Central Area Mode Choice and Parking Demand

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Two versions of a disaggregate model of central area work trip mode choice that incorporates a detailed treatment of parking supply and cost impacts are presented. One version was estimated using 1980 travel survey data; the other version was based on more recent 1986 data. The results obtained from the two models are very consistent in terms of the aggregate elasticities displayed with respect to walk time from parking, parking cost, and other automobile and transit-related variables. The models indicate that central area commuters are very sensitive to changes in parking walk times and parking cost, somewhat less sensitive to automobile and transit in-vehicle travel times (in order of decreasing sensitivity), and less sensitive again to changes in transit out-of-vehicle travel time and fare. Additional, more detailed survey information concerning automobile driver attitudes, reasons for automobile use, and other related information, however, would be very useful in providing additional insight into the role of parking in determining central area work trip mode choice.

Parking supply and pricing in urban central areas have long been considered important mechanisms for controling automobile use by central area commuters because (a) commuters are sensitive to parking cost and walk time from parking in choosing their work trip travel mode and (b) parking supply and price are at least partially controllable by means of public policy levers, such as zoning, regulation, and taxation. The result is a long tradition of empirical and methodological research into parking demand-supply relationships and the effectiveness of various parking policies (*1–13*). The study presented here is also an empirical investigation into the sensitivity of central area commuters in Toronto, Ontario, to parking cost and walk time, relative to other factors affecting work trip mode choice (in-vehicle travel time, transit service levels, etc.).

A unique feature of the disaggregate nested logit model of central area work trip travel mode and parking location choice presented here is that it employs a relatively little used approximation for the nested model's inclusive value term (*14*) that allows full estimation of the nested model parameters using sample data that do not include observations of parking location choices. This model is then used in a sample enumeration framework to assess aggregate central area commuter sensitivities to a range of generic changes in transportation service characteristics, including parking cost and walk time.

Two versions of the model are presented. The first, based on 1980 travel survey data, was developed as part of an earlier study of Toronto Central Area parking supply and use (*15*). The second is based on a much smaller, but more spatially disaggregate, 1986 sample and was developed as an update of the first study (*16*). Both models were used in the policy analysis section of this paper. It was found that both models yield very similar results.

The following section, Modeling Method, presents the model of work trip mode and parking location choice. Model Estimation Results presents the statistical estimation results for both the 1980 and 1986 versions of the model. Sensitivity to Level-of-Service Changes discusses the implications of the models developed with respect to central area commuters' sensitivities to transportation service characteristics of general policy interest. Some methodological findings of interest are then briefly discussed in the Methodological Issues.

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MODELING METHOD

In general, selection of an automobile-related mode involves a secondary choice of parking location. This choice process can in principle be modeled by a nested logit model, which can be expressed as (*14*):

$$P_{jt} = \exp(V_{jt}) \Big/ \sum_{j' \in J_t} \exp(V_{j't}) \tag{1}$$

$$P_{k|jt} = \exp(V_{k|jt}/\phi_j) \Big/ \sum_{k' \in K_t} \exp(V_{k'|jt}/\phi_j) \qquad j = a, p \tag{2}$$

$$V_{jt} = \beta' W_{jt} + \phi_j I_{jt} \qquad j = a, p$$

$$= \beta' W_{jt} \qquad j \neq a, p$$

where

P_{jt} = probability of individual t choosing mode j, from set of modes J_t;
$P_{k|jt}$ = probability of individual t choosing parking location k, from set of locations K_t, given choice of automobile-related mode j;
V_{jt} = systematic utility of mode j for individual t;
$V_{k|jt}$ = systematic utility of parking location k for individual t, conditional on automobile-related mode j being chosen;
W_{jt} = vector of explanatory variables, excluding parking-related variables;
I_{jt} = the inclusive value term, which equals the expected maximum utility for individual t associated with lower-level choice of parking location, given choice of mode j

$$= \log\left\{ \sum_{k \in K_t} \exp(V_{k|jt}/\phi_j) \right\}; \tag{3}$$

ϕ_j = scale parameter for alternative j ($0 \leq \phi_j \leq 1$ for a properly specified model);
β = vector of parameters; and
a, p = subscripts, indicating automobile-drive and automobile-passenger modes, respectively.

In practice, the choice of parking location given the use of an automobile-related mode is not observed in conventional travel surveys. Thus, the lower-level parking choice model cannot be explicitly estimated, nor can the inclusive value terms for each individual be calculated. To circumvent this difficulty, let $V_{k|a,t}$ be the utility of the kth parking location for individual t, given that this individual uses the auto-drive mode. If:

$$V_{k|a,t} = \gamma' X_{kt} \tag{4}$$

where X_{kt} is a vector of attributes for individual t's kth possible parking location (cost, walk time to place of employment, etc.) and γ is a vector of parameters, then McFadden (*14*) shows that the inclusive value term for the automobile mode for individual t, I_{at} asymptotically equals:

$$I_{at} = \gamma' M_t/\phi_a + \gamma' Z_t \gamma/(2\phi_a^2) + \log(n_t) \tag{5}$$

where

n_t = number of parking location alternatives in choice set K_t for individual t;
M_t = column vector of average parking-related variables faced by individual t in choosing a parking location; for example, if m_{it} is the ith element of this vector (e.g., average daily parking cost) and x_{kit} is value of ith variable for the kth lot in t's choice set, then

$$m_{it} = \left\{ \sum_{k \in K_t} x_{kit} \right\} \bigg/ n_t; \tag{6}$$

Z_t = variance-covariance matrix for joint distribution of parking characteristics observed across set of feasible parking locations; for example, if z_{ijt} is value in cell ij of matrix (i.e., covariance between attribute i and attribute j, for example, covariance between daily parking cost and walk time to workplace), then

$$z_{ijt} = \left\{ \sum_{k \in K_t} (x_{kit} - m_{it})(x_{kjt} - m_{jt}) \right\} \bigg/ (n_t - 1). \tag{7}$$

Thus the auto-drive systematic utility becomes:

$$V_{at} = \beta' X_{at} + \gamma' M_t + (\gamma' Z_t \gamma)/(2\phi_a) + \phi_a \log(n_t), \tag{8}$$

and a similar equation can be derived for V_{pt}, the automobile-passenger systematic utility.

