the important gap in our knowledge is the system performance characteristics of paratransit, express bus, and travel controls, such as freeway monitoring.

Demand and system performance models for policy evaluation of these strategies have data requirements similar to those utilized in this report. It is also good research strategy to have information which validates the model predictions.

Appendix A. TRAVEL DEMAND MODEL

This appendix explains the travel demand model used in the evaluation of policies in Chapters 3, 4 and 5. The actual estimates of individual choice probability functions are first presented. An approach is then developed to apply these probability functions to zonal aggregates of travel behavior and system performance; the resulting model predicts interzonal travel patterns under assumed policy scenarios. This model is tested for consistency against 1967 Los Angeles Regional Transportation Study data to determine the level of certainty which can be placed on the results of its application.

As explained below, the estimates of individual choice behavior need to be adjusted in order to apply the model to data of the zonal interchange level of observation. This is commonly called the aggregation problem -- namely, that variation of attributes among individual travelers in a zonal interchange biases forecasts made with zonal data. The approach taken to reduce this bias involves making a Taylor's series expansion about the mean of the zonal values of independent variables (system performance and socioeconomic variables) in order to approximate the expected frequency of travel by mode and destination for each zonal interchange. The Taylor's series approximation requires estimation of variances and covariances among the independent variables in the model. These estimates are made using assumed probability distribution functions for system performance variables and census data for socioeconomic variables.

The adjusted model is then tested for consistency against 1967 LARTS Household Trip Survey data. Several new modes are added to the original model to account for carpools, driver serve passenger trips and walking trips. The model is used to predict round trips by mode for work and shopping. This procedure yields accurate forecasts of auto trips and vehicle miles traveled.

THE CRA DISAGGREGATED DEMAND MODEL

The estimated relationships in CRA's disaggregated demand model are presented in Table 39. The numerical terms and coefficients in the equations were estimated from data on individual trips made in Pittsburgh in 1967. The model is behavioral in the sense that the estimated parameters should apply to individuals regardless of location. It is policy sensitive in that demand for travel is a function of system performance variables.*

Each estimated relationship gives the ratio of probabilities (or the odds) between choosing two alternatives. This ratio is determined by a comparison of the attributes of the alternatives. In the case of mode choice (Equation 13 for work and 14 for shopping), the relative level of service associated with each mode (auto or transit) determines the odds. For choice of shopping destination (Equation 15), a comparison is made between the costs of travel to the destinations and between the shopping opportunities available at each destination. The odds of taking one trip versus no trip (Equation 16) depend on a comparison

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*Other than the cursory comments contained in this section, we will not describe the estimation of the model or many of its properties. For a complete analysis, see Domencich, Thomas A., and Daniel McFadden. *Urban Travel Demand: A Behavioral Approach.* Amsterdam, North-Holland, 1975. 215 p.

Table 39. ESTIMATED RELATIONSHIPS IN CRA DISAGGREGATED DEMAND MODEL

Work Modal Split

$$\ln \frac{P(A:i,j)}{P(B:i,j)} = -4.77 - 2.24(C_{Aij} - C_{Bij}) - .0411(T_{Aij} - T_{Bij})$$

$$- .114(S_{Aij} - S_{Bij}) + 3.79Y \qquad (13)$$

Shopping Modal Split

$$\ln \frac{P(A:i,j)}{P(B:i,j)} = -6.77 - 4.11(C_{Aij} - C_{Bij}) - .0654(T_{Aij} - T_{Bij})$$

$$-.374(S_{Aij} - S_{Bij}) + 2.24Y \qquad (14)$$

Shopping Destination

$$\ln \frac{P(j:i)}{P(k:i)} = -1.06(X_{ij} - X_{ik}) + .844(E_j - E_k) \qquad (15)$$

Shopping Frequency

$$\ln \frac{P(1:i)}{P(0:i)} = -1.71\overline{X}_i + 3.90\overline{E}_i \qquad (16)$$

Identities

$$X_{ij} = P(A:i,j)(4.11C_{Aij} + .0654T_{Aij} + .374S_{Aij})$$

$$+ P(B:i,j)(4.11C_{Bij} + .0654T_{Aij} + .374S_{Aij}) \qquad (17)$$

$$\overline{X}_i = \sum_j P(j:i)X_{ij} \qquad (18)$$

$$\overline{E}_i = \sum_j P(j:i)E_j \qquad (19)$$

Table continued on following page.

Table 39 (continued). ESTIMATED RELATIONSHIPS IN CRA DISAGGREGATED DEMAND MODEL

Variable Definitions

$P(A:i,j)$ = probability that an individual will choose auto for a given round trip between origin i and destination j for a given purpose.

$P(B:i,j)$ = probability that an individual will choose transit for a given round trip between origin i and destination j for a given purpose.

C_{Aij} = variable costs per mile for a round trip by auto between i and j.

C_{Bij} = total fares for a round trip by transit between i and j.

T_{Aij} = total travel time, excluding walk time, for a round trip by auto between i and j.

T_{Bij} = total line-haul and wait time for a round trip by transit between i and j.

S_{Aij} = total access (walk) time to auto for a round trip by auto between i and j.

S_{Bij} = total access (walk) time to transit for a round trip by transit between i and j.

Y = number of autos per trip maker.

$P(j:i)$ = probability that an individual will choose destination j for a round trip by any mode from origin i for shopping purposes.

X_{ij} = generalized cost of travel between i and j for an individual making a round trip for shopping purposes.

$P(0:i)$ = probability that an individual at i will make no round trip for shopping purposes in a given 24 hour period.

$P(1:i)$ = probability that an individual at i will make a round trip to any destination for shopping purposes in a given 24 hour period.

Table continued on following page.

Table 39 (continued). ESTIMATED RELATIONSHIPS IN CRA DISAGGREGATED DEMAND MODEL

Variable Definitions (Continued)

E_j = proportion of retail employment in zone j relative to total retail employment in the region.

$\overline{X}_i$ = generalized cost of travel to all destinations from i for an individual making a round trip for shopping purposes.

$\overline{E}_i$ = generalized availability of shopping opportunities for an individual in zone i.

between the generalized costs and opportunities associated with the trip as opposed to the zero costs and opportunities which occur when no trip is made.

The probability of an individual choosing any given alternative can be calculated from the following formula:

$$P(a) = \frac{1}{1 + \sum_{\substack{b=1 \\ b \neq a}}^{n} e^{-Y_{ab}}} \qquad (20)$$

where a is one among n alternatives and Y_{ab} is the function comparing costs and attributes of alternatives a and b. One may view Y_{ab} as the right hand side of estimated Equations 13 through 16, depending on whether the choice set is mode, destination or frequency.

The model as estimated has three major limitations in application to the policy options addressed in this report:

1. The mode split equation was estimated for only two alternatives -- auto driver and transit.
2. There are demand relationships for only two (round) trip purposes -- home-to-work and home-to-shop.
3. The model cannot be directly used to predict zonal aggregate behavior unless data on individuals are available.

The second and third problems are considered in later sections of this appendix. The first problem is discussed below.

Since mode choices are restricted to the two alternatives represented in Equations 13 and 14, the model will not accurately predict the range of modes resulting from a policy which significantly alters system performance. This is especially pertinent in the case of work trips, where destination and frequency are assumed to remain unchanged in the short run. It is reasonable to suspect, for example, that an increase in the variable costs per mile of an auto trip will cause more walking trips and carpooling besides diverting motorists to transit. Also, a parking tax would probably cause more driver serve passenger (chauffeured) trips.

To consider these new modes, it is necessary to construct new comparison functions, Y_{ab}. These functions are formed by attributing to each new mode a variable cost per mile, a time spent in vehicle and waiting, and a walk or access time for round trips between each i,j zone pair. Each of these trip system performance variables could then be substituted for their transit counterparts in Equations 13 and 14 to derive the odds between choosing auto drive alone and a given new mode. Using Equation 20 one could derive the probability of choosing a given alternative over all other modes -- auto drive alone, transit, carpool, serve passenger and walking. The actual calculations and assumptions used in specifying the attributes of new modes are presented in a later section of this appendix.

APPLICATION OF THE MODEL TO ZONAL AGGREGATES

The disaggregated demand model has been estimated on individual household data and is most appropriate when used to predict the individual probabilities of a household's choice among alternatives. However, most existing transportation data sets only maintain data at the aggregate or zonal level. Even if household data existed, the attributes of all alternatives are generally not specified at the household level. If one wishes to develop a technique for analyzing the effects of pollution control strategies which can be generalized over urban areas, it is advisable to derive behavioral equations capable of being applied to zonal aggregations of data.

Approximation of Zonal Frequencies

Consider an individual t choosing among n alternatives (mode, destination, etc.). The multivariate, multinomial logit model estimate of t's probability of choosing alternative a (using notation similar to that presented in Equation 20) is the following:

$$P_t(a) = \frac{1}{1 + \sum_{\substack{b=1 \\ b \neq a}}^{n} e^{-Y_{ab}}} \tag{21}$$

where Y_{ab} is the "comparison" function between choices a and b. We will return to this function later. For our purposes, it is necessary to have an estimate of the total number of choices of a, such as auto trips per 24-hour period N in a zone of T individuals:

$$N_a = \sum_{t=1}^{T} P_t(a) \tag{22}$$

when the only information we have about the argument of the Y's is their means for the zone and, perhaps, the variances and covariances of the terms in Y. There is no analytical form which translates this information into an estimate of N_a.

Qualitatively, the problem is that the zonal means of, say, system attributes cannot simply be used in Equations 13 and 14 in order to compute the average, or expected, probabilities among mode choices for individuals in a given zone. Such an approach would tell us the choice an individual would make if he were confronted with that system performance for alternative modes which is the zonal average. However, individuals in a given zone face a great many different levels of system performance, and their choices vary accordingly. When there is such intrazonal variation, it is unlikely that the expected value of an individual's choice will equal the choice made when confronted with the average system performance throughout the system.

To take a pertinent example, consider the access time to transit for a given origin zone. If bus routes through a zone are relatively few, then the average distance of households from a bus stop may be quite large, especially in the zones in the LARTS region which are typically twenty-five square miles. Average access time may easily be on the order of thirty minutes each way. An individual who faces a thirty minute walk to the bus has virtually zero probability of taking transit. Thus the predicted mode split for such a zone would be negligible. Yet there are a number of households who live relatively close to bus stops, say within a ten minute walk, and for whom transit may consequently be an attractive alternative. Thus the observed mode split for transit, though small, would be greater than the predicted mode split, unless the model were adjusted.

In order to develop an approximation to N_a, first note that:

$$N_a = T \cdot E[P_t(a)] \tag{23}$$

where the E operator stands for the expected value of the term in brackets. We use the following Taylor's series:[1]

$$P(a|Y) = \frac{1}{1 + \sum_{b=1}^{n} e^{-\overline{Y}_{ab}}} + \sum_{b=1}^{n} \left[\left(Y_{ab} - \overline{Y}_{ab}\right) \cdot \frac{\partial \left(\dfrac{1}{1 + \sum_{c=1}^{n} e^{-Y_{ac}}} \right)}{\partial [Y_{ab}]} \right]_{\substack{b \neq a \\ c \neq a}}$$

$$+ \sum_{b=1}^{n} \left[\frac{\left(Y_{ab} - \overline{Y}_{ab}\right)^2}{2} \cdot \frac{\partial^2 \left(\dfrac{1}{1 + \sum_{c=1}^{n} e^{-Y_{ac}}} \right)}{\partial [Y_{ab}]^2} \right] + R_n \tag{24}$$

where Y is a vector of the attributes of all modes confronting an individual and $P(a|Y)$ is the probability of choosing a. A bar over a variable indicates the mean; all derivatives are calculated at the mean of the Y_{ab}'s. R_n stands for the remaining terms of the series.

The second order partials will thus be functions of the probabilities evaluated at $\overline{Y}$:

$$\frac{\partial^2 \left(\dfrac{1}{1 + \sum\limits_{\substack{c=1 \\ c\neq a}}^{n} e^{-Y_{ac}}} \right)}{\partial (Y_{ab})^2} = P(a|\overline{Y}) \left[2P(b|\overline{Y})^2 - P(b|\overline{Y}) \right] \tag{25}$$

By taking the expected value of Equation 24 and truncating R_n (which will be considered later), the following operational expression is derived:

$$E[P(a|Y)] = P(a|\overline{Y}) \cdot \left[1 + \sum_{\substack{b=1 \\ b\neq a}}^{n} var[Y_{ab}] \cdot P(b|\overline{Y}) \cdot (P(b|\overline{Y}) - \tfrac{1}{2}) \right] \tag{26}$$

Estimation of Variance-Covariance Terms

Consider the comparison function, Y_{ab}. There are three distinct functional types corresponding to mode choice, destination choice, and frequency of trips. Of initial interest are the mode choice probabilities; for these the functional form of Y is:

$$Y_{ab} = \alpha_0 + \alpha_C(C_a - C_b) + \alpha_T(T_a - T_b) + \alpha_S(S_a - S_b) + \beta O \tag{27}$$

where $C.$ = operating cost of the trip;

$T.$ = waiting and line-haul time of the trip;

$S.$ = walk time for the trip;

O = availability of an automobile;

$\alpha.,\beta$ = estimated constants;

a,b = mode indices.

For this equation there are 28 possible variance-covariance terms. Fortunately, about half can be presumed to be zero because of stochastic independence or constancy over a zone. Of the others, one may assume that many are proportional to, or simple functions of, the variance of the distance traveled in a zone interchange.

One cannot be very precise in measuring the variance in distance in zonal interchanges with the available information. The approach here is to assume that distances (or origin and destination points) are distributed over the area of a zone pair according to a well defined probability density function. This approach ultimately allows estimates of the variance of distance as a function of the areas of the two zones in a given zonal interchange.

Density Function for Trip Distances -- There are a large number of potential probability density functions which one can assume for this problem. Several of these -- including exponential distributions and the rectangular distribution -- were investigated in some detail, and the probability density function described below appeared to give the best results.

In deriving the appropriate density function, it was presumed that, for a given zone pair, trips are distributed over a range which reflects both the distance between the zone centroids (geographic centers) and the sizes of the zones. In symbols:

$$D \; \varepsilon \; \left(D' - \frac{Y_i + Y_j}{2} \, , \; D' + \frac{Y_i + Y_j}{2} \right) \tag{28}$$

where D = a stochastic variable representing distance between zone i and zone j for person trips;

D' = the distance between the geographic centers of zones i and j;

Y_i, Y_j = some measure of the size of zones i and j (to be considered in more detail later.)

We now introduce another stochastic variable, X, which takes on values in the range from 0 to $Y_i + Y_j$. The distance for any trip can then be represented by the sum of two variables; one represents the distance between zones and is nonstochastic, and the other distributes trips within zones and is stochastic:

$$D = \left(D' - \frac{Y_i + Y_j}{2} \right) + X \tag{29}$$

Another way of viewing the above relationship is to consider that trips must travel a minimum distance (the term in parentheses) but that the rest of the distance varies randomly between zero and $Y_i + Y_j$.

The next problem is to determine the variance of D. Note that:

$$\begin{aligned} var[D] &= E[D^2] - (E[D])^2 \\ &= E[X^2] - (E[D])^2 \end{aligned} \tag{30}$$

The distribution function which has been assumed for X is:

$$f(X) = \frac{3}{2(Y_i + Y_j)} - \frac{X}{(Y_i + Y_j)^2} \tag{31}$$

$$\text{for } 0 \le X \le Y_i + Y_j$$

Though this formula is rather uncommon, it seems well suited for distributing trip lengths. Its graph is depicted in Figure 3.

The premise of the density function is that the distribution of trips can be approximated by a linear declining over the relatively short range bounded by Y_i+Y_j. The first two moments about zero of the distribution are:

$$E(X) = \frac{5(Y_i+Y_j)}{12} \tag{32}$$

$$E(X^2) = \frac{(Y_i+Y_j)^2}{4} \tag{33}$$

From Equation 31 the variance of distance can be calculated from the above moments:

$$var[D] = var[X] = \frac{11(Y_i+Y_j)^2}{144} \tag{34}$$

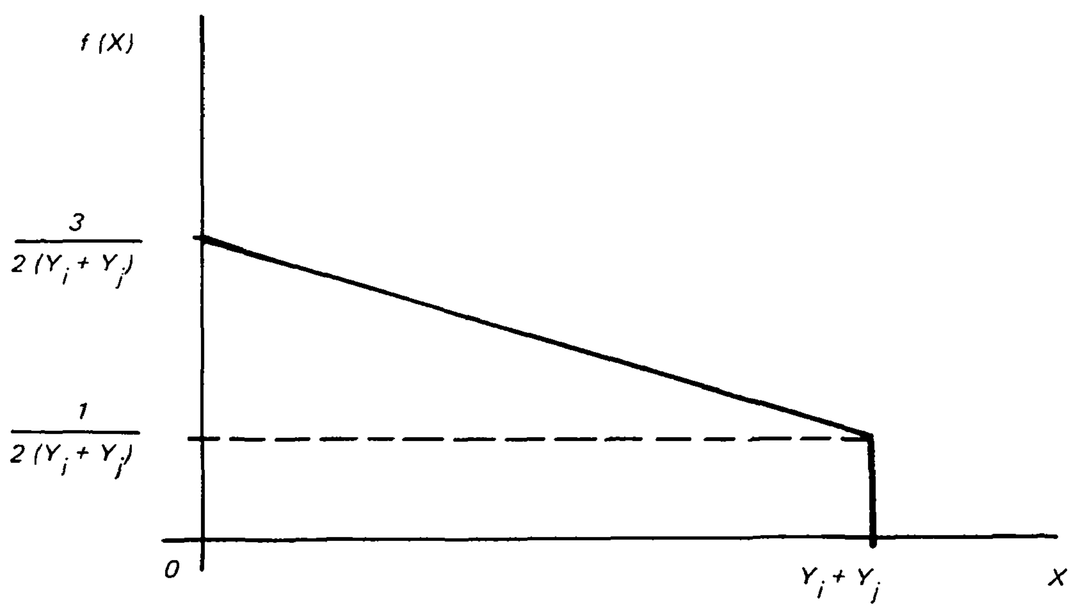
The measures of zone size over which trips are distributed should reflect the "length" of the zone. An intuitive measure of length, appropriate to square-shaped zones, is the square root of area. This leads to the following formula for variance of distance:

$$var[D] = \frac{11(\sqrt{A_i} + \sqrt{A_j})^2}{144} = \frac{11(A_i + 2\sqrt{A_iA_j} + A_j)}{144}, \quad i \neq j \tag{35}$$

In the range of zone sizes generally found in Los Angeles and Orange Counties -- 12 to 40 square miles -- the range of variance within zones is about 4 to 12 square miles.

Figure 3

The distribution function for distance of trips between zones



For intrazonal trips, the above equation must be modified to account for the stochastic part of the range being only half, on average, that of interzonal trips. This leads to the following relationship:

$$var[D] = \frac{11A_j}{144} \text{ for intrazonal trips in zone } j. \qquad (36)$$

In the range of zone sizes normally encountered, the variance ranges from 1 to 3 square miles for intrazonal trips; the expected trip length implied by making a similar correction in Equation 32 is 1.44 to 2.64 miles, which is consistent with the data.

Constraints on Variance-Covariance Terms -- We now turn to the remaining terms in the Taylor expansion (Equation 24). These approach zero as n increases. The third order derivative of $P(a|Y)$ reaches a maximum at P=0.5 (as do the cross derivatives) with a value equal to -0.125. However, for most mode splits in the Los Angeles region (those between 0.3 and 0 or between 0.7 and 1), the value of the third order derivative will be between -0.05 and -0.04. The central moments of the assumed distribution of distance tend to increase (in absolute value), but at a rate which is less than exponential. It is clear that the nth moment divided by n factorial approaches zero. Thus we conclude that the Taylor series can be truncated after the third term with a fairly insignificant loss in accuracy.

