Energy Consumption of the Journey to Work With and Without a Suburban Rapid Transit Line

David E. Boyce and Mark E. Ferris, Department of Civil Engineering, University of Illinois at Urbana-Champaign
Khanh Nguyen, World Bank, Washington, D.C.

In an effort to provide an improved framework for evaluating alternative transportation systems with respect to energy conservation, the Philadelphia-Lindenwold rail rapid transit line was studied. The energy consumed by journey-to-work trips on the Lindenwold Line in 1970—including not only the energy required to operate the line but also the energy required for access and egress—was estimated (along with the cost of the fuel consumed by these trips). The energy that would have been consumed by these trips if the former modes of travel were used was also estimated. Comparison of these two amounts of energy consumption provides a basis for evaluating the energy conservation potential of the Lindenwold Line. It is found that (a) the slightly indirect nature of the park-and-ride mode results in longer travel distances than did the automobile and bus modes it replaced and (b) the lower energy intensiveness of park-and-ride relative to the automobile does not offset these longer travel distances because many users of the line are former bus riders. Thus, the park-and-ride system consumes slightly more energy than did the former travel modes. It is concluded that the added travel distance of park-and-ride systems and the extent to which users of such systems are attracted from buses rather than from automobiles should be considered in evaluating rapid transit park-and-ride systems with respect to energy conservation.

The importance of conserving energy is now accepted by most Americans. The current debate concerns how energy should be conserved. As in most planning situations, energy conservation requires a choice among alternative strategies. For example, alternative strategies in urban public transportation include rail rapid transit, bus rapid transit, and paratransit. Unfortunately, comparison of energy consumption for these alternatives is not necessarily straightforward or simple. In the course of making such a comparison for a new transit system and the system it replaced, several unexpected methodological issues were encountered. The two issues examined in this paper are the computation of travel distances for alternative modes and the estimation of factors of vehicle occupancy.

Issues not examined here concern the effect of the rapid transit system on trip frequency, trip length, and residence and job location. If a rapid transit system facilitates travel, its users may tend to make longer trips or to consider relocating to residences and workplaces that require more travel.

The method used in making the comparisons in this study is limited in that several simplifying approximations and assumptions are made. The results, therefore, provide only a tentative indication of the energy-conserving potential of the modes examined. More definitive studies might indicate somewhat different results. Moreover, the findings may not be valid if generalized and applied to other urban areas.

This paper summarizes the main findings of a study of the impact of a modern rail rapid transit line on energy consumption for the journey to work (1). The Philadelphia-Lindenwold rail rapid transit line (known locally as the Lindenwold High-Speed Line) is a modern, two-rail, electrically powered transit line that connects the suburban New Jersey portion of the Philadelphia metropolitan area with central Philadelphia. The Lindenwold Line began operations in 1969 and now has 13 stations including 6 suburban stations with more than 9000 parking spaces (Figure 1). Six-car trains that seat about 450 people are operated at about 5-min headways during peak periods; frequent midday and evening service is also provided.

The Lindewold Line is owned by the Delaware River Port Authority and operated by its subsidiary, the Port Authority Transit Corporation. Locally, the line is regarded as reliable, convenient, efficiently operated, and an important asset of the South Jersey suburban community. It serves about 45 000 riders/d, or more than 20 000 round-trip commuters. Additional details concerning the impact of the line on modal choice, residential property values, and commercial office location may be found elsewhere (2,3,4).

The main objective of this paper is to compare the aggregate energy consumption of the journey to work for New Jersey residents who used the Lindenwold Line on April 1, 1970 (the decennial census date), with an estimate of the energy consumption required for the same trips by other modes. This comparison was feasible because of the availability of two sets of data: (a) journey-to-work counts by origin, destination, and mode from the 1970 census of population and housing (5,6) and (b) a 1970 survey of rapid transit riders regarding their former mode of travel.

