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A SIMULTANEOUS ROUTE-LEVEL TRANSIT PATRONAGE MODEL

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16. Abstract

Transit patronage and service supply are highly interrelated. Transit patronage on a route is affected by other parallel and intersecting routes. An analytic toll is needed to examine these complex relationships in the transit system. This study has developed a quantitative model by incorporating these interactions into a simultaneous system. The combined transit demand, supply and inter-route effects are addressed in a three-equation simultaneous model: a demand equation, a supply equation and an equation for competing routes. These simultaneous equations are estimated using the three-stage-least-squares estimation method. The model is estimated at the route-segment level by time of day, and by inbound and outbound directions. Data from Portland, Oregon metropolitan area are used as an extended case study. This study is the first research to discuss the net effects of a service change at the route level.

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ABSTRACT

Transit riders respond to service changes while transit planers respond to ridership changes, meaning that transit patronage and service supply are highly interrelated. Also noticed transit riders transfer and shift from route to route. A new route may draw some riders from existing routes. Thus, transit patronage on a route is also affected by other parallel and intersecting routes. An analytic tool is needed to examine these complex relationships in the transit system. This study has developed a quantitative model by incorporating these interactions into a simultaneous system.

The combined transit demand, supply and inter-route effects are addressed in a three-equation simultaneous model: a demand equation, a supply equation and an equation for competing routes. These simultaneous equations are estimated using the three-stage-least-squares estimation method. The model is estimated at the route-segment level by time of a day, and by inbound and outbound directions. Data from Portland, Oregon metropolitan area are used as an extended case study.

The estimation results show that a service change on a route increases the transit patronage on that route, but it also decreases the ridership on its competing routes, so the net effect of that service improvement is smaller than the ridership increase on the subject route. A conventional single-equation model under-estimates the ridership responses on the subject route, and over-estimates the net patronage response.

This study is the first research to discuss the net effects of a service change at the route level. The model can be implemented for system-level policy analysis and route-level service and land use planning. It is especially useful for "what-if" scenario analysis at the route level to simulate the ridership impacts of service and land use changes.

INTRODUCTION

Two familiar phenomena are usually observed in a transit system, but are often overlooked in transit modeling. The first one is the mutual causality of transit demand and supply. Transit riders are responding to service changes while transit planning is responding to ridership changes, which means that transit patronage and service supply are highly interrelated. There is a feedback effect of patronage changes and service changes.

The second phenomenon is the interaction among intersecting and parallel transit routes. Transit riders transfer from one route to the other, and some of them have a choice of routes. Introducing a new route, such as a new express bus service may draw some riders from existing routes. The ridership increase on the new route is not the net increase generated by that service change. Ridership on a route affects and is affected by other parallel and intersecting routes.

These issues must be incorporated in a robust analytic model. Unfortunately, they are ignored in most previous route-level transit models. Some prior studies have pointed out the importance of incorporating these observations in a route-level transit patronage model, as well as the limitations of ignoring the feedback effect of transit demand and supply, and the inter-relationship among parallel and intersecting routes (Multisystems, Inc., 1982; Menhard and Ruprecht, 1983; Kyte *et al*, 1988; Stopher & Mulhall, 1992; Stopher, 1992).

The primary objective of this research is to address the interrelationship between transit demand and supply and the interactive relationship among related routes, and to develop a simultaneous route-level transit patronage model.

Data from the Tri-County Metropolitan Transportation District of Oregon (Tri-Met) service area in Portland, Oregon are used as an extended case study. Tri-Met is the transit agency that provides transit service to the Portland, Oregon metropolitan area.

This paper contains six major analyses to develop a simultaneous route-level transit ridership model: 1) the simultaneous process of transit demand and supply, 2) the interactions among transit routes, 3) a simultaneous-equation model to integrate the interactive system of transit demand and supply, and the inter-route relationship, 4) calibration of the simultaneous-equations model using observed ridership and service data, 5) discussion of the estimation results and their implications, and 6) a summary of findings.

SIMULTANEITY OF TRANSIT DEMAND AND SUPPLY

The ridership on a transit system is the result of two decision-making processes: that of the riders and that of the transit planners or schedulers. The riders' decision making process determines the demand for transit services, and the planners' or schedulers' decision-making process determines the supply of transit services. These two decision-making processes constitute a interactive demand and supply system. Transit riders respond to service changes, while the transit planners adjust transit services based on the observed ridership fluctuation and their expectation of future ridership, as well as other factors.

Many single regression equation models are based on the understanding that transit demand is a function of transit service. The single-equation model assumes causality in one direction: the level of transit service determines transit ridership. In the extreme, this one-directional causality assumes that the transit planner can randomly put bus service on the road and riders will respond to it. It ignores the important decision making process in the service supply side, and does not reflect the transit planners' or schedulers' feedback process. Therefore, the single-equation model is static and deterministic in nature. It cannot reflect the dynamic process and the feedback effect of the whole system.

The current spatial distribution of transit service and ridership among routes is the result of an equilibrium process of transit demand and supply. A single-equation regression model that uses transit level of service as one of independent variables, will generate a single coefficient that could be an estimate of the demand parameter, the supply parameter, or, some combination of the transit demand response to service changes and transit planners' response to ridership changes. If we consider that the coefficient of service variable is the only contribution of service changes to ridership changes, the demand response to transit service changes would be over-estimated or under-estimated. Such models often prove to be overly sensitive to frequency of service (Multisystems, Inc., 1982).

Transit demand and supply is an interdependent process. But this interdependence between demand and supply does not imply demand and supply can adjust instantaneously. It takes time for transit planners to respond to demand changes and for transit users to respond to service changes. However, there is little documented evidence about response times for transit service changes and patronage responses.

Cherwony and Polin (1977) fits logistic growth curves to the early growth in patronage on a number of newly established bus routes. They found that 99 percent of the ultimate stable ridership level would be achieved in periods ranging from about 3 months to 7 months after inauguration, with a median growth time of roughly 5 months. For a marginal service change such as headway changes on an existing route, there is no report on its possible response time.

There are two different opinions about the response times of service supply on ridership changes. Gaudry (1975) developed a simultaneous equation model for the bus demand function and supply function, using systemwide aggregate data from the Montreal Urban Community Transit Commission system. He states that on the demand side, transit ridership is a function of present transit service and other exogenous variables. On the supply side, the transit service is a function of ridership at the previous year, and other exogenous variables with a lagged time period. He argues that the service supply is unlikely to have been influenced by the current level of demand, it is generally fixed once a year at the time of budget planning. Therefore, in Gaudry's supply equation, only the ridership in previous planning year is considered to influence transit supply. The service quantity supplied during any time period depends primarily on past (rather than current) levels of demand, expected costs, and some other factors.