This truncation raises the possibility that for values of Y which are rather far from $\overline{Y}$, expression 26 will not be well-behaved in the sense of providing a measure of probability which increases monotonically with $P(a|Y)$. Thus, terms should be constrained such that the following three conditions hold:

$$\sum_{a=1}^{n} E[P(a|Y)] = 1 \tag{37}$$

$$0 \leq E[P(a|Y)] \quad \text{for all } a \tag{38}$$

$$\frac{\partial E[P(a|Y)]}{\partial P(a|\overline{Y})} \geq 0 \quad \text{for all } P(a|\overline{Y}) \in [0,1] \tag{39}$$

Conditions 37, 38 and 39 ensure that $E[P(a|Y)]$ is a probability measure. However, much stronger constraints will be needed if $E[P(a|Y)]$ is to have properties which are plausible in terms of mode split or other individual choice behavior. One such condition is that the elasticity be greatest at $E[P(a|Y)]=0.5$. This will occur if the following conditions are also met:

$$\frac{\partial^2 E[P(a|Y)]}{\partial Y^2} = 0 \text{ at } E[P(a|Y)] = 0.5 \tag{40}$$

$$\frac{\partial^3 E[P(a|Y)]}{\partial Y^3} \leq 0 \text{ at } E[P(a|Y)] = 0.5 \tag{41}$$

Of the five above conditions, 37 and 40 hold for all values of the variances. The following constraints on the variances are sufficient to ensure that the other conditions are met:

$$\sum_{\substack{b=1 \\ b\neq a}}^{n} var[Y_{ab}] \leq 16 \tag{42}$$

$$var[Y_{ab}] \leq 1 \quad \text{for all } b\neq a \tag{43}$$

The latter constraint also appears to be necessary for condition 41 to be met. (This proposition was proved only for the binary choice case. It was presumed to be true when the number of nonzero probability alternatives was greater than two.)

Estimated Formulas for Variance-Covariance Terms -- Tables 40 through 43 present the expressions and assumptions used in calculating the variances for mode split equations. Only pairwise comparisons between auto and other modes are presented because these probability function estimates are sufficient for computing any mode choice probability (see the following section for actual probability calculations). However, with this approach the probability choice functions differ somewhat from that presented in Equation 21.

If the subscript a denotes auto and the subscript c denotes some other given mode, then individual t's probability of choosing the cth mode can be computed as follows:

$$P_t(c) = \frac{e^{-Y_{ac}}}{1 + \sum_{\substack{b=1 \\ b \neq a}}^{n} e^{-Y_{ab}}} \tag{44}$$

where only pairwise comparisons between auto and other modes appear in the arguments.

Computing probability choices this way entails a somewhat different Taylor's series approximation for mode c than for auto choices. To see this, note that the second order derivatives of $P_t(c)$ with respect to comparison functions are as follows:

$$\frac{\partial^2 P(c|Y)}{\partial \left(Y_{ab}\right)^2} = P(c|Y) \cdot \left(P(b|Y) \cdot (2P(b|Y)-1)\right) \text{ for } b \neq c \tag{45}$$

Table 40. NONZERO VARIANCE-COVARIANCE TERMS FOR BUS (b) AND AUTO (a) CHOICE*

$$\alpha_C^2 var[C_b] = \alpha_C^2 (.05)^2 var[D]$$

$$\alpha_C^2 var[C_a] = \alpha_C^2 (.03)^2 var[D]$$

$$\alpha_T^2 var[T_b] = \alpha_T^2 (4)^2 var[D]$$

$$\alpha_T^2 var[T_a] = \alpha_T^2 (3)^2 var[D]$$

$$\alpha_S^2 var[S_b] = \alpha_S^2 \frac{1}{3}(\bar{S}_b)^2$$

$$\beta^2 var[O] = \beta^2 (.086)$$

$$-2\alpha_C^2 cov[C_b, C_a] = -2\alpha_C^2 (.05)(.03) var[D]$$

$$-2\alpha_T^2 cov[T_b, T_a] = -2\alpha_T^2 (4)(3) var[D]$$

$$2\alpha_C \alpha_T cov[C_b, T_b] = 2\alpha_C \alpha_T (.05)(4) var[D]$$

$$-2\alpha_C \alpha_T cov[C_b, T_a] = -2\alpha_C \alpha_T (.05)(3) var[D]$$

$$-2\alpha_C \alpha_T cov[C_a, T_b] = -2\alpha_C \alpha_T (.03)(4) var[D]$$

$$2\alpha_C \alpha_T cov[C_a, T_a] = 2\alpha_C \alpha_T (.03)(3) var[D]$$

*See notes on assumptions (pp. 173-174).

Table 41. NONZERO VARIANCE-COVARIANCE TERMS FOR WALK (w) AND AUTO (a) CHOICE*

$$\alpha_C^2 var[C_a] = \alpha_C^2(.03)^2 var[D]$$

$$\alpha_T^2 var[C_a] = \alpha_T^2(3)^2 var[D]$$

$$\alpha_S^2 var[S_w] = \alpha_S^2(17.14)^2 var[D]$$

$$\beta^2 var[O] = \beta^2(.086)$$

$$-2\alpha_C\alpha_S cov[C_a, S_w] = -2\alpha_C\alpha_S(.03)(18.99) var[D]$$

$$-2\alpha_T\alpha_S cov[T_a, S_w] = -2\alpha_T\alpha_S(3)(18.99) var[D]$$

*For intrazonal trips only; also, see notes on assumptions, pp. 173-174.

Table 42. NONZERO VARIANCE-COVARIANCE TERMS FOR CAR POOL WITH h PASSENGERS (ch) AND AUTO (a) CHOICE*

$$\alpha_T^2 var[T_a - T_{ch}] = \alpha_T^2\left(h^2(3)^2 var[D] + \frac{225}{3}\right)$$

*See notes on assumptions, pp. 173-174.

Table 43. NONZERO VARIANCE-COVARIANCE TERMS FOR DRIVER SERVE PASSENGER (s) AND AUTO (a) CHOICE*

$$\alpha_C^2 var[C_a] = \alpha_C^2 (.0571)^2 var[D]$$

$$\alpha_C^2 var[C_s] = \alpha_C^2 (2)^2 (.0571)^2 var[D]$$

$$\alpha_T^2 var[T_a] = \alpha_T^2 (3)^2 var[D]$$

$$\alpha_T^2 var[T_s] = \alpha_T^2 (3)^2 (3)^2 var[D]$$

$$2\alpha_C \alpha_T cov[C_a, T_a] = 2\alpha_C \alpha_T (.0571)(3) var[D]$$

$$2\alpha_C \alpha_T cov[C_s, T_s] = 12\alpha_C \alpha_T (.0571)(3) var[D]$$

$$2\alpha_C \alpha_T cov[C_s, T_a] = 6\alpha_C \alpha_T (.0571)(3) var[D]$$

$$2\alpha_C \alpha_T cov[C_s, T_a] = 4\alpha_C \alpha_T (.0571)(3) var[D]$$

$$\beta^2 var[O] = \beta^2 (.086)$$

*See notes on assumptions, pp. 173-174.

Notes on Assumptions for Tables 40-43

a. Bus fares are \$0.05 per mile in 1967. (Los Angeles currently has a flat fare system which will require putting to zero all variance-covariance terms involving C_b when the model is applied to current conditions.

b. Auto operating costs are \$0.03 per mile in 1967.

c. Bus speeds on city streets are 15 miles per hour, implying a rate of 4 minutes per mile.

d. Auto speeds average 20 miles per hour, implying a rate of 3 minutes per mile.

e. The variability of wait time and schedule delay time within a given zone interchange is negligible; (this assumption is verified by the data).

f. The distribution of access time to buses is uniform within a zone -- this implies a rectangular distribution; thus, the variance is one-third the square of the mean:

$$var[S_b] = \frac{1}{3}(\bar{S}_b)^2$$

g. The variance on auto availability is calculated as the variance of households owning no cars -- the average within-zone variance across the zones in Los Angeles and Orange Counties is tightly clustered around a mean of 0.086 (calculated from 1970 Census of Households data).

h. The speed of walking trips is assumed to be 3.16 miles per hour, or a rate of 18.99 minutes per mile.

i. The variance of costs for carpooling compared to auto with a driver only is zero. To explain, further, refer to Equation 29. The expected costs of auto with driver only are:

$$E[C_a] = (.03)D = (.03)\left\{(D' - \frac{Y_i+Y_j}{2}) + E[X]\right\}$$

whereas the cost per person of a carpool (equally shared) with h passengers would be:

$$E[C_{ch}] = \frac{.03}{h+1}(D) = \frac{.03}{h+1}\left(C(D' - \frac{Y_i+Y_j}{2}) + (h+1)\cdot E[X]\right)$$

where it is assumed that the extra intrazonal travel incurred by a randomly selected carpool is proportional to the number of vehicle occupants. The above implies that:

$$var[C_a - C_{ch}] = 0$$

j. It is assumed that the extra time incurred in carpooling is directly proportional to the intrazonal travel time with the constant of proportionality equal to the number of vehicle occupants. That is,

$$var[T_a - T_{ch}] = (3)^2 var[X-(h+1)X] + var[SD]$$

where $var[SD]$ represents the variance in schedule delay. An average schedule delay of 15 minutes is assumed with a rectangular distribution between 0 and 30 minutes. The variance in schedule delay is, therefore, $1/3(15)^2$. Schedule delay and travel time are assumed to be stochastically independent.

The following chart gives the values of the estimated parameters used in the preceding tables.

Parameter	Work Trip	Shopping Trip
α_C	2.24	4.11
α_T	0.0411	0.0654
α_S	0.114	0.374
β	3.79	2.24

$$\frac{\partial^2 P(c|Y)}{\partial (Y_{ac})^2} = P(c|Y) \cdot \left((P(c|Y)-1)(2P(c|Y)-1\right) \qquad (46)$$

Using this result, one can derive the expected value of the truncated Taylor's series about $\overline{Y}$ for $P(c|Y)$:

$$E[P(c|Y)] = P(c|\overline{Y}) \cdot \left\{ 1 + \sum_{\substack{b=1 \\ b \neq a}}^{n} var[Y_{ab}] \cdot [P(b|\overline{Y}) - \delta)(P(b|\overline{Y}) - \tfrac{1}{2})] \right\}$$

$$\text{where } \delta = \begin{cases} 1 \text{ if } b=c \\ 0 \text{ if } b \neq c \end{cases} \qquad (47)$$

<u>Examples of Calculations</u> -- The following is an example of a variance calculation.

$\alpha_C^2 var[C_b]$	$= \alpha_C^2 (.05)^2 var[D]$	Table 40
	$= (2.24)^2 (.05)^2 var[D]$	chart p. 174
	$= (.0125) var[D]$	

For interzonal trips, $var[D] = \dfrac{11\left(A_i + 2\sqrt{A_i A_j} + A_j\right)}{144}$ (from Equation 35) thus implying:

$$\alpha_C^2 var[C_b] = (.000958)\left(A_i + 2\sqrt{A_i A_j} + A_j\right)$$

while for intrazonal trips, $var[D] = \dfrac{11(A_i)}{144}$ (from Equation 36) which implies:

$$\alpha_C^2 var[C_b] = (.000958) A_i$$

By combining like terms from the preceding tables, the following expressions for the variance of Y are developed.

Auto vs. transit -- work trip:

1. Add up all terms with $var[D]$ from Table 40 to get

$$.00056(A_i + 2\sqrt{A_i A_j} + A_j) \quad \text{for interzonal trips}$$

$$.00056(A_i) \quad \text{for intrazonal trips}$$

2. Add $\alpha_S^2 \frac{1}{3}(\overline{S}_b)^2$ from Table 40

$$= .114(\tfrac{1}{3})\overline{S}_b^2 \quad \text{chart p. 174}$$

$$= .00433(\overline{S}_b)^2$$

3. Add $\beta^2(.086)$ from Table 40

$$= (3.79)^2(.086)$$

$$= 1.2353$$

This yields the following equations:

$$var[Y_{ab}] = .00056\left(A_i + 2\sqrt{A_i A_j} + A_j\right) + .00433(\overline{S}_b)^2 + 1.23531$$

(for interzonal trips, that is, for $i \neq j$)

$$var[Y_{ab}] = .00056(A_i) + .00433(\overline{S}_b)^2 + 1.23531$$

(for intrazonal trips)

Table 44 lists $var[Y_{ab}]$'s obtained in this manner for other types of comparisons such as auto vs. transit -- shopping trip and auto vs. walking -- work trip.

Table 44. VARIANCE OF SEVERAL COMPARISON FUNCTIONS

Auto vs. Transit -- Work Trip

$$var[Y_{ab}] = .00056\left(A_i + 2\sqrt{A_i A_j} + A_j\right) + .00433(\bar{S}_b)^2 + 1.23531 \qquad i\neq j$$

$$var[Y_{ab}] = .00056(A_i) + .00433(\bar{S}_b)^2 + 1.23531 \qquad i=j$$

Auto vs. Transit -- Shopping Trip

$$var[Y_{ab}] = .00164\left(A_i + 2\sqrt{A_i A_j} + A_j\right) + .04663(\bar{S}_b)^2 + 0.43151 \qquad i\neq j$$

$$var[Y_{ab}] = .00164(A_i) + .04663(\bar{S}_b)^2 + 0.43151 \qquad i=j$$

Auto vs. Walking (intrazonal trips only) -- Work Trip

$$var[Y_{aw}] = .29651(A_i) + 1.23531$$

Auto vs. Walking (intrazonal trips only) -- Shopping Trip

$$var[Y_{aw}] = 3.51064(A_i) + .43151$$

Auto vs. Carpool (with h passengers) -- Work Trip

$$var[Y_{ach}] = h^2(.00116)\left(A_i + 2\sqrt{A_i A_j} + A_j\right) + .12668 \qquad i\neq j$$

$$var[Y_{ach}] = h^2(.00116)(A_i) + .12668 \qquad i=j$$

Auto vs. Carpool (with h passengers) -- Shopping Trip

$$var[Y_{ach}] = h^2(.00294)\left(A_i + 2\sqrt{A_i A_j} + A_j\right) + .320775 \qquad i\neq j$$

$$var[Y_{ach}] = h^2(.00294)(A_i) + .320775 \qquad i=j$$

Table continued on following page.

Table 44 (continued). VARIANCE OF SEVERAL COMPARISON FUNCTIONS

Auto vs. Auto Serve Passenger -- Work Trip

$$var[Y_{as}] = .028554\left(A_i + 2\sqrt{A_i A_j} + A_j\right) + 1.2353 \qquad i \neq j$$

$$var[Y_{as}] = .028554(A_i) + 1.2353 \qquad i = j$$

Auto vs. Auto Serve Passenger -- Shopping Trip

$$var[Y_{as}] = 1.04154\left(A_i + 2\sqrt{A_i A_j} + A_j\right) + .431514 \qquad i \neq j$$

$$var[Y_{as}] = 1.04154(A_i) + .431514 \qquad i = j$$

Note: For choice types other than mode split, it was assumed that the constraint of Equation 43 was binding, and all variances of comparison functions were set identically equal to one. This assumption was made after inspecting a Taylor's series expansion of the destination choice model; the number of nonzero variance-covariance terms is quite high, and this assumption appeared to be warranted.

APPLICATION AND TESTS OF THE TRAVEL DEMAND MODEL WITH 1967 LARTS DATA

This section tests the travel demand model for consistency with the 1967 LARTS Household Survey results on inter- and intrazonal trips by mode and purpose.* Such a test of the model is instructive because it shows, step by step, how the model is applied in order to obtain forecasts of travel for zonal interchanges. The approach for applying the model can be summarized in the following steps:

- Home-Work Mode Split
  - -Odds functions for auto vs. other modes are estimated for each zonal interchange using the zonal averages for system performance data and assumptions about the system performance of modes other than auto driver or transit (carpooling, driver serve passenger, and walking); these functions are based on the estimated relationship in Equation 13 given in Table 39.
  - -Probabilities of each mode choice for each zonal interchange are calculated from application of Equation 21 or 44, whichever is appropriate to adjust for aggregation.
  - -The mode shares for each zonal interchange are calculated using the probabilities from the previous step and the calculated variance-covariance terms from the formulas in the previous section in Equation 26 or 47, whichever is appropriate to adjust for aggregation.
  - -The estimated mode shares are checked against the actual mode shares to determine the reasonableness of the model

*The construction of zonal trip tables from the records of the 1967 Household Survey is described in Appendix D. Data for the independent variables generally came from other sources, also as described in Appendix D.

- Home-Shopping Mode Split
  - -The same procedures are applied for the home-shopping model as are used for the home-work model except that the estimated relationship in Equation 14 is used in the first step.
- Home-Shopping Destination Choice
  - -Odds functions among destination choices are calculated for zonal interchanges with Equation 15.
  - -The probabilities of choosing among alternative zone destinations from a given origin are computed with Equation 20.
  - -The shares of trips among alternative zone destinations from a given origin are estimated from Equation 26, assuming all variance terms are equal to unity.
  - -The estimated shares are compared to a sample of actual shares to determine the reasonableness of the model.
- Home-Shopping Frequency
  - -The odds of a household in a zone taking a shopping trip rather than no such trip over a twenty-four hour period are computed using Equation 16 from Table 39.
  - -The probability of a household in a given zone taking a trip is calculated from Equation 20.
  - -The average number of trips per household in a given zone is calculated from Equation 26, assuming the variance term is unity.
  - -The estimated trips per household are compared to the actual trips per household in a sample of zones to determine the reasonableness of the model.

Work Trip Mode Split

This section will compare the actual LARTS data for 1967 against predictions from the disaggregate demand model. The data given are the number of person-trips between zone pairs by travelers surveyed in the 1967 Household Survey. (See Appendix D for details on the LARTS Household Survey.) The following modes are represented in the survey: auto driver, transit, passenger, and driver serve passenger.* In order for mode choices to be more indicative of the actual decisions made by households, seven modes were modeled: auto driver, transit, carpooling with one passenger, carpooling with two passengers, carpooling with three passengers, driver serve passenger, and walking. The LARTS survey did not tabulate walking trips and driver serve passenger trips (as defined here). The other estimates of mode choice could be transformed into the LARTS mode categories.

The following equation from Table 39 is used for all work trip mode split estimates:

$$ln \frac{P_{Aij}}{P_{Bij}} = -4.77 - 2.24(C_{Aij} - C_{Bij}) - 0.0411(T_{Aij} - T_{Bij}) - 0.114(S_{Aij} - S_{Bij}) + 3.79Y \qquad (13)$$

where P_{Aij} = probability of an auto round trip from home i to work j;

P_{Bij} = probability of an alternative mode choice round trip from home i to work j;

C_{Aij} = auto variable costs per mile for a round trip between i and j;

C_{Bij} = alternative mode cost (in fares) for a round trip between i and j;

T_{Aij} = auto round trip line-haul time between i and j;

T_{Bij} = alternative mode round trip line-haul time between i and j;

---

*Note that the definition of driver serve passenger used here is different from that used in the LARTS Household Survey. This issue is discussed in more detail below.

S_{Aij} = access time for auto round trip between i and j;

S_{Bij} = access time for alternative mode round trip between i and j;

Y = number of vehicles per tripmaker.

The above equation estimates the odds function for two modes of transportation. In the following sections, the equation will be applied to the following mode pairings:

1) auto vs. transit;
2) auto vs. carpool;
    a) with one passenger;
    b) with two passengers;
    c) with three passengers;
3) auto vs. serve passenger;
4) auto vs. walking.

The estimates of these six pairwise odds will be used to estimate the mode split for the seven alternatives for each zonal pair (i,j). A random sample of 400 zonal pairs was taken from the 10,000 zonal pairs in the LARTS data. Of these, 172 pairs were located exclusively in Los Angeles and Orange Counties and were selected for further analysis because of the availability of transit data. In order to show the development of the model in the following sections, 12 zonal pairs for which transit trips were recorded are examined in detail. The mode split estimates of the aggregate sample of 172 pairs are compared to the actual data at the end of this section.