Energy comparisons may be portrayed in three ways: (a) by comparing passenger kilometers of travel by mode with and without the rail rapid transit line; (b) by applying average rates of energy consumption per passenger kilometer to these estimates to obtain total energy consumption by mode (to compare energy consumption by automobile, bus, and rail, actual fuel consumption by mode must be transformed into a common unit of energy measurement such as megajoules); and (c) by comparing the cost of the energy consumed. This third comparison is not usually made. If the average cost of the energy consumed per passenger kilometer is known, then the aggregate passenger kilometers of travel can be transformed into estimates of the total cost of energy for each mode. All three estimates are presented in a subsequent section of this paper.

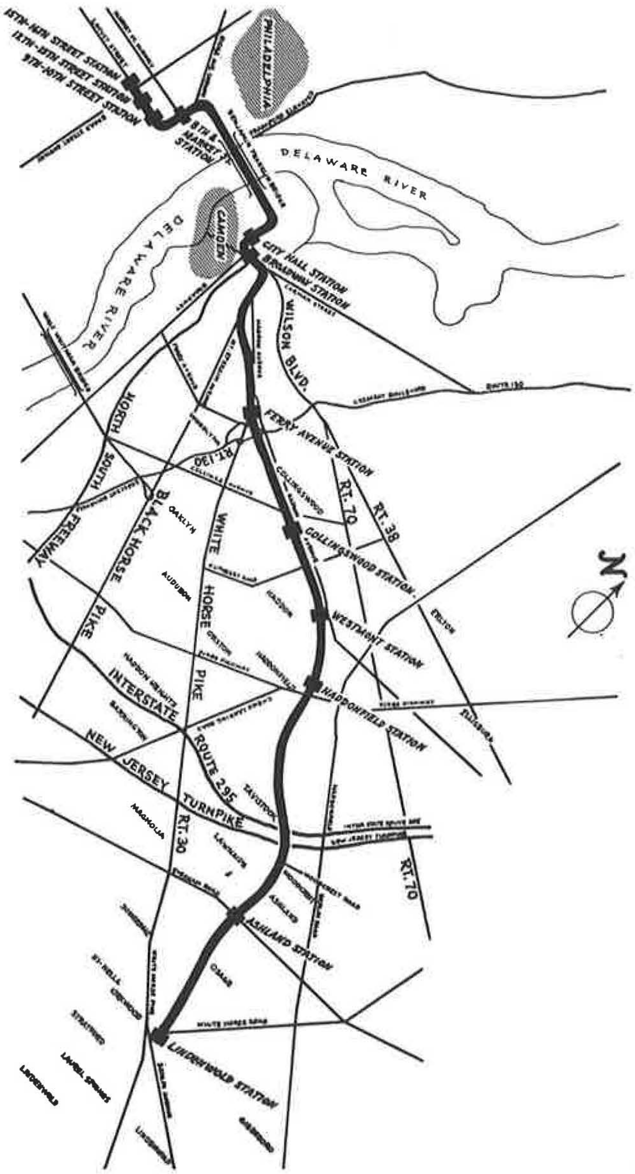
CONCEPTUAL FRAMEWORK

The Congressional Budget Office (CBO) defined a general conceptual framework for the analysis of energy consumption by urban transportation (7). The following is a four-level hierarchy of energy consumption based on the CBO framework:

1. Operating energy—vehicle traction energy plus energy consumed for lighting, heating, and air conditioning;
2. Line-haul energy—vehicle operating energy plus energy consumed in vehicle and way maintenance, station operation, parking and related access functions, vehicle manufacture, and facility construction;
3. Modal energy—line-haul energy plus energy required for access and egress modes; and
4. Program energy—net energy savings (or losses) of a mode, including access and egress, compared with those of another mode or group of modes.

Elements of line-haul energy other than operating energy were not estimated. Line-haul vehicle operating

Figure 1. Philadelphia-Lindenwold rail rapid transit line.



energy was combined with access and egress operating energy to obtain a limited estimate of modal energy. These estimates were combined to form a limited estimate of program energy for the rapid transit line versus the automobile and bus modes it replaced.

Thus, the paper illustrates the application of the CBO accounting framework to a rail rapid transit system; the example is incomplete, however, in that not all elements of line-haul energy are included. Nevertheless, some important conclusions can be drawn from this limited analysis, and areas that require more detailed estimates can be pinpointed.

