Modeling Intermodal Auto-Rail Commuter Networks

MARIA P. BOILE, LAZAR N. SPASOVIC, AND ATHANASSIOS K. BLADIKAS

This study is a methodological framework for evaluating the operating and pricing policies in an intermodal auto-rail network. Commuters departing from their homes access their final destination, a Central Business District (CBD), via auto, rail, and intermodal auto-to-rail modes (e.g., park and ride). If a commuter chooses to begin the trip by auto, there are numerous paths to reach the final destination. Once on the highway, the commuter can switch to rail at stations along the rail route. The commuter may also choose to walk to the rail station closest to the trip's origin. The intermodal network is considered as one system, and traffic flows and travel costs are optimized for the whole system and not for separate auto and transit networks, as is the case in most previous studies. The central part of the framework is an equilibrium demand-supply model that consists of a mode choice and a traffic assignment submodel. The commuters' choice of using auto or rail is represented by a mode choice submodel. The traffic assignment submodel assigns transit (walk-to-rail and drive-to-rail) and pure auto trips to routes in the network, based on the minimization of an individual traveler's generalized (travel time and out-of-pocket) cost. The model yields modal shares, equilibrium flow pattern, and resulting generalized costs of the network assignment. The framework is applied to an intermodal network, modeled closely after a northern New Jersey commuter corridor, and used to analyze policies that include increasing parking capacity on commuter rail lots, increasing tolls on highways, increasing the parking fee at the CBD, decreasing rail fares, and improving rail service quality. These policies are evaluated based on user costs, and transit and highway operators' costs and revenues.

This study is a methodological framework for analyzing the effects of various operating and pricing policies for assigning traffic flows according to the performance of intermodal passenger transportation systems. In an intermodal transportation network, commuters leaving their homes can access their final destination via auto, transit, and intermodal auto-to-transit modes. If a commuter chooses to begin a trip by auto, there are numerous paths to reach the final destination. Once on the highway, the commuter can switch to transit at any station along the transit route. The commuter may also choose to walk to the transit station closest to the trip's origin.

Central to the methodological framework is a combined mode choice-traffic assignment model. This model allocates trips over the auto and transit modes of the network, and assigns pure transit (walk-to-transit), intermodal (auto-to-transit), and auto trips over the network routes, yielding equilibrium flows between demand and supply.

The primary motivation for this work was the necessity to include all transportation modes in a unified, interconnected manner to form a National Intermodal System as dictated by the Intermodal Surface Transportation Efficiency Act of 1991. In addition, the Clean Air Act Amendments of 1990 require employers located in non-attainment areas and having more than 100 employees to increase average vehicle occupancy by 25 percent. The objective is to use the proposed framework to evaluate various policies that can induce a commuter shift to public transit. More precisely, the framework could be used to evaluate the effects of policies on network performance, the cost of capital improvements, and operating cost changes for highway and rail operators. To demonstrate its capabilities, the framework is used to evaluate a variety of policies in an intermodal commuter network.

LITERATURE REVIEW

A review of the literature revealed several papers related to the development of demand-supply network equilibrium models, the formulation of mode and transit station choice models, and the analysis of multimodal networks.

Network equilibrium models that consider travel by private car and one or more public transit modes have been developed by Florian (*1*), Florian and Nguyen (2), Abdulaal and LeBlanc (*3*), Dafermos (*4*), LeBlanc and Farhangian (*5*), and Florian and Spiess (*6*). All these formulations consider only pure modes. Once travelers have chosen modes, they are assigned over separate modal networks without the possibility of switching modes during their journey. A recent paper by Fernandez et al. (*7*) is the only published work that explicitly analyzes intermodal trips in a network equilibrium framework. The paper presents three model formulations with auto, metro, and a combined mode (auto-to-metro), and analyzes the resulting equilibrium conditions. The underlying assumption is that the combined mode is considered only at those origins where metro is not available. When metro is available, travelers can choose only between auto and metro. This assumption does not consider that even when there is a metro station at an origin, a traveler may prefer to drive to or be dropped off at a station along the metro route.

Mode and station choice model formulations, Fan et al. (*8*), Miller (*9*), and Ortuzar (*10*), concentrate on estimating travel volumes by mode, transit station, or both. They have not been implemented within a network equilibrium context.

Turnquist et al. (*11*), developed a framework to evaluate improvements in transit operating strategies that meet various service objectives. It was assumed that transit and the competing modes have fixed travel impedance, thus precluding the consideration of competitive interactions among modes.

Manheim (*12*) presented a conceptual framework for analyzing transportation improvements using a simple intermodal network with one origin, one destination and three paths (auto, rail, and auto-to-rail). A software package was used to obtain modal splits and

---

M. P. Boile, Department of Civil and Environmental Engineering, Lafayette College, Easton, Penn. 18042-1775. L. N. Spasovic and A. K. Bladikas, National Center for Transportation and Industrial Productivity, NJIT, Newark, N.J. 07102.

traffic assignment. It was not clear what method was used to equilibrate demand and supply.

Current Urban Transportation Planning Software

The majority of planning software packages such as QRSII (*13*), MINUTP (*14*), and TRANPLAN (*15*), follow the Urban Transportation Modeling System (UTMS), which consists of four steps: (a) trip generation, (b) distribution, (c) modal split, and (d) traffic assignment. Although, in theory, the UTMS should consider the effect of network performance (*i.e.,* travel times) on demand, this is not how the software actually works.

These software have three shortcomings. First, an inexact methodology is used for assigning flows over the networks. When assignment is completed using the all-or-nothing method, the impact of congestion on travel times is not recognized, because travel times are assumed to be constant. When the minimization of networkwide cost is used (*13*), the assignment is inconsistent with driver behavior, because according to Wardrop's First Principle (*16*), drivers will attempt to switch paths between an origin-destination (O-D) as long as this can decrease their individual travel times. This inconsistency could lead to unrealistic flows, especially in networks with moderate congestion. In rare cases when an "equilibrium solution" (Sheffi (*17*)) is computed, this is accomplished using an inexact heuristic (*14*).