Auto Versus Transit -- Table 45 gives the variables and data for the 12 zonal pairs. Subscript A is auto and subscript T is transit. Transit is alternative mode B in the generalized Equation 13. In the auto vs. transit comparison, the data are substituted directly into the generalized equation, giving $ln(P_{Aij}/P_{Tij})$. This result will be used later in the mode split calculations.

Table 45. VARIABLES AND SOURCES FOR AUTO VS. TRANSIT

Zone I	Zone J	C_{Aij} (in dollars)	C_{Tij} (in dollars)	T_{Aij} (in minutes)	T_{Tij} (in minutes)	S_{Aij} (in minutes)	S_{Tij} (in minutes)	Y
2	2	$0.10	$0.64	24.8	43.0	4	18	0.7187
2	41	0.96	1.65	86.6	277.0	4	18	0.7187
3	1	0.80	1.42	71.0	139.0	6	16	0.9068
3	3	0.11	0.62	23.2	51.0	4	24	0.9068
4	7	0.30	0.72	30.8	103.0	4	34	0.9328
12	1	0.80	1.42	75.5	145.0	6	12	0.9119
12	3	0.24	0.72	31.2	113.0	4	20	0.9119
15	32	0.30	0.88	37.6	102.3	4	18	0.5918
23	1	0.88	1.32	72.4	113.9	6	16	0.8781
30	1	1.98	2.46	125.6	196.3	6	12	0.8800
33	33	0.12	0.62	21.3	93.8	4	18	0.9263
45	19	0.90	1.58	72.0	176.0	4	14	0.6843

Variable	Definition	Source
C_{Aij}	$.03(2D_{ij})$	.03 is the assumed auto operating cost for one mile. D_{ij} is the average one-way mileage from zone i to zone j from Time and Distance file (see Appendix D).
C_{Tij}	if $D_{ij} < 5$ -- $.60 + TR$ if $5 \leq D_{ij} \leq 33$ -- $TR + 2[.30 + .08(D_{ij}/3)]$ if $D_{ij} > 33$ -- $TR + 2[1.18 + .07(D_{ij}-33)/3]$	Based on zonal transit fares which were in effect in 1967. TR = 0.10 (Average number of peak transfers).

Table continued on following page.

Table 45 (continued). VARIABLES AND SOURCES FOR AUTO VS. TRANSIT

Variable	Definition	Source
T_{Aij}	$HWADT - HWADIWT - HWADJWT$	LARTS data where: $HWADT$ = round trip line-haul time for home-work purpose in auto driver mode; $HWADIWT$ = amount of walking time in zone i; $HWADJWT$ = amount of walking time in zone j.
T_{Tij}	2(peak line-haul + ½peak headway)	Los Angeles bus schedules -- see Appendix D for a detailed explanation.
S_{Aij}	4 if $i \neq 1$ and $j \neq 1$ 6 if $i = 1$ or $j = 1$ 8 if $i = 1$ and $j = 1$	Assumption -- one minute of access time at each end of each trip except in Zone 1 (CBD) where there would be two minutes.
S_{Tij}	Approximations of average walk times for potential bus riders to bus stops in the zone.	Bus route maps -- see Appendix D for more details.
Y	$\frac{A_1 + A_2 + A_3}{HH}$	1970 Census data: A_1 = number of households in zone i with one car; A_2 = number of households in zone i with two cars; A_3 = number of households in zone i with three cars; HH = number of households in zone i.

Auto Versus Carpool -- Because carpooling is a mode not used in the estimation of Equation 13, the formula does not apply directly. In particular, the mode specific constant and the vehicle-per-tripmaker variable do not appear to be applicable to this mode choice situation; therefore, the following equation was applied:

$$\ln \frac{P_{Aij}}{P_{C_k ij}} = -2.24(C_{Aij}-C_{C_k ij}) - 0.0411(T_{Aij}-T_{C_k ij})$$
$$-0.114(S_{Aij}-S_{C_k ij}) \qquad (13.1)$$

where the subscript C denotes carpooling as the alternative mode in Equation 13 and k denotes the number of passengers in the carpool.

In addition to the above change, it is assumed that $S_{C_k ij}$ is equal to S_{Aij}; that is, access time for the traveler is equal whether he is in a carpool or is a driver alone. Therefore, only time and cost will be factors in estimating $P_{Aij}/P_{C_k ij}$.

Several different methods for inferring the costs and times of trips by carpools based on mileage between zones, schedule delay and additional line-haul time based on number of passengers were tried. The two approaches below seem to give the most reasonable estimate of the modal split between single passenger trips and carpools.

Both approaches take into account the number of people in a car and the distance that will be driven. In Method I the cost of a multipassenger trip is found by multiplying the cost per mile ($0.03) of an auto trip times the round trip distance between zones of origin and destination plus an estimate of additional miles driven because of the pick-ups and delivery of members in the carpool. For each person-trip, this cost will then be divided by the number of people in the car, since they will be assumed to share the cost equally.

In Method II line-haul time is based on the number of passengers and the extra mileage driven for a carpool. Carpool line-haul time equals auto driver alone line-haul time (*HWADT*) for the zonal interchange, plus the time, based on intrazonal distances and 15 miles per hour driving speeds, to pick up and deliver the additional passengers and a schedule delay based on number of passengers.

The above descriptions are represented by the following equations for Method I and Method II. Note that 20 minutes schedule delay is added for each passenger to account for additional wait times associated with carpool pickups and deliveries. Zone areas originally in acres are divided by 640 to convert them to square miles.

Method I

$$C_{C_k ij} = \frac{.03\left(2D_{ij} + k(A_{ii} + A_{jj})\right)}{k+1}$$

$$T_{C_k ij} = HWADT + \frac{A_{ii} + A_{jj}}{15/60} + k(20)$$

Method II

$$C_{C_k ij} = \frac{.03\left(2D_{ij} + 2k(A_{ii} + A_{jj})\right)}{k+1}$$

$$T_{C_k ij} = HWADT + \frac{2k\left(A_{ii} + A_{jj}\right)}{15/60} + k(20)$$

k = number of passengers

$$A_{ii} = \frac{5}{12}\sqrt{\frac{\text{Area of zone } i}{640}} \qquad A_{jj} = \frac{5}{12}\sqrt{\frac{\text{Area of zone } j}{640}}$$

Method I is used when the distance between zone i and zone j is relatively short. The reasoning behind this is that with short trips there are relatively more work trips in the zonal interchange, and so there is more chance of a convenient carpool. Method II is used with longer distances because with fewer work trips in a zonal interchange, there is less likelihood that a carpool can be formed. By testing it was found that if the round trip distance of the trip ($2D_{ij}$) is less than or equal to 16 miles, then Method I is appropriate; otherwise Method II is used. (For trips of great distances, such as zonal pair (30,1) in the sample, Method II over-estimates carpooling because of the great savings it appears to produce; in actuality, the opportunity for carpooling is quite limited.)

Table 46 shows the estimates for $C_{C_k ij}$ and $T_{C_k ij}$ for k = 1, 2 and 3. Substituting these estimates and the ones for C_{Aij} and T_{Aij} listed in Table 39, $P_{Aij}/P_{C_1 ij}$ $(P_{Aij}/P_{C_2 ij})$ and $(P_{Aij}/P_{C_3 ij})$ can all be found.

Auto Versus Serve Passenger -- The serve passenger mode actually involves three round trips: one for the passenger and two for the driver chauffeuring the passenger to a given destination.* These three trips are combined into one (vehicle) trip for modeling purposes; i.e., the serve passenger process is one trip with the cost elements of three trips. After the number of such trips is predicted, they are transformed to actual driver and passenger trips. The estimating equation is:

*Note that our definition of driver serve passenger is substantially different from the LARTS definition. There is, in fact, no LARTS data category which corresponds to this type of trip though they are presumably captured under a different purpose category. See Appendix D for more details on this subject.

Table 46. CARPOOLING VARIABLES

Zone I	Zone J	$C_{C_1 ij}$	$C_{C_2 ij}$	$C_{C_3 ij}$	$T_{A_1 ij}$[a]	$T_{A_2 ij}$[a]	$T_{A_3 ij}$[a]
2	2	$0.10	$0.10	$0.10	59.5	94.2	129.0
2	41	0.60	0.48	0.42	138.2	189.8	241.4
3	1	0.49	0.39	0.34	116.4	161.7	207.1
3	3	0.11	0.12	0.12	60.2	80.2	100.1
4	7	0.22	0.19	0.18	69.8	108.7	147.7
12	1	0.48	0.38	0.33	118.0	160.5	202.9
12	3	0.18	0.16	0.15	66.7	102.2	137.8
15	32	0.21	0.18	0.16	73.0	108.3	143.7
23	1	0.52	0.40	0.35	114.9	157.4	199.8
30	1	1.08	0.77	0.62	166.2	206.9	247.5
33	33	0.12	0.12	0.12	57.2	93.1	129.1
45	19	0.55	0.43	0.37	118.8	165.6	212.4

[a]All times are in minutes.

$$\ln \frac{P_{Aij}}{P_{Sij}} = -4.77 - 2.24(C_{Aij} - C_{Sij}) - 0.0411(T_{Aij} - T_{Sij})$$

$$-0.114(S_{Aij} - S_{Sij}) + 3.79Y \qquad (13.2)$$

where P_{Sij} = probability of making a serve passenger trip;
C_{Sij} = cost of a serve passenger trip;
T_{Sij} = line-haul time of a serve passenger trip;
S_{Sij} = access time of a serve passenger trip;
and the other variables have been previously defined.

In order to find the cost and line-haul time for serve passenger trips, the parameters of cost and line-haul time for the home-work purpose and for the home-shopping purpose were compared. The chart below shows these parameters.

	Cost	Line-haul Time
Home-work	2.24	0.0411
Home-shopping	4.11	0.0654

It is assumed that the driver in the serve passenger mode places the same value on time and costs as shopping trip makers (that is, they are non-work travelers more closely resembling shopping trip motorists). The extra cost of a serve passenger trip incurred by the driver will be equivalent to:

$$\frac{2(\text{home-shopping cost})}{\text{home-work cost}} \cdot (C_{Aij})$$

and likewise the extra line-haul time will be:

$$\frac{2(\text{home-shopping line-haul})}{\text{home-work line-haul}} \cdot (T_{Aij})$$

Thus,

$$C_{Sij} = \frac{2.24 + 2(4.11)}{2.24} \cdot (C_{Aij}) = 4.67(C_{Aij})$$

$$T_{Sij} = \frac{.0411 + 2(.0654)}{.0411} \cdot (T_{Aij}) = 4.18(T_{Aij})$$

The assumption is made that total access time for a serve passenger trip is 8 minutes for all zonal pairs, except for trips originating in zone 1, where S_{Sij} equals 14 minutes. This is based on the prior assumption that 1 minute of access time per person occurs at each terminus of the trip. For most trips, the driver will have 4 minutes of access time and the passenger will have 4 minutes of access time. If the trip originates in zone 1, the driver will incur 8 minutes of access time and the passenger 6 minutes.

Table 47 shows the system performance variables for the serve passenger mode and their estimates for the observations used in testing the model. When these are combined with the variables for C_{Aij}, T_{Aij} and S_{Aij} found in Table 39, (P_{Aij}/P_{Sij}) can be calculated.

Auto Versus Walking -- The LARTS data base has no information on walking trips, but this mode of transportation should be included when it is a reasonable alternative. Walking trip related variables are estimated as follows: cost is zero; line-haul time is zero; access time (walking time in other modes) is calculated as a function of distance. Assuming that the average person can walk 3.16 miles per hour or 0.0526 miles per minute, the formula for access time is:

$$S_{Wij} = \frac{2D_{ij}}{.0526}$$

Table 47. DRIVER SERVE PASSENGER VARIABLES

Zone I	Zone J	C_{Sij}, dollars	T_{Sij}, minutes	S_{Sij}, minutes
2	2	\$0.47	103.7	8
2	41	4.48	362.0	8
3	1	3.74	296.8	8
3	3	0.51	97.0	8
4	7	1.40	128.7	8
12	1	3.74	315.6	8
12	3	1.12	130.4	8
15	32	1.40	157.2	8
23	1	4.11	302.6	8
30	1	9.25	525.0	8
33	33	0.56	89.0	8
45	19	4.20	301.0	8

It is further assumed that S_{Wij} must be less than 90 minutes for a round trip by walking to be a legitimate alternative.

The estimating equation for (P_{Aij}/P_{Wij}) is:

$$\ln \frac{P_{Aij}}{P_{Wij}} = -4.77 - 2.24C_{Aij} - .0411T_{Aij} - .114(S_{Aij} - S_{Wij}) + 3.79Y \qquad (13.3)$$

Only three of the observations being tested allow for walking trips. S_{Wij} is given in Table 48 for these observations, which are for intrazonal trips.

Table 48. WALKING VARIABLE
(minutes)

Zone I	Zone J	S_{Wij}
2	2	60.84
3	3	69.96
33	33	68.82

Mode Probabilities -- The odds functions for six alternative modes of transportation have been estimated in relation to auto driver trips. In order to combine all seven alternatives to find the modal splits for all trips between the zonal pairs, the following equations are used:

$$\text{Auto probability} = \frac{1}{1 + D_{ij}}$$

$$\text{Transit probability} = \frac{P_{Bij}/P_{Aij}}{1 + D_{ij}}$$

$$\text{Carpool 1 probability} = \frac{P_{C_1ij}/P_{Aij}}{1 + D_{ij}}$$

$$\text{Carpool 2 probability} = \frac{P_{C_2ij}/P_{Aij}}{1 + D_{ij}}$$

$$\text{Carpool 3 probability} = \frac{P_{C_3ij}/P_{Aij}}{1 + D_{ij}}$$

$$\text{Serve passenger probability} = \frac{P_{Sij}/P_{Aij}}{1 + D_{ij}}$$

$$\text{Walk probability} = \frac{P_{Wij}/P_{Aij}}{1 + D_{ij}}$$

where $D_{ij} = \frac{P_{Bij}}{P_{Aij}} + \frac{P_{C_1ij}}{P_{Aij}} + \frac{P_{C_2ij}}{P_{Aij}} + \frac{P_{C_3ij}}{P_{Aij}} + \frac{P_{Wij}}{P_{Aij}} + \frac{P_{Sij}}{P_{Aij}}$

Carpool 1 = carpool mode with one passenger;
Carpool 2 = carpool mode with two passengers;
Carpool 3 = carpool mode with three passengers.

It can be seen that auto share is calculated from an equation of the form given in Equation 21, whereas for the others Equation 43 is applied.

Table 49 shows the estimated choice probabilities for the observations tested.

Table 49. ESTIMATED MODE PROBABILITIES (percentages)

Zone I	Zone J	Auto	Transit	Car-pool 1	Car-pool 2	Car-pool 3	Serve passenger	Walk
2	2	68	13	15	4	1	5	3
2	41	76	--	21	3	--	--	--
3	1	72	1	22	4	1	--	--
3	3	72	3	16	4	1	3	1
4	7	76	--	18	4	1	--	--
12	1	68	2	24	5	1	--	--
12	3	74	1	20	5	1	--	--
15	32	70	4	20	5	1	--	--
23	1	63	6	25	6	1	--	--
30	1	32	1	45	17	5	--	--
33	33	73	1	17	4	1	4	1
45	19	72	1	23	4	1	--	--

Estimated Trips by Mode -- In order to estimate the mode shares for a zonal interchange, the figures from Table 49 must be adjusted for the variance-covariance of independent variables within each zonal interchange. Equations 26 and 47 are applied to make these calculations.

The variance of comparison functions between auto and each other mode pair is given in Table 50 for each zonal pair. These figures are computed from the formulas derived in the previous section.

By a method described in Appendix D, home-work and work-other trips are combined to form the actual 1967 LARTS number of residence-based round trips to work for any given zonal interchange. Then:

Actual auto trips = $HWADC_{ij} + WOADC_{ij} + HWASC_{ij} + WOASC_{ij}$

Actual transit trips = $HWBAC_{ij} + WOBAC_{ij} + HWBNC_{ij} + WOBNC_{ij}$

Actual passenger trips = $HWAPC_{ij} + WOAPC_{ij}$

where $HWADC_{ij}$ = total home-work round trips for auto driver from zone i to zone j;

$WOADC_{ij}$ = total work-other round trips for auto driver from zone i to zone j;

$HWBAC_{ij}$ = total home-work round trips for transit, car available, from zone i to zone j;

$WOBAC_{ij}$ = total work-other round trips for transit, car available, from zone i to zone j;

$HWBNC_{ij}$ = total home-work round trips for transit, car not available, from zone i to zone j;

$WOBNC_{ij}$ = total work-other round trips for transit, car not available, from residence zone i to zone j;

Table 50. VARIANCE OF COMPARISON FUNCTION BETWEEN AUTO AND OTHER MODES[a]

Zone I	Zone J	Transit	Carpool 1	Carpool 2	Carpool 2	Serve passenger	Walk
2	2	1.00	0.149	0.217	0.330	1.00	1.00
2	41	1.00	0.231	0.542	1.000	1.00	
3	1	1.00	0.194	0.396	0.732	1.00	
3	3	1.00	0.156	0.246	0.396	1.00	1.00
4	7	1.00	0.277	0.727	1.000	1.00	
12	1	1.00	0.179	0.338	0.603	1.00	
12	3	1.00	0.227	0.528	1.000	1.00	
15	32	1.00	0.225	0.521	1.000	1.00	
23	1	1.00	0.179	0.336	0.597	1.00	
30	1	1.00	0.171	0.305	0.527	1.00	
33	33	1.00	0.153	0.233	0.365	1.00	1.00
45	19	1.00	0.201	0.425	0.799	1.00	

[a]Constrained to be between 0 and 1.

$HWAPC_{ij}$ = total home-work round trips for passenger from zone i to zone j;

$WOAPC_{ij}$ = total work-other round trips for passenger from residence zone i to zone j;

$HWASC_{ij}$ = total home-work round trips for LARTS-defined serve passenger from zone i to zone j;

$WOASC_{ij}$ = total work-other round trips for LARTS-defined serve passenger from residence zone i to zone j.

Results of these computations are presented in Table 51.

In order to compare the estimates to the actual results, the trips from the seven estimated modes must be distributed among the five data categories. The following equations show how this distribution is made, while also finding the estimated round trip person count for each mode for a given zonal interchange.

Est. auto trips = *[Est. auto share + .5(Est. carpool 1 share) + .333(Est. carpool 2 share) + .25(Est. carpool 3 share)](Total trips)*

Est. transit trips = *(Est. transit share)(Total trips)*

Est. passenger trips = *[.5(Est. carpool 1 share) + .667(Est. carpool 2 share) + .75(Est. carpool 3 share) + (Est. serve passenger share)] (Total trips)*

Est. serve passenger trips = *(Est. serve passenger share)(Total trips)*

Est. Walk Trips = *(Est. Walk Share)(Total Trips)*

Table 51. ACTUAL WORK TRIPS

Zone I	Zone J	Auto Driver	Transit	Auto passenger
2	2	173.2	20.2	30.9
2	41	5.5	1.0	0.5
3	1	32.0	2.5	6.0
3	3	139.9	1.0	16.0
4	7	54.7	2.0	5.6
12	1	13.8	2.0	2.5
12	3	28.9	2.0	2.7
15	32	20.7	3.0	4.1
23	1	6.1	0.6	3.1
30	1	1.4	0.5	0.0
33	33	167.3	0.5	12.7
45	19	1.6	1.0	0.0

Table 52. ESTIMATED WORK TRIPS

Zone I	Zone J	Auto driver	Transit	Auto passenger	Driver serve passenger	Walk
2	2	152.4	31.4	40.5	16.7	8.8
2	41	6.0	0.0	1.0	0.0	
3	1	33.5	0.8	6.2	0.0	
3	3	124.5	6.5	25.9	7.5	1.2
4	7	53.2	0.2	8.9	0.2	
12	1	14.7	0.5	3.1	0.0	
12	3	28.1	0.3	5.2	0.2	
15	32	21.9	1.4	4.5	0.1	
23	1	7.3	0.8	1.7	0.0	
30	1	1.1	0.0	0.8	0.0	
33	33	146.6	2.2	31.8	9.8	1.4
45	19	2.2	0.0	0.4	0.0	

where $(Total\ home\ based\ trips)_{ij} = HWADC_{ij} + WOADC_{ij} + HWBAC_{ij} + WOBAC_{ij} + HWBNC_{ij} + WOBNC_{ij} + HWAPC_{ij} + WOAPC_{ij} + HWASC_{ij} + WOASC_{ij} + WALK_{ij}$

The results of the estimations are given in Table 52.