An attractive feature of this model is that it can be estimated without observing the actual parking locations chosen by the workers in the sample. The parking-related M vector and Z matrix, however, must be calculated for each observed worker, based on the known distribution of parking locations (and their known characteristics) and the known workplace for each of these workers.

Note in Equation 8, the parameters of the parking variable averages (γ) interact with each other as well as with the scale parameter (ϕ_a) to determine the parameter values for the Z_t terms. For example, if the first parking variable is daily parking cost, then the parameter for the parking cost variance term would be $\gamma_1^2/(2\phi_a)$, where γ_1 is the parking cost parameter. If one ignores these constraints on the variance-covariance term parameters, then Equation 8 can be approximated by:

$$V_{at} \approx \beta' X_{at} + \gamma' M_t + \delta' D_t + \phi_a \log(n_t) \tag{9}$$

where D_t is the column vector containing the unique variance-covariance elements of Z_t to be included in the automobile-drive utility function and δ is the vector of parameters.

The advantage of the approximate "unconstrained" utility function (*9*) is that its parameters can be statistically estimated using standard logit model estimation software. The theoretically correct "constrained" model represented by Equation 8, on the other hand, requires developing a specialized computer program for its estimation. This program uses Newton-Raphson root-finding to find maximum likelihood estimates of the constrained model parameter values (i.e., the same procedure used to estimate standard logit models, but with a modified system of log-likelihood derivatives to solve, given the more complex utility functions involved). Similar to more general nested models, the log-likelihood function is not guaranteed to possess a single global maximum. Hence care must be taken to ensure that convergence to the global maximum is achieved. In this case, consistently best results were obtained if the parameter values obtained from estimation of the unconstrained model were used to initialize the constrained model estimation. Thus, the parameter estimation approach adopted in this study involves two steps: (a) the "unconstrained" version of the model using Equation 9 is estimated and (b) the unconstrained parameter estimates are then used as the initial values for the constrained model estimation of Equation 8.

MODEL ESTIMATION RESULTS

Model 1: 1980 Metro Toronto Employment Transportation Study Data Base

The original version of the model, the 1980 Metro Toronto Employment Transportation Study (MTETS) Data Base, was developed as part of an earlier study of Toronto Central Area parking issues and policies (*15*). The best travel behavior data base available at the time of the study was the 1980 MTETS, which provided 3,010 usable observations of Toronto Central Area morning peak-period work trip mode choices. The 1979 Toronto Area Regional Modelling System (TARMS) network data provided zone centroid to zone centroid travel times and costs for automobile, transit, and commuter rail modes. The 1980 parking inventory data, which are comparable to the 1986 data, were obtained from the City of Toronto Department of Public Works.

The following five modes were included in this model:

- Automobile-drive (the worker drives a car all the way to work);

- Automobile-passenger (the worker rides as a passenger in a car all the way to work);
- Transit, all-way (the worker walks to a transit stop and takes transit all the way to work, without using commuter rail during any part of the trip);
- Transit, part-way (the worker drives or is driven to a subway station and then takes the transit the rest of the way to work); and
- Commuter rail (commuter rail is used for the "line-haul" portion of the trip).

A detailed discussion of the data base, modeling assumptions, and estimation results in provided by Miller (*17*). Two points should be noted concerning this model. First, geocoded workplace and parking lot locations were unavailable within the 1980 data set. Instead, both trip and parking supply data were provided on a zonal basis only. Thus, the construction of the means and variances of the parking cost and walk time variables necessarily involved less precise calculations than those applied to the geocoded 1986 data (discussed later). Second, the constrained model estimation software was not developed at the time of the original study. Thus, only the unconstrained version of the model was estimated during the original study.

Figure 1 defines the utility function variables that were included in the final version of the 1980 model. Table 1 presents the estimated model parameters and associated goodness-of-fit statistics. Points to note from these tables include the following:

- Overall, the model estimation results are very encouraging. An adjusted ρ^2 value of 0.3676 is quite typical for models of this type, and the coefficient values all have expected signs and generally are statistically significant.
- The magnitudes of the in-vehicle travel time (IVTT) parameter and the parking cost (PCOST) and walk time (PWALK) parameters are all quite credible, given other model results from Metro and elsewhere. For example, the relative values of the parking cost and walk time terms imply that workers will pay 32 cents (in 1980 Canadian dollars) to walk 1 min less from their parking location—a tradeoff that appears to be consistent with the literature in this area.
- The transit out-of-vehicle time ($OVTT_T$) and in-vehicle travel cost ($IVTC_T$) parameters are less credible. The $OVTT_T$ is less in magnitude than the IVTT term (generally it is expected to be larger in magnitude), and the $IVTC_T$ is not statistically significant. These problems might well be attributed to the use of the TARMS network data, which are not