Gaudry's model is actually a recursive model. The supply and demand functions can be regarded as shifting independently, or nearly so. And the supply and demand equation can be solved independently using ordinary-least-square (OLS) method. There is no immediate feedback effects from the demand equation to the supply equation, because the service supply depends on the previous year's ridership, not the current ridership.

In contrast, Alperovich, *et al* (1977) argue that transit management has the flexibility to make both short-run and long-run adjustments in service supply to match the expectations of demand. In their supply model, both current and previous ridership are considered as factors affecting service supply. The authors admit, however, that if the transit agency is reasonably adept at predicting patronage levels, the inclusion of current demand in the supply function may make the past demand data superfluous.

Three equations of the supply function and two equations of the demand function are designed to address the simultaneity of demand and supply in Alperovich, *et al*'s model. But their simultaneous model totally ignores the route-specific demographic and socioeconomic information in its supply and demand equations. Although the five-equation model looks promising, a better model specification is needed because of the lack of socioeconomic and demographic variables and the complexity of the model (Multisystems, Inc. 1982).

This study considers transit demand and supply as both recursive and simultaneous. On the one hand, the relationship between ridership and level of service is recursive because there is a lagged time period for transit service and transit users to respond to the changes of each other. On the other hand, if the available data are averages over a long period (longer than the response time), and if transit planners have the flexibility to adjust short-run demand changes, the transit ridership responses can be considered simultaneous with service changes.

Service standards are applied and evaluated periodically in Tri-Met. Based on the review and evaluations of route performances transit service is modified accordingly. Service is adjusted to accommodate changes in passenger demand, to respond to service requests from customers or communities, and/or to overcome specific operating problems such as overloads or schedule adherence problems. Major service changes occur once a year (in September). Minor schedule changes of up to plus-or-minus three minutes and minor route changes may be implemented as necessary any time. More significant changes (i.e., changes greater than plus-or-minus three minutes) and major route changes will be implemented only in September (Tri-Met, 1989).

In addition to the service adjustments at fixed times, there is also an on-going fine-tuning process to analyze schedule efficiency and patronage changes. This includes adjustments to schedules, the elimination and addition of selected trips, changes in through-route combinations and minor route changes.

Furthermore, anticipated land use or employment level changes are also reviewed to determine whether an increase in patronage can be expected. For example, if a new shopping center were scheduled to open along an existing line, then the service might be changed in anticipation of future increase of patronage.

Service supply is also constrained by the available budget. Transit service supply varies in responding to budget fluctuations over time. But it is more appropriate to consider budget constraint in the time series model at the system level since the total budget is more variable in the long period of time. In the short-term the total transit budget can be treated as constant. Therefore, the budget constraint need not be included in the short-term cross-sectional model.

The simultaneous system of transit demand and supply can be represented by the following regression models:

$$R_{iz}^{d} = F(S_{iz}^{s}, X_{iz}^{d}) + \varepsilon_{iz} \tag{1}$$

$$S_{iz}^{s} = F(R_{iz}^{d}, R_{-1i}, X_{iz}^{s}) + \eta_{iz} \tag{2}$$

Here R_{iz}^{d} and S_{iz}^{s} are observed transit ridership and level of service variables, representing transit demand and supply at route i and fare zone z. R_{-1i} is the ridership in the previous planning year. The demand function will describe the transit riders' decision-making process. A theory of transit riders' behavior suggests the function form of $R_{iz}^{d}(.)$ and the vector of explanatory variables X_{iz}^{d}. The supply function will describe the transit planners' or schedulers' decision-making process. A theory of transit planners' behavior suggests the function form of $S_{iz}^{s}(.)$ and the elements of vector of determinant variables X_{iz}^{s}, and ϵ and η are stochastic error terms.

The major role of the simultaneous equation model is to reflect the interrelationship and feedback between transit ridership and level of service and obtain efficient and consistent parameters of exogenous and endogenous variables. This cannot be achieved by any single-equation models.

INTER-ROUTE RELATIONSHIPS

A transit system is not a set of independent routes. Most transit routes are interconnected. A change of service and ridership on one route may have an impact on other related routes. The inter-route relationship is therefore an important factor in estimating transit ridership at the route level.

From the planning point of view, an inter-route relationship is a physical relationship among two or more routes. For the purpose of modeling, an inter-route relationship is the service and ridership influence of one route upon the other. It is therefore necessary to differentiate between the inter-route physical relationship and ridership impact. The former is defined as inter-route linkages while the latter as inter-route effects in this study.

The physical relationship among transit routes can be identified using the Geographic Information Systems (GIS) technology. Each bus route and light rail stop was first buffered by a quarter mile distance. These transit buffers were overlaid with each other. The inter-route relationship can be identified by analyzing the relationship of these route buffers. There are three kinds of inter-route relations: independent, complimentary and competing.

If two route buffers have no overlay at any part of the routes, i.e., they are at least half a mile apart, these two routes are independent, like route 71 (RT71) and 75 (RT75) in Figure 1. Transferring and competition between them is unlikely because there is no overlapping area within walking distance of both. These independent routes can be treated as independent from each other in the route-level modeling. A service change in one route presumably has no impact on the other.

If two route buffers overlap, they are linked. The relationship between them can be identified by the configuration of the routes and topographic constraints. Two inter-route linkages can be identified: complementary and competing.

If two route buffers overlap only at one end of transit routes, such as at a transit transfer center, and the other ends are in different directions. The relationship between these two routes is considered complementary. Riders from one route may transfer to the other. A service change in one route will have a direct impact on the other. A typical example is the relationship between a radial bus and a feeder bus.

If two route buffers intersect at one point other than the ends of routes, and the two routes have different origins and destinations, such as radial bus and crosstown bus, these two transit routes are also considered as complementary. For example, route 71 and 75 are complementary routes of route 19 (RT19) and 20 (RT20) in Figure 1, and vice verse. Potential riders may transfer from one route to the other at their intersection point.

The common characteristics of these two types of complementary routes are that they are connected with each other at one point, at least one end of the routes is different from each other, and there are potential riders who may transfer from one route to the other. The service and ridership impact of one route upon the other is complementary.