METHOD OF ANALYSIS

Data Base

Included in the 1970 census of population and housing were a series of questions on place of work and mode of travel to work for all workers over age 14. These questions were asked of a 15 percent sample of all households. The responses were coded by place of work as well as place of residence, tabulated for a system of 977 zones defined by the Delaware Valley Regional Planning Commission (DVRPC), and factored to estimate the total number of work trips by mode of travel on April 1, 1970 (5). These estimates, known as the 1970 Census Urban Transportation Planning Package, were subsequently adjusted to account for deficiencies in the coding of destinations and related problems (6). Inasmuch as the census estimates of work trip by mode pertain to April 1, 1970—the decennial census date—the comparison reported here of travel with and without the Lindenwold Line is done for that date. No attempt has been made to examine trends in modal choice, employment location, or residential location that may alter these findings for subsequent years.

On selected days between December 1969 and April 1970, the Delaware River Port Authority administered an on-board written questionnaire to all persons who boarded the Lindenwold Line at its six suburban stations. Among the questions asked was the mode of commuting used before the operation of the line. The possible responses were (a) automobile driver; (b) automobile passenger, (c) bus, (d) Philadelphia Camden Bridge Line (predecessor of the Lindenwold High-Speed Line), (e) other, or (f) did not make the trip before. These responses were coded to the same DVRPC zonal system and tabulated by zones of residence and workplace and by former mode. In this manner, the proportion of users who would have chosen each mode in early 1970 had the rapid transit line not been in operation was estimated.

Geographic System

The DVRPC transportation analysis zones used in coding the census and on-board survey define the study area. These zones were used in computing the travel distance estimates described below. For presentation purposes, the zones were aggregated to indicate the main flows of trips in the region. The level of aggregation used in this paper is defined as

1. Origin areas—origins of all work trips from the urbanized portion of the New Jersey counties in the Philadelphia area: (a) inner market area [New Jersey zones entirely or partly within walking distance of a Lindenwold Line station including the Camden central business district (CBD)], (b) middle market area [other New Jersey zones within 6.4 km (4 miles) of a station, which corresponds roughly to the remainder of urbanized Camden County], and (c) outer market area [all other urbanized zones in the New Jersey counties (parts of Gloucester and Burlington Counties)]; and
2. Destination areas—destinations of all work trips in the Philadelphia urbanized area: (a) Philadelphia and Camden CBDs and (b) Pennsylvania and New Jersey urban areas, including all of Philadelphia and Camden outside their CBDs as well as the suburban areas within the Philadelphia urbanized area.

These areas are shown in Figure 2. Additional details are provided elsewhere (1).

Estimation of Travel Distances

An estimate of passenger kilometers of travel for each origin-destination zonal pair and mode was required for the calculation of energy consumption. As interzonal highway and transit network distances were not available, straight-line distances were used as a first approximation of automobile and bus distances. The calculation procedure is shown in Figure 3.

Automobile distances within New Jersey were defined to be zone centroid-to-centroid straight-line segments. Automobile distances from New Jersey origin zones to Pennsylvania zones reported in this paper consist of two straight-line segments via the Delaware River

Figure 2. Origin and destination areas.