D_{AD}	=	1 for auto-drive mode; = 0 otherwise
D_{AP}	=	1 for auto-passenger mode; = 0 otherwise
D_T	=	1 for transit-allway mode; = 0 otherwise
$D_{P\&R}$	=	1 for transit-partway mode; = 0 otherwise
$FEMALE_{AP}$	=	1 if worker is female for the auto-passenger mode; = 0 otherwise
$FEMALE_1$	=	1 if worker is female & in occupation group 1 for transit-allway mode <u>or</u> if the worker is female for the transit-partway mode; = 0 otherwise
$FEMALE_{78}$	=	1 if worker is female and in occupation group 7 or 8 for transit-allway mode; = 0 otherwise
$NCAR_{D,1}$	=	number of cars in the household if the worker is in occupation group 1 for the auto-drive mode; = 0 otherwise
$NCAR_{P,1}$	=	number of cars in the household if the worker is in occupation group 1 for the auto-passenger mode; = 0 otherwise
$NCAR_{78}$	=	number of cars in the household if the worker is in occupation group 7 or 8 for auto modes; = 0 otherwise
NSHFW	=	1 if the worker did <u>not</u> got straight home from work for auto-drive mode; = 0 otherwise
TAVAIL	=	transit availability code (question 7 of the MTETS survey) for transit-allway mode; = 0 otherwise
IVTT	=	in-vehicle travel time (min.), all modes
$OVTT_T$	=	out-of-vehicle travel time (min.), transit modes; = 0 for auto modes
$IVTC_T$	=	travel cost ($), transit modes; = 0 for auto modes
$IVTC_A$	=	"in-vehicle" travel cost ($), auto modes; = 0 otherwise = full cost for auto-drive = 1/2 cost for auto-passenger, if the worker pays; = 0 if worker does not pay
PCOST	=	1/2 average daily parking cost ($), if the worker pays for auto modes; = 0 otherwise
PWALK	=	average walk time from parking (min.) for auto modes; = 0 otherwise
COV(c-w)	=	covariance between walk time from parking and 1/2 parking cost for auto modes if the worker pays for parking; = 0 otherwise

FIGURE 1 Variable definitions, 1980 MTETS model.

TABLE 1 1980 MTETS Model Estimation Results

Variable	Parameter Value	T-Statistic
D_{AD}	6.2489	8.38
D_{AP}	4.2428	5.64
D_T	1.7429	9.71
$D_{P\&R}$	-0.66041	-3.82
$FEMALE_{AP}$	1.511	7.52
$FEMALE_I$	0.71469	5.73
$FEMALE_{78}$	0.37055	2.33
$NCAR_{D,1}$	0.35609	4.36
$NCAR_{P,1}$	0.13227	1.27
$NCAR_{78}$	0.64719	8.02
NSHFW	0.98269	7.60
TAVAIL	-0.62205	-9.71
IVTT	-0.073697	-13.19
$OVTT_T$	-0.045695	-4.66
$IVTC_T$	-0.0040419	-0.82
$IVTC_A$	-0.41370	-6.81
PCOST	-1.6449	-19.90
PWALK	-0.52143	-6.48
COV(c-w)	0.57380	9.28
No. of observations	3010	
Log-likelihood ratio	2802.6	
Adjusted ρ^2	0.3676	
Expected percent right	58.2	

very precise with respect to these variables and which also generally do not vary much in value across trip-makers within the sample.

• Because of a combination of collinearity and lack of variability problems, only one Z_t matrix value—the parking cost and walk time covariance—could be estimated, and the $\phi\log(n_t)$ term could not be included within the model. The parking cost and walk time parameter [COV(c-w)], however, is strongly significant with the expected sign. That is, because both the PCOST and the PWALK parameters are negative, their product [and hence the COV(c-w) parameter] is positive.

• The definition of the automobile-passenger travel cost terms (one-half the IVTC and the full parking cost) is based on the empirical results in that alternative-specific parameter estimates for these two terms indicated that the automobile-passenger values were 0.5 and 1.0 times the magnitudes of the automobile-drive terms, respectively.

Model 2: 1986 TDS Data Base

The 1986 Travel Diary Survey (TDS) used to develop the second version of the model is a 1-day diary survey of 0.4 percent of the households in the Greater Toronto Area (GTA), which provides detailed trip and personal characteristics of all household members in the sample. A particularly useful feature of the data set is that all trip origins and destinations are geocoded to the mid-blockface level, thereby permitting detailed spatial analysis and network level-of-service calculations. Detailed information concerning every Central Area off-street parking location was obtained from the City of Toronto Department of Public Works and the Environment. On the basis of the street addresses provided in this data set, these parking locations were also geocoded. Combined with the geocoded worker employment location data, this permitted very detailed calculations of parking supply and cost mean values and variance-covariance matrices faced by each worker in the sample, on the basis of an assumed maximum walking distance of 1.0 km. For further details concerning the TDS and parking data sets, as well as the calculation of the parking-related variable means and variances-covariances, see Miller (*16*). Automobile in-vehicle travel times were computed on the basis of a user-equilibrium assignment of observed 1986 vehicle flows to the road network within the EMME/2 network modeling package, while transit in- and out-of-vehicle travel times were generated using a "disaggregate" origin point to destination point transit assignment procedure within EMME/2 for each observed work trip.

Five modes are defined in this model:

1. Automobile-drive all-way,
2. Automobile-passenger all-way,
3. Transit all-way (automobile access to the transit system is ignored to simplify the network level-of-service calculations),
4. Commuter rail (all commuter rail users are assumed to use the automobile mode to access the system, again to simplify level-of-service calculations), and
5. Walk all-way.

Figure 2 defines the set of variables included in the final version of the 1986 model. Table 2 presents both the unconstrained and constrained estimation results for this final model. Points to note from this table include the following:

• All coefficient estimates have the correct sign and plausible magnitudes.

• All coefficients are statistically significant at the 95 percent confidence level or better, except for a few minor variables, such as LSDUM and JBS234. Note that *t*-statistics for the constrained model were not generated by the estimation program because of numerical matrix inversion problems associated with this particular model. Experience with other model runs, however, indicates that the *t*-statistics will not be significantly different from those for the unconstrained model.

• Both models exhibit very good goodness-of-fit statistics, which compare favorably with the 1980 model fit statistics reported in Table 1.

• With the exception of the alternative-specific constants, the parameters of the "non-parking" variables tend to be quite stable in value from one model version to another. This is an encouraging result, in that it indicates a considerable degree of independence between the two types of variables as well as a desirable robustness in model specification.