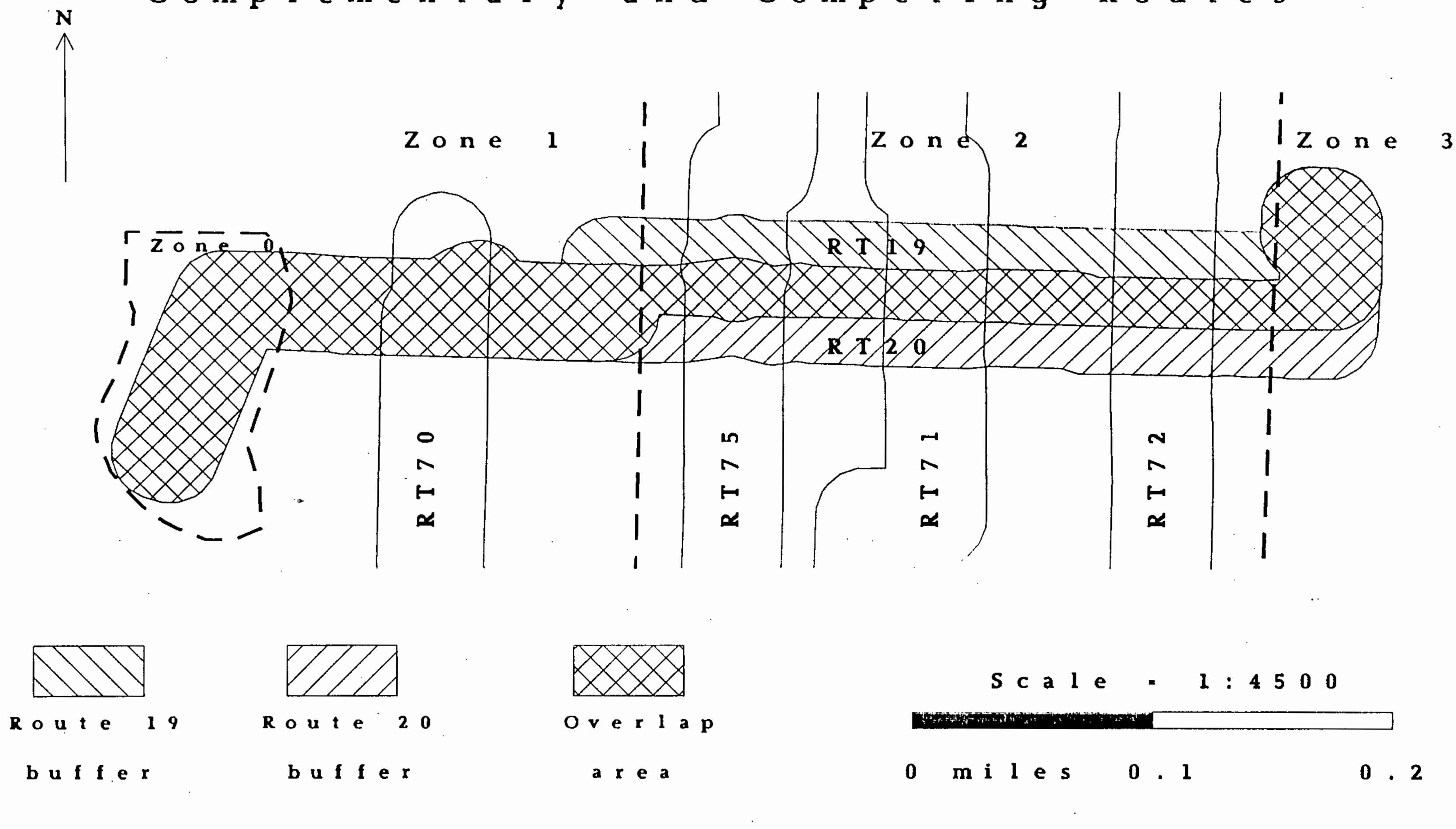
If two route buffers overlap linearly with each other, and have at least one common end, they are considered as competing routes. Routes 19 and 20 in Figure 1 are examples of competing routes. Competing routes share some common service areas with each other. A service and ridership change on one route have two possible impacts on other competing routes: competing and synergistic effects. That is, a service increase on one of the two routes that serve the same service areas may draw riders from the other route. It may also attract more riders from the service areas because of the total level of service increase in that area. The net effect of the service increase on one route may be a simple redistribution of current riders with little or no increase of total transit ridership, or a combination of redistribution and net increase of ridership.

Taking an example of two competing routes 19 and 20 in Figure 1, assume the transit service frequency is increased on route 19. Some current riders on route 20 may shift to route 19. As a result, the ridership on route 19 may increase while the ridership on route 20 may decrease. This negative ridership impact of service changes on the other routes, or the redistribution of current ridership among competing routes, is the competing effect.

On the other hand, because of the service increases on one route, the total transit service available to the residents at the overlap service area increases, which may attract more transit users. The total ridership of these two routes may increase. This positive impact of service increase of one competing route on the other is the synergistic effect. The synergistic effect can be observed in some transit trunk lines where several bus routes share a common road, particularly on roads converging on the

Figure 1 Cross-Route Relationship

Complementary and Competing Routes



downtown area.

Both competing and synergistic effects are a function of how close the two competing routes are to each other. If two route buffers overlap in only a small area, both competing effects and synergistic effects will be small. If two routes run very closely or even on the same road, a service change in one route will have a greater impact on the other. In other words, the competing and synergistic effects will become larger when two competing routes have a larger overlap.

The area of overlap between the two competing routes determines the inter-route effects. Or, more precisely, the population in the overlap area of two competing routes affects the strength of the relationship between them. The population percentage in the overlap area of two competing routes can be conveniently estimated using GIS. It is defined as in Equation (3).

$$OVPOPPC_{ijz} = \frac{POP_{ijz}}{POP_{jz}} \tag{3}$$

Where, $OVPOPPC_{ijz}$ is the proportion of population in the overlap areas (POP_{ijz}) to the population in the competing route buffer (POP_{jz}), The subscript of i refers to the route of interest, j refers to the competing routes. The subscript of z refers to the route segment or fare zone number.

The final net ridership response of route 19 and 20 to the service change in route 19 will be determined by the combination of the competing effect and the synergistic effect. If the competing effect is dominant, current transit riders will shift from route 20 to 19, the net effect of service changes in route 19 is only a redistribution of current transit riders between route 19 and 20. If the synergistic effect is larger than the competing effect, total ridership in routes 19 and 20 will increase. Therefore, the final ridership changes in route 20 corresponding to service changes in route A may decrease, increase or stay the same, depending on the magnitude of the difference between the competing and synergistic effects.