Second, the software do not recognize the interaction between network performance and modal splits. The final resulting equilibrium travel times are not considered in adjusting the initial modal splits. However, because of the previously mentioned flaws with the traffic assignment, this interaction, even if established, will likely produce unrealistic flows.

Third, the UTMS packages ignore intermodal flows by not permitting trips to shift between the auto and transit networks. This is critical because the highway portion of an intermodal trip will affect highway travel times and thus modal splits. This shortcoming makes it difficult, if not impossible, to use the packages for evaluating the effects of transit on highway network performance. An exception in the ability to model intermodal trips is the new version of EMME/2—Release 7 (*18*). A new module, "Matrix Convolutions," allows the enumeration of intermediate zones between an origin and a destination. By having an intermediate zone, for example, serve as a destination zone for the highway network, and as an origin zone for the transit network, it is possible to consider intermodal trips.

In marked contrast to the current software, the model presented here performs an interactive mode choice-traffic assignment over an integrated highway-transit network, wherein different performance (time-volume) functions are used to model travel over each portion of an intermodal trip. Therefore, the model can be used to evaluate effects of transit improvement policies on highway network performance.

METHODOLOGICAL FRAMEWORK

The framework for analyzing the effects of various policies on network flow patterns and associated travel costs in an intermodal network is shown in Figure 1. The framework is designed to answer questions of interest to transportation planners (Is it possible to assign travelers to the network more efficiently? What are the benefits of the improved assignment? At what cost are these benefits achieved?) and to investigate trade-offs between travel time reductions and the cost of capacity increases. The model answers these questions by providing:

- Equilibrium assignment of flows over an intermodal network that minimizes user costs;
- Total network travel cost for each policy;
- Incremental changes in cost;
- Estimation of benefits for each alternative; and
- Rail service and parking capacity additions needed to accommodate rail ridership increase.

Given an intermodal highway-rail transportation network, the framework starts with the collection of network data, costs, and travel demand parameters. The data include capacities of highway and rail links, performance functions that relate traffic volumes, capacities and travel times, time impedances, out-of-pocket costs (e.g., rail fares, tolls, parking fees, auto operating cost), commuter rail data (frequency and capacity of trains and capacities of station parking facilities), and travel volumes for each O-D. In addition,

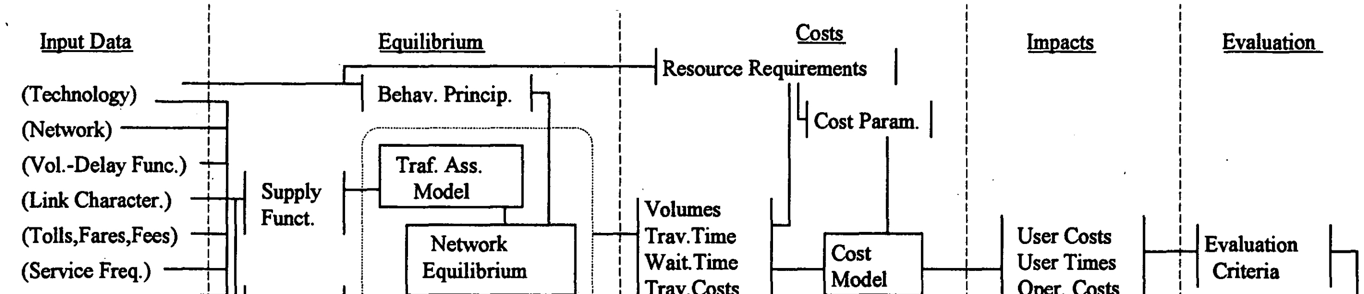


FIGURE 1 Methodological framework.

background traffic volumes that originate, terminate, or both, outside the study network, are also collected.

The data are entered into a combined mode choice-traffic assignment network equilibrium model. The model calculates modal shares, equilibrium flow patterns, and the resulting generalized cost (a sum of out-of-pocket costs, in-vehicle, and out-of-vehicle time costs) of the network assignment, and can perform sensitivity analysis by varying input parameters such as congestion levels, out-of-pocket costs, and demand data.

Several policies can be developed by selecting (and later changing) the input parameters. The cost module estimates the policy costs. Finally, the evaluation module evaluates the effect of policies by trading off user costs and travel times with operators' costs and revenues, and determining the desirability of each policy.

MODELING INTERMODAL DECISIONS

There are basically three distinctive approaches for modeling mode choice and route choice decisions in an intermodal setting as shown in Figure 2. They differ on what choices are modeled within the demand side and what choices are modeled within the supply side of the formulation. Within the demand side, a mode choice could be formulated using disaggregate mode choice models, such as multinomial, or nested logit. This formulation assumes that each mode is chosen with some finite probability and considers the relative attractiveness of one mode over the others. Within the supply side, a choice is performed as a route choice (routing) problem, in which a traveler chooses the mode-specific routes that minimize generalized travel cost.

In the first approach, shown in Part *a* of Figure 2, mode choice is modeled within the supply side of the formulation as a routing problem. As a result, the total demand is distributed among auto, rail, and intermodal routes, to minimize the individual travelers' generalized cost. The summation of the resulting route flows over the auto, rail, and intermodal routes yields modal shares.

The second approach, shown in Part *b* of Figure 2, formulates the commuters' choice of auto or rail transit within the demand side of the model formulation via a binomial logit model, which splits the total demand between auto and transit. Then, within transit, the choice between pure rail (walk-to-rail) and intermodal (auto-to-rail) trips is treated as a least-cost routing problem.