• Moving from the unconstrained to the constrained version of the model has the following impacts:

—The non-automobile alternative-specific constants typically become considerably more positive in value. This reflects the positive shift in the average automobile utility function introduced by the introduction of the parking cost

d-ttc	=	1 if "local transit" mode; = 0 otherwise
d-go	=	1 if "commuter rail" mode; = 0 otherwise
d-pass	=	1 if "auto passenger" mode; = 0 otherwise
ivtt	=	in-vehicle travel time (min.), all modes
ovtt	=	out-of-vehicle travel time (min.), transit and rail modes; = 0 otherwise
ct/inc	=	travel cost ($) divided by personal income (10^3 $), transit and rail modes; = 0 otherwise
mindst	=	minimum walk distance (km.) from a subway station to the final destination (Manhattan metric), transit and rail modes; = 0 otherwise
dsttrm	=	minimum straightline distance to a subway station (km.) for residents in York and Peel Regions, for transit mode; = 0 otherwise
male30	=	1 if worker is male and over 30 years of age, for transit mode; = 0 otherwise
fem123	=	1 if worker is female and in occupation group 1, 2 or 3, for transit mode; = 0 otherwise
lsdum	=	1 if Lakeshore East or West lines used, rail mode; = 0 otherwise
union	=	1 if closest subway station to the worker's destination is Union, King or St. Andrew, rail mode; = 0 otherwise
apt-wk	=	1 if worker lives in an apartment (TDS code 4), walk mode; = 0 otherwise
pincd	=	worker's personal income (10^3 $), auto-drive mode; = 0 otherwise
pincp	=	worker's personal income (10^3 $), auto-passenger mode; = 0 otherwise
jbs234	=	1 if worker's jobsite is category 2, 3, or 4 (factory/warehouse, construction site, or no fixed place of work), auto mode(s); = 0 otherwise
dlic	=	1 if the worker has a driver's licence, auto-passenger mode; = 0 otherwise
tavail	=	1 if the worker reports "always" having transit available for the work trip, auto-passenger mode; = 0 otherwise
pcost	=	1/2 average daily parking cost ($), auto or auto-drive mode, if the worker pays for parking; = 0 otherwise
pwalkd	=	average walk time from parking (min.), auto-drive mode; = 0 otherwise
pwalkp	=	average walk time from parking (min.), auto-passenger mode; = 0 otherwise
c(c-w)	=	covariance between 1/2 daily parking cost and walk time from parking, auto or auto-drive mode, if the worker pays for parking; = 0 otherwise
l(lot)	=	natural logarithm of the number of parking lots within a 1.0 km. walk of the worker's place of work, auto or auto-drive mode; = 0 otherwise

FIGURE 2 Variable definitions, 1986 TDS model.

and walk time variance terms into the constrained model. As in the 1980 model, the variance terms could not be included in the unconstrained model because of their covariance with the mean value terms. The composite coefficients on the parking cost and walk time variance terms in the constrained model are, respectively, $\gamma_c^2/(2\phi)$ and $\gamma_t^2/(2\phi)$, where γ_c and γ_t are the mean parking cost and mean walk time parameters. These composite coefficients are both positive in value, meaning that the constrained model's automobile utilities will be more positive in value than the corresponding unconstrained automobile utilities. All else being equal, this must result in more positive non-automobile alternative-specific constants for the model to explain the observed modal choices.

—The parking cost parameter nearly doubles in magnitude, although the walk time term remains nearly constant. This implies that the trouble of estimating the constrained model versions may be worthwhile in terms of obtaining better estimates of the relative magnitudes of the parking-related variables.

• The scale parameter (ϕ) is the parameter associated with the variable L(LOT) in Table 2. It must lie between 0 and 1 in value for a properly specified model. Although the estimated value for this parameter is 1.14, it is quite unlikely that this estimate is statistically different from 1.0 in value.

SENSITIVITY TO LEVEL-OF-SERVICE CHANGES

To explore the implications these modeling results have for Toronto Central Area transportation policy, several simulations were conducted. In each simulation, the modal choices of the observed trip makers were estimated using both models under a hypothesized "across the board" change in a single variable (such as average parking cost), while holding all other variables constant at their observed values. Thus, for example, the impact of a 5 percent (10 percent, 20 percent, etc.) change in average daily parking cost or transit in-vehicle travel time was predicted. In all such cases, it is assumed that all trip makers face exactly the same percentage change in the given variable. In the case of the parking-related variables it is also assumed that the change is in the *mean* value of the variable only, with the associated variance-covariance structure of the parking variables remaining unchanged.

Figure 3 summarizes the results of this exercise for the case of changes in average daily Toronto Central Area parking

TABLE 2 1986 TDS Model Estimation Results

Variable	Unconstrained Model Parameter Value	Unconstrained Model T-Statistic	Constrained Model Parameter Value[1]
d-ttc	1.7256	1.38	2.8225
d-go	-0.86817	-0.59	0.14610
d-pass	--[2]	--	3.0817
ivtt	-0.054281	-3.21	-0.054307
ovtt	-0.089042	-2.58	-0.092474
ct/inc	-8.6637	-2.85	-8.3984
mindst	-0.85197	-1.64	-0.92304
dsttrm	-0.052535	-1.55	-0.054302
male30	-0.61982	-1.57	-0.69711
fem123	1.5729	3.42	1.6061
lsdum	0.46676	0.75	0.45430
union	1.4319	2.38	1.4428
apt-wk	2.2829	1.87	3.3719
pincd	0.021553	1.70	0.024237
pincp	0.045406	2.54	0.043323
jbs234	0.79884	1.51	0.64856
dlic	-1.2809	-2.11	-1.3770
tavail	1.0811	1.89	1.0716
pcost	-0.68057	-4.22	-1.1937
pwalkd	-0.35335	-2.56	-0.36515
pwalkp	-0.35335[3]	-2.56	-0.56945
c(c-w)	0.22866	1.17	--[4]
l(lot)	0.90383	5.01	1.1436
No. of weighted obs.	337		337
No. of cases	632		632
No. of parameters	21		22
Degrees of freedom	611		610
Log-likelihood @ zero parameter values	-347.1		-347.1
Log-likelihood @ conv.	-184.1		-186.3
Likelihood ratio	326.0		321.6
Adjusted ρ^2	0.4517		0.4443
Expected percent right	68.9%		69.4%

Notes:

1. T-statistics not computed for the constrained model due to failure to invert the log-likelihood information matrix. This problem appears to be related to the auto passenger mode, whose inclusion in the model tends to introduce some instability in parameter estimates, etc. In other model runs in which the information matrix was inverted, the t-statistics changed very little between the unconstrained and the constrained models.
2. Parameter not estimated for this model.
3. Parameter constrained to equal the pwalkd parameter value.
4. Parameters for variance-covariance terms constrained to equal products of the parking cost and parking walk time parameters.

costs. The horizontal axis in this graph indicates the hypothesized across-the-board *increase* in average daily parking cost. The vertical axis indicates the corresponding predicted total automobile use by Toronto Central Area morning peak-period commuters given the hypothesized parking cost change. This use is expressed as a fraction of the observed "base case" (i.e., no change in variable) automobile use. The two curves shown in Figure 3 correspond to the responses predicted by the 1980 MTETS-based model and for the constrained version of the 1986 model. The 1980 model curve is generated using the 1980 data base and is expressed using the observed 1980 automobile use as its base reference level. Similarly, the 1986 curve uses the 1986 TDS data base and the observed 1986 automobile use as its base reference level.

It is seen in Figure 3 that, despite differences in the data base and model specification details, the 1980 and 1986 results are very comparable. The 1986 model is slightly less sensitive to parking cost than the 1980 model, but it is unlikely that this difference is statistically significant. In particular, both models exhibit aggregate elasticities of automobile use with respect to average daily parking cost, which are slightly greater than 1.0 in magnitude over much of the range of parking charges investigated. The dashed line in Figure 3 represents unit elasticity, that is, the percentage change in automobile use given the percentage change in parking cost if the automobile use (arc) elasticity equals −1.0. Any point falling below and to the left of this line indicates an arc elasticity of greater than 1.0 in magnitude (i.e., elastic demand). Any point lying above and to the right indicates an arc elasticity of magnitude less than 1.0 (i.e., inelastic demand). Figure 3 implies parking cost elasticities greater than or equal to 1.0 for up to a 30 percent increase in parking charges relative to 1986 values for model 1986 and up to a 40 percent increase relative to 1980 values for the 1980 model.

Figure 4 similarly plots predicted 1986 automobile use as a function in changes in average walk times from parking, changes in automobile in-vehicle travel time (due, presumably, to increased road congestion effects), and changes in three transit-related variables: transit fare, transit out-of-vehicle travel time (walk plus wait time), and transit in-vehicle travel time. In the case of each transit variable, the change indicated corresponds to an across-the-board percentage decrease in the variable (i.e., an improvement in the transit service). Walk time from parking appears to have by far the greatest impact

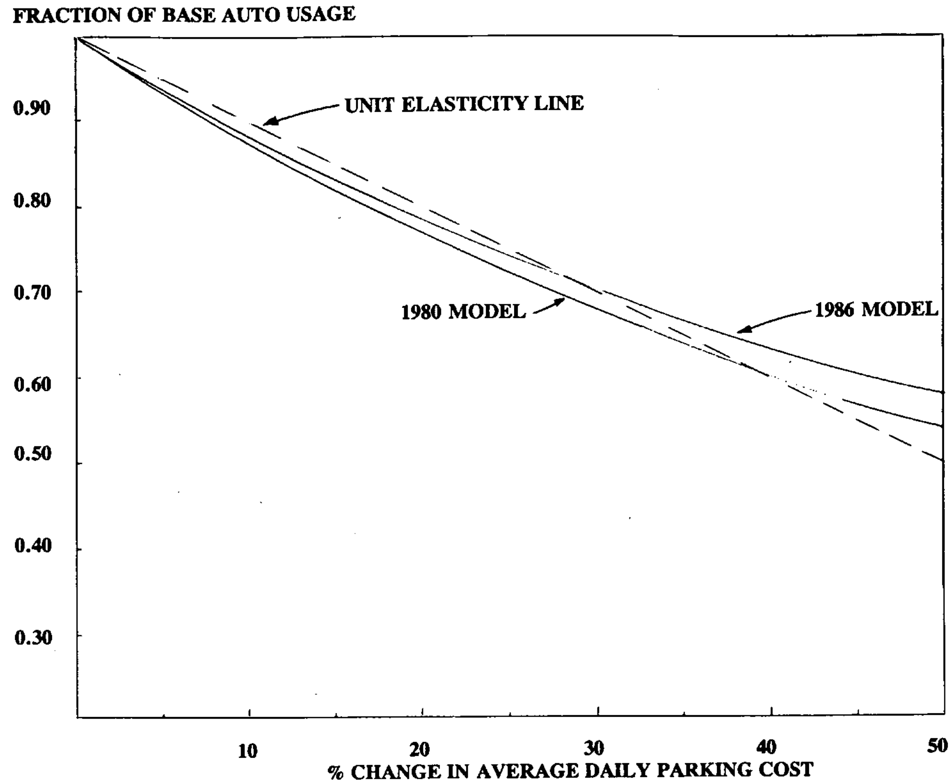

FIGURE 3 Predicted changes in Toronto Central Area automobile use given changes in average daily parking cost.