A comparison of Tables 51 and 52 shows how well the model predicts and highlights some of the biases which may result in applying the model. These will be discussed in more detail after the aggregate results of estimating trips by mode and total VMT's for all 172 zonal interchanges are presented.

Aggregate Work Trips -- Another test of the performance of the model is to compare its predictions of travel behavior with both the observed travel in the random sample of 172 zonal interchanges and the modal split over the entire Los Angeles region. The first such comparison is presented in Table 53, where the actual number of person-trips by mode and VMT's for passenger vehicles are compared to the estimates given by applying the model. VMT's are calculated as follows:

$$VMT = \sum_{ij}\Big(2D_{ij}(Driver\ trips_{ij} + 2\cdot Serve\ passenger\ trips_{ij}) + (D_{ii} + D_{jj})(Passenger\ trips)\Big) \qquad (48)$$

The first term in the above brackets is self-evident from the definition of driver trips and driver serve passenger trips. (Driver serve passenger trips are zero in the LARTS data for work trips owing to the way their data is classified. See Appendix D for more details on the LARTS data.) The second term accounts for extra distance which must be traveled in order to pick up and deliver passengers within zones.

Table 53. ESTIMATED VS. ACTUAL TRIPS BY MODE FOR 172 ZONAL INTERCHANGES

Mode	Actual	Estimated
Auto driver	1040	960
Transit	47	54
Auto passenger	123	196
Driver serve passenger	--	40
Walk	--	10
VMT's	15302	15451[a]

[a]Includes driver serve passenger VMT's of approximately 240 miles.

Table 54. ESTIMATED VS. ACTUAL MODE SHARES FOR LARTS REGION (percentages)

Mode	Actual	Estimated[a]
Auto driver	0.84	0.79
Transit	0.04	0.04
Auto passenger	0.12	0.16

[a]Excludes driver serve passenger and walk.

Table 54 presents the modal shares estimated for the sample of 172 observations as compared to the modal shares for the region as a whole. This comparison will allow a determination of whether predictions based on the sample will be representative of the entire LARTS area.

Evaluation of Work Trip Model

In general, the model performs reasonably well, although certain of its biases should be noted in order to better evaluate its application to policy scenarios in Chapter 3. A comparison of Tables 51 and 52 shows that there is a tendency for auto driver alone trips to be underpredicted, whereas passenger trips are somewhat overpredicted. It is possible to "calibrate" the model further to decrease passenger trips and increase auto driver trips. Unfortunately, it is not known to what extent driver serve passenger trips would be decreased relative to carpooling. In the absence of extraneous information, it was decided not to proceed with adjustments which would cause the model to give better predictions for 1967. However, it appears that the serve passenger mode is overpredicted for short (typically intrazonal) trips and that carpooling is overpredicted for long (say, greater than 25 miles round trip) distances. The model also predicts more variation in transit usage than appears in the sample of 12 observations; this is to be expected, since a criterion for including an observation in the sample was the existence of at least one (one-way) transit trip.

Examining the aggregate results in Tables 53 and 54 shows that some of the above-mentioned errors tend to cancel when the model is used to predict regionwide auto trips and VMT's. From Table 53 it can be seen that total vehicle trips, exclusive of driver serve passenger, are underpredicted by 7.69 percent. The two figures are not comparable because the predicted VMT's, which include miles traveled attributable to driver serve passenger trips, are intrazonal with an average distance for each of four legs of approximately 1.5 miles; deducting the aggregate approximate total of 240 miles from the estimated 15,451 yields 15,211. From this rough calculation it appears that aggregate VMT's are underestimated by about 1 percent.

Shopping Trip Mode Split

The shopping mode split model is part of a larger travel demand model which also predicts destination choice and frequency of shopping trips per household per day. It was found that in order to test these latter relationships, the shopping trip sample of zonal interchanges had to be augmented to include observations where more than one destination zone was associated with a given origin zone. In the sample of zonal interchanges finally selected, each observation represents a destination-choice with another destination alternative in the sample. This constraint lowered considerably the number of useful observations for determining the effects of system changes on destination choice. Nonetheless, the fifteen zone interchanges were selected to be highly representative of the regional population. Also, because shopping trips are clustered into fewer zonal interchanges, the percentage sample of total shopping trips is comparable to the work-trip sample (about 4 percent).

In order to test the model, three series of computations were made corresponding to mode choice, destination choice, and frequency of trips per household. Rather than give the values of variables at every step, as was done in the work trip model, we will present the formulas and assumptions at each step and then give the predicted vs. actual travel behavior. We shall first consider mode split.

As in the work trip mode split equations, odds functions for auto vs. other modes were first generated, and from these probabilities of mode choice were calculated. The probabilities were then adjusted for variation in order to forecast modal shares for each zonal interchange. The following sections present the equations and assumptions for each odds function.

The basic home-shopping odds function from Table 39 is:

$$ln \frac{P_{Aij}}{P_{Bij}} = -6.77 - 4.11(C_{Aij} - C_{Bij}) - .0654(T_{Aij} - T_{Bij}) - .374(S_{Aij} - S_{Bij}) + 2.24Y \qquad (14)$$

where P_{Aij} = probability of an auto driver home-shopping round trip from zone i to zone j, given a trip will be made;

P_{Bij} = probability of a given alternative mode home-shopping round trip from zone i to zone j, given a trip will be made;

C_{Aij} = variable cost per mile of an auto round trip from zone i to zone j;

C_{Bij} = cost of an alternative mode round trip from zone i to zone j;

T_{Aij} = line-haul time for auto round trip from zone i to zone j;

T_{Bij} = line-haul time for alternative mode round trip from zone i to zone j;

S_{Aij} = access time to auto for a round trip between zone i and zone j;

S_{Bij} = access time to alternative mode for a round trip between zone i and zone j;

Y = number of autos per tripmaker.

Auto vs. Transit -- The variables defined in Table 55 are substituted into Equation 14 for the home-shopping model. The subscript B has been replaced by a T to denote transit as the alternative mode. The source of each variable B is given in the table. As in the work trip model, the result P_{Aij}/P_{Tij} will be used to find the mode splits.

Auto vs. Carpooling -- The carpooling assumptions used in the home-work purpose proved inappropriate for the home-shopping purpose. New carpooling options were added based on reasonable inferences about shopping trip behavior. C_1 and C_2 are equivalent to the home-work carpooling, in that cost is shared by the occupants of the car and line-haul time is auto time plus an additional time for pickup and delivery of passengers. Only one and two passenger type carpools are provided for. C_{1A} and C_{2A} are similar to family carpooling. That is, the carpool with one passenger replaces the alternative of two trips by the occupants. Likewise, C_{2A} has two passengers who would have the option of separate trips had the carpool not been utilized. C_{1B} is a home-shopping carpool trip in which the passenger only took the trip for companionship.

As in the home-work model, access time will be equal for each person, whether in a carpool or driving alone, and the constant and availability of a vehicle are suppressed. The carpooling equation will be as follows:

$$ln \frac{P_{Aij}}{P_{C_{kij}}} = -4.11(C_{Aij} - C_{Ckij}) -.0654(T_{Aij} - T_{Ckij}) \quad (14.1)$$

where P_{Ckij} = probability of an individual making a round trip carpool trip with k passengers.

Table 56 defines the variables for each of the five different types of carpooling. The auto variables are the same as in Table 55.

Table 55. AUTO VS. TRANSIT VARIABLES

Variable	Definition	Source
C_{Aij}	$.03(2D_{ij})$	.03 is the assumed auto operating cost for one mile. D_{ij} is the average one-way mileage from zone i to zone j from Time and Distance file.
C_{Tij}	if $D_{ij} < 5$; $.06 + TR$ if $5 \leq D_{ij} \leq 33$; $TR + 2(.30 + .08(D_{ij}/3))$ if $D_{ij} > 33$; $TR + 2(1.18 + .07(D_{ij}-33)/3)$	Based on zonal transit fares which were in effect in 1967. TR = .10 (Average number of off-peak transfers.)
T_{Aij}	$HSADT - HSADIWT - HSADJWT$	LARTS data where (in minutes): $HSADT$ = home-shop purpose, auto driver mode, round trip line-haul time; $HSADIWT$ = amount of walking time in zone i; $HSADJWT$ = amount of walkint time in zone j.
T_{Tij}	2(Off-peak line-haul + off-peak schedule delay)	Los Angeles bus schedules -- see Appendix D for a detailed explanation (times are in minutes).
S_{Aij}	6 minutes	Assumption -- one and one-half minutes of access time at each end of each trip.
S_{Tij}	Approximations of average walk times for potential bus riders to bus stops in the zone.	Bus route maps -- see Appendix D for more details.
Y	$\frac{A_2 + 2.1(A_3)}{HH}$	1970 Census data: A_2 = number of households in zone i with two cars; A_3 = number of households in zone i with three cars; HH = number of households in zone i

Table 56. CARPOOL VARIABLES

Variable	Definition	Source
C_{C1ij}	$\frac{.03(2D_{ij} + A_i + A_j)}{2}$	See carpooling in home-work purpose.
C_{C2ij}	$\frac{.03(D_{ij} + A_i + A_j)2}{3}$	See carpooling in home-work purpose.
C_{C1Aij}	$C_{Aij}/2$	Assumption (no extra cost for pick-up and delivery).
C_{C2Aij}	$C_{Aij}/3$	Assumption (no extra cost for pick-up and delivery).
C_{C1Bij}	C_{Aij}	Assumption (no extra cost for pick-up and delivery; no sharing of costs).
T_{C1ij}	$4(A_i + A_j) + 20 + T_{Aij}$	See carpooling in home-work purpose.
T_{C2ij}	$8(A_i + A_j) + 40 + T_{Aij}$	See carpooling in home-work purpose.
T_{C1Aij}	$T_{Aij} + 20$	Assumption (additional time for divergences in personal schedules).
T_{C2Aij}	$T_{Aij} + 40$	Assumption (additional time for divergences in personal schedules).
T_{C1Bij}	$T_{Aij} + 20$	Assumption (additional time for divergences in personal schedules).

Auto vs. Serve Passenger -- The auto vs. serve passenger odds function required an adjustment to the constant term in order to give reasonable results. The resulting equation is:

$$ln \frac{P_{Aij}}{P_{Sij}} = -4.77 - 4.11(C_{Aij} - C_{Sij}) - .0654(T_{Aij} - T_{Sij})$$
$$-.374(S_{Aij} - S_{Sij}) + 2.24Y \qquad (14.2)$$

where P_{Sij} = probability of a round trip by a driver serving passenger and a passenger from zone i to zone j.

The reason for increasing the constant from -6.77 to -4.77 appears to be that the original constant (in Equation 14) is mode specific for transit only. The adjustment is necessary to prevent the serve passenger mode from dominating other modes to an unreasonable degree. The definitions of auto serve passenger variables are presented in Table 57; their assumptions are based on the reasoning discussed in the work trip section on the serve passenger mode. Auto variables are the same as the ones used in Table 55.

Mode Probabilities -- The seven odds functions described above, auto vs. other modes, are calculated for each zonal interchange. (It was found that the estimated walk probabilities were negligible. Hence, they were ignored.) In order to find the model probabilities for each of the eight alternatives, the following equations were used:

$$\text{Auto probability} = \frac{1}{1 + D_{ij}}$$

$$\text{Transit probability} = \frac{P_{Bij}/P_{Aij}}{1 + D_{ij}}$$

Table 57. SERVE PASSENGER VARIABLES

Variable	Definition	Source
C_{Sij}	$2(C_{Aij})$	Assumption (two vehicle round trips for each serve passenger mode trip).
T_{Sij}	$3(T_{Aij}) + 40$	Assumption (three person round trips for each serve passenger mode trip plus an additional time penalty for personal schedule divergences).
S_{Sij}	$2(S_{Aij})$	Assumption (access time for two person round trips).

$$\text{Carpool 1 probability} = \frac{P_{C1ij}/P_{Aij}}{1 + D_{ij}}$$

$$\text{Carpool 2 probability} = \frac{P_{C2ij}/P_{Aij}}{1 + D_{ij}}$$

$$\text{Carpool 1A probability} = \frac{P_{C1Aij}/P_{Aij}}{1 + D_{ij}}$$

$$\text{Carpool 2A probability} = \frac{P_{C2Aij}/P_{Aij}}{1 + D_{ij}}$$

$$\text{Carpool 1B probability} = \frac{P_{C1Bij}/P_{Aij}}{1 + D_{ij}}$$

$$\text{Serve passenger probability} = \frac{P_{Sij}/P_{Aij}}{1 + D_{ij}}$$

where:

$$D_{ij} = \frac{P_{Bij}}{P_{Aij}} + \frac{P_{C1ij}}{P_{Aij}} + \frac{P_{C2ij}}{P_{Aij}} + \frac{P_{C1Aij}}{P_{Aij}} + \frac{P_{C2Aij}}{P_{Aij}} + \frac{P_{C1Bij}}{P_{Aij}} + \frac{P_{Sij}}{P_{Aij}}$$

Estimated Trips by Mode -- Several more steps are necessary in order to estimate the number of trips by mode. First, the mode probabilities calculated as above must be adjusted for variance within zonal interchanges in order to determine modal shares. This approach is the same as that used for the home-work model. Then the carpool mode is divided into drivers and passengers. The serve passenger mode is assumed to have one passenger round trip and one serve passenger round trip for each round trip estimated. The following equations show how the estimates of modal trips for each zonal interchange are derived.

Est. auto trips = {*Est. auto share + .5(Est. carpool* <u>*1*</u> *share + Est. carpool* <u>*1A*</u> *share + Est. carpool* <u>*1B*</u> *share) + .33(Est. carpool* <u>*2*</u> *share + Est. carpool* <u>*2A*</u> *share)*}*(Total trips)*

Est. transit trips = *(Est. transit share)(Total trips)*

Est. passenger trips = {*.5(Est. Carpool* <u>*1*</u> *share + Est. carpool* <u>*1B*</u> *share) + .667(Est. carpool* <u>*2*</u> *share + Est. carpool* <u>*2A*</u> *share) + Est. serve passenger share*}*(Total trips)*

Est. serve passenger trips = *(Total trips)(Est. serve passenger share)*

where $Total\ trips_{ij} = HSADC_{ij} + HSBAC_{ij} + HSBNC_{ij} + HSAPC_{ij} + HSASC_{ij}$ *from the LARTS data*

$Actual\ auto\ trips = HSADC_{ij}$

$Actual\ transit\ trips = HSBAC_{ij} + HSBNC_{ij}$

$Actual\ Passenger\ trips = HSAPC_{ij}$

$Actual\ LARTS\text{-}defined\ serve\ passenger\ trips = HSASC_{ij}$

The actual trips by mode for the 15 observations are given in Table 58; the estimated trips by mode are given in Table 59.

A summary of the performance of the mode choice relationship in the shopping trip model is presented in Table 60. Actual and predicted VMT's are also shown; VMT's are computed here as they were for the work trip using Equation 48.

Table 58. ACTUAL SHOPPING TRIPS BY MODE FOR 15 ZONAL INTERCHANGES

Zone I	Zone J	Auto driver	Transit	Auto passenger
2	2	183.9	4.8	79.0
2	14	4.5	0.7	3.0
2	56	0.6	0.0	0.0
3	1	0.7	0.0	0.0
3	3	210.7	5.2	58.1
12	3	21.0	0.4	10.5
12	12	151.6	0.7	63.0
14	2	16.3	0.2	6.4
14	13	37.2	1.4	18.2
14	14	62.9	1.0	35.9
31	7	1.4	0.0	0.0
31	31	129.4	11.0	44.7
31	32	14.7	0.9	2.6
31	35	13.0	3.5	10.5
31	46		3.6	9.3

Table 59. ESTIMATED SHOPPING TRIPS BY MODE FOR 15 ZONAL INTERCHANGES

Zone I	Zone J	Auto driver	Transit	Auto passenger	Driver serve passenger
2	2	181.4	18.0	68.1	6.3
2	14	5.5	0.0	2.7	0.2
2	56	0.2	0.0	0.3	0.0
3	1	0.4	0.0	0.3	0.0
3	3	201.0	0.8	72.2	3.6
12	3	22.4	0.0	9.5	0.0
12	12	156.4	1.6	57.2	3.4
14	2	15.7	0.0	7.2	0.1
14	13	40.3	0.0	16.5	0.6
14	14	72.1	0.0	27.7	2.9
31	7	0.6	0.0	0.6	0.0
31	31	116.9	25.3	42.8	3.2
31	32	12.7	0.0	5.5	0.1
31	35	18.5	0.7	7.8	0.1
31	46	12.1	8.8	5.4	0.0

Table 60. SUMMARY OF ESTIMATED VS. ACTUAL SHOPPING TRIPS BY MODE FOR 15 ZONAL INTERCHANGES

Mode	Actual	Estimated
Auto driver	861.3	856.1
Transit	33.4	55.3
Auto passenger	341.2	324.1
Driver serve passenger	---	20.4
VMT's	4001.0	4065.0[a]

[a]Includes approximately 122 miles attributable to driver serve passenger.

Shopping Trip Destination Choice

This section shows how the destination choice relationship in the shopping trip demand model is applied to estimate the shares of trips among alternative destinations from any given origin. The results of predicting destination choice using the approach described below are compared to the actual shares for the 15 zonal interchanges used in simulating shopping travel behavior. The odds function for destination choice is:

$$ln \frac{P_{\cdot ij}}{P_{\cdot ik}} = (-1.06)\sum_a \left(\frac{N_{aij}}{N_{\cdot ij}} \cdot X_{aij} - \frac{N_{aik}}{N_{\cdot ik}} \cdot X_{aik} \right) + .844(E_j - E_k) \tag{15.1}$$

where $P_{\cdot ij}$ = the probability of taking a shopping round trip from zone i to zone j using any mode;

$P_{\cdot ik}$ = the probability of taking a shopping round trip from zone i to zone k using any mode;

N_{aij} = the number of shopping round trips from zone i to zone j using the ath mode;

N_{aik} = the number of shopping round trips from zone i to zone k using the ath mode;

E_j = retail employment in zone j as a percentage of total regional retail employment;

E_k = retail employment in zone k as a percentage of total regional retail employment;

$N_{\cdot ij} = \sum_a N_{aij}$

$N_{\cdot ik} = \sum_a N_{aik}$

X_{aij} = the generalized cost of a round trip between zone i and zone j by the ath mode;

X_{aik} = the generalized cost of a round trip between zone i and zone k by the ath mode.

In applications of this model, auto and transit are the only modes used to compute the generalized cost of travel. Using the estimated trips from Table 59, the mode shares for weighting the generalized cost of travel are calculated as follows:

$$\text{Auto share} = \frac{\text{Est. auto trips}}{\text{Est. auto trips + Est. transit trips}}$$

$$= \frac{N_{Aij}}{N_{\cdot ij}}$$

$$\text{Transit share} = \frac{\text{Est. transit trips}}{\text{Est. auto trips + Est. transit trips}}$$

$$= \frac{N_{Tij}}{N_{\cdot ij}}$$

where A = auto mode;
T = transit mode.