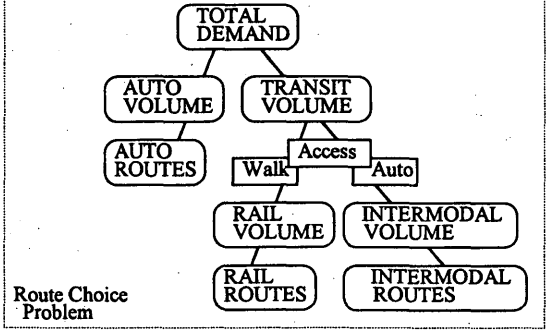
The third approach, shown in Part *c* of Figure 2, performs the choice among auto, rail, and intermodal trips within the demand side of the formulation via a nested logit model. The model splits the total demand between auto and transit in the so-called upper-level decision. Then, the demand for transit is split between rail and intermodal in the lower-level decision. After the modal shares have been determined, the choice of routes within each mode is performed within the supply side as a routing problem.

A detailed discussion of these three approaches, mathematical formulations of the models, derivations of the equilibrium conditions, and selected case studies are presented by Boile (*19*).

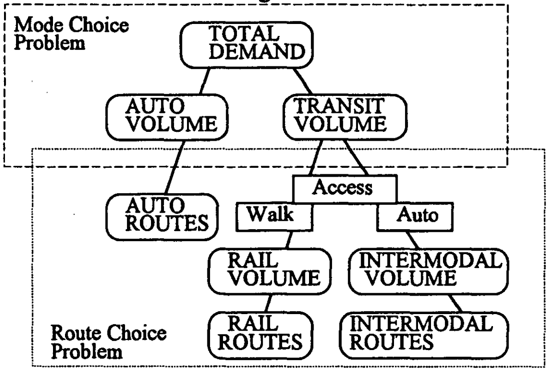
THE MODE CHOICE-TRAFFIC ASSIGNMENT MODEL

The second approach has been adopted here for the formulation of the model, which is essentially a mathematical program with a nonlinear objective function and linear constraints. Its objective function follows the formulation of user equilibrium with elastic demand by Beckmann et al. (*20*). Its conceptual statement is:

a. Routing Approach



b. Combined Binomial Logit Mode Choice-Route Choice Model



c. Combined Nested Logit Mode Choice-Route Choice Model

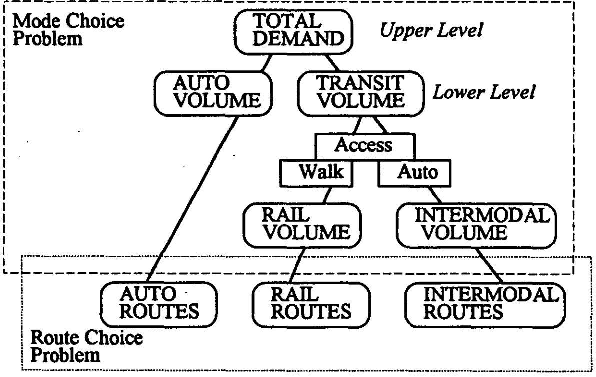


FIGURE 2 Approaches for modeling intermodal decisions.

Minimize:

Total Individual User Cost minus the Integral of the Inverse Demand Function subject to:

- Demand conservation constraints;
- Link flow conservation constraints;
- Rail and transfer link capacity constraints; and
- Non-negativity constraints.

The mathematical formulation is shown in Table 1. Equation 1.1 ensures that all trips between an O-D pair are accounted for. Equa-

TABLE 1 Combined Mode Choice-Traffic Assignment Model

Nodes and Links:	Choice Variables:	Sets:
i,j = origin, destination	f_l = flow on link l	E = all O-D pairs
l, p = link, path.	h_p = flow on path p	L = all links
		$R(L)$, $A(L)$, $T(L)$, $W(L)$ = all rail, highway, transfer, walking links Pa, Pr, Pm = all auto, rail, intermodal paths $CR(R)$ = highest passenger load rail links

Parameters:

T^{ij} = demand between origin i and destination j

T_t^{ij} = demand for transit between i and j $[T^{ij} * \exp(a_t + b * GC_t^{ij}) \; / \sum_{k=auto,transit} \exp(a_k + b * GC_k^{ij})]$,

$D^{-1}{}_{ij}$ = inverted demand function,

δ_{lp} = binary parameter, 1 if link l is in path p, and 0 otherwise,

c_l = generalized cost on link l.

occ = occupancy rate for autos,

$Space_l$ = number of parking spaces at a rail station (link l), $Seats$ = number of train seats per peak hour,

λ = transit vehicle load factor,

$$\text{Minimize } Z = \sum_{l \in L} \int_0^{fl} c_l(\phi)d\phi - \sum_{ij \in E} \int_0^{T^{ij}} D_{ij}^{-1}(\omega)d\omega$$

subject to:

$$T^{ij} = T_a^{ij} + T_t^{ij} \qquad \forall\, i,j \in E \tag{1.1}$$

$$T_a^{ij} = \sum_{p \in P_a^{ij}} hp \qquad \forall\, i,j \in E \tag{1.2}$$

$$T_t^{ij} = \sum_{p \in P_r^{ij}} hp + \sum_{p \in P_m^{ij}} hp \qquad \forall\, i,j \in E \tag{1.3}$$

$$fl = \frac{1}{occ}[\sum_p \delta lp * hp] \qquad \forall\, l \in A,T \tag{1.4}$$

$$fl = \sum_p \delta lp * hp \qquad \forall\, l \in R,W \tag{1.5}$$

$$fl \le Space_l \qquad \forall\, l \in T \tag{1.6}$$

$$fl \le (Seats) * \lambda \qquad \forall\, l \in CR \tag{1.7}$$

$$h_p \ge 0 \qquad \forall p \in Pa,\, Pr,\, Pm \tag{1.8}$$

tions 1.2 and 1.3 are the definitional constraints for auto and transit shares of the travel volume. Equations 1.4 and 1.5 equate flows on a link with the sum of the flows on all the paths through that link. Equations 1.6 and 1.7, respectively, ensure that the number of commuters using parking lots, and the number of rail users, do not exceed the parking and rail line capacities. Equation 1.8 ensures that all path flows are non-negative.