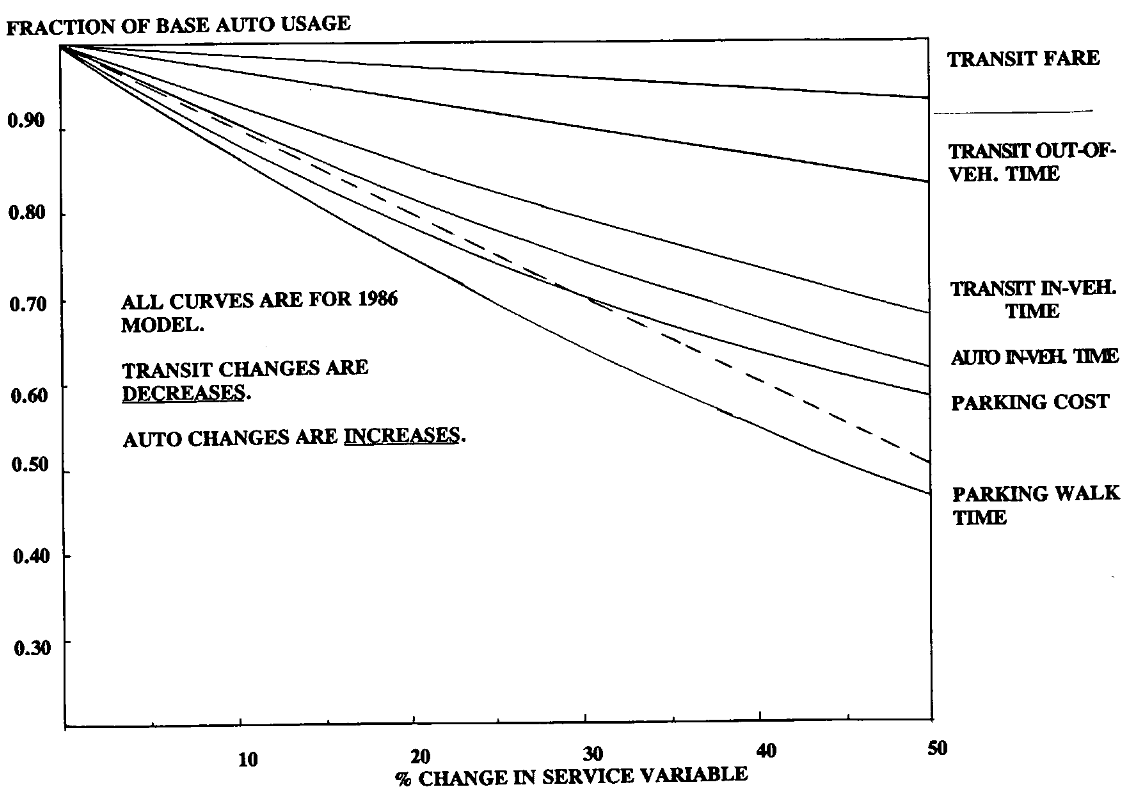

FIGURE 4 Predicted Changes in Toronto Central Area automobile use given changes in selected automobile and transit service characteristics.

on automobile use, generating arc elasticities greater than 1.0 over the entire range of times examined. Parking cost and automobile in-vehicle travel time are the next most important determinants of automobile use (with automobile use being slightly inelastic over the entire range of values examined). Finally, Figure 4 illustrates that improvements in transit service levels are predicted to have less impact than corresponding percentage reductions in auto service levels on Toronto Central Area automobile use. As in the parking cost case, the elasticities obtained from the 1980 model for each of these variables are very similar to the 1986 results shown in Figure 4.

Two other experiments were conducted using this model. In the first, it is assumed that free parking is eliminated for all Central Area commuters, thus requiring all commuters who drive to pay full, unsubsidized parking prices. In the second, it is assumed that a free transit pass is provided to all commuters. Figure 5 indicates the predicted impacts of each policy on automobile use, with and without associated changes in average parking price, and compares these impacts with the status quo case (i.e., no free pass, free parking for some). Note that the vertical axis in this case is the actual automobile-drive mode split.

As indicated by Figure 5, providing free transit passes to all Central Area commuters is predicted to reduce automobile-drive use from the base case of 20 percent to 16.9 percent. Elimination of free parking for commuters is predicted to yield an even greater reduction in automobile drivers to 15.8 percent. These reductions are comparable in their impacts to increase in average Central Area parking prices of 23.5 percent and 32.5 percent under status quo conditions. If increased parking charges are implemented in combination with one of these two policies, the net impact is, of course, greater.

The preceding policies are very abstract in nature (e.g., increase average daily parking cost by 25 percent). The model, however, can be readily extended to more realistic policy analyses as well as incorporated within a more generalized modeling framework. Points to note in this regard include the following:

- Because parking location utility function parameters (γ) are estimated within the model, the lower-level parking location choice model (Equation 2) can be reconstructed from the results presented here and used to predict explicitly parking location choices, given known employment distributions and automobile use levels (as defined by Equation 1). This model could be used to determine parking market potentials at various points, compute spatially distributed parking price elasticities, combine with a parking supply model to model parking market interactions, and accomplish other objectives as well.
- Without engaging in full supply-demand modeling of the parking market, more realistic parking policies could be analyzed by changing the spatial price/supply distributions on a scenario basis (e.g., eliminate all parking within x meters of subway stations; increase parking prices only within the Central Business District).
- Walk times from parking locations to employment sites were computed within this analysis on a simple rectilinear or "Manhattan" basis (which, given the dense grid street layout within the Central Area, undoubtedly represents a close ap-