The generalized cost (X_a) for each mode was computed using the following formulas. For the auto driver mode:

$$X_{Aij} = 4.11(C_{Aij}) + .0654(T_{Aij}) + .374(S_{Aij})$$

while for transit (T):

$$X_{Tij} = -6.77 + 4.11(C_{Tij}) + .0654(T_{Tij}) + .374(S_{Tij})$$
$$+ 2.24Y$$

where the variables are defined in Table 55.

The retail employment variables (E_j and E_k) are computed as follows:

$$E_j = \frac{retail\ employment\ in\ zone\ j}{retail\ employment\ in\ region} \cdot 100$$

$$E_k = \frac{retail\ employment\ in\ zone\ k}{retail\ employment\ in\ region} \cdot 100$$

The probability of an individual in zone i choosing to go to zone j, given a shopping trip will be made, is calculated using Equation 21. In order to estimate the share of trips to destination j among all those made from origin i, the probability must be adjusted for variation among individuals by using Equation 26. This is done by assuming that the variance terms in Equation 26 are all unity.

Table 61 presents the actual and estimated shares for the 15 zonal interchanges in the sample. For each origin zone, the number of shopping trips to the alternative destinations in the sample varied from 85 percent to 100 percent of the total trips from the origin. Thus, the sample captures most of the shopping trips which would be affected by a change in the transportation system.

Table 62 presents the estimated VMT's which result when both mode split and destination choice are estimated from the data. Comparing this figure to the actual VMT's is an important test of the travel demand model.

Shopping Trip Frequency

The third stage of the shopping model estimates the odds that a household will take one shopping trip vs. no shopping trips in a twenty-four hour period. This section describes how the model is applied to determine the number of trips per household in a twenty-four hour period in a given origin zone. The results of the application are tested against the data for the 15 zonal interchanges which comprise the shopping trip sample. The odds function for frequency of trips is as follows:

Table 61. ACTUAL VS. ESTIMATED DESTINATION SHARES FOR SHOPPING TRIPS FROM 15 ZONAL INTERCHANGES

Zone I	Zone J	Actual share	Estimated share
2	2	0.964	0.775
2	14	0.032	0.225
2	56	0.004	0.000
3	1	0.004	0.017
3	3	0.996	0.983
12	3	0.364	0.276
12	12	0.636	0.724
14	2	0.124	0.340
14	13	0.315	0.274
14	14	0.561	0.386
31	7	0.000	0.000
31	31	0.718	0.479
31	32	0.073	0.253
31	35	0.108	0.102
31	46	0.101	0.166

Table 62. ACTUAL VS. ESTIMATED VMT'S FOR SHOPPING TRIPS INCLUDING MODE AND FREQUENCY CHOICE FOR 15 ZONAL INTERCHANGES

	Actual	Estimated
VMT's	4001.4	3954.3[a]

[a]Includes approximately 122 miles of driver serve passenger VMT's.

$$\ln \frac{P_i}{(1-P_i)} = (-1.72)\sum_j \left[\frac{N._{ij}}{N._{i}.} \cdot \sum_a \left(\frac{N_{aij}}{N._{ij}} \cdot \alpha X_{aij} \right) \right]$$

$$+ (3.90)\sum_j \left[\frac{N._{ij}}{N._{i}.} \cdot E_j \right] \quad (16.1)$$

where P_i = the probability of making a shopping round trip in a twenty-four hour period by any mode to any destination from zone i;

$N._{i}.$ = the number of shopping round trips in a twenty-four hour period from zone i by all modes to all other zones.

All other variables have been previously defined.

In order to test this function against the LARTS data, the predicted values for all independent variables are calculated for each origin zone. The probability of an individual household making a trip is estimated using Equation 21. The frequency of trips per household is estimated by adjusting the probability for variation using Equation 26; the variance term is assumed to be unity.

Table 63 presents the actual vs. estimated frequency for the five origin zones in the shopping trip sample. The actual observations are the total number of shopping round trips from the origin zone to all other destinations, including those not in the sample of 15 shopping trip zonal interchange.

Table 64 gives the results of predicting VMT's using the frequency model on estimated VMT's from mode choice and destination choice.

Evaluation of Shopping Trip Model

Inspection of Tables 58 through 60 indicates that the mode choice model replicates travel behavior in the shopping trip sample with a high degree of accuracy. Because these

Table 63. ACTUAL VS. ESTIMATED SHOPPING TRIP FREQUENCY FOR 5 ZONE ORIGINS

Zone I	Actual	Estimated
2	0.426	0.914
3	0.606	0.510
12	0.848	0.263
14	0.538	0.203
31	0.330	0.423

Table 64. ACTUAL VS. ESTIMATED VMT'S, INCLUDING MODE CHOICE, DESTINATION CHOICE AND FREQUENCY OF TRIP, FOR 15 ZONAL INTERCHANGES

	Actual	Estimated
VMT's	4001.4	4821.2[a]

[a]Includes driver serve passenger VMT's.

results will be extrapolated to the rest of the region, it is also worth considering how the mode split projections from the 15 zonal interchanges in the shopping trip model compare to the mode share for the region as a whole. These data are presented below in Table 65. It will be recalled that the zonal interchanges in the sample were originally preselected because the 1967 data suggested they were somewhat representative; thus the comparison in Table 65 is not as strong a test as would have been the case had the sample been randomly selected.

The evaluation of the two stage model -- applying both the mode choice estimates and the destination choice estimates -- rests on the evidence presented in Tables 61 and 62. As in the work trip model, VMT calculations are not strictly comparable because driver serve passenger VMT's are included in the estimated results. Deducting the estimated 20.4 serve passenger trips at an average 6 miles per trip yields 3832 VMT's exclusive of serve passenger trips; this approximation implies that the shopping trip model underpredicts VMT's by about 4 percent. The one potentially important bias in the model is that it tends to underpredict somewhat the share of intrazonal shopping trips.

The results of applying the trip frequency model are given in Tables 63 and 64. This part of the travel demand model appears to be significantly more inaccurate than the others. Part of the problem lies with the data -- number of shopping trips divided by households is not a good representation of what the model is actually supposed to predict. If this were the only problem, the model would still be acceptable in that predicted VMT's were only 17 percent greater than the actual. There is, however, another aspect of the estimated frequency equation which makes it use inappropriate. The implied elasticity of trips with respect

Table 65. ACTUAL VS. ESTIMATED MODE SHARES FOR LARTS REGION

Mode	Actual	Estimated
Auto driver	0.68	0.69
Transit	0.02	0.04
Auto passenger	0.30	0.27

to a change in auto variable costs per mile is on the order of -4. This is much too elastic, as the discussion on *a priori* information about travel elasticities in Chapter 2 indicates. Application of this model to policy scenarios of auto disincentives greatly overpredicts their effects.

In the policy simulations in Chapter 3, it is assumed that frequency of trips do not change with respect to a change in the auto variable costs per mile. Because shopping trips are relatively short in Los Angeles, this assumption may be relatively accurate for modeling the effects of gasoline or emissions taxes. Reasonable assumptions about changes in trip frequency are also applied in Chapter 3.

List of References, Appendix A

[1]Aggregate Travel Demand Analysis with Disaggregate or Aggregate Travel Demand Models. *Proceedings of Transportation Research Forum Fourteenth Annual Meeting.* 13(1): 583-603, October 1973.

Appendix B. AUTO STOCK ADJUSTMENT MODEL

This appendix presents the model used in determining the effects of emissions taxes on the auto stock in the Los Angeles region. The relationships in the model determine the total fleet size, new car sales, used car price, aggregate scrappage rate from the auto stock, and the scrappage rate for each model year of autos in the stock. Table 66 presents the equations and identities used in the model. An explanation for each follows.

CALIBRATION OF THE MODEL

New Car Sales

New car demand is assumed to have the following functional relationship:

$$NC \equiv PN^{-\alpha} KN \qquad (49.1)$$

where α is an assumed constant and KN is a variable which takes account of all other factors determining new auto demand. In order to determine α, the price elasticity of demand, previous studies of new car demand were reviewed.*

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*See reviews of econometric models of automobile demand in: *The Effects of Automotive Fuel Conservation on Automotive Air Pollution.* Charles River Associates Incorporated. Cambridge. Prepared for Environmental Protection Agency. 1976; and Dewees, Donald N. *Economics and Public Policy: The Automotibile Pollution Case.* Cambridge, MIT Press, 1974. 214 p.

Table 66. EQUATIONS AND IDENTITIES IN THE AUTO STOCK MODEL

$$NC_t \equiv (PN_t)^{-1}(1.555)(10^9) \tag{49}$$

$$PU_t \equiv \frac{5.3933(10^9)}{T_{t-1}} \tag{50}$$

$$r_t \equiv 302.6868\left(\frac{NC}{T_{t-1}}\right)^{.7424}(PU_t)^{-.9121} \tag{51}$$

$$T_t \equiv T_{t-1} + NC_t - S_t \tag{52}$$

$$S_t \equiv r_t(T_{t-1}) \tag{53}$$

$$L_i \equiv \frac{.9182}{3.8032 + 846.36e^{-.7617i}} \tag{54}$$

where NC_t = new car sales for Los Angeles and Orange Counties in period t

PN_t = average price of new cars in period t

PU_t = average price of used cars in period t

T_t = stock of cars in Los Angeles and Orange Counties in period t

r_t = rate of scrappage in period t

S_t = number of cars scrapped in Los Angeles and Orange Counties in period t

L_i = rate of scrappage of autos of age i owing to the effects of age alone

Estimated elasticities tend to vary between -.75 and -1.2. Consequently, it is assumed for the purposes of this project that α equals unity.

In order to calculate *KN* for 1975, the following procedure was applied:

- *KN* was computed for the years 1970 through 1973 (the years for which consistent data on Los Angeles and Orange Counties is available) according to the formula:

$$NC_t PN_t = KN_t$$

which is derived from Equation 49.1 with α equal to one.

- The average rate of growth of KN_t was calculated (equal to 2.4 percent).
- This growth factor was applied to determine KN_t in 1974 and 1975.

In order to determine the effect of new car demand on sales, it was further assumed that the supply of cars to Los Angeles at the market clearing price is perfectly elastic. Thus, in the absence of any additional ownership costs imposed by pollution control policies, Equation 49.1 is sufficient to project 1975 new car sales in Los Angeles, given a value for *PN*.

Used Car Price

The following demand/supply relationships are used to develop the used car price equation:

$$DU_t = PU_t^{-\beta} KU_t \qquad (50.1)$$

$$SU_t = T_{t-1} \qquad (50.2)$$

where DU_t = demand for used cars in period t;

KU_t = variable combining all other factors determining used car demand in period t;

SU_t = supply of used cars in period t;

β = assumed constant equal to the elasticity of used car demand.

As discussed in Chapter 2, the used car market is viewed as one where all existing autos have a price or opportunity cost to the owner. Some used cars are sold in a well-defined used car market where the transactions determine the market price for used cars, and consequently, the opportunity cost associated with owners not selling their cars. The market clearing condition for this market is:

$$DU_t = SU_t$$

Substition from Equations 50.1 and 50.2 gives:

$$PU_t^{-\beta} KU_t = T_{t-1}$$

which upon rearrangement yields the following price determination identity:

$$PU_t = \left(\frac{KU_t}{T_{t-1}} \right)^{\beta}$$

In order to determine a value of β, it was assumed that the price elasticity of used car demand was equal to the price elasticity of new car demand. This assumption is partially verified by a study of the demand for new and used automobiles by Gregory Chow.[1] Thus, β is set at unity. KU for 1975 was calculated by solving the equation:

$$PU_t T_{t-1} = KU_t$$

T_{t-1} (the stock of cars in Los Angeles and Orange Counties in 1974) was computed by simulating the model described by Equations 49 through 52. Data on the first nine months of 1974 indicate that the average used car price increased by 5 percent over the 1973 price. A further increase of 8 percent over 1974 was assumed for the 1975 price. With these estimates and assumptions about the 1974 stock of used cars and the 1975 price of used cars, *KU* was calibrated for 1975.

Scrappage Rate

A scrappage equation, originally estimated on national data, was adjusted for application to the Los Angeles region. The estimate of national scrappage rates was:*

$$r_t = L_t (5.5234) \left(\frac{NC_t}{T_{t-1}} \right)^{.7424} \cdot \left(\frac{PIU_t}{PMU_t} \right)^{-.912142} \qquad (51.1)$$

where PIU_t = national consumer price index for used cars in period t;

PMU_t = national price index on auto maintenance and repair in period t;

L_t = scrappage rate owing to the effects of aging alone (discussed in more detail in the following section).

*See *The Effects of Automotive Fuel Conservation on Automotive Air Pollution*. Report for the Environmental Protection Agency. Charles River Associates Incorporated. Cambridge, 1976. The estimated equation is based on a specification which appears in: Walker, Franklin V. Determinants of Auto Scrappage. *Review of Economics and Statistics*. 503-506, November 1968.

All t-statistics on parameters are significant at the 1 percent level of confidence; the standard error of the estimated equation is 11.1 percent; the coefficient of determination (R^2 corrected) is .6346.

When data for Orange and Los Angeles Counties on new car sales and stock of autos was substituted into Equation 51.1, it was found that the resulting estimates were consistently 10 percent higher than the actual scrappage rate. It was inferred from this that the estimate of scrappage owing to age alone (L_t) was higher for the rest of the country than for the southern California region. Though no research was performed to determine why this should be the case, one possible explanation is that both the climate and road conditions in the Los Angeles area are more benign toward automobiles than would be the case in more northern regions of the country.

This result led to an adjustment in the equation which predicts scrappage owing to age alone. A multiplicative constant factor was calculated which gave the best fit between observed and predicted scrappage rates over the four year period covered by the data. The value of the constant factor is .9182.

The indices for used car prices and maintenance/repair costs were also changed so that the average price of used cars (rather than the price index) was isolated in the equation. The following equation shows the relationship between the 1975 average price of used cars and the indices used in the estimated scrappage equation:

$$\frac{\frac{PU_{1975}}{PU_b}}{PMU_{1975}} = \frac{PIU_{1975}}{PMU_{1975}}$$

where b is the base year in formulation of the used car price index. In order to isolate PU_{1975} in the scrappage equation, it is necessary to have a value for PMU_{1975}. In the absence of any recent data, it was assumed that PMU increases at the same annual rate as PU over the two year period from 1973 to 1975. Using this assumption, the following relationship was computed:

$$\left(\frac{PIU_{1975}}{PMU_{1975}}\right)^{-.9121} = \left(PU_{1975}\right)^{-.9121}\left(\frac{1}{1538.0817}\right)^{-.9121}$$

$$= \left(PU_{1975}\right)806.9449$$

Making the above substitution into Equation 51.1, and multiplying by the adjustment factor for scrappage owing to age alone (.9182) yielded Equation 51 in Table 66.

Identities

The auto stock changes over time according to the following identity:

$$T_t \equiv T_{t-1} + NC_t - S_t \tag{52}$$

This equation assumes that there is no net change in the auto stock owing to migration of auto owners or the import/export of used cars from the region by other means.

The total scrappage of used cars in the region is determined by:

$$S_t \equiv r_t\left(T_{t-1}\right) \tag{53}$$

Scrappage Rate by Age of Auto

Using a logit specification, Franklin Walker[2] estimated a scrappage rate by model year equation on national data:

$$m_i = \frac{1}{3.8032 + 846.36e^{-.7617i}} \qquad (54.1)$$

where i is the age of the auto model. All standard errors on parameter estimates are less than 5 percent; the standard error of the estimate is .29 percent; and the coefficient of determination (R^2 corrected) is .9994.

As discussed above, when the results of this equation were used in scrappage rate Equation 51.1, the estimated scrappage rates were higher than those observed in the Los Angeles area. Consequently, it was assumed that the scrappage rate owing to age alone, calculated from Equation 54.1, was overpredicting for Los Angeles, and an adjustment factor was calculated. Applying this factor to Equation 54.1 yields Equation 54 in Table 66.

APPLICATION OF THE MODEL TO POLICY SCENARIOS

Chapter 4 presents the results of simulating the auto stock model under assumed policy scenarios. This section of the appendix briefly discusses the use of the model under various policy assumptions.

New Car Sales

It is assumed that the extra costs of ownership associated with emissions taxes dc not add to the customer's utility in owning the car. The consequences of this assumption is that the demand for new cars can be represented by substituting into the demand equation price minus the present value of future taxes. In equation form, the sales of new cars can be computed as follows:

$$NC_t \equiv (PN_t - PC_t)^{-1}(1.555)10^9 \qquad (49.2)$$

where PC_t is the present discounted value of future costs of ownership associated with pollution control strategies (and is equal to zero in the base case).

Stock of Used Cars

The same reasoning applies to the demand for used cars. However, because the stock, or supply, of used cars is initially fixed, the first reaction to the increased costs of ownership will be a decline in the market price of used cars equal to the amount of the discounted present value of future taxes. As explained in Chapter 2, this decline in average used car prices will cause the scrappage rate to increase and, consequently, the stock of used cars will decline. The lower supply of used cars will then cause an increase in the used car price. The system of changes in used car price, scrappage rates, and used car stocks will continue until a new equilibrium is reached.

In order to determine the new equilibrium, Equations 50 through 53 are iterated with PU_t-PC_t substituted into Equation 51 in the initial iteration.

Scrappage Rate by Age of Car

Emissions taxes will vary in amount depending upon the age of the car. Generally, older autos will have higher pollution rates and larger taxes. (This generalization is not necessarily true for NOx. Precontrolled cars tend to have lower rates than early vintages of HC and CO controlled cars.) Also, the market value of older cars is less, and hence the emissions taxes will be greater in proportion to market price taxes for older cars.

In order to distribute the effects of emissions taxes over scrappage rates by age of auto, the following approach was used. First, the following assumption was made:

$$\frac{\Delta L_i}{L_i} - \frac{\Delta r}{r} = \frac{PC_i}{PU_i} - \frac{PC}{PU} \qquad (55)$$

where L_i = scrappage rate due to age alone for auto of age i;

r = average scrappage rate for whole auto stock;

PC_i = present discounted value of taxes for auto of age i;

PU_i = average used car price for auto of age i;

PC = average present discounted value of taxes for all used cars;

PU = average used car price.

In other words, the above relationship states that the difference between the percentage change in scrappage rate for an auto of vintage i, $\Delta L_i/L_i$, and the percentage change in the aggregate scrappage rate, $\Delta r/r$, is equal to the difference between the policy costs as a percentage of used car price for vintage i, PC_i/PU_i, and policy costs as a percentage of the average used car price, PC/PU. Equation 55 gives quantitative form to the notion that scrappage rate changes will be higher for those automobiles which carry the greater tax burden.

Equation 55 cannot be used directly because data do not exist on the market price of used cars by age of auto. However, the theory behind the scrappage model suggests that used car prices are inversely related to their scrappage rates caused by age alone. Equation 56 incorporates this assumption:

$$\frac{PU_i}{PU} = \frac{r}{L_i} \tag{56}$$

That is, the ratio of used car prices by age (PU_i) to average used car prices (PU) is equal to the inverse of the ratio of used car scrappage rates (L_i) to the average scrappage rate (r).

Solving Equation 56 for PU_i and substituting the result into Equation 55 yields the following formula for calculating the proportionate change of scrappage rates owing to an emissions tax:

$$\frac{\Delta L_i}{L_i} = \frac{\Delta r}{r} - \frac{PC}{PU} + \frac{PC_i}{\frac{r}{L_i}(PU)} \tag{57}$$

The resulting scrappage rate by vintage of car is then calculated as follows:

$$L_i^* = L_i(1 + \Delta L_i/L_i) \tag{58}$$

where L_i^* is the new scrappage rate for autos of age i after the imposition of a tax.