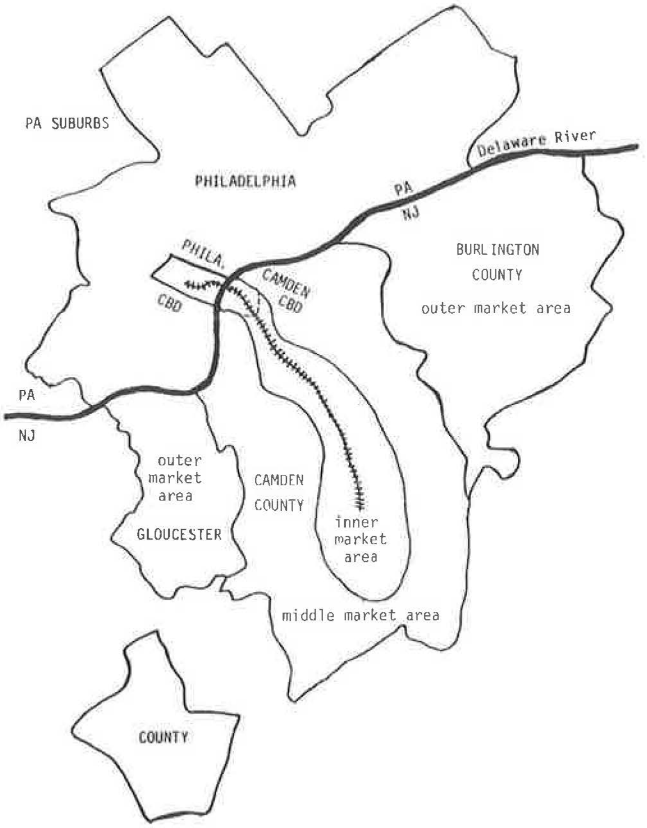
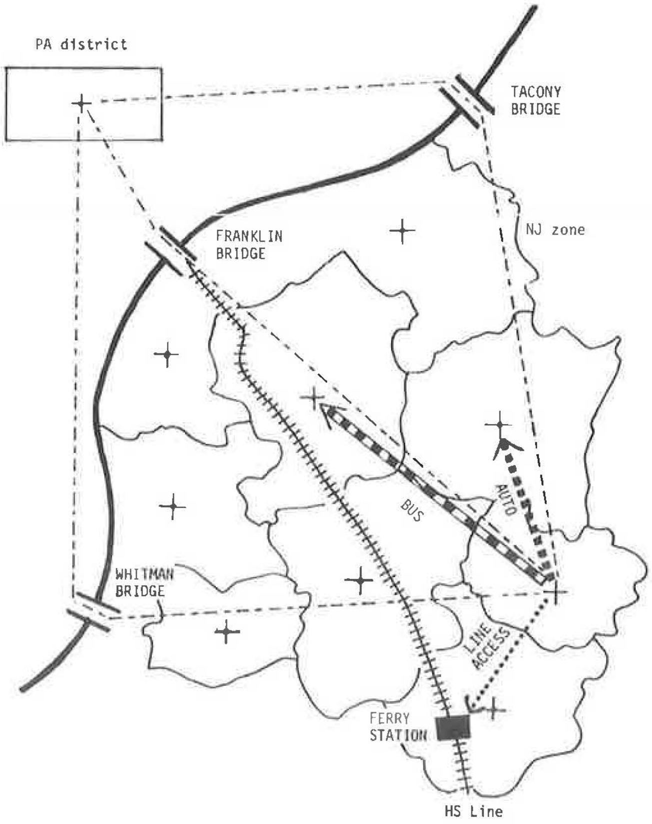


Figure 3. Procedure for calculating distance.



bridge, which results in the minimum travel time route. For example, according to information supplied in 1978 by Vuchic and List, the minimum travel time route to all Philadelphia CBD destinations is that via the Franklin Bridge. In contrast, automobile distances to Pennsylvania were calculated via the minimum straight-line distance bridge in the earlier report (1). Bus distances were defined similarly but were restricted to radial segments centered on Camden; circumferential segments were excluded since no bus service along such routes was available.

Lindenwold Line trip distances consist of an automobile-access, straight-line distance from origin zone to the nearest station, a straight-line distance from that station (via the Franklin Bridge for Philadelphia destinations) to the destination station, and an egress distance for subway or bus depending on the destination location. In this paper, straight-line distances were used for each trip segment. Actual rail line-haul distances reported earlier (1) were converted to straight-line distances to permit consistent comparisons among the rail, automobile, and bus modes.

Use of zone-to-zone straight-line distances underestimates actual journey-to-work travel distances by automobile, bus, and park-and-ride (automobile access plus rail line-haul). Thus, the comparisons of these travel distances presented below are valid only in a relative sense. Based on some detailed comparisons of the ratios of actual over-the-road distances via minimum travel time routes with these straight-line distances, there is no apparent systematic modal variation for the entire study area. Therefore, conclusions based on these comparisons may be regarded as unbiased with respect to mode.