Equilibrium Conditions

An equilibrium solution to the model must satisfy two conditions. First, for each O-D pair and mode, namely auto and transit, no traveler has an incentive to unilaterally change routes, because travel cost cannot be minimized further. This is known as Wardrop's First Principle (*16*), and for this model it is expressed as:

$$GC^{ij}_{pk} - C^{ij}_{k} \begin{cases} = 0, \text{ if } h^{ij}_{p} > 0 \\ \geq 0, \text{ if } h^{ij}_{p} = 0 \end{cases} \qquad \forall i,j,k \tag{1}$$

where

GC^{ij}_{pk} = generalized cost on path p from origin i to destination j via mode k;
C^{ij}_{k} = minimum generalized cost from origin i to destination j via mode k; and
h^{ij}_{p} = flow on path p from origin i to destination j.

This condition indicates that for a given O-D pair i, j and a mode k, a path p is used only if its generalized cost equals the minimum generalized cost. If the flow on this path is zero, its cost must be greater than (or equal to) the cost on the least cost path.

Second, at equilibrium, no traveler has an incentive to unilaterally change modes. This condition is derived from the inverted demand function (given as a logit model):

$$T^{ij}_{t} = T^{ij} \frac{\exp(a_t + b * GC^{ij}_{t})}{\exp(a_t + b * GC^{ij}_{t}) + \exp(a_a + b * GC^{ij}_{a})} \qquad \forall i,j \tag{2}$$

where

T^{ij}_{t} = number of travelers from i to j by transit;
T^{ij} = total number of travelers from i to j;
T^{ij}_{a} = number of travelers from i to j by auto, $T^{ij}_{a} = T^{ij} - T^{ij}_{t}$;
a_a, a_t = mode-specific parameters;
b = mode-independent parameter; and
GC^{ij}_{k} = the generalized cost of traveling from i to j via mode k (k = auto, transit).

Then, the inverse of this function:

$$GC^{ij}_{a} - GC^{ij}_{t} = \frac{1}{b}\left[\ln \frac{T^{ij}_{t}}{T^{ij}_{a}} - (a_a - a_t)\right] \qquad \forall i,j \tag{3}$$

becomes the second equilibrium condition that gives the relationship between the generalized costs of the two utilized modes. Details on the equilibrium condition derivations are explained by Boile (*19*).

CASE STUDY

The methodological framework was applied to an intermodal network shown in Figure 3. The network is a realistic representation of a portion of the Raritan Valley Corridor located in Union County, NJ. It consists of five origins: Westfield, Garwood, Cranford, Kenilworth, and Roselle Park (designated O1 through O5); and one destination, which is Newark (D). The network is composed of three major highways, I-78, Route 22, and the Garden State Parkway (GSP), local county roads that run between the major highways, and a NJ Transit commuter rail line. According to 1980 U.S. Bureau of the Census data, there were 540, 130, 620, 220, and 920 peak-hour work trips, respectively from Westfield, Garwood, Cranford, Kenilworth, and Roselle Park, to Newark (*22*).

Assumptions and Input Data

While actual demand and traffic volume data are used in the analysis, the mode choice model coefficients for Equation 3 were estimated to be: $a_t = 0$, $a_a = 0.02$, and $b = 0.33$. Currently, NJ Transit and the regional MPO are attempting to calibrate access choice models in the corridor. Obviously, the mode choice-traffic assignment model can be easily re-run once accurate and origin-specific mode choice coefficients are available.

The highway links are congested and travel times were modeled using the Bureau of Public Roads (*23*) congestion curves. For each link (road) type (*i.e.,* arterial and freeway), the capacities used in the curve were calculated using the 1985 Highway Capacity Manual (*24*). Transfer link travel times were assumed constant and included time to park and wait for the train. It was assumed that travelers are experiencing an average waiting time of one-half the headway (Manheim (*12*)). Walking times were determined by dividing the walking link length by an average walking speed of 4.39 km/hr (2.73 mph). Rail link travel times were estimated from a service schedule. Trains on the route operate in local service (*i.e.,* stop at each station).

Regarding out-of-pocket costs, there is a standard toll of $0.35 on the GSP. Rail fares are $2.15 from O1 and from O2, $1.75 from O3 and $1.50 from O5. There is no train station at O4. Parking fees are $3.00, $1.15, $1.50, and $5.00 for the parking lots at O1, O3, O5, and D, respectively. There is no commuter parking at O2. Vehicle operating cost is calculated by multiplying the distance traveled by $0.40 per vehicle-km ($0.25/vehicle-m). Travel time was translated into cost by multiplying it by $15/hr.

Train seating capacity was estimated at 500 seats (four cars at 125 seats each). Trains run every 20 minutes yielding a line capacity of 1,500 seats per peak hour. The number of parking spaces at O1, O3, and O5 is 759, 373, and 239, respectively. There is no constraint on parking capacity at D.

The Cost Model

A cost model was developed to estimate the cost of capital investments such as parking expansion and train capacity improvements. An annual cost of $805.90 per parking space was obtained by spreading the acquisition cost of $10,000 over a 30-year period and using 7 percent interest (capital recovery factor 0.08059). Assuming that half of this cost was allocated to the peak hour during 265 working days per year, the daily cost per peak hour was $1.52 per space.