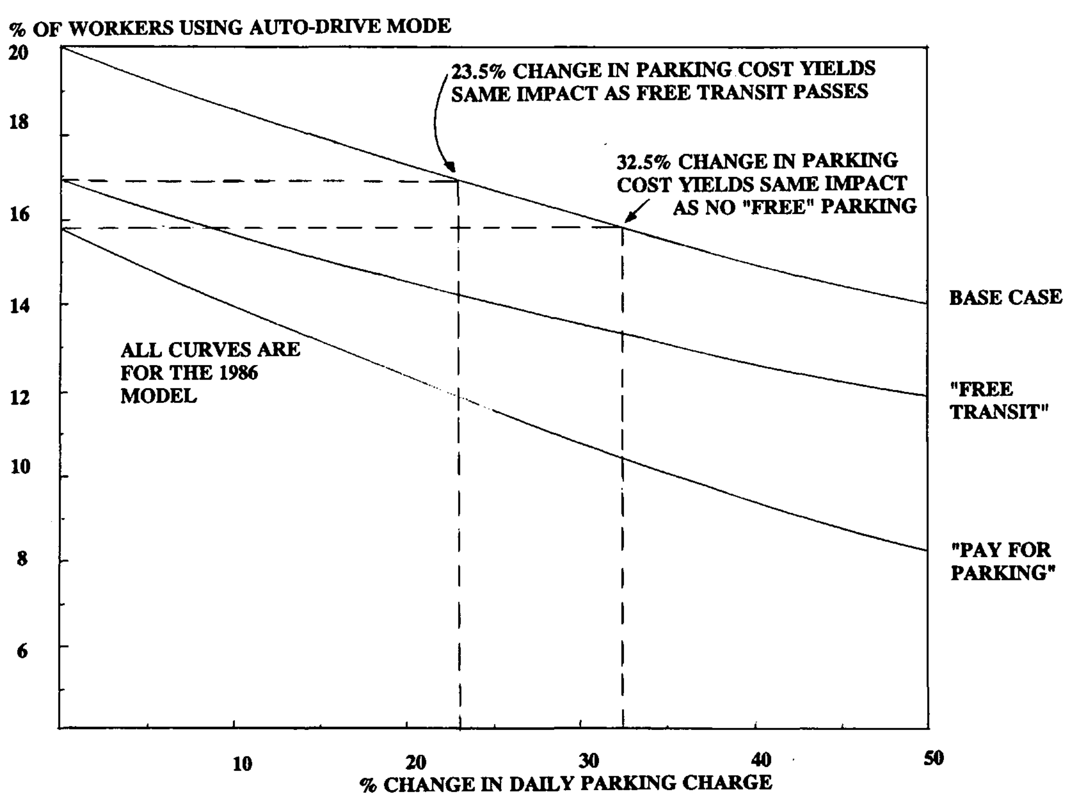

FIGURE 5 Predicted changes in Toronto Central Area automobile use given fundamental changes in cost of parking and transit.

proximation to actual shortest-path walk times). If more detailed treatment of walk paths is required, the geocoded nature of the data base readily permits its incorporation within a geographic information system capable of performing such detailed calculations.

- The overall mode choice model is readily incorporated within a larger demand modeling system because it is simply a multinomial logit model with an expanded set of parking-related variables in its automobile-mode utility functions.

METHODOLOGICAL ISSUES

Although this paper primarily focuses on the empirical investigation of Central Area work mode choice sensitivity to parking-policy-related variables, three points of somewhat more general methodological interest emerge from this work that should be briefly noted.

First, McFadden's (*14*) approximation for the inclusive value term permits theoretically sound nested logit models to be empirically estimated in the absence of explicit information concerning lower-level choices (in this example, the choice of parking location given use of the automobile for the work trip). Specifically, in cases in which heterogeneity within and covariance among the lower-level attributes exist (in this example, considerable variation exists in parking costs and walk times associated with the set of parking locations in any worker's choice set). Typically the assumption is made that the unobserved lower-level is homogeneous (e.g., a residential location and type choice model may assume that all houses of a given type within a given zone possess identical characteristics). Under this assumption, the variance-covariance terms in the upper-level utility function equivalent to Equation 5 is identically zero in value, thereby considerably simplifying the analysis. The preceding, however, demonstrates that, in the presence of significant lower-level heterogeneity, this assumption can bias model parameter estimations.

Second, the relative transferrability of the aggregate elasticities of the 1980 and 1986 models is noteworthy, especially given that these models would undoubtedly fail most normal transferrability tests (similarity in parameter values, etc.). This result is reasonably similar to that recently found by Laferriere in the case of disaggregate intercity mode choice models, in which models from Canada, the United Kingdom, and the United States are found to have fairly consistent aggregate own and cross-price elasticities, despite great variations in calibration study area and base year and despite little evidence of parameter transferability (*18*).

Finally, problems in developing a stable model that included the automobile-passenger mode prompted some early model estimations in which the automobile-drive and automobile-passenger modes were combined into a composite automobile mode. In addition, runs were performed in which information concerning whether or not the worker paid for parking was ignored, so that the model assumed that all workers paid for parking. In both cases, the overall utility function specification remained the same (with the obvious exception that automobile-passenger-related variables disappear in the "composite" models). Very little change occurred in parameter estimates across the three models, except in the case of the parking cost parameter, which changed from −0.220 ("composite" model, no allowance for free parking) to −0.706 ("composite" model, free parking accounted for) to −1.194 (separate drive and passenger modes plus free parking). Figure 6 summarizes the impacts these assumptions have on model sensitivity to parking cost.

Figure 6 also illustrates the dramatic effect the improved model specification has on model sensitivity to parking cost (and, more generally, on eliminating parameter bias). The composite-automobile, no-free-parking model appears to be quite insensitive to parking cost changes. Introducing the free parking effect significantly increases the model sensitivity. Introduction of explicit representation of automobile passengers (who are likely to be less sensitive to parking costs than automobile drivers) further improves the model sensitivity.

This result may seem trivially self-evident: obviously improving model specification will yield improved model results. In the development of practical, operational planning models, however, considerable pressure exists to simplify model specification so as to simplify the forecasting problem. The net result, as indicated by Figure 6, is often a model that possesses biased coefficients and hence is much less useful as a forecasting and policy analysis tool. Further, such biases are typically difficult if not impossible to identify within the model development and application process. This is primarily because more general model specifications (which provide an analytical and statistical framework for testing the simplifying assumptions) are simply not considered.

SUMMARY

This paper has presented a disaggregate model of central area work trip mode choice that incorporates a detailed treatment of parking supply and cost impacts. Two versions of this model are presented: one estimated using 1980 travel survey data and one based on more recent 1986 data. The results obtained from the two models are very consistent in terms of the aggregate elasticities displayed with respect to walk time from parking, parking cost, and other automobile- and transit-related variables. The models indicate that central area commuters are very sensitive to changes in parking walk times and parking cost, somewhat less sensitive to automobile and transit in-vehicle travel times (in order of decreasing sensitivity) and less sensitive again to changes in transit out-of-vehicle travel time and fare. Additional, more detailed survey information concerning automobile-driver attitudes, reasons for automobile use, and other related information, however, would be very useful in providing additional insight into the role of parking in determining central area work trip mode choice.