The inter-route relationship discussed above assumes a homogeneous and barrier-free surface. These inter-route physical linkages have to be checked against geographical barriers, such as freeways, rivers and steep slopes. Two routes may be in parallel and their buffers overlap, but if there is a freeway or a river between them, they cannot compete for rides with each other. Potential riders cannot cross the freeway or the river to ride the bus on the other side. All bus routes have to be checked against these geographic barriers in the identification of inter-route linkages.

The issue of inter-route relationships has been dealt with by using network-type models (Horowitz, 1984; Horowitz & Metzger, 1985), but has been ignored in most previous studies of direct demand route-level models. The shortcoming of not taking account of inter-route relationship is a lack of a systematic view of the whole transit system. The traditional single-equation model assumes that the transit ridership on a particular route is determined primarily by the level of service on that route and the socioeconomic and demographic characteristics along that route. The route is assumed to have no relationship with other transit routes. Such invalid assumptions usually lead to inaccurate patronage estimations of service changes.

A study by Alperovich, Kemp and Goodman (1977) has addressed the issue of inter-route transfers. The amount of transfer passengers on the subject route from other routes are modeled as a function of the total ridership on the subject route, the number of interconnecting routes, and a set of route type dummy variables. It is interesting to note that the number of transfer passengers are modeled as a function of the total ridership on the subject route, not the total ridership on those intersecting routes. The authors experience some difficulties in using a sample of routes in the analysis. By using a sample rather than a whole population of the routes, the necessary patronage volumes cannot all be generated endogenously within the model. Using total ridership on the subject routes to estimate the transfer passenger volume is an unfortunate proxy. In addition, their model does not discuss another important inter-route relationship: competition, i.e., the relationship between competing routes.

This study considers both complementary and competing relationship in a simultaneous model. Ridership on a subject route is modeled as a function of the alighting of complementary routes and the ridership on the competing routes, while ridership on competing routes is modeled as a function of service on the subject route.

AN ANALYSIS OF A SIMULTANEOUS TRANSIT SYSTEM

Combining transit supply, demand and inter-route relationship, a transit system can be considered as a simultaneous system as shown in Figure 2. Transit service and network are planned based on and responding to transit ridership, transit ridership is affected by the level of service and the inter-relationships of routes in the transit route network. Ridership changes further affect the level of service supply and the alignment of the network.

The diagram in Figure 2 shows the relationship between ridership and the level of service in a simultaneous transit system. The level of service of a subject route i (LOS_i) affects the ridership on that route (R_i) and the ridership of its competing routes j (R_j). The change of ridership on the competing routes also affects the ridership on the route i. In other words, the level of service on the route of interest (LOS_i) influences ridership on the route i (R_i) in two ways: a direct effect and an indirect effect. Level of service can directly affect ridership, it can also affect ridership indirectly through ridership changes on the competing routes. The ridership changes on the route i in turn influence the supply of service (LOS_i) on that route.

There are many other factors that affect both transit service supply and demand. Those general exogenous variables are shown in Figure 3. The service supply and distribution among routes are determined by the current ridership (R_i), ridership in the previous planning year (R_{-1i}), socioeconomic and demographic factors, and some political considerations. Route-level ridership (R_i) is affected by the level of service on the route, the total ridership on the competing routes (R_j) and alighting from the complementary routes (R_k), and socioeconomic and

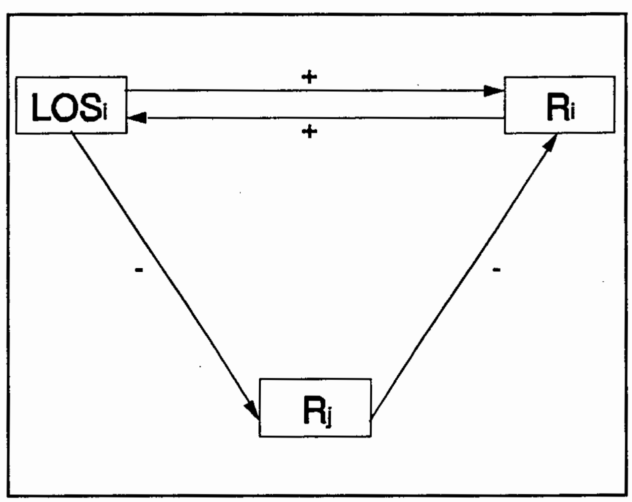


Figure 2. Representation of the Relationship between Transit Ridership and Level of Service in A Simultaneous Model

demographic factors. The total ridership on the competing routes (R_j) is affected by the level of service on the route i and route j, as well as the degree of interaction among routes, which is measured by the percentage of population in the overlap area with route i ($OVPOPPC_i$).

In summary, a service change on one route will have four impacts. The first impact is on the ridership on the route of service change. The second impact is on the ridership of the competing routes, ridership on the competing routes may decrease (or increase) if the service on the route of interest increases (or decreases). The riders have choices to shift between the route of interest and its competing routes. The third impact is on the net effects of all ridership changes considering both the route of interest and its competing routes. And the final impact is that the ridership changes will influence further transit service supplies.

This interacting transit system can be represented by a simultaneous-equations model, expressed by the following three equations:

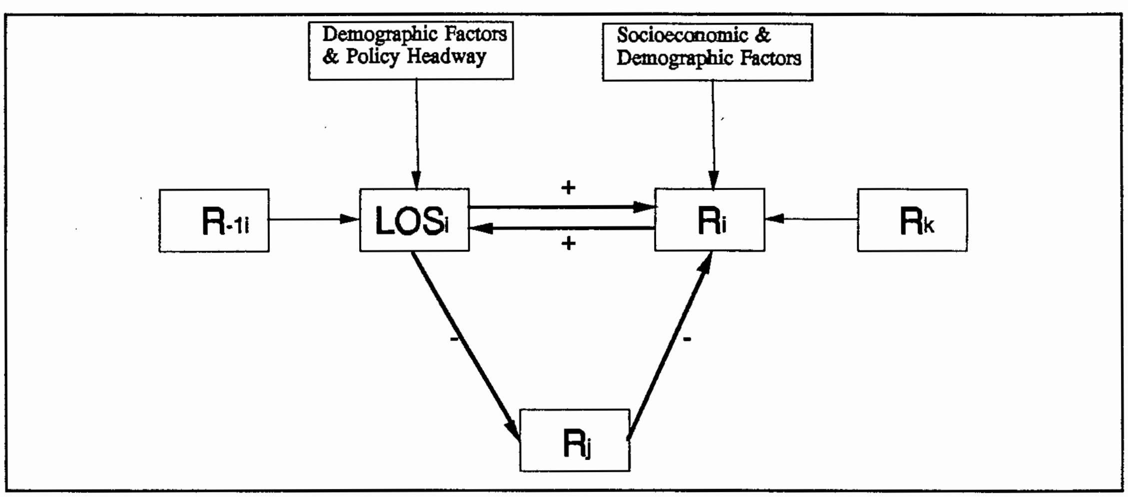


Figure 3. General Factors Influencing Transit Demand and Supply

Demand Equation:

$$R_{iz} = F(LOS_{iz}, \sum_j R_{jz}, \sum_k R_{kz}, OVPOPPC_{ijz}, POP, INC, PARK) \qquad (4)$$