The transit operator cost includes maintenance and overhead as well as the more direct cost of operation (wages, power, etc.), and is represented by the all-inclusive hourly operating cost per vehicle c. The total hourly operator cost is obtained by multiplying the active fleet (defined as the ratio of the total round trip time over the headway) with the hourly operating cost per vehicle. The total round trip time is the round trip route length divided by the average speed. The total hourly operator cost is then:

$$C = \frac{2cL}{HV} \tag{4}$$

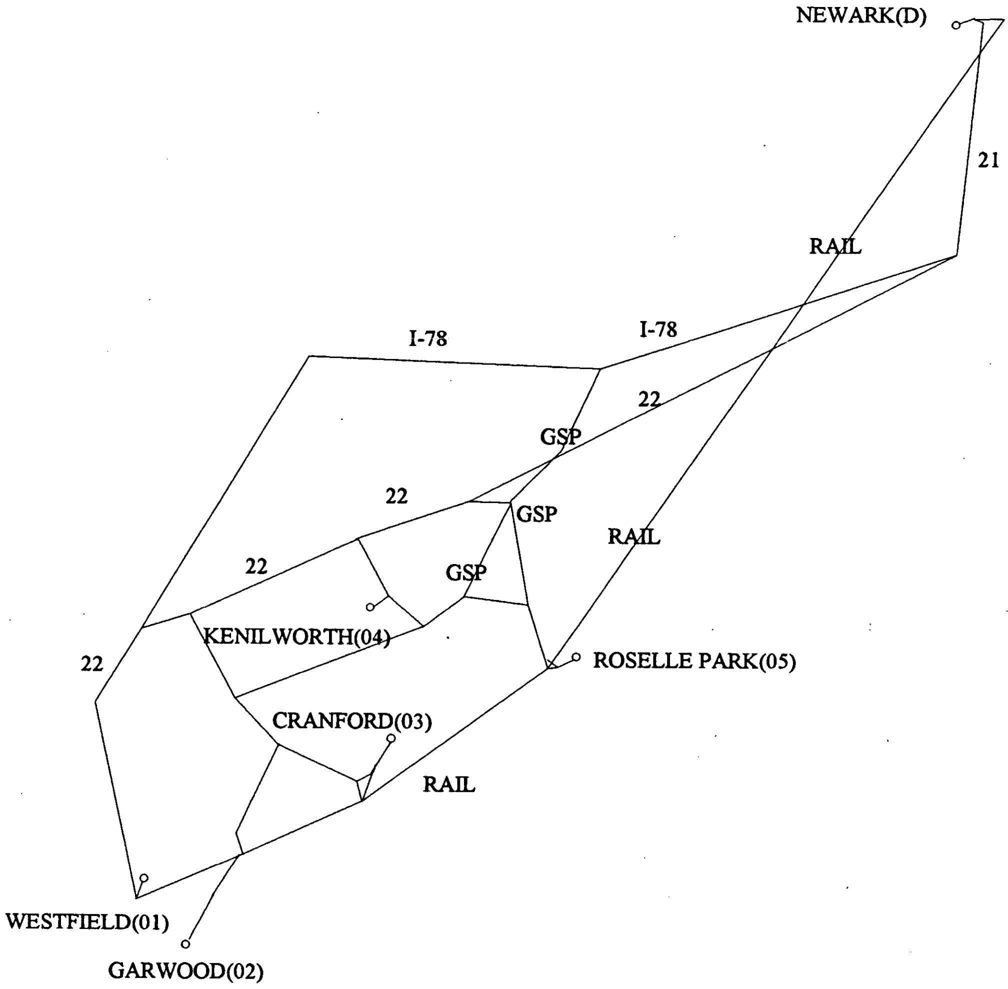


FIGURE 3 **Experimental network.**

where the variables and their assumed values are:

c = vehicle operating cost	500 [\$/vehicle-hr]
L = length of transit route	5.47 [km] (3.4 [mi])
H = route headway	0.333 [hr/vehicle]
V = average transit speed	32.2 [km/hr] (20 [mi/hr])

With the above assumptions, the total hourly operating cost (C) is \$510.51/hr.

Policies Analyzed

Six policies were analyzed to determine the best alternative in terms of its impact on the users and transportation system (highway and rail) operators. They are as follows:

Policy 1: Baseline Case

It models the current situation, represents the "Do Nothing" alternative, and serves as a basis for comparison.

Policy 2: Increase Parking Capacity

Currently, some of the parking lots operate at capacity, preventing an increase in intermodal travel. This policy expands parking capacity by adding 60 new spaces to the lot at O3 and 300 new spaces to the lot at O5.

Policy 3: Increase Tolls

Highway tolls were doubled (from \$0.35 to \$0.70) to induce travelers to shift from auto to rail.

Policy 4: Increase Parking Fees at the CBD

The CBD parking fee was increased 40 percent (\$2.00), to make auto trips less attractive and reduce the number of auto commuters.

Policy 5: Decrease Rail Fares

The rail fare was reduced by $1.00 for all trips.

Policy 6: Increase Train Frequency

The train frequency was doubled from three to six trains per hour, halving the average waiting time from 10 to 5 min.

RESULTS

For each policy, the model generated equilibrium modal splits and network flow assignments, and calculated generalized costs. Table 2 presents the flows and costs by mode for each O-D pair and policy.

Evaluation of Policies

The policy effects in terms of modal shares are shown in Table 3. The effects of policies, in terms of user and operator impacts are presented in Table 4. The operator gross revenues are estimated by multiplying the toll (for highways) and fare (for transit) by the number of users. The last column of the table labeled "Net User and Operator Cost" is the sum of all operator (rail, highway, and CBD parking) revenues, which are included in the three preceding columns, minus the user costs (first column). It is assumed that the rail operator is responsible for the rail line and the station parking lots. Therefore, net rail operator revenues are computed by subtracting rail operating costs and parking capital investments from the fare-box and station parking revenues.