Estimation of Former Mode Use

Rapid transit trips in 1970 were assigned to their previous mode according to the responses given to the onboard survey. Proportions of trips on the four previous modes (automobile driver, automobile passenger, bus passenger, and bridge line passenger) were calculated for groups of origin and destination zones and examined for sensitivity to small sample size. Groupings with flows of less than 100 trips were aggregated to achieve more stable proportions.

The proportion of trips by former mode for all origins is given below. Automobile driver and bus are clearly the dominant modes.

	Destination	
Mode	New Jersey	Pennsylvania
Automobile driver	0.61	0.38
Automobile passenger	0.06	0.06
Bus passenger	0.33	0.52
Bridge line passenger	0.0	0.04

For major destinations such as the Camden and Philadelphia CBDs, the proportion of bus trips is substantially higher than that given here. These more detailed proportions were used in the actual allocation of major flows of trips to their former modes.

The hypothetical estimate of 1970 travel without the Lindenwold Line was prepared as follows. Lindenwold Line trips were allocated to the four former modes by applying the on-board survey proportions to the 1970 census data. Each trip was assumed to be made in the without-the-line estimate in order that the total number of trips would remain constant. Thus, new trips (trips not made before the line opened) were allocated to the former modes according to the above proportions.

An alternate procedure would have been to regard these new trips as an increase in energy consumption caused by the rail rapid transit line. Some of these so-called new trips, however, probably resulted from persons entering the work force after the line opened and were not attributable to the line itself. Others may have resulted from relocations of jobs and residences unrelated to the line. A few may have been relocations brought about by the availability of the line and therefore should perhaps be considered as an increase in energy consumption. Because data were not available on these aspects, all trips were treated as if they would have been made on another mode if the rail rapid transit line had not existed. This point also serves to illustrate the difference in point of view between a with-and-without analysis and a before-and-after analysis.

Summary of Accounting Procedure

The analysis performed may be regarded as the construction of a set of energy consumption and cost accounts by mode, origin, and destination for the journey to work. The procedure consists of four steps:

1. Estimate the rate of energy consumption and cost per passenger kilometer for each mode;
2. Estimate passenger kilometers of travel on each mode based on the 1970 census;
3. Allocate trips made on the Lindenwold Line to the mode they would have used in 1970 had the line not existed; and
4. Transform these with and without estimates of passenger kilometers of travel to estimates of energy consumption and cost by using the rates from step 1.

It should be noted here that this procedure depends heavily on the use of typical rates of energy consumption and cost for each mode. The actual values may differ substantially from these values—for example, by time of day, time of year, bus route, socioeconomic status of the automobile driver, and so forth. Moreover, the possible indirect effects of the transit line on reducing highway congestion on radial arterials that serve Philadelphia are ignored. Reduced congestion may result in improved rates of energy consumption by automobiles. On the other hand, reductions in automobile and bus occupancy caused by diversion of riders to the line could increase energy consumption per passenger kilometer.

FINDINGS

The estimates of energy consumption and cost used in constructing these energy accounts are given in Table 1; more details are given in the report by Boyce and others (1). Estimates of energy consumption per vehicle kilometer for automobile, bus, and subway are drawn from other sources. The estimate of energy consumption per vehicle kilometer for the Lindenwold Line is based on a historical analysis of its total energy consumption. The estimates of vehicle occupancy are based on the 1970 census and surveys of transportation modes in the study area. The estimates for automobile and rail rapid transit are considered to be accurate; those for bus and subway-elevated are more judgmental.

Estimates of fuel cost were prepared by determining the cost of fuels (in U.S. customary units, per kilowatt-hour or gallon) to the energy supplier net of taxes, distribution costs, and retail markups. For the Lindenwold Line, this is the cost of fuel to the electric utility. For the bus operator, it is the cost of diesel fuel at the refinery. A comparable cost of gasoline was obtained for the automobile mode.

The estimates of energy consumption and cost for park-and-ride trips given in Table 1 are derived from the energy accounts given in Tables 2 through 4. They are given in Table 1 to illustrate the importance of automobile access in park-and-ride trips.

According to the accounting procedure outlined above, calculation of modal energy depends on an estimate of passenger kilometers of travel by mode. An estimate of travel with and without the rail rapid transit line for the 8734 persons who used the line on April 1, 1970, is given in Table 2 (1).