Supply Equation:

$$LOS_{iz} = F(R_{iz}, R_{-1i}, POP, EMPDEN) \qquad (5)$$

Equation for Competing Routes:

$$\sum_j R_{jz} = F(LOS_{iz}, \sum_j FRQ_{jz}, OVPOPPC_{ijz}) \qquad (6)$$

Where

$$LOS_{iz} \equiv \frac{\text{SERVICE TIME}_{iz}}{\text{HEADWAY}_{iz}} * \text{SEATS PER BUS}_{iz} \qquad (7)$$

R = Boarding rides.

R_{kz} = Alighting from complementary routes k in zone z.

SERVICE TIME = the total minutes of service in a service time period, such as AM peak, midday, PM peak.

HEADWAY is the time interval between two buses in a bus route, i.e. the number of minutes per bus. The service time over headway is the total number of buses served during a time period. Therefore, the LOS variable is the total number of seats supplied during a time period.

POP = Population within a transit service area. A service area is defined as a quarter mile distance around a bus route or a quarter mile circle around a light rail stop.

INC = Number of households with income less than $25,000 within the route buffer. The median income in Portland Metropolitan area is about $30,000, the $25,000 represents the lower than median income range.

EMPDEN = Employment density, expressed by the number of employees per acre.

PARK = Total number of parking spaces available in Tri-Met owned park-and-ride lots within a bus route buffer.

R_{-1i} = The ridership of the route i in the previous planning year (1989).

OVPOPPC = The percentage of population in the overlap area of two competing route buffers over the total population on the competing routes. It is defined as in Equation (3).

FRQ = The frequency of transit service, expressed by the number of buses per hour.

The subscript of i refers to the route of interest, j refers to the competing route of i, and k is the complementary route. The subscript of z refers to the route segment number.

MODEL ESTIMATION

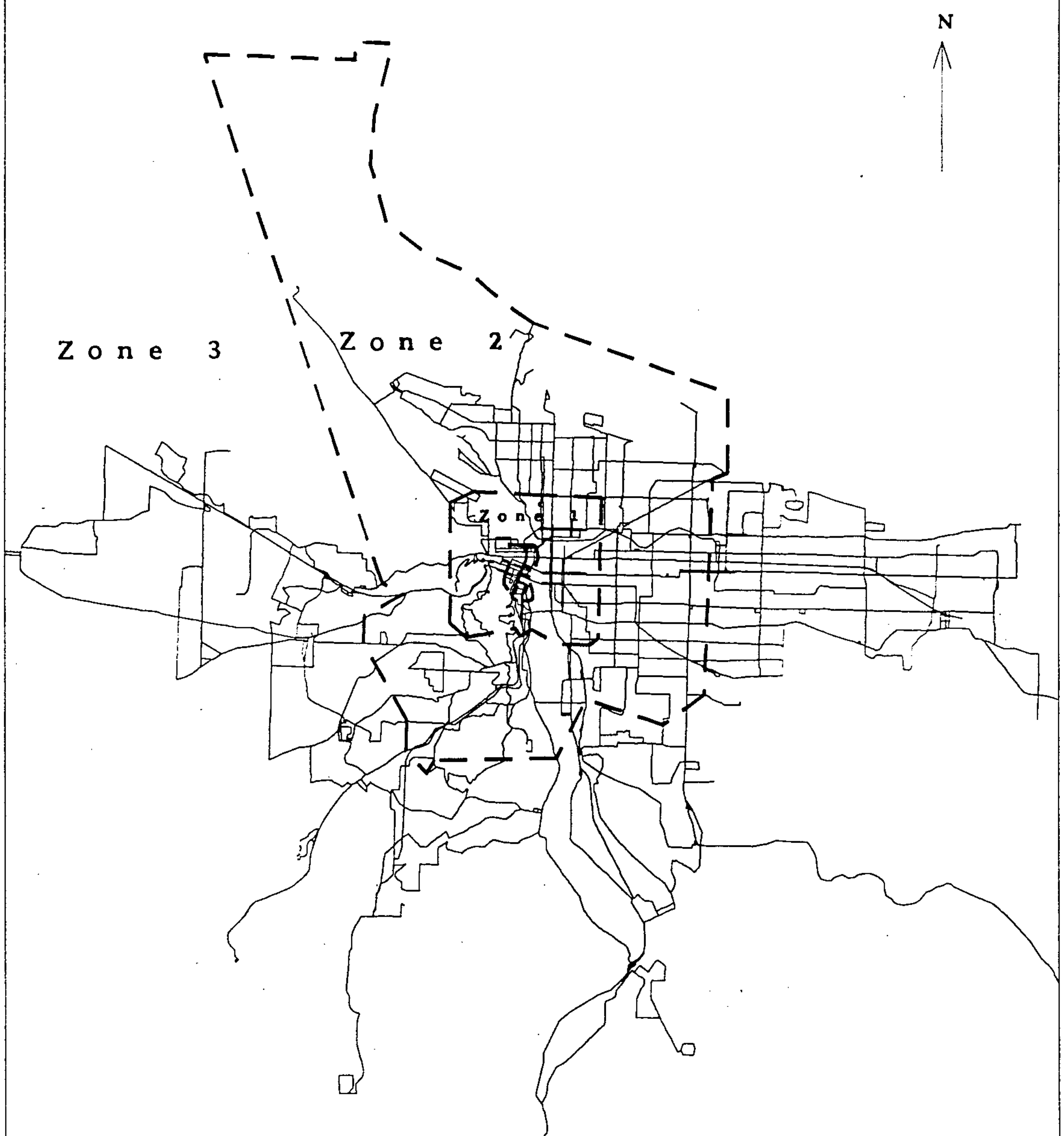
The basic spatial unit of observation of the model is the route segment, a route segmented by fare zones. In the Tri-Met service area, there are four fare zones: fareless square (zone 0), zone 1, zone 2, and zone 3 based on the transit fare structure. These four fare zones are concentric squares surrounding the downtown Portland (Figure 4).