The highest reduction in user cost (and time), results from the doubling of rail frequency. User cost decreased by 9.11 percent (and time by 15.44 percent) in comparison with the Baseline. Rail operator's revenues and station parking lot revenues increased by 20.5 percent and 27.7 percent, respectively, and the highway and the CBD parking operators' revenues decreased by 20.3 percent. The rail revenue came primarily from 281 travelers who shifted from auto to rail and intermodal. Of the people who shifted to transit, 200 or 71.17 percent were shifted to pure rail and 81 or 28.83 percent to intermodal trips. The increase in rail frequency doubled the operator costs to $1021.02/peak hr, but the net rail operator revenue increased by $226.3.

The increase in station parking lot capacities resulted in a decrease of user cost by 3.4 percent (and time by 3.6 percent) compared to the Baseline. The $547.4 capital investment in 360 spaces increased station parking and rail revenues by $511.5 and $40.5, respectively. Thus, per $1 invested, $1.008 was generated in revenues for station parking and rail combined. The increase in rail revenue came both from highway and rail travelers who could not have driven to rail in the Baseline because of parking lot capacity constraints. The increase in parking capacities reduced the total number of auto users by 2.8 percent.

The increase in CBD parking lot fees increased the user cost by 3.5 percent and reduced the time by 5.36 percent compared to the Baseline. This policy increased CBD parking revenues by 20.4%. It also increased rail and station parking revenues by 14.3 percent and 19.2 percent, respectively. Note that this policy also reduced highway toll revenues by 14 percent. The increase in rail revenue came from 194 travelers shifting from auto to rail and intermodal. As

TABLE 2 Results of the Mode Choice-Traffic Assignment Model

		Policy											
		1 -- Baseline		2 -- Increase Parking Capacity		3 -- Increase Tolls		4 -- Increase CBD Parking Fee		5 -- Decrease Rail Fare		6 - Double Rail Frequency	
Origin -- Destination	Path Type	flow users/peak hr.	cost $/user	flow users/peak hr.	cost $/user	flow users/peak hr.	cost $/user	flow users/peak hr.	cost $/user	flow users/peak hr.	cost $/user	flow users/peak hr.	cost $/user
	Auto	410	20.1	412	20.1	401	20.4	354	21.7	383	19.9	329	19.5
O1-D	Rail	--	--	--	--	--	--	--	--	--	--	--	--
	Intermod.	130	23.6	128	23.6	139	23.6	186	23.6	157	22.6	211	20.8
	Auto	63	21.7	67	21.3	60	21.9	51	22.8	56	21.3	46	20.5
O2-D	Rail	67	21.4	11	21.4	70	21.4	79	21.4	74	20.4	84	18.6
	Intermod.	--	--	52	20.0	--	--	--	--	--	--	--	--
	Auto	247	22	239	21.6	247	22.2	219	23.1	244	21.6	200	20.8
O3-D	Rail	--	--	--	--	--	--	28	21.2	3	20.2	47	18.5
	Intermod.	373	18.7	381	18.7	373	18.7	373	18.7	373	17.7	373	15.9
	Auto	166	19.4	155	19	163	19.6	149	20.6	157	19	142	18.2
O4-D	Rail	--	--	--	--	--	--	--	--	--	--	--	--
	Intermod.	54	18.6	65	18.6	57	18.6	71	18.6	63	17.6	78	15.8
	Auto	500	20.7	446	20.3	485	20.9	419	21.8	457	20.3	388	19.4
O5-D	Rail	235	21.2	--	--	253	21.2	333	21.2	286	20.2	371	18.4
	Intermod.	185	17.1	474	17.1	182	17.1	168	17.1	177	16.1	161	14.3
	Auto	1,386		1,319		1,356		1,192		1,297		1,105	
Total	Rail	302		11		323		440		363		502	
	Intermod.	742		1,100		751		798		770		823	

TABLE 3 Mode Shares

Policy	O-D Pair	Auto (%)	Rail (%)	Intermodal (%)
1 -- Baseline	O1 - D	75.9	0.0	24.1
	O2 - D	48.2	51.8	0.0
	O3 - D	39.8	0.0	60.2
	O4 - D	75.6	0.0	24.4
	O5 - D	54.4	25.6	20.0
	TOTAL	57.1	12.4	30.5
2 -- Increase in Parking Capacity	O1 - D	76.4	0.0	23.6
	O2 - D	51.4	8.4	40.2
	O3 - D	38.6	0.0	61.4
	O4 - D	70.6	0.0	29.4
	O5 - D	48.4	0.0	51.6
	TOTAL	54.3	0.4	45.3
3 --Increase Tolls	O1 - D	74.2	0.0	25.8
	O2 - D	46.4	53.6	0.0
	O3 - D	39.8	0.0	60.2
	O4 - D	74.2	0.0	25.8
	O5 - D	52.7	27.5	19.8
	TOTAL	56.0	13.1	30.9
4 -- Increase Parking Fees	O1 - D	65.5	0.0	34.5
	O2 - D	38.9	61.1	0.0
	O3 - D	35.3	4.5	60.2
	O4 - D	67.7	0.0	32.3
	O5 - D	45.5	36.2	18.3
	TOTAL	49.0	18.2	32.8
5 --Decrease Rail Fares	O1 - D	71.0	0.0	29.0
	O2 - D	43.2	56.8	0.0
	O3 - D	39.4	0.4	60.2
	O4 - D	71.6	0.0	28.4
	O5 - D	49.7	31.1	19.2
	TOTAL	53.4	15.0	31.6
6 -- Double the Rail Frequency	O1 - D	61.0	0.0	39.0
	O2 - D	35.5	64.5	0.0
	O3 - D	32.1	7.7	60.2
	O4 - D	64.4	0.0	35.6
	O5 - D	42.0	40.5	17.5
	TOTAL	45.5	20.7	33.8

shown in Table 3, the increase in rail and parking revenue came primarily from auto travelers shifting to intermodal (56 travelers) and rail (138 travelers). An increase in the CBD parking lot fee by $2.00 decreased auto's share by 8.1 percent.