All the data necessary to calculate Equation 57 come from simulation of the model represented by Equations 49 through 54. Δr is determined after all used car demand/supply interaction effects have been calculated. The methods for estimating PC and PC_i are given in Chapter 4 where the effects of emission taxes on the stock of autos are presented.

List of References, Appendix B

[1]Chow, Gregory C. *Demand for Automobiles in the United States.* Amsterdam, North-Holland Publishing Company, 1957.

[2]Walker, Franklin V. Determinants of Auto Scrappage. *Review of Economics and Statistics.* 503-506, November 1968.

Appendix C. BUS COST MODEL

This appendix derives the method used in Chapter 5 for estimating the change in operating and capital costs of bus services. The method uses the following:

- A cost model to estimate long-run operating costs of conventional bus service and capital costs of conventional bus, express bus and minibus service. The operating cost model is defined as a function of the number of bus miles and bus hours operated, as well as the number of vehicles maintained for service.
- Functional relationships defining, for alternative services, the number of bus hours and bus miles operated as well as the number of vehicles maintained for service. These output variables are defined as a function of the headway, route length, and average vehicle speeds along the routes.

The incremental cost due to a change in service is estimated by using the cost model and the operating relationships describing output. In general, the system costs before and after the service change can be estimated using the cost model, the system output variables before the service change, and the change in variables due to the service change. The cost model is described in the next section; output variables are defined in a separate section; and a method of calculating incremental costs by using the model and variables is defined in the final section.

ESTIMATES OF OPERATING AND CAPITAL COSTS FOR BUS SERVICE

To estimate the long-run incremental costs of alternative bus services in this study, estimates of total operating costs and capital costs of conventional bus are used. We also present the costs of minibus and express bus, though such options are not considered explicitly in the policy scenarios in Chapters 3 and 5. The total operating costs include the following cost categories, defined in the ATA Transit Operating Report: equipment, maintenance and garage, transportation, station, traffic and advertising, insurance and safety, administration and general, operating taxes and licenses. The capital costs for equipment and shop and yards are represented. Estimates of the capital costs of CBD terminals and stations are not estimated, since the service improvements considered do not affect these costs.

Operating Costs

The total operating cost of conventional bus service is defined as a function of annual bus miles, annual bus hours, and the average number of vehicles available for service. All components of operating costs except fuel and oil for conventional and express bus are estimated using the same cost model. As a result, the average cost per bus mile will differ among modes principally as a result of differences in the speed of operating the various services.

The operating cost model for the conventional bus was calibrated using data on conventional bus operations. The operating cost model in 1973 dollars is as follows:

$$TOC_{73} = 1.15845(7.14788H + .00000109H^2 + .091647M + 2739.02U) \quad (59)$$

where TOC_{73} = total operating costs in 1973 dollars;
H = annual bus hours operated;
M = annual bus miles operated;
U = number of buses owned available for service.

The method used to estimate the cost model parameters for conventional bus service is described below.

The costs of bus service are modeled in this study using the functional form of the model for conventional bus service selected in a prior CRA analysis of bus costs.* In particular, for cost categories analyzed in the previous study, cost/output relationships selected in that study were used. The parameters of the relationship were estimated for this study using regression analysis and 1973 data of a cross-section of bus services. This approach reflects the quite different rate of cost increase in 1967 and 1973 for various cost categories. For cost categories not analyzed in the previous study, simple cost/output relationships were selected and the parameters estimated using 1973 data.

The data used in this study to estimate parameters for the operating cost model were taken from the 1973 ATA Transit Operating Report. Data for a sample of 24 firms reporting in Part II of the report, Motor Bus Transit System, were used. This sample included all firms reporting in that section whose data had the following three properties: the cost categories were ICC rather than ATA cost categories; diesel fuel was at least 99 percent of all fuel used in the operation; all cost and operating statistics categories used in the analysis were reported.

Ten cost categories and three types of operating statistics were used to define the cost model. The ten cost categories are combinations or subdivisions of the cost

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*Conventional bus costs for 1967 were analyzed by CRA as described in: Mack, Ruth, *et al.* Chapter 4. In: *Urban Transportation and Recreation. Summary and Import.* New York, Institute of Public Administration, July 1970.

categories presented in the ATA Transit Operating Report.*
The functional form used for each of these cost categories and the parameters estimated using 1973 data are shown in Table 67; t-statistics are presented in parentheses.

The cost/output relationship for cost categories 1, 3, 4, 5, 8 and 10 in Table 67 are identical to those selected in the CRA analysis of 1967 bus costs. Of the remaining cost categories 2, 6, 7 and 9, categories 2 and 6 were analyzed in the previous study. The forms used for categories 2 and 6 in this study are simpler than those used in the previous analysis. They were estimated satisfactorily without a weighted refression by assuming a proportional relationship between cost and hours.

Traffic and advertising expense plotted against any of the output variables show considerable random variation. Bus mileage was chosen as the output variable in this study. The proportional relationship shown in Table 67 was selected since the constant term in a regression using a linear form was not significant.

Operating taxes and licenses were expected to vary with the number of active buses (buses maintained in condition for service) chosen as the output variable. For this category,

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*The operating cost categories were:

	ATA Line Entry (1973)
1. Repairs to revenue equipment	5
2. Tires and tubes	6
3. Miscellaneous maintenance	4-5-6
4. Wages (drivers and helpers)	8
5. Fuel and oil	9+10+11
6. Miscellaneous transportation	7+12-8-9-10-11
7. Traffic and advertising	13
8. Insurance and safety	14
9. Operating taxes and licenses	19
10. Administration and general	16

The output variables:

1. Bus miles	36
2. Bus hours	39
3. Buses active	33

Table 67. COST ESTIMATION EQUATIONS FOR 1973

Operating costs	Variables and parameters	R^2
1. Repairs to revenue equipment	*1.08306(HR)* (20.390)	0.8905
2. Tires and Tubes	*0.0095719(MI)* (16.683)	0.8190
3. Miscellaneous maintenance	*0.0820747(MI)* (15.402)	0.8402
4. Wages (drivers and helpers)	$4.77097(HR) + 0.00000108836(HR^2)$ (9.636) (2.904)	0.9710
5. Fuel and oil	*0.464492(HR)* (13.031)	0.7839
6. Miscellaneous transportation	*0.829355(HR)* (15.569)	0.8371
7. Traffic and advertising	*0.0122232(MI)* (8.766)	0.6183
8. Insurance and safety	*1067.78(NBA)* (11.817)	0.7126
9. Operating taxes and licenses	*1671.24(NBA)* (11.585)	0.7379
10. Administration and general	*0.158845(EX)* (14.726)	0.8181

NBA = number of active buses

MI = bus miles

HR = bus hours

EX = total operating expenses exclusive of administrative and general costs

t-statistics are in parentheses

a linear regression yielded a constant term that was not statistically significant. Therefore, the form chosen was the proportional relationship between costs and the number of buses shown in Table 67.

These costs are aggregated into the total operating cost function in 1973 dollars shown in Equation 59. The categories one through nine in Table 67 are summed and the coefficients of each output variable are multiplied by one plus the coefficient of total operating expenses used to estimate category 10.

Express and Conventional Bus -- The primary difference between the operation of conventional and express buses is that express buses operate at higher speeds. Therefore, if the functional forms used to estimate costs for conventional buses are not affected by changes in the speed at which buses are operated, then the conventional bus cost model can be used to estimate the costs of express buses.

In particular, we assume that categories 1, 4 and 5 -- repairs to revenue equipment, wages, and miscellaneous transportation -- are a function of the bus hours of service independent of the speed. Similarly, we assume that categories 8 and 9 (insurance and safety, and operating taxes and licenses) are a function of the number of buses used. Therefore, for express bus service the average cost per mile in these categories will be slightly less than for conventional bus service. These assumptions are consistent with the approach and costing methodology used in the IDA study.*

*See Institute for Defense Analyses. *Evaluation of Rail Rapid Transit and Express Bus Service in the Urban Commuter Market*. p. A-7. The average cost per mile for conventional bus service is allocated to express bus on the basis of hours of bus service per mile consistent with the treatment of these three categories here. Also, a comparison of the category which includes repairs to revenue equipment for conventional and intercity bus service supports the decrease per mile in the category.

In addition, we assume categories 2, 3 and 7 (tires and tubes, miscellaneous maintenance, and traffic and advertising) all vary with bus miles independent of speed. That is, the cost per mile in these categories would be the same for express and conventional bus.

However, category 5, fuel and oil, calibrated using data which reflect average speed of conventional bus operations, will overestimate the fuel and oil expenses of express buses. Therefore we have calculated factors to adjust the estimates of fuel and oil costs for conventional bus to estimates for express bus. In particular, the fuel and oil costs per mile for express bus are obtained by multiplying the fuel and oil costs per mile for conventional buses by the following factors:

- .61 for express bus operations averaging 30 miles/hour;
- .51 for express bus operations averaging 40 miles/hour.

These factors were calculated by dividing average bus fuel consumption at speeds of 30 (or 40) miles per hour by average bus fuel consumption at 10 miles per hour.* The average bus speed in the sample of bus firms used to calibrate the conventional cost model was 11 miles per hour. (Note that this includes bus wait time.) Therefore, the operating costs for service including express bus are estimated as:

$$TOC_{73} = 1.15845\big(6.68338H + .464492(H_C + f_E H_E) + .00000109H^2 + .091647M + 2739.02U\big) \quad (60)$$

*The data on fuel consumption were taken from Table 23 in: *Characteristics of Urban Transportation Systems*. U.S. Department of Transportation. Washington, D.C. May 1974.

where H, M, U = same as defined for the conventional bus model;

H_C ≡ the annual bus hours operated in conventional bus service;

H_E ≡ the annual bus hours operated in express bus service;

f_E ≡ the factor: .61 for buses averaging 30 mph
.51 for buses averaging 40 mph.

Minibus and Conventional Bus -- Recent experience in operating minibuses indicates that the vehicle operating and maintenance costs are approximately the same as those of conventional buses.* To our knowledge no model of minibus costs as a function of output variables has been calibrated. However, initial OCTD (Orange County Transit District) operating costs in the first year of operation (February 1973 to January 1973) were approximately $1.00 per mile. OCTD indicates that the wage rate for dial-a-ride was no greater than three-fifths of the wage rate for their fixed route system. The actual average operating cost per bus mile is calculated at $1.27 per mile using data comparable to that in the 1973 ATA Transit Operating Report for SCRTD. When the labor costs in ATA category 8 are adjusted downward by three-fifths, the average cost per mile is reduced to $1.04, approximately the cost experienced by OCTD.

Therefore it can be assumed that the average operating cost per mile for minibuses is the same as the average cost per mile for conventional bus when the service is operated by the same management. If the service is operated as a taxi service with lower labor rates, then the labor costs are adjusted to represent three-fifths of the labor costs.

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*Conversation with N. Wilson at MIT and P. Conway at SCRTD (Southern California Rapid Transit District). At present, maintenance costs are slightly higher than conventional bus and offset any savings in other operating costs.

In 1973, SCRTD's average cost per mile was about $1.27 based on published figures. Using the operating cost model in this study for the same volume, we estimated $1.36 per mile. Correspondingly, when the labor rate is adjusted downward, we obtain an average cost of $1.04 per mile using published figures and a cost estimate of $0.98 per mile using the model. (Note that the nonlinear form of category 4 is probably reflecting the difference in labor rate (unionized vs. nonunionized) between large and small firms.)

Capital Costs

Several types of capital costs can be affected by changes in the service offered. These are equipment costs, related costs in shop and yard, costs of CBD terminals and stations, and subsidiary costs. For the service changes considered in this study, the only capital costs affected will be equipment costs and costs in shop and yard.

Equipment Costs -- Annual capital costs for bus in 1972 and 1974 dollars are presented in Table 68. These costs are developed from two sources. One is average purchase costs in 1972, published in the IDA study:[1]

Bus Type	Passengers	Purchase Cost
Conventional	50	$43,000
Express	50	48,000
Mini	19	14,000

The other is bus costs of the type used by SCRTD at the beginning of 1975. These are as follows:

Bus Type	Passengers	Purchase Cost
Conventional	50	$62,000
Mini	19	32,000

Table 68. APPROXIMATE PURCHASE AND ANNUAL CAPITAL COSTS IN 1973 DOLLARS

Purchase Costs

Bus type	IDA source average	SCRTD source	Selected
Conventional	$43,331	$58,050	$58,000
Express	48,370	48,370	48,370
Mini	14,108	29,961	30,000

Annual Capital Costs in 1973 Dollars

Bus type	IDA source average	SCRTD source	Selected
Conventional	$5,689	$7,622	$7,622
Mini	2,644	5,615	5,615

SCRTD notes that while there are less expensive minibuses on the market, the more expensive models are cost effective when maintenance costs are considered.

To calculate the annual cost the following capital recovery factors were used:

Bus Type	CRF	Interest Rate	Residual Rate	Life
Conventional	0.1313	10	0	15
Express	0.1468	10	0	12
Mini	0.1874	10	0	8

The figures for 1973 were obtained by using the following Wholesale Price Index -- Motor Buses[2] applied to the capital costs:

Year	Average Annual Wholesale Price Index
1971	115.0
1972	116.8
1973	117.7
1974	125.7*

Shop and Yard -- For the estimate of investment in shops and yards required to support each bus owned, we use the same procedure as that cited in the IDA study (that is, the 1964 estimate of investment of $4,500 per bus used in the Meyer, Kain and Wohl study, "The Urban Transportation Problem"[3]). The IDA study adjusted these costs to 1972 dollars giving an estimate of $6,100.[4]

These costs were then put on an annual basis assuming a life of 50 years, no residual value, and an interest rate of 10 percent. The corresponding capital recovery factor is 0.1009.

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*Based on the first eight months of 1974.

The consumer price index for 1972 was 125.3; for 1973, 133.1. Therefore, the estimate of investment in shop and yard used for 1973 is $6480, and the estimate of 1973 annualized cost is $654.

CHANGES IN BUS SERVICE OUTPUT VARIABLES RESULTING FROM CHANGES IN SERVICE CHARACTERISTICS

General Approach for Conventional Bus Service

The changes in transport services considered in this study include changes in departure frequency and routes. Ideally, the service change would be specified so that the total annual change in the variables of the cost model (annual bus hours, annual bus miles, and number of vehicles available for service) due to introducing the alternative can be calculated. The cost model can then be applied to calculate the incremental change.

In particular, the following variables should be specified for each bus route or mode introduced or removed:

v ≡ vehicle type -- conventional, express, or minibus;

$i_1, i_2 \ldots i_n$ ≡ labels of the bus stops on the route;

$m_{i_j i_{j+1}}$ ≡ the distance (in miles) between bus stop i_j and i_{j+1} for all j;

$s^p_{i_j i_{j+1}}$ ≡ the average speed (in miles/hour) in the peak hours between stops i_j and i_{j+1}, including the effect of acceleration and deceleration. For off-peak hours, the average speed is represented as $s^o_{i_j i_{j+1}}$;

$w^p_{i_j}$ ≡ the average stop time (in hours) in peak hours at stop i_j for loading and unloading. For off-peak hours, the average stop time is represented as $w^o_{i_j}$;

h_r^p ≡ the average headway or time between buses (in hours) in peak hours on route r. For off-peak hours, the average headway is represented as h_r^o;

dt_{i_o} ≡ the average time at origin i_o between trips.

The changes in annual bus miles, bus hours, and active buses expected to result from a proposed alternative are calculated from this data as described below. As the first step, the bus miles per trip, bus hours per trip and number of scheduled buses per hour are calculated for peak and off-peak service for each bus route or mode introduced or removed. The variables for each trip are calculated as:

mt_r Bus miles per trip on route r where:

$$mt_r = \sum_{j \varepsilon r} m_{i_j i_{j+1}}$$

ht_r^p Bus hours per trip on route r in peak hours:

$$ht_r^p = \sum_{j \varepsilon r} \frac{m_{i_j i_{j+1}}}{s^p_{i_j i_{j+1}}} + \sum_{j \varepsilon r} w^p_{i_j} + dt_{i_o}$$

ht_r^o Bus hours per trip on route r, off-peak hours:

$$ht_r^o = \sum_{j \varepsilon r} \frac{m_{i_j i_{j+1}}}{s^o_{i_j i_{j+1}}} + \sum_{j \varepsilon r} w^o_{i_j} + dt_{i_o}$$

U_r^p Buses required per hour in peak hours to provide service on route r:

$$U_r^p = \frac{ht_r^p}{h_r^p}$$

U_r^o Buses required per hour in off-peak hours to provide service on route r:

$$U_r^o = \frac{ht_r^o}{h_r^o}$$

Annual variables are then calculated for route r as follows:

AM_r Annual bus miles on route r is defined as:

$$AM = \frac{mt_r k^p}{h_r^p} + \frac{mt_r k^o}{h_r^o}$$

where k^p is peak hours per year;
k^o is off-peak hours per year;
other parameters are defined above.

AH_r Annual bus hours on route r is defined as:

$$AH_r = k^p U_r^p + k^o U_r^o$$

where parameters are as defined above.

NBA_r Number of active buses servicing route r:

$$NBA_r = N_1 U_r^P$$

where N_1 is the ratio of active buses to buses used in peak hours.

If the transport alternative consists of the addition of several routes, say R^A, and the deletion of several routes, say R^D, then the incremental annual bus hours, miles, and buses are defined as shown below.

ΔAM The change in annual bus miles is defined as:

$$\Delta AM = \sum_{r \epsilon R^A} AM_r - \sum_{r \epsilon R^D} AM_r$$

ΔAH The change in annual bus hours is defined as:

$$\Delta AH = \sum_{r \epsilon R^A} AH_r - \sum_{r \epsilon R^D} AH_r$$

ΔNBA The change in the number of active buses is:

$$\Delta NBA = \sum_{r \epsilon R^A} NBA_r - \sum_{r \epsilon R^D} NBA_r$$

Ratio of Active to Peak Buses -- The ratio N_1 of active to peak buses used in this analysis is 1.25. The average of the ratio of active to peak buses in the sample used to estimate bus operating costs is 1.28. The average of the ratio of the largest ten companies in the sample was 1.22. Therefore, as an approximate value we selected 1.25.

Calculation Method of Bus Outputs for Conventional Bus

In practice, the only improvements considered were direct service for certain segments of routes. Possible interconnections of routes, which can have some effect on costs, were ignored. Two sets of output variables were calculated. One represents the bus miles, bus hours, and buses required for the improved service for one-way trips. The other represents the output when the bus must make the reverse trip as well. For each improved segment the following were specified:

$m_{i_1 i_2}$ segment distance;

$tt_{i_1 i_2}$ trip time for direct (improved) service from pickup to delivery point;

$h^p_{i_1 i_2}$ headway in peak hours for the improved service on this route;

$h^o_{i_1 i_2}$ headway in off-peak hours for the improved service on this route.

The following output variables are calculated for one-way trips on the segment:

$mt_{i_1 i_2}$ one-way bus miles per segment trip are equal to $m_{i_1 i_2}$;

$ht_{i_1 i_2}$ one-way bus hours per segment trip are equal to $tt_{i_1 i_2}$;

U_r^p, U_r^o Buses required per segment are equal to:

$$U_r^p = \frac{ht_{i_1 i_2}}{h^p_{i_1 i_2}} \text{ per peak hour;}$$

$$U_r^o = \frac{ht_{i_1 i_2}}{h^o_{i_1 i_2}} \text{ per off-peak hour.}$$

Then annual output variables per segment due to the new service are calculated as:

AM_r Annual bus miles on route r:

$$AM_r = \left(\frac{mt_{i_1 i_2}}{h^p_{i_1 i_2}}(30) + (70)\frac{mt_{i_1 i_2}}{h^o_{i_1 i_2}} \right) \cdot 52$$

AH_r Annual bus hours on route r:

$$AH_r = \left(30(U_r^p) + 70(U_r^o)\right)(52)$$

NBA_r Number of active buses required for service improvement on route r in peak hours:

$$NBA_r = 1.25(U_r^p)$$

Improvements in off-peak service are assumed to be operated with available buses.