There are significant differences of transit ridership among different fare zones. Most transit riders board transit in Zone 2. Boarding rides in Zone 2 account for about one-third (33 percent) of the total daily ridership without considering direction. Zone 0 comes second (30 percent). Followed by Zone 3 (20 percent). Zone 1 has the smallest share (17 percent) of the total daily ridership because it is substantially smaller than Zones 2 and 3 (see Figure 4).

FIGURE 4

Transit Routes and Fare Zones

Portland, Oregon (1990)



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These zonal effects are also affected by direction. For the outbound direction, boarding rides are dominant in Zone 0, the downtown employment center. More than half of outbound rides (about 51 percent) board transit in Zone 0. Boarding rides in Zone 2 account for about 22 percent of outbound rides. Zone 1 and 3 have only a small portion of outbound boarding rides. For the inbound direction, a little less than half (about 44 percent) of the rides are from Zone 2. Zones 3 and 1 account for another half of the ridership (about 27.4 and 20.5 percent, respectively). Boarding rides in Zone 0 is very small (only about 8 percent).

Because of the zonal variations of boarding rides, using the fare zone as the basic spatial observation unit has an important implication for transit planning and transit patronage modeling. The use of the fare zone as the basic observation unit can capture the spatial variation, while the use of the entire route as the basic unit cannot. For example, for a transit route that goes across four fare zones, transit rides may be mainly from Zones 2 and 1. The ridership aggregated at the route level will be unable to identify the major sources of boarding rides and its causes.

However, there are some limitations of using the route segment as the basic observation. The first limitation is that the length of each segment or the size of each fare zone is not equal. For example, Zone 1 is much smaller than Zone 3. To avoid this problem, the length of a transit route in each segment could be included in the model implicitly, or using the density variable such as ridership per mile and seats per mile. This study originally included the segment length in the model to take into account this variation, but it is highly correlated with the total population variable.

Since the measurement of population is a more direct estimate of transit demand, this study includes only the population variable not the route segment length in the model.

The second limitation is that not every route serves all fare zones because of the different route configuration. Some routes serve only one or two fare zones, especially for those crosstown and feeder routes. However, most routes in Tri-Met service area serve four fare zones and have four route segments.

The third limitation is that the transit service variable is harder to measure at the segment level. In most cases, the service frequency and hours of service are the same for a transit route throughout all fare zones. A few routes operate more frequently over a portion of the line than over the entire line. The major problem is that On Time Performance at transit stops, a variable represents service quality, becomes less important when it is aggregated to the route segment.

Lastly, using the route segment as the basic observation unit makes it harder to analyze the inter-route relationship. Two routes may compete with each other in only part of a segment. There are some diagonally oriented routes which intersect and compete with different routes in different subsegments. To take these inter-route effects into account, aggregation is needed. In the process of aggregation, some variations within a route segment are reduced.

Because of these limitations, a stop level model is more appropriate than a route segment model. A stop level model, however, requires more reliable and accurate data than is available, and requires more detailed data allocation. Therefore, the route segment rather than transit stop is used as the basic observation unit in this study.

Perhaps the next generation of transit demand models will be the stop level as the unit of observation.

GIS is used to allocate all demographic data like population, income and employment to the service area of each transit route, a quarter mile buffer around the transit route. (See Peng and Dueker (1993, 1994) for a detailed discussion on the spatial data allocation.) The data allocation to the route-specific level reduces measurement errors substantially.

Several functional forms of the simultaneous system model have been tested. The linear model seems to perform better in terms of goodness of fit and the significance of variables. Other function forms tested include logarithmic form and logarithm-linear form.

The system model has been calibrated for five time periods (morning peak, mid-day, afternoon peak, evening and night period) in two directions (inbound and outbound direction). Therefore ten models are estimated altogether. Different variables are used in different models because of the different travel patterns and influencing factors.

A sample of the calibration results of ten models using three stage least square (3SLS) estimation method are shown in Table 1. Table 1 shows the estimation results for the morning peak inbound model. The other model results are presented in Peng (1994).

Table 1. Estimation Results of AM Peak Inbound Model

Independent Variables	Demand Equation	Supply Equation	Equation for Competing Route
Boarding Rides (R_{iz})		0.162***(2.06)	
Total Seat Supply (LOS_{iz})	0.289*** (7.892)		
Ridership in 1989 (R_{-1i})	0.505*** (18.95)		
Population (POP_{iz})	0.0134*** (4.687)	-0.0047*** (-2.982)	
Household with income less than $25,000 ($INCLS25B_{iz}$)	0.015 (1.211)		
Employment Density ($EMPDEN_{iz}$)		0.344***(3.11)	
Tri-Met Park-and-ride lot capacity ($PARK_{iz}$)	0.516*** (9.627)		
Total alighting from complementary routes ($\sum R_{kz}$)	0.189*** (2.00)		
Population in the Overlap Area ($OVPOP_{ijz}$)			-0.019*** (-7.918)
Population on the Competing Routes (POP_{jz})			0.0181*** (14.51)
Total Rides on competing routes ($\sum R_{jz}$) *$OVPOPPC_{ijz}$	-0.197*** (-2.416)		
LOS_{iz} * $OVPOPPC_{ijz}$			-0.182 (-1.27)
Frequency on Competing Routes (FRQ_{jz})			8.692*** (3.034)
Crosstown route dummy ($CROSTWND_i$)	-1.355 (-0.034)	-127.37*** (-4.763)	
Feeder route dummy ($FEEDERD_i$)	-66.34** (-1.844)	93.736*** (3.518)	-45.27*** (-2.262)
Fare zone 1 dummy	120.51*** (4.612)	64.40*** (4.385)	44.273*** (3.144)
Fare zone 2 dummy	146.00*** (4.850)	170.89*** (3.748)	34.268*** (1.979)
Fare zone 3 dummy	-2.821 (-0.08)	17.519 (0.336)	11.274 (0.568)
Constant	-188.79 (-6.41)***	131.52*** (7.959)	31.347 (0.774)
R^2	0.76	0.88	0.65

Numbers in Parentheses are calculated t statistics.
*** Significant at the five percent level;
** Significant at the ten percent level.

DISCUSSION ON MODEL RESULTS

The models show that the level of service significantly contributes to transit ridership. This finding is consistent across all time-periods and both directions. Service supply is mainly determined by the ridership in the previous planning years and is also affected by the current ridership. This strong simultaneous relationship between transit demand and supply implies that planners and schedulers are flexible of adjusting the service level according to ridership fluctuations.