The remaining policies can be examined in the same manner to determine the most attractive one, in terms of its impacts on users and operators. The increase in highway tolls increased the highway operator's revenue by 95.7 percent (from $485.1 to $949.5). This increase caused 15 auto and 3 intermodal users to shift to rail, thus increasing the rail operator's revenue by $51.6. User costs increased marginally by 0.7%, while the time savings decreased marginally by 0.9%.

The decrease in rail fare does not have a substantial impact on rail ridership. Only 89 auto travelers diverted to rail and intermodal. This policy also resulted in a large loss of farebox revenue (a 54.7 percent reduction compared to the Baseline).

In terms of their effect on the net user and operator costs, the order of preference of the policies is as follows:

1. Double the rail frequency.
2. Increase station parking capacity.
3. Increase the CBD parking fee.
4. Decrease rail fare.
5. Increase tolls.

Combinations of Policies

Two additional policies were developed. The first increased station parking lot capacities and parking fees at the CBD. The second, in addition to the changes included in the first, decreased parking fees at an underused lot, added more capacity to the O3 and O5 station lots, and doubled the rail frequency. These policies were deemed to have the best potential for further reducing user cost while increasing rail revenues.

The previous discussion of equilibrium flows indicated that user cost could have been reduced further if parking capacity constraints

TABLE 4 User and Operator Impacts

Policy	User Cost ($/peak hour)	User Time (min/ peak hour)	Parking Capital Investm. ($/peak hour)	Station Parking Reven. ($/peak hour)	Rail Operating Cost ($/peak hour)	Rail Fare-Box Reven. ($/peak hour)	Net Rail Operator Revenues ($/peak hour)	Highway Toll Revenues ($/peak hour)	CBD Parking Reven. ($/peak hour)	Net User & Oper. Cost ($/peak hour)
a. 1--Baseline	49,282	81,005	0	1,177.8	510.51	1,787.7	2,455	485.1	6,930	39,412
b. 2--Increase park. capacity	47,610	78,084	547.4	1,689.3	510.51	1,864.1	2,495.5	461.8	6,597.5	38,055
c. 3--Increase tolls	49,638	80,277	0	1,204.8	510.51	1,839.3	2,533.6	949.5	6,782	39,373
d. 4--Increase CBD park. fee	51,017	76,663	0	1,345.7	510.51	2,130.7	2,965.9	417.0	8,340	39,294
e. 5--Decrease rail fare	47,825	78,927	0	1,257.6	510.51	809.7	1,556.8	454.4	6,491	39,323
f. 6--Double rail Frequency	44,793	68,498	0	1,419.3	1021.02	2,283	2,681.3	386.9	5,527	36,198
R* (-) or I* (+) of *b* over *a* (%)	-3.4	-3.6	N/A	+43.4	0	+4.3	+1.65	-4.8	-4.8	-3.44
R (-) or I (+) of*c* over *a* (%)	+0.7	-0.9	0	+2.3	0	+2.9	+3.2	+95.73	-2.14	-0.10
R (-) or I (+) of*d* over *a* (%)	+3.5	-5.36	0	+14.3	0	+19.2	+20.81	-14	+20.4	-0.30
R (-) or I (+) of*e* over *a* (%)	-2.96	-2.6	0	+0.7	0	-54.7	-36.58	-6.3	-6.3	-0.22
R (-) or I (+) of*f* over *a* (%)	-9.11	-15.44	0	+20.5	+100	+27.7	+9.22	-20.3	-20.24	-8.15

R*: Reduction, I*: Increase

were relaxed. The model provides a convenient measure for evaluating the effect of such a capacity increase on user cost in the form of dual prices. In optimization terminology, dual prices indicate a change in the objective function (in this case user costs) resulting from a marginal increase in the availability of scarce resources (parking spaces). A careful review of dual prices indicated that providing an additional parking space at O3 or O5 would decrease user costs by $1.95/traveler and $4.13/traveler, respectively. Based on this observation, the first combination policy added 170 spaces at O5, in addition to the spaces already added under Policy 2. In addition, the parking charge at the CBD was doubled to $10. This policy increased user costs by 3.92 percent while time decreased by 11.67 percent compared to the Baseline. The CBD parking, rail operator and station parking revenues increased by 43 percent, 37.6 percent, and 87.6 percent, respectively, while highway revenues decreased by 28.5 percent. The rail revenue came primarily from 395 travelers who shifted from auto to intermodal. This policy, implemented with a total capital investment of $805.9 for 530 spaces resulted in an increase of $1031.9 and $672.1 in station parking and rail revenues, respectively. Thus, per $1 invested, $2.1 were generated in revenues from station parking and rail.

The results indicated that out of 759 spaces at the O1 parking lot, only 216 spaces were occupied. In addition, a marginal increase in the parking lot capacity at O3 and O5 would further decrease user costs by $1.95/traveler and $2.7/traveler, respectively. This led to the second combination policy that added 60 additional spaces at O3 and 100 at O5. Since there was no point to further increase station parking capacity without increasing rail capacity, this policy also included the doubling of rail frequency. In addition, the parking fee at O1 was decreased from $3 to $1.

This policy decreased user costs by 13.2 percent and reduced time by 28.7 percent compared to the Baseline. Rail and station parking revenues increased by 90.7 percent and 88.4 percent, respectively, while the CBD parking revenues decreased by 30.2 percent. The increase in rail revenue came primarily from 903 travelers shifting from auto to intermodal. The expenditures of $1079.6 for 690 spaces, and $510.51 for more frequent rail operations resulted in increases of $1041.7 and $1621 in station parking and rail revenues respectively. Therefore, the combined revenues for station parking and rail increased by $1.67 per $1 invested.