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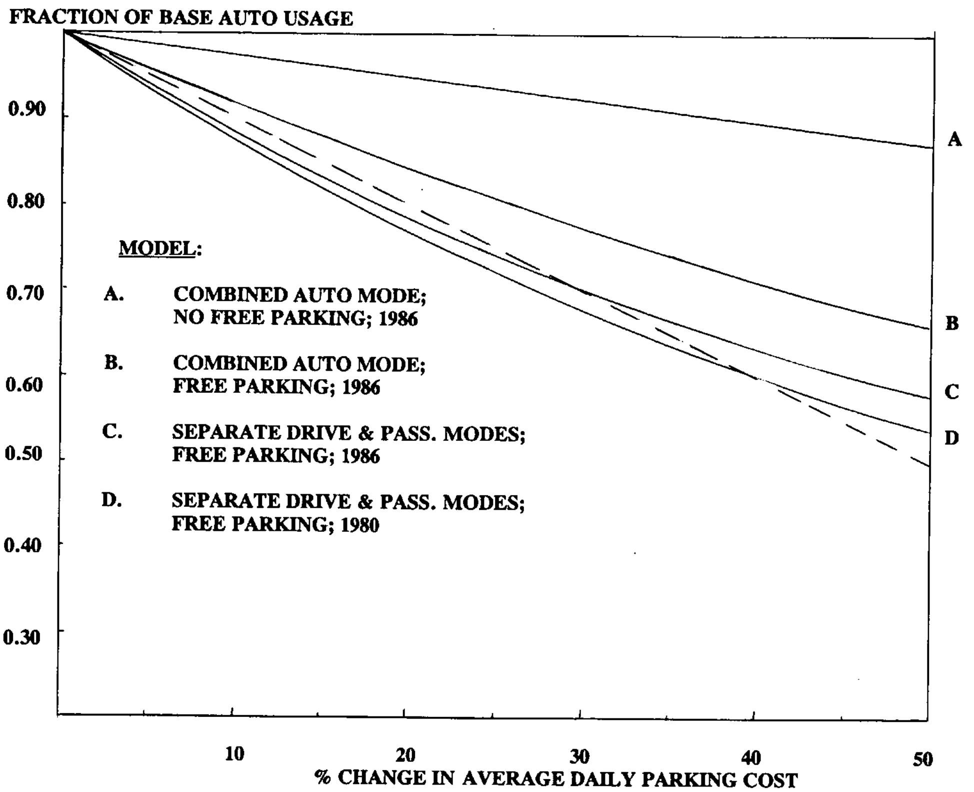

FIGURE 6 Impact of model specification on sensitivity to parking cost.

Public Works and the Environment, and travel behavior and transport level-of-service data were provided by the University of Toronto Joint Program in Transportation. Computer costs were paid for by a grant from the Natural Sciences and Engineering Research Council (Canada). Finally, special thanks are due to Giles Bailey for his work in the initial preparation and analysis of the data base used in this study.

REFERENCES

1. *Highway Research Record 444: Parking Demand and Allocation.* HRB, National Research Council, Washington, D.C., 1973.
2. *Highway Research Record 474: Parking as an Alterant to the Traffic Pattern.* HRB, National Research Council, Washington, D.C., 1973.
3. May, A. D. The Restraint of Vehicular Traffic. *Traffic Engineering*, Vol. 46, No. 1, Feb. 1976, pp. 15–18.
4. Gillen, D. W. Parking Policy, Parking Location Decisions and the Distribution of Congestion. *Transportation*, Vol. 7, No. 1, March 1978, pp. 69–86.
5. *The Effects of Imposition of Parking Charges on Urban Travel in Ottawa.* Summary Report TP 291. Department of Supply and Services, Transport Canada, Ottawa, Canada, 1978.
6. *Transportation Research Record 786:* Parking. TRB, National Research Council, Washington, D.C., 1980.
7. *Transportation Research Record 845: Transportation System Management and Parking.* TRB, National Research Council, Washington, D.C., 1982.
8. Loudon, W. R. The Influence of Parking on CBD Retail Sales; A Case Study. Presented at the 61st Annual Meeting of the Transportation Research Board, Washington, D.C., 1982.
9. Feeney, B. P. *A Review of the Impact of Parking Policy Measures on Travel Demand.* VTI Rapport 308A. Swedish Road and Traffic Research Institute, Linkoping, 1986.
10. Bhatt, K. Parking Policies for Downtown and Metrorail Stations (A Case Study). Presented at 67th Annual Meeting of the Transportation Research Board, Washington, D.C., 1988.
11. Willson, R. W. Parking Subsidies and the Drive-Alone Commuter: New Evidence and Implications. In *Transportation Research Record 1181*, TRB, National Research Council, Washington, D.C., 1988.
12. Higgins, T. Parking Management and Traffic Mitigation in Six Cities: Implications for Local Policy. In *Transportation Research Record 1232,* TRB, National Research Council, Washington, D.C., 1989.
13. Polak, J., and K. W. Axhausen. CLAMP: A Macroscopic Simulation Model for Parking Policy Analysis. Presented at 68th Annual Meeting of the Transportation Research Board, Washington, D.C., Jan. 1989.
14. McFadden, D. Modeling the Choice of Residential Location. In *Transportation Research Record 673*, TRB, National Research Council, Washington, D.C., 1978, pp. 72–77.
15. Berger Planning Consultants. *Using Parking Controls to Achieve a Target Modal Split.* Draft final report. City of Toronto Planning and Development Department, Thornhill, Ontario, Aug. 1987.
16. Miller, E. J. *Modelling Central Area Work Trip Modal Choice Parking Demand.* Report to City of Toronto Planning and Development Department. University of Toronto Joint Program in Transportation, Toronto, June 1992.
17. Miller, E. J. *A Disaggregate Mode Choice Model for Central Area Parking Policy Analysis.* Draft report. Berger Planning Consultants; City of Toronto Planning and Development Department, Thornhill, Ontario, Aug. 1987.
18. Laferriere, R. Price Elasticities of Intercity Passenger Travel Demand. In *Directions, The Final Report of the Royal Commission on National Passenger Transportation,* Vol. IV. Department of Supply and Services, Ottawa, Canada, 1992, pp. 1597–1644.

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