The model results reveal that about 19 percent of alightings transfer to other related routes in the morning peak period. A competing effect is also observed. Increasing service on a route will increase patronage on the subject route, but will reduce ridership on competing routes.

In addition to the level of service, inbound demand is mostly determined by the number of persons at places of residence, while outbound demand is mostly determined by the employment density. Park-and-ride lots provided by Tri-Met are also highly significant to explain variations of transit ridership in the morning peak and mid-day periods on inbound routes.

Furthermore, the model results indicate a significant spatial variation of transit ridership. For the inbound direction, route segments in the urban areas (fare zones 1 and 2) have more boarding rides than in suburban areas (fare zone 3), after controlling for other variables. For the outbound direction, transit ridership is concentrated in downtown Portland area, that is ridership in the fareless zone is significantly larger than any other fare zone.

The model results show that the simultaneous equation model is superior to the single-equation model in addressing the interactive relationships among variables. The major difference between a single-equation and a simultaneous-equations model is that the single-equation model does not consider cross-equation interactions, there is only one-way relationship between dependent and independent variables and no feedback effects between them. A simultaneous-equations model considers the transit ridership and the level of service simultaneously. A service change will affect ridership, the subsequent ridership changes will also affect service, the service change will further affect ridership, and so on. This iteration process is shown in Figure 5. The iteration process will not stop until it converges, i.e., until both endogenous variables reach an equilibrium point and there are no further changes in either ridership or service.

For example, assume there is one unit of level of service (one seat) increase on a route i. This route has a competing route which are 100 percent overlaid with a competing route. Using the coefficients from the morning peak inbound model, the iteration process is shown in Table 2.

In the first iteration, a seat increase on the route i increase 0.289 rides on the route i, but it also decrease 0.182 rides on the competing route j. This ridership decrease on route j will increase 0.0359 (=(-0.182)*(-0.197)) rides on the route i. So the ridership on the route i is 0.3249 (0.0359+0.289). The ridership increase on route i will increase service supply by 0.0526 seats, and the increased service supply will further increase ridership on the route i and decrease ridership on route j, and so on. Table 2 shows that after five iterations, the simultaneous equations converge. So the final ridership impact of one unit of service increase on route i will increase 0.3432 rides on the route i and decrease 0.1923 rides on the competing route j, and the net effect is 0.1509 rides.

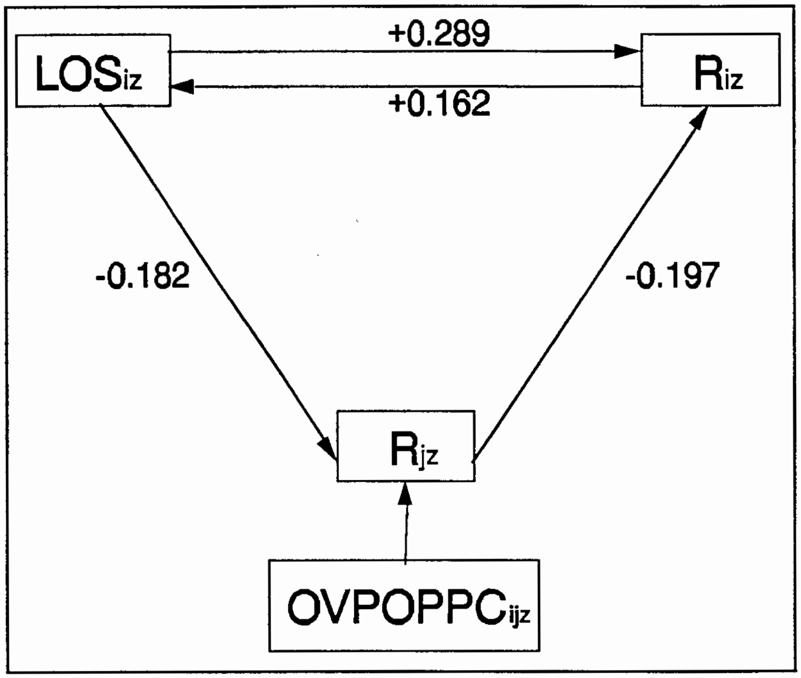

Figure 5. Estimated Simultaneous Effects of Endogenous Variables.

Table 2 Iterative Process of Estimating Ridership Impacts of One Unit of Service Change

Iterations	Ridership Changes on the Route of Interest (R_i)	Ridership Changes on the Competing Routes (R_j)	Neat Ridership Changes (R_i + R_j)
1	0.3249	-0.1822	0.1429
2	0.3421	-0.1918	0.1504
3	0.3431	-0.1923	0.1508
4	0.3432	-0.1923	0.1509
5	0.3432	-0.1923	0.1509

This final ridership impact is the total impact of service change, which is different from the initial impact (the coefficient in the equations). For the morning peak inbound model, the initial ridership impact of one unit service change is 0.289, but the total impact is 0.3432. This difference reflects the cross-equation interactions in the simultaneous equation model. This is one of the major differences between a single-equation and a simultaneous-equation model.

The second major difference between the single-equation and a simultaneous-equation model is that in a single-equation model, the dependent variable is only determined by variables in that equation. But in a simultaneous-equations model, a change of exogenous variables of one equation will have impacts on the endogenous (dependent) variables in other equations too, even though this variable is not included in that equation. For example, the employment density is only included in the supply equation in the inbound models, so a change of employment density will first affect the service supply (LOS_{iz}). The change of service supply will affect the ridership on the route of interest (R_{iz}) in the demand equation, it will also affect ridership on the competing routes (R_{jz}) through the equation for competing routes. The ridership changes on competing routes will further affect ridership on the route of interest (R_{iz}), and the ridership change on the route of interest will in turn affect the service in the supply equation. Therefore, the change of employment can affect all three endogenous variables: service supply, ridership on the route of interest and ridership on competing routes through cross-equation relationship, although the employment variable is only included in the supply equation.

This iterative process of endogenous variable changes across equations corresponding to an exogenous variable change can be illustrated by a concept of an impact multiplier (Greene, 1993). An impact multiplier is the effect of any exogenous variable changes upon all endogenous variables at the current time period. It shows how the initial changes in an exogenous variable impact all the endogenous variables in the whole system.

In a simultaneous-equation model, a service change on one route is assumed to have impacts on both the subject route with service changes and its competing routes, and the net effect of the service changes is the sum of ridership changes on the subject route and its competing routes. While in a single-equation model, the ridership increase on a route with service improvement is assumed as the net effect of that service change, and ridership on other routes are assumed as constant.