The change in annual output variables for all improvements are then given by:

$$\Delta AM = \sum AM_r$$

$$\Delta AH = \sum AH_r$$

$$\Delta NBA = \sum NBA_r$$

ESTIMATES OF INCREMENTAL COSTS OF CHANGES IN BUS SERVICE

General Method for Conventional Bus

In theory, the incremental cost of changes in bus service is calculated by taking the difference of the cost under the previous and changed service. Using the cost model in the previous section, the change is defined as:

$$\Delta TOC_{73} = 1.15845\big(6.68338(H^*-H) + .464492[(H_C^*-H_C) + f_E(H_E^*-H_E)] + .00000109[(H^2)^*-H^2] + .091647(M^*-M) + 2739.02(U^*-U)\big)$$

where H^*, H_C^*, H_E^*, M^*, U^* are the annual output of bus hours, bus miles, and active levels after the service change; H, H_C, H_E, M, U are the annual output of these variables before the service change; and ΔTOC_{73} is the change in operating cost. This can be written in a simpler form in terms of the change in each of the output variables, ΔH, ΔH_C, ΔH_E, and ΔU as follows:

$$\Delta TOC_{73} = 1.15845\big(6.68338(\Delta H) + .464492(\Delta H_C + f_E\Delta H_E) + .00000109[\Delta H(2H + \Delta H)] + .091647(\Delta M) + 2739.02(\Delta U)\big) \quad (61)$$

The change in annual capital costs for conventional (and express) bus resulting from the type of changes introduced in this study is due to increased purchase of equipment and expansion of shop and yard. Therefore the changes in annual capital costs for conventional and express service (using the data in Equation 61) is described by the following equation:

$$\Delta TOC_{73} = (\$7615 + \$654)\Delta U \qquad (62)$$

where ΔU is the change in the number of active buses.

Calculation of Incremental Costs of Bus Service Changes

The changes in bus service considered in this study require additions to service. Therefore, the changes in output variables (ΔH, ΔM and ΔU) are equal to the annual hours, routes and buses required to provide additional frequency on new routes. Thus these can be calculated by the method described in the previous section.

An adjustment in the model is necessary to make it equivalent to 1974 experience -- the base case year for travel demand forecasts in Chapter 3. A 10 percent inflationary increase in costs is assumed between 1973 and 1974; this is accounted for by increasing the multiplicative constant in Equation 59 by 10 percent.

List of References, Appendix C

[1]U.S. Department of Transportation, Institute for Defense Analyses. *Evaluation of Rapid Transit and Express Bus Service.* Washington, D.C., Government Printing Office, October 1973. p. 27.

[2]U.S. Department of Labor, Bureau of Labor Statistics. *Wholesale Prices and Price Index.* Washington, D.C., Government Printing Office.

[3]Meyer, J. R., J. F. Kain, and M. Wohl. *The Urban Transportation Problem.* Cambridge, Harvard University Press, 1966.

[4]U.S. Department of Transportation, Institute for Defense Analyses. *op. cit.* p. A-32.

Appendix D. MODELS AND DATA

TRAVEL DATA

The only comprehensive primary data describing travel in the Los Angeles region is the Los Angeles Regional Transportation Study (LARTS) Origin-Destination Survey conducted in 1967. LARTS, organized within the California Division of Highways and under the surveillance of the Southern California Association of Governments (SCAG), was charged with developing a comprehensive transportation plan for Los Angeles, Orange, Ventura and parts of Riverside and San Bernardino Counties. Approximately 9,000 square miles fall within the LARTS study area. Because all LARTS travel data refer to the year 1967, this year was taken as the base year for development of the demand model.

Two surveys were conducted by LARTS during the 1966-67 period. The major survey was the Home Interview Origin-Destination Survey of a 1 in 100 sample of households within the study area. Data from this survey consist of 33,030 records of households interviewed and 221,895 records of individual one-way trips made by these households. The particular information items from the household interviews which we have incorporated into our research are discussed in detail in this appendix.

The Home Interview Survey forms appear in Figure 4. For each household, one housing unit form was completed together with as many trip interview records as were necessary to describe all of the trips made the day before

Figure 4. Excerpt from LARTS Travel Interview Form

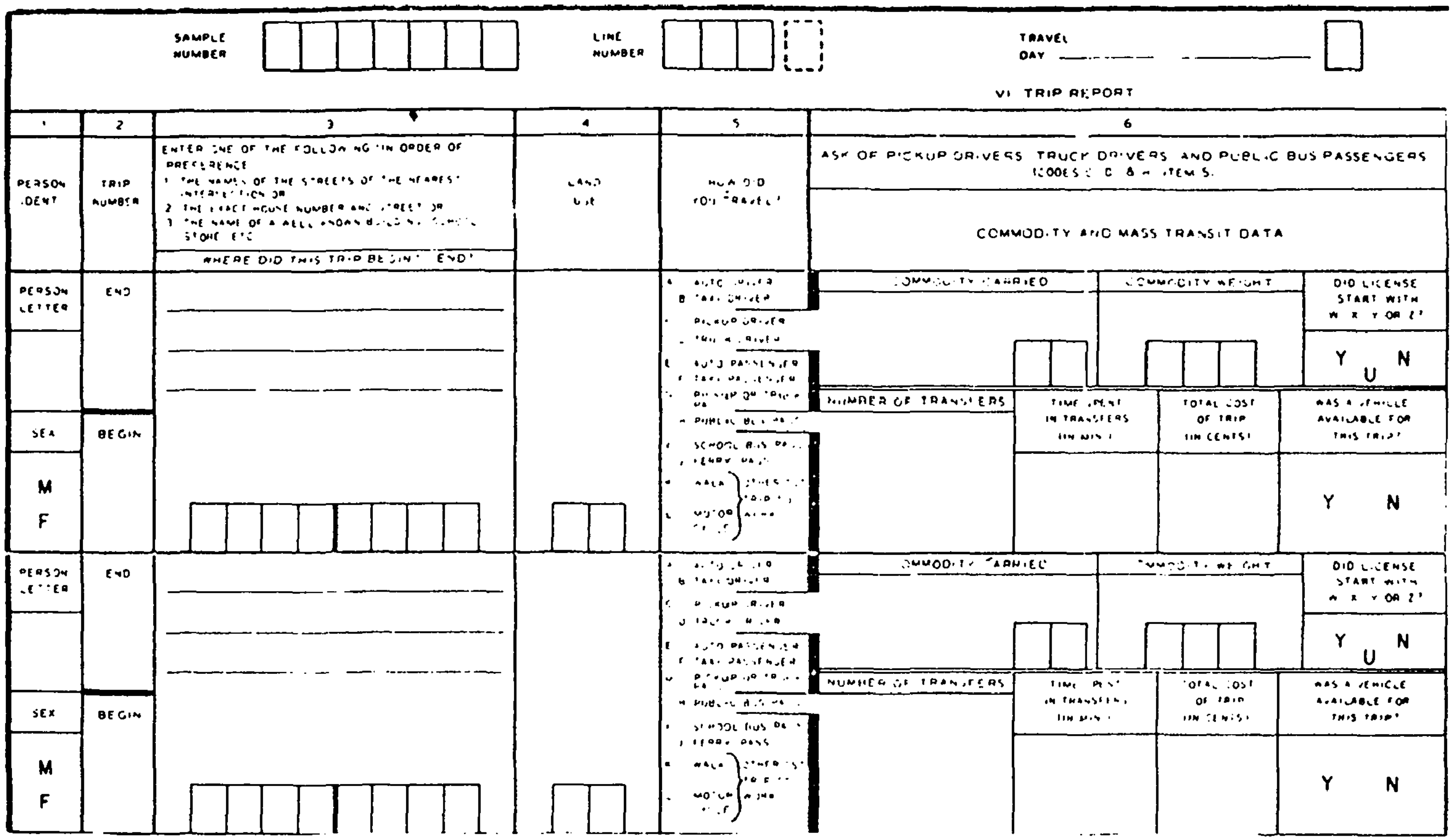
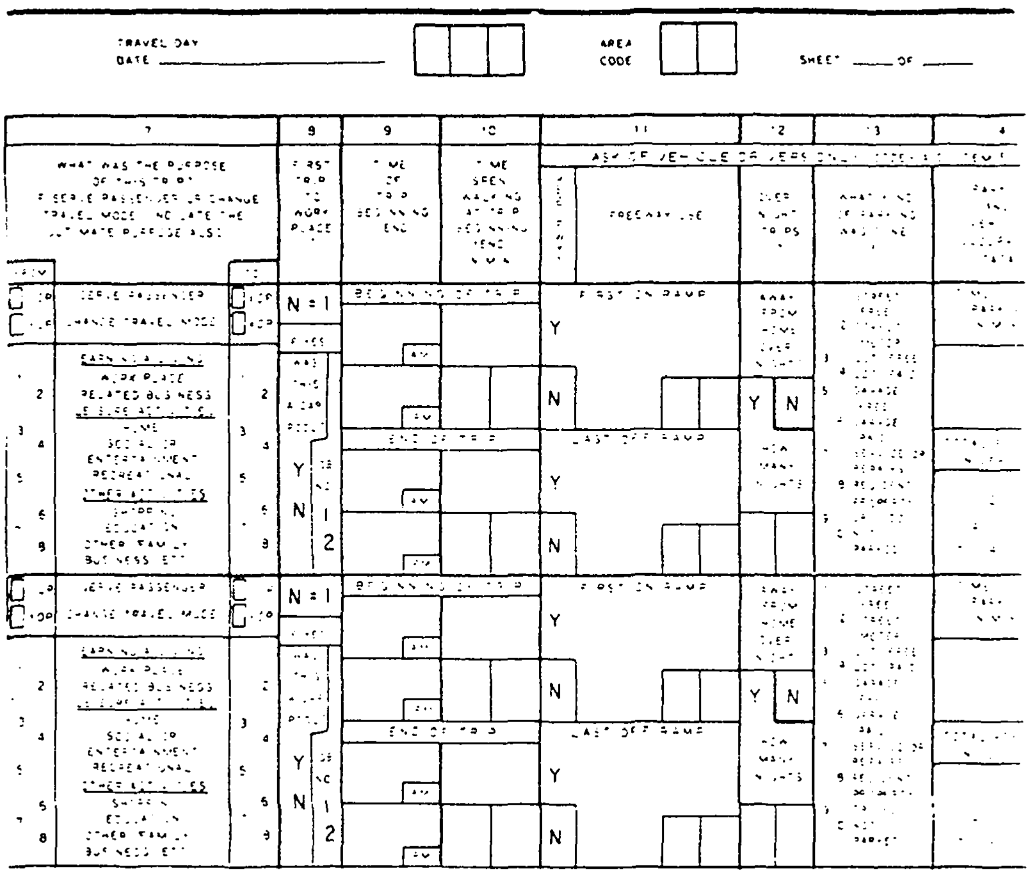


Figure continued on following page.

Figure 4 (continued). Excerpt from LARTS Travel Interview Form



by all occupants of the housing unit. These forms are referred to in subsequent discussion of the specific data items.

LARTS also conducted a roadside interview survey at various points along a cordon encircling the study area in order to obtain data concerning travelers who do not reside in the study area as well as to check the accuracy of some of the home interview data. All in all, there were 47,130 roadside interviews. In addition, LARTS took actual counts of vehicular traffic crossing two selected screenlines and passing through each of seven corridors. Because LARTS has not released the actual records and/or counts from these roadside interviews and ground counts, particular items from these interviews are not included in our data analyses. However, LARTS has compared the results of the Home Interview Survey counts and external counts and has calculated and released adjustment factors to be used when dealing with data from the Home Interview Survey; we have used these factors to adjust the trip counts estimated by the Home Interview Survey.

Zonal System

In our analysis we divided the LARTS study area into zones and organized all data with respect to these zones. We chose our zonal system from previously existing LARTS breakdowns. The records from the LARTS survey were originally coded and tabulated using a system consisting of 1,246 traffic analysis zones (AZ's). These AZ's were primarily based on aggregations of 1960 census tracts. In 1970 LARTS revised its zonal system into a new arrangement of 1,285 AZ's based on 1970 census tracts. These AZ's were further aggregated to 107 regional analysis zones (RAZ's) for sketch planning. Because of census tract redefinitions, the 1967 and 1970 analysis zones are considerably different.

Since the Los Angeles study area is so large, the size of an average 1970 RAZ is on the order of 25 square miles, with some in less densely populated areas being considerably larger. Applying transportation system data to these zones must be done with great care since much information is lost in aggregations of this size. However, using a larger number of smaller zones exponentially increases the number of zonal pairs and makes the data base too cumbersome for in-depth analysis. Consequently, the 1970 RAZ's were chosen as the zonal system to be used in this study.

In order to convert data referring to the 1,246 original 1967 AZ's to the 107 larger 1970 RAZ's, it was necessary to prepare a zone dictionary. This dictionary was prepared from maps of the respective zone systems provided by LARTS. A considerable number of the 1967 AZ's were split when the zone system was revised in 1970. The zone dictionary accounted for this by making fractional allocations (to the nearest tenth) of split AZ's based on land area.

Seven of the original 107 zones have been excluded from our analysis; these lie to the extreme north and west of the major metropolitan areas which are normally thought to comprise Los Angeles; they are also separated by natural boundaries and long driving distances.

Trip Counts

The number of interzonal round trips, the unit measure of the dependent variable, was obtained from the 1967 LARTS household survey. Our total data base consists of 100 zones, or 10,000 zonal pair observations.

Trip Purpose and Coding of Round Trips -- LARTS recorded each one-way leg of a trip separately, associating it with a purpose defined by land use at the origin and destination of the trip. The different land uses that were specified were as follows (see questionnaire): work place, related business, home, social or entertainment, recreational, shopping, educational, and other. This allows for 64 actual trip purpose categories, i.e., any combination of land uses at origin and destination. The number of categories was reduced in two ways. First, since the relevant unit measure of trips was the round trip, a method was devised to identify each one-way trip leg as the initial or return portion of the round trip, using assumptions listed in the following pages. Trips in either direction between any two land uses were then grouped into one trip purpose category, e.g., home-shopping. This automatically halves the number of trip purposes.

In order to make certain that this approach to classifying one-way legs as round trips was valid, we took a 1 in 500 sample of all trip records and checked to see whether the number of trips between each combination of the eight LARTS land use purposes was approximately the same in each direction. The results of this exercise assured us of the appropriateness of our approach. For example, there were 51 home-to-work one-way legs captured by the sample and 50 work-to-home one-way legs; 26 home-to-shopping one-way legs and 30 shopping-to-home one-way legs; and 40 home-to-other one-way legs and 39 other-to-home one-way legs.

The number of trip purpose categories was further reduced for the purpose of modeling by aggregating land use purposes when the number of trips in a particular land use was small and when that land use could conceptually be grouped with others.

The final set of trip purposes as used in our analysis is as follows:

1. home-work (includes home-related business)
2. home-shopping
3. home-social, entertainment, and recreation
4. home-education

5. home-other
6. home-home
7. work (or related business)-work (or related business)
8. other-work ("other" here refers to any non-home and non-work land use)
9. other-other (i.e., non-home, non-work-non-home, non-work).

After specifying the trip purpose breakdown, each one-way leg was then assigned to one of the 90,000 possible combinations of trip purpose (9 possibilities) and zonal pair (100 x 100 possibilities). As previously explained, the end nodes of each one-way leg were identified as origin or destination not according to the direction of travel specified in the LARTS survey records, but rather according to the assumed origin and destination of the round trip of which this one-way leg was considered a part. The assumptions that were made to associate one-way legs with a round trip purpose and to identify the end-points as origin or destination of a round trip are as follows. For all trips which had home at either end of the trip, home was considered to be the origin of the assumed round trip. The other end of each of these one-way legs was assumed to be the destination of the round trip. These trips account for the trip purposes: home-work, home-shopping, home-social/entertainment/recreation, home-education, home-other, home-home. All one-way legs which did not record home at either their beginning or end, but had work at one end (and one end only), were assumed to be journeys to/from work in which the tripmaker had made an intermediate stopover along the way, such as a shopping errand on the way home from the office. In keeping with this logic, the residence of the person making these trips was recorded as the origin of the total journey-to work round trip, the workplace was recorded as the destination, and the secondary stopover was ignored. These trips were stored separately in our data base as other-work trips (purpose 8) but were included in the home-work model. For one-way legs not included in either of these two categories, neither end node could automatically be identified as an origin or destination of a round trip. These trips were therefore aggregated by their recorded origin and destination.

After one-way legs were identified with a trip purpose, the legs associated with each purpose-zonal pair combination were counted and then divided by two to obtain the number of round trips.

An example of a hypothetical tripmaker's trips during the survey will illustrate how trips were aggregated by purpose and associated with a zonal pair. If the person left his home in the morning, went to work, went shopping, returned home and in the evening went out to a movie and again returned home, his day's trip record would be recorded on our data base as:

1 round trip, home-work, origin of round trip = home zone; destination of round trip = zone of work place

½ round trip, work-other, origin of round trip = zone of work place; destination of round trip = zone of shopping place

1 round trip, home-social, entertainment and recreation, origin of round trip = home zone; destination of round trip = zone of theater.

The assignment of each of the 64 possible combinations of LARTS trip purposes to the 9 round-trip purposes is summarized by the matrix in Table 69.

Table 69. ALLOCATION OF ONE-WAY TRIPS BETWEEN LAND USES (LARTS CATEGORIES) TO ROUND TRIP PURPOSE CATEGORIES

Origin \ Destination	Work place	Related business	Home	Social or entertainment
Work place	7 work-work	7 work-work	1 home-work	8 work-other
Related business	7 work-work	7 work-work	1 home-work	9 other-other
Home	1 home-work	1 home-work	6 home-home	3 home-soc/ent/rec
Social or entertainment	8 work-other	9 other-other	3 home-soc/ent/rec	9 other-other
Recreational	8 work-other	9 other-other	3 home-soc/ent/rec	9 other-other
Shopping	8 work-other	9 other-other	2 home-shopping	9 other-other
Educational	8 work-other	9 other-other	4 home-education	9 other-other
Other	8 work-other	9 other-other	5 home-other	9 other-other

Table continued on following page.

Table 69 (continued). ALLOCATION OF ONE-WAY TRIPS BETWEEN LAND USES (LARTS CATEGORIES) TO ROUND TRIP PURPOSE CATEGORIES

Origin \ Destination	Recreational	Shopping	Educational	Other
Work place	8 work-other	8 work-other	8 work-other	8 work-other
Related business	9 other-other	9 other-other	9 other-other	9 other-other
Home	3 home-soc/ent/rec	2 home-shopping	4 home-education	5 home-other
Social or entertainment	9 other-other	9 other-other	9 other-other	9 other-other
Recreational	9 other-other	9 other-other	9 other-other	9 other-other
Shopping	9 other-other	9 other-other	9 other-other	9 other-other
Educational	9 other-other	9 other-other	9 other-other	9 other-other
Other	9 other-other	9 other-other	9 other-other	9 other-other

Mode Categories -- In the LARTS data, the mode of travel was specified for each trip record (see questionnaire, column 5 of trip record). These modes were aggregated as follows:

1. auto drivers, including pick-up truck drivers;
2. auto passengers, including pick-up passengers;
3. transit trips.

Several of the modes listed in the questionnaire were not incorporated in our model because they comprise less than a quarter of one percent of the total trips captured by the survey and had little relevance to the issues being considered. These include ferry, taxi, school bus, and motorcycle trips.