CONCLUSIONS

The cases analyzed in this study are a small sample of all possible policies that the outlined methodological framework is capable of evaluating. The results can be used to screen policies aimed at affecting travel demand. Policies aimed at improving rail service and making it more accessible are the best in terms of their ability to divert auto drivers to transit. The best deterrent to driving appears to be an increase in the CBD parking fee. Direct user fee charges for rail or highway users appear to be the least able to affect travelers' choices. However, it needs to be recognized that, in general, the final decision on policy selection is likely to depend on social, political, economic and environmental considerations as well.

FUTURE EXTENSIONS

The model presented here can be improved to consider travelers' preferences between pure rail (walk-to-rail) and intermodal (auto-to-rail) trips, as well as between transfer points. Second, the assumption of constant travel time on rail needs to be relaxed, and accelerated regimes such as skip stop and express services could be considered. These regimes would be advantageous for rail, because as auto commuters are shifted to rail, the average travel time on rail can decrease (Morlok (*25*)). Of course, this is true only if there is excess physical rail capacity to accommodate accelerated operations. Therefore, the model can be improved to handle accelerated regimes on rail, and to select optimal operating schedules. Third, the assumption of travelers having perfect information on travel times and making rational decisions was rather strong and needs to be relaxed. In the real world, lack of information is likely to yield traffic assignment with worse total travel costs than those predicted by the model. Finally, each policy was examined for current levels of congestion. The model can be rerun to analyze policies under congestion levels that might be encountered in future years.

ACKNOWLEDGMENT

The research results presented here were partially supported by a grant from the U.S. Department of Transportation, University Transportation Centers Program, through the National Center for Transportation and Industrial Productivity (NCTIP) at NJIT.

REFERENCES

1. Florian, M. A Traffic Equilibrium Model of Travel by Car and Public Transit Modes. *Transportation Science,* Vol. 8, 1977, pp. 166–179.
2. Florian, M., and S. Nguyen. A Combined Distribution Modal Split and Trip Assignment Model. *Transportation Research,* 12-B, 1978, pp. 241–246.
3. Abdulaal, M., and L. LeBlanc. Methods for Combining Modal Split and Equilibrium Assignment Models. *Transportation Science,* Vol. 13, 1979, pp. 292–314.
4. Dafermos, S. C. The General Multimodal Network Equilibrium Problem with Elastic Demand. *Networks,* Vol. 12, 1982, pp. 57–72.
5. LeBlanc, L. J., and K. Farhangian. Efficient Algorithms for Solving Elastic Demand Traffic Assignment Problems and Mode Split-Assignment Problems. *Transportation Science,* Vol. 15, No. 4, 1981, pp. 306–317.
6. Florian, M., and H. Spiess. On Binary Mode Choice/Assignment Models. *Transportation Science*, Vol. 17, No. 1, 1983, pp. 32–47.
7. Fernandez, E., J. DeCea, M. Florian, and E. Cabrera. Network Equilibrium Models with Combined Modes. *Transportation Science,* Vol. 28, No. 3, 1994, pp. 182–192.
8. Fan, K., E. Miller, and D. Badoe. Modeling Rail Access Mode and Station Choice. *Transportation Research Record,* 1413, 1993, pp. 49–59.
9. Miller, E. Central Area Mode Choice and Parking Demand. *Transportation Research Record,* 1413, 1993, pp. 60–69.
10. Ortuzar, J. Nested Logit Models for Mixed-Mode Travel in Urban Corridors. *Transportation Research A,* Vol. 17A, No. 4, 1983, pp. 283–299.
11. Turnquist, M. A., A. H. Meyburg, and S. G. Ritchie. Innovative Transit Service Planning Model that Uses a Microcomputer. *Transportation Research Record,* 854, 1982.
12. Manheim, M. *Fundamentals of Transportation Systems Analysis: Volume 1: Basic Concepts,* MIT Press, 1979.
13. National Cooperative Highway Research Program, Report 187. *Quick-Response Urban Travel Estimation Techniques and Transferable Parameters: User's Guide.* TRB, 1978.
14. Comsis. *MinUTP Technical User Manual,* 92 B-Version, 1992.
15. The Urban Analysis Group. *TRANPLAN: User Manual,* Version 7.0, 1990.
16. Wardrop, J. G. Some Theoretical Aspects of Road Traffic Research. *Proceedings Institute of Civil Engineers Part II,* 1952.
17. Sheffi, Y. *Urban Transportation Networks: Equilibrium Analysis with Mathematical Programming Methods,* Prentice-Hall Inc., 1985.
18. INRO Consultants. *Users Manual EMME/2 Release 7,* Montreal, Canada, June 1994.
19. Boile, M. P. *Demand–Supply Equilibrium over Intermodal Transportation Networks.* National Center for Transportation and Industrial Productivity (NCTIP), NJIT, NCTIP-WP94-01, 1994, 89 pages.
20. Beckmann, M. J., C. B. McGuire, and C. B. Winsten. *Studies in the Economics of Transportation,* Yale University Press, New Haven, Conn.
21. *A Manual on User Benefit Analyses of Highway and Bus Transit Improvements,* AASHTO, 1965.
22. *1980 Census of Population.* U.S. Bureau of Census, U.S. Department of Commerce.
23. U.S. Bureau of Public Roads. *Traffic Assignment Manual.* U.S. Department of Commerce, 1964.
24. Transportation Research Board. *Highway Capacity Manual.* Special Report 209, 1985.
25. Morlok, E. K. *Introduction ot Transportation Planning and Engineering.* McGraw Hill, 1978.

Publication of this paper sponsored by Committee on Transportation Supply Analysis.