The strength of the net effect is determined by how strong the competing routes relate to the subject route. That is the net effect is related with the population percentage in the overlap area. The more overlap, the more competing effects and the less the net effects.

An example using the results from the morning peak inbound model is shown in Table 3. It assumes that there is an additional 100 seats increase on a route i, the total ridership impact on the route i and its competing routes j, and the net ridership impact are calculated in Table 3.

The results from Table 3 shows that the stronger the relationship of two routes, the smaller the net ridership effect corresponding to a service change. As the percentage of population in the overlap area decrease, the ridership decrease on the competing routes diminishes, but the net effect increases. If the two routes totally overlap, an 100 seat increase on the route i will increase about 34 rides, but it will reduce about 19 rides, so the net effect is about 15 more rides. If the two routes have a 50 percent overlap, an 100 seat increase on the route i will increase about 31 rides on that route, and it will also decrease about 10 rides on the competing routes, so the net effect is about 21 more rides.

Table 3. **Net Effects** of Service Changes of Additional One Hundred Seats on an Inbound Route in the Morning Peak Period

Percentage of Population in Overlap Area (%)	Ridership Changes on the Route of Interest (R_{iz})	Ridership Changes on Competing Routes (R_{jz})	Net Ridership Changes (R_{iz} $+R_{jz}$)
100	34.32	-19.23	15.09
80	32.88	-15.35	17.53
60	31.77	-11.49	20.28
50	31.33	-9.57	21.76
30	30.70	-5.74	24.96
10	30.38	-1.91	28.47
0	30.34	0.00	30.34

In contrast, according to the results of a single-equation model, an 100 seat increase will generate about 26 more rides. This increased rides are assumed to be new rides and are net effects of the service changes, regardless of the relationship with other routes. Comparing the results of a single-equation and a simultaneous-equation model, the single-equation model under-estimate the ridership responses on the route with service changes and over-estimate the net effects, if the route has competing routes and the overlap population is over 20 percent.

From the analysis above, it is possible to differentiate between the synergistic effect and competing effect corresponding to service changes on one of the routes. The synergistic effect is represented by the net effects, while the competing effect is represented by the ridership reduction on the competing routes. Both competing and synergistic effects are related with the percentage of population in the overlap area. For the example shown, the synergistic effect of one hundred seats increase is 10 rides while the competing effect is 19 rides if two routes operate on the same road. The synergistic effect is smaller than the competing effect, indicating that the major ridership response to service changes is from current riders shifting among routes rather than new rides being generated. If two routes overlap 50 percent, the synergistic effect (19 rides) is larger than the competing effect (about 10 rides).

The models developed in this study can be implemented both at the system level and at the route or route segment level. Transit service planning and land use planning policies can be analyzed at the system level. There are two important policy implications. The first one is that the different spatial distributions of transit service and population growth will have different impacts on transit uses. Service increase and population growth in urban areas (fare zones 1 and 2) will have higher impact on transit uses than in suburban areas. The second implication is that the transit service increase will cause ridership redistribution among routes. The new ridership (or the net ridership changes) will be small corresponding to transit service increases, if most of the route overlap with competing routes.

The models are especially useful for route-level what-if scenario analysis. They are suitable for estimating ridership responses to service changes in different forms, such as frequency changes, changes of hours of service, and changes of route configurations. They can be also used for new route analysis. The models are not only suitable for single variable changes but also appropriate for multiple variable changes. They can be used to analyze proposed transit intensive corridors, and estimate possible ridership responses corresponding to changes in the level of service and land use density.

CONCLUSIONS

This study has identified two issues in the route-level transit patronage estimate modeling: the simultaneous effects of transit demand and supply, and interaction among transit lines.

The major focus of this study has been to address these two issues in developing a route-level transit patronage model. The empirical evidence indicates that simultaneity exists between transit demand and supply, and there is a strong interrelationship among related routes in a transit network. Transit demand is affected by the level of service supplied, while the service supply is influenced by the past ridership and current demand changes. A service change on a subject route not only affects the ridership on that route, it also affects the ridership on its competing routes that share the same road or on closely parallel roads.

An important finding of the simultaneous-equation model is that a service improvement will increase boarding rides on the subject route, but it may cause a decrease in boarding rides on its competing routes, so the net effects of that service increase is smaller than the boarding ride increase on the subject route. The magnitude of the net effects depends on the strength of the relationship with competing routes. The more the two routes overlap, the more competing effects and the less of the net effects of service changes. This is an important contribution of this study.

Empirical results show that a simultaneous-equations model has an advantage over a single-equation model. It considers the cross-equation effects or feedback effects among endogenous variables. While in a single-equation model, the relationship between ridership and level of service is one-way, i.e., ridership is determined by the level of service. If service is increased on a route, ridership increases accordingly. Furthermore, all the ridership increase on that route is assumed to be new riders, and ridership on other routes are assumed unchanged. The empirical work in this study reveals that a single-equation model over-estimates the net effects of a service increase at the system level, and under-estimates the ridership on the route with service changes.

This research represents an important extension of previous work in the area. It has made a major effort to address the service and ridership impacts on parallel and intersecting routes and to incorporate it into a simultaneous-equations model with transit demand and supply. This study is the first research to discuss the net effects of a service increase at the route level.

However, it should also be recognized that a simultaneous-equations system model is very sensitive to specification errors, especially for a three-stage-least-squares and other full-information estimation methods. A specification error in one equation will impact other equations.

A potential improvement is to estimate the model at the transit stop level if reliable stop level data are available. Stop level estimation can reduce some aggregation errors in some variables like on time performance, and increase the accuracy of the measurement of variables. But the allocation of demographic variables like population and income to individual stop may cause some difficulties and errors, especially when the data are not available at the block level.

Finally, this study has only estimated cross-sectional models. These models can not capture the temporal variation of transit demand and supply over longer period of time. They are applicable to a short time period and in the relatively stable environment. They cannot answer questions such as, what if gas price rises dramatically, and what if there is a transit worker strike. Future research needs to take the temporal variation of transit demand and supply over time into account. A transfer function is more appropriate in this regard.

In spite of these limitations, this research has advanced substantially the state-of-the-art of transit route-level modeling. It is ready for implementation, and can be used in several ways. The model results can address system level transit service policy and land use policy questions. The model can also be used for analysis of individual routes, such as increasing service to achieve transit-intensive corridors, and new routes. The model is especially useful for route-level "what-if" scenario analysis.

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