A fourth mode considered in the demand model was auto serve passenger trips; however, the LARTS definition was different from ours. These trips were indicated in answer to a question concerning the purpose of the trips (see questionnaire, column 7). As the questionnaire shows, in addition to defining trip purpose by land use at the origin and destination, it asks whether the primary purpose of making a particular stop was to assist a passenger arriving at his destination. This question was asked separately for the origin of the trip leg and the destination of the leg. (Note: if, in a continuous trip linking several legs, the destination of one leg was "serve passenger," then the origin of the next leg would also be recorded as "serve passenger.") Drivers who indicated that their purpose was to serve a passenger were then asked to indicate the "'ultimate purpose' that the driver has in reaching his desired destination."[1] If the entire excursion was made by the driver expressly to serve the passenger, and the driver began and ended his trip in the same place, no land-use related purpose was recorded at the end nodes of legs identified as serve-passenger stops.

In our aggregations of the LARTS records, we linked together all continuous trips which had serve passenger at either end mode, and considered this to be a single one-way trip. (Trip legs were recorded in consecutive order on the LARTS files, and therefore linking was possible.) This trip was then classified as serve passenger mode, and the purpose of the trip was inferred from the land uses at the origin of the first leg and the destination of the final leg.

It would have been preferable to be able to record the serve passenger trips with respect to the purpose of the passenger being served; however, this information was not available from the LARTS records. For instance, if a wife left her home with her husband, dropped him off at work, and went shopping, LARTS records would show two legs:

1. non-serve passenger,* home to serve passenger, shopping
2. serve passenger, shopping+ to non-serve passenger, shopping.

Rather than considering this half of a home-shopping round trip and half of a shopping-shopping round trip, we

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*Since the driver's purpose in being at the origin of the entire trip, home, was not to serve a passenger but rather for personal reasons, the origin point is classified as non-serve passenger even though, in this example, the passenger began his trip at this point.

+LARTS interviewers were instructed to consider the purpose at the origin of a trip leg to be the purpose at the destination of the previous trip leg if it was part of the same excursion. While this was functional in non-serve passenger trips when considering trip purpose as defined by actual land use at that location, it is meaningless when considering trip purpose as defined by the ultimate purpose of the driver.

considered this to be a single one-way leg, whose mode of travel was "auto, serve passenger" and whose purpose was "home-shopping."

It will be noted that in Appendix A we aggregated serve passenger trips into auto driver trips, associating them with the land use of the driver's origin-destination. There are some VMT's that are not counted within any trip purpose, owing to the added circuity of serving a passenger. These are, however, estimated in the demand model. Note that the passenger's trip was recorded in a separate trip record, and therefore all passenger trips were captured and the proper purpose assigned to them.

Automobile System Performance Variables

The variables listed in this section were used to characterize Los Angeles automobile travel. Separate data for each trip purpose were compiled for all auto mode variables.

Auto Line-Haul Time -- Interzonal auto line-haul time was averaged from the times recorded on the LARTS survey for each purpose and mode specific interzonal one-way trip. The times appear on a questionnaire as actual clock times of trip beginning and trip end, from which time in minutes was calculated. The trip times were then converted into line-haul times by subtracting out the time spent walking at both trip beginning and trip end, as recorded by the LARTS survey, and then doubled to represent round trips.

Auto Trip Distance -- In addition to its household survey, LARTS coded and skimmed networks to compile centroid-to-centroid automobile distances between each of the 1,246 1967 analysis zones. These distances represent the shortest route from one zone to another using any combination of city streets and expressways. The distances between the 100 larger regional analysis zones were obtained from these inter-analysis zone distances by weighting the inter-AZ distances pertaining to each RAZ pair by the proportional frequency of inter-AZ trips. These trip frequency distribution figures were made available from a 1970 LARTS estimated auto driver trip table.

Auto Costs -- 1967 automobile operating costs were estimated as $0.03 per mile and multiplied by the interzonal (RAZ) distances (explained above) to arrive at the average cost for trips made between each RAZ pair.

Transit System Performance Variables

The LARTS survey included data on the performance of the bus system, the only form of transit in the Los Angeles region. However, due to the low level of bus usage in Los Angeles, the number of bus trip records available from the LARTS survey is small. A random 1 in 500 survey taken of the LARTS records indicates that only 2.3 percent of trips were made by bus; when expanded to the size of the actual LARTS survey, this means that of the 220,000 trips described, only about 5,000 were transit trips. A 5,000 trip sample is clearly inadequate to describe the performance of the transit system at the zonal pair level of accuracy, since there are 10,000 possible zonal pair combinations (100 x 100).

Instead, transit network data had to be extracted directly from Los Angeles area bus maps and schedules. This material was obtained for the 1967 bus systems run by the Southern California Rapid Transit District (SCRTD), the Long Beach Public Transit Company, the Santa Ana Transit Company and the South Coast Transit Company. These companies provided transit service for most of Los Angeles and Orange Counties in 1967.

To reduce the number of zonal pairs for which transit system data were developed, a random sample of 400 zonal pairs was taken from the actual 10,000. Of these 400 zonal pairs, only 172 lay within the service area covered by the transit companies listed above. Detailed transit data were derived for these 172 zonal pairs only. It was assumed that for any interzonal round trip between these 172 zones, the transit system performance characteristics of the return trip were exactly the same as the transit data computed for the original trip.

Description of the bus service for each leg of the interzonal traffic was a three-step process:

- measuring accessibility to bus lines in each zone;
- identifying the bus line(s) or sequence of bus lines that connect the zonal pair; and
- quantifying the characteristics associated with interzonal transit trips by use of the schedules of the bus lines identified.

These three steps are described in greater detail below.

Access Time -- Average access time, or average walk time to transit within a zone, was calculated separately from the other transit system variables. Average access time in any zone was defined as the average time that it takes to walk to the *nearest* transit line. (The method used to calculate these times is explained below.) Given this definition, the same average access time figure could be used for all interzonal transit trips originating or ending in a particular zone. The task of calculating access times was involved and time-consuming, even given this simplifying definition. Because most zones have many different bus routes traversing them, calculating access times separately for each zonal pair would have meant calculating them for each possible interzonal route for all the 172 pairs, and so would have greatly increased the task of measuring access times. Moreover, doing this most likely would not have yielded significantly different access times -- since walk time is usually weighted about three times as heavily as line-haul time in tripmakers' perceptions, transit users are most likely to use the bus line nearest them.* In addition, the Los Angeles bus system is such that usually either the second closest bus line to any point is so far away that the tripmaker would always take the nearest bus, or else the second closest bus line is approximately as far as the first closest bus line.

Given this definition of access time, average access times were calculated by first superimposing the zonal maps on bus route maps. Using these maps, the populated area of each zone considered was then divided into market areas such that each market area was served by one and only one bus line. The market areas were defined by the layout of the bus lines and, due to intersecting bus lines, were each usually associated with only a small segment of that bus line's entire route through the zone. The market areas were often quite small, on the scale of 1 to 10 square blocks.

For each market area, the average distance to the associated bus line was calculated by hand. Ideally, these distances would then have been weighted by the population within the market area. The amount of detailed calculation that this would entail, necessitating use of census block statistics, rendered the task impossible within time and budget limits. Instead, the distances were weighted by a rough estimator of the population living within each market area from the number of census tracts (usually a fraction) within the market area. (The Bureau of the Census defines census tracts so that they are all on the same scale, with approximately 4,000 inhabitants.)

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*Domencich, Thomas A. and Gerald Kraft. *Free Transit.* A Charles River Associates Incorporated Report. Cambridge, Lexington Books, 1970. This relationship also obtains for the models used in this study.

The as-the-crow-flies average distances derived in this manner were converted to walking distances along a street grid by a 1.28 expansion factor. A walking speed of 3.16 miles per hour was then applied to arrive at final figures for access times.

Identifying Interzonal Routes -- Our objective in identifying interzonal transit routes was to choose the route* that a transit user would be most likely to take in traveling between any particular zonal pair. This task involved a great deal of discretion, especially in making the trade-offs between the different positive and negative aspects of the various routes. As a general rule-of-thumb, it was assumed that tripmakers perceive walk time to a bus as being approximately three times more onerous than the time actually spent on the bus.[2]

Because of the large size of the zones, the most likely interzonal route via transit varied depending on the exact location within the zones of the tripmaker's origin and destination. Therefore, if there were five or fewer likely interzonal routes via transit, each route was identified separately. If there were more than five likely routes, interzonal line-haul times, the number of transfers and bus headways were found for all possible routes, and then up to five routes were chosen which together represented all the possible interzonal routes embodying these three characteristics.

The different typical routes thus identified were then weighted by the percentage of the populated area within the origin and destination zones respectively for which either the typical route was the most likely one to be taken in an

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*In the following discussion, "route" will refer to the total sequence of buses necessary to complete a specified interzonal trip rather than to individual bus lines.

interzonal trip, or for which the typical route was similar to the most likely route to be taken in an interzonal trip (in terms of such factors as line-haul time). For instance, in a very simple case, there may be only one bus line passing through the origin zone and it may also be more convenient than any nearby bus line to all points in that zone. This same bus line runs through the destination zone; however, a feeder line runs perpendicular to the interzonal line, and people living in a quarter* of the populated area of the destination zone use the feeder line to reach the main interzonal bus. In this case the two likely routes would be 1) interzonal line only and 2) interzonal line, feeder line. All variables describing these two routes (e.g., average line-haul time, wait time, etc.) would have been weighted by .75 and .25 respectively.

Quantification of Characteristics of Interzonal Bus Travel -- After identifying the interzonal routes and determining the appropriate weights of these routes, the following variables were collected to describe interzonal bus transit travel along these routes.

Line-Haul Time -- Line-haul times were measured from the mid-point in each zone of the identified typical interzonal routes. Two different line-haul times were collected, one for peak hours and another for offpeak hours. Peak hours were defined as approximately 6:30 to 9:00 a.m. and 3:00 to 5:30 p.m., varying slightly with distance from the CBD.

Wait Time -- The headways for the different bus lines in each interzonal route were used to compute the average wait time which passengers would spend at bus stops when taking each route. The average headways were calculated directly

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*The exact proportion was derived from maps, using rules-of-thumb described earlier to make trade-offs between walk time to the interzonal bus and time spent waiting for and traveling on the feeder line.

from actual schedules of individual bus lines; peak and off-peak headways were calculated separately. All calculations described below were carried out twice for each interzonal route, once for peak hour schedules and once for offpeak schedules.

In order to derive average wait times from these headways, it was necessary to make several behavioral assumptions about the rationality of tripmakers' decisions. Specifically, it was assumed that passengers were familiar with the schedules of the bus lines, planned their trips to minimize wait time, all other things being equal, and perceived time spent waiting at a bus stop as more onerous than time spent waiting at the origin point before starting their trip.[3]

The method by which average wait times were derived is best explained by describing a typical trip. If more than one bus must be taken to travel from a specified origin to a specified destination, a tripmaker will first examine the bus schedules before starting on his trip. If he finds that the last bus he must take runs more infrequently than the previous buses along his interzonal route (or, more generally, if any bus along the route is more infrequent than previous ones), the tripmaker will plan his trip around the more infrequent bus. He would first calculate which specific bus along the more infrequent bus line he could catch if he left his origin immediately. He would then take the last possible combination of previous buses that would bring him to the bus stop of the more infrequent bus line in time to catch that specific bus. For instance, if a particular interzonal trip included taking three different buses whose headways were 5, 10 and 30 minutes respectively, the tripmaker would first consult his schedule to find the first #3 bus he could catch, including the wait times and line-haul times of the first two buses in his calculations. Should he find that, leaving immediately, he would arrive at the #3 bus stop just after a bus has left, he would wait at his origin to catch the last combination of previous buses that would bring him to bus stop #3 in time for the next bus to leave. The longest time he would ever wait at the #3 bus stop is 10 minutes, since he would be able to take a later series of buses if he had to wait more than 10 minutes.

This examples can be generalized to the overall rule that the maximum waiting time for each bus in an interzonal route is the headway of that bus itself, or the largest headway of the previous buses along that route, whichever is less. Once maximum wait times were calculated, average wait time was obtained by taking the average of the maximum and the minimum, or in other words, by halving the maximum figures, since the minimum wait time is zero.

This rule was used to calculate maximum wait times for all buses along a route except the first. For the first bus, tripmakers can time their departure in order to minimize wait time at the bus stop. Because people typically will time themselves to arrive at the first bus stop slightly before the bus is scheduled to leave, the *average* wait time for the first bus was taken to be 5 minutes, or one-half the headway of that bus line, whichever was less.

Using these rules, the average wait times for each bus along an interzonal route were computed and then added together. After this process was completed for each route between any designated zonal pair, a weighted average was calculated for each zonal pair, using the system of weighting the routes explained above.

For the return leg of the round trip, buses are used in the opposite order of the original trip. For this reason, the wait times would be somewhat dissimilar. However, as a result of the method by which wait times were calculated from headways, the maximum difference that can occur is five minutes, and in most cases there would be no difference at all. To illustrate this point, assume that the interzonal bus route is composed of three bus lines with different headways, with the smallest headway being larger than 10 minutes. Recalling that the maximum wait time for any bus along an interzonal route is the headway of the bus itself, or the largest headway of the previous buses along the route, whichever is less, then no matter how the three buses are ordered along the route, the following will hold:

a) The largest headway will never be counted in wait time calculations -- if it is the first bus along the route, five minutes will be the average wait for that bus itself; if it is the second or third bus along the route, either the medium or smallest headway will be counted as the maximum wait for the infrequent bus.

b) The bus with the second largest headway will always be counted once in wait time calculations: if it is the first bus along the interzonal route, five minutes will be the average wait time for that bus itself, and the medium-sized headway will be the maximum wait for the bus with the largest headway; if the bus with the second largest headway is the second or third bus along the route and the bus with the largest headway comes somewhere before it along the interzonal route, the maximum wait at the medium frequency bus will be the headway of that bus itself; if it is the second bus along the route and the bus with the largest headway comes after it, the maximum wait for the medium frequency bus will be the smallest headway, and the middle-sized headway will be the maximum wait for the bus with the largest headway.

c) The smallest headway will always be counted once in wait time calculations: if it is the first bus along the interzonal route, five minutes will be the average wait for that bus itself, and the smallest headway will be the maximum wait for whichever bus follows it along the route; if it is the second or third bus along the route, the maximum wait for the bus will be its own headway.

The only time that the direction of travel (i.e., the ordering of the buses along the route) will make a difference in wait time calculations is when the smallest headway is less than 10 minutes, and when it is the first bus along the route in either direction. In this case, in one direction the average wait time for the first bus will be half the headway itself instead of five minutes. The total average wait time would be half (smallest headway plus medium headway plus smallest headway). In the other direction, the average wait time would be five plus half (medium headway plus smallest headway). The difference is five minutes minus one-half of the smallest headway. This difference can clearly never be more than five minutes.

Because five minutes is insignificant compared to the total trip time, the wait times for return trips were not calculated, but were assumed to be identical to the original figure.

<u>Schedule Delay</u> -- In any trip the passenger will choose the last series of buses that will get him to his destination before his preferred arrival time. The difference between the time that this chosen series of buses will bring him to his destination and his preferred arrival time, or the schedule delay, is a measure of the inconvenience cost to the tripmaker as a result of the bus scheduling. The maximum possible schedule delay is the sum of the headways of the buses along any particular route; the average is one-half of this sum. This calculation assumes a symmetric distribution of bus arrival times around preferred arrival time.

Total Line-Haul Time -- One variable was created from the previous three variables to represent the total round trip transit time excluding access time for each zonal pair in the sample. This variable was named line-haul time to distinguish it from access time; however, it includes not only time spent on the buses along the interzonal route but also time spent waiting for the buses as well as the schedule delay at one end of the round trip. The primary reason for including schedule delay at one end of the trip only is that in a typical trip, a person will be concerned about arriving on time at only one end of the trip. For instance, in home-work round trips, the tripmaker must arrive at work by a certain hour, whereas his return timing is more flexible. This treatment of schedule delay also reflects the fact that people consider time spent at origin and destination to be less onerous than time spent en route. Total line-haul time was calculated separately for peak and offpeak hours.

Number of Transfers -- The average number of transfers necessary to complete each interzonal bus trip was recorded along with the other variables describing interzonal transit trips.

Transit Fares -- During 1967 fares charged by the SCRTD varied by distance at a formula of $0.30 initial fare for travel within and between up to two transit fare zones, $0.08 per zone up to a $1.18 fare, and $0.07 per zone thereafter. There were 320 transit zones in the SCRTD system; these zones were determined by historical and political factors as well as by distance. As a result fares did not vary evenly with distance traveled. However, because zones usually ranged from approximately 2 to 4 miles, a 3 mile figure was taken as an approximation of typical zone breadth. Transfers were an additional $0.05, and were added to our fare calculations for all routed trips which involved more than one bus.

SOCIOECONOMIC AND DESCRIPTIVE VARIABLES

The following data on zones were also used in application of the travel demand model: area, number of households, vehicle availability, income, and retail employment.

Area

Data on areas of 1970 census tracts were aggregated to the RAZ level by National Planning Data Associates.

Number of Households

Data on number of households in 1970 census tracts were similarly aggregated to the RAZ level.

Vehicle Availability

Vehicle availability was calculated from *1970 U.S. Census of Population* data, which record the number of households in each zone having zero, one, two and three or more cars.

Vehicle availability for different trip purposes was calculated from these figures. For home-work trips, it was assumed that the number of vehicles available for work trips in a zone was proportional to the number of families with one or more cars. The vehicle availability per household for work trips was therefore estimated as the sum of the number of households with one, two, and three or more available vehicles divided by the total number of households.

The number of cars per household available for shopping trips was computed to be the sum of the number of households with two vehicles (one of which was already used for the work trip) plus 2.1 times the number of households with three or more vehicles (i.e., 3.1 cars minus one car used for the work trip), divided by the total number of households.

Income

Median income of households in each zone was obtained from *1970 U.S. Census of Population* tapes. The actual figure available was the 1969 median income reported by sample households as part of the 1970 census.

Retail Employment

Employment figures by place of work for retail trade were used as a proxy for shopping-oriented land uses. The initial source of these figures is the Bureau of Census *1970 Urban Transportation Planning Package*. The Bureau of the Census obtained this information from the locations of work places given by census respondents interviewed at their place of residence, rather than from a direct census taken at the work locations themselves. There were severe underestimates caused by wrong addresses, etc. For its own purposes, LARTS adjusted the *Urban Transportation Planning Package (UTPP)* figures to compensate for these irregularities, using control totals from other sources. The LARTS data were then aggregated to correspond to the regional analysis zones used in this study.

List of References, Appendix D

[1]LARTS. *Manual of Instructions to Home Interviewers.* January 1967. p. 46.

[2]Domencich, Thomas A. and Gerald Kraft. *Free Transit.* A Charles River Associates Incorporated Report. Cambridge, Lexington Books, 1970.

[3]Domencich and Kraft. *Free Transit. op. cit.*

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15. SUPPLEMENTARY NOTES

16. ABSTRACT This study has two objectives: first, to develop procedures to evaluate policies for controlling automobile emissions; and second, to use these procedures to evaluate specific pollution control strategies for Los Angeles.

The first objective is achieved by developing a relatively quick and reliable method for estimating the cost effectiveness of travel related policies. The methods used include application of a behavioral demand model for automobile travel by mode, purpose and destination, and a model which predicts the size of the auto stock and its age distribution. These models are used to compute the costs to society and individual travelers of various policies, and to compute the emission reduction effects of various policies.

In applying these procedures to Los Angeles, the following specific strategies were evaluated:

- increased gas taxes;
- taxes on vehicle emissions per mile based on odometer readings and emissions tests;
- nonresidential parking surcharges;
- extensions of route miles by conventional bus;
- annual taxes based on vehicle model, make and year.

The report's findings indicate that implementation of these policies could significantly decrease pollution. Emission taxes and gasoline taxes are particularly effective strategies; parking taxes are a less effective but still viable policy. Tax-induced decreases in pollution are reinforced by improvements in conventional bus service.

17. KEY WORDS AND DOCUMENT ANALYSIS

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