The estimates of travel with the line show that rail line-haul accounts for 74 percent of total passenger kilometers, automobile access accounts for 18 percent, and bus with rail egress accounts for 8 percent. For the two CBDs, rail accounts for a somewhat higher proportion of total travel (81 percent). Without the line, bus is the primary mode of travel, accounting for 51 percent of total passenger kilometers. For the two CBDs, bus is slightly higher (52 percent). Without the line, automobiles account for 47 percent of passenger kilometers of travel.

This park-and-ride system relies primarily on the automobile for access; it is not surprising, then, that passenger kilometers of automobile travel with the line amount to nearly half the without-the-line estimate. In contrast, travel by bus with the line, which in 1970 was used for egress purposes, is less than one-fifth of bus travel without the line.

Comparison of total passenger kilometers of travel with and without the rail rapid transit line in Table 2 (1) reveals that the estimates with the line are higher by 29 400 passenger-km or 3.4 km/trip. This difference in estimates of straight-line travel distance indicates that the park-and-ride trips are less direct than the corresponding automobile and bus trips. In general, transit stations are not located on a direct route from origin to destination. Instead, a dogleg route is often traveled that consists of an automobile segment to the station followed by a rail line-haul segment to the destination (Figure 3).

Application of this general observation to the study area results in two cases that it is useful to discuss. Workers who reside northeast of the Lindenwold Line tend to drive southwest to their nearest station (2) and then travel on the line in a northwesterly direction. In contrast, their automobile or bus trips without the line are generally made along east-west radial highways. Thus, these workers incur significant additional travel distances when they use the line. In contrast, workers who reside southwest of the Lindenwold Line tend to use stations along arterial routes to the Philadelphia CBD. Their actual travel distances with the line may be slightly less than the usual highway or bus route because of the layout of the highway system in the Camden area.

On balance, the estimates of travel distances with and without the line appear to be correct in a relative sense; both are underestimates of the actual travel distances. The dogleg effect northeast of the line more than offsets the effect of highway circuity to the southwest. Further, more users of the Lindenwold Line reside in the areas northeast of the line than in areas to the southwest. Table 2, then, gives the cumulative result of these effects.

By applying rates of energy consumption per passenger kilometer to estimates of passenger kilometers, fuel consumption was estimated and is given in Table 3 (1). The mean trip on the Lindenwold Line required about 21.5 MJ (20 400 Btu) for automobile access, 34.6 MJ (32 800 Btu) for rail line-haul, and 2.2 MJ (2100 Btu) for bus with rail egress, or a total of 58.3 MJ (55 300 Btu) per trip. By the former modes of travel, these trips on the average consumed about 54.2 MJ (51 400 Btu) per trip.

As discussed above in the analysis of travel distances, passenger kilometers of automobile, bus, and park-and-ride travel are underestimated by the straight-line distance procedure. Thus, fuel consumption with and without the line is also underestimated (Table 3). If the distance estimates are correct in a relative sense, however, fuel consumption is slightly less without the line. For CBD-destined trips in particular, total fuel consumption with the line is more than 10 percent higher than without the line. For suburban destinations, the park-and-ride mode consumes somewhat less fuel than the automobile-bus system.

In view of the substantial efficiency of rail line-haul fuel consumption per passenger kilometer given in Table 1, it is surprising that the Lindenwold Line does not conserve energy in comparison with the without-the-line case. The reasons for this unexpected result are twofold: (a) Travel by bus is more efficient than travel by the Lindenwold Line, and (b) the park-and-ride system requires somewhat longer travel distances than does the automobile-bus system. Although buses are generally regarded as more energy efficient than rail transit, the extent of their advantage depends

Table 1. Modal fuel consumption and cost per vehicle kilometer and passenger kilometer.

			Fuel Consumption (MJ)		Fuel Cost ($)	
Mode	Seats Per Vehicle	Average Work-Trip Occupancy	Per Vehicle Kilometer	Per Passenger Kilometer	Per Vehicle Kilometer	Per Passenger Kilometer
Automobile	4-6	1.1	7.2	6.3	0.01	0.009
Bus	45-55	15	23.3	1.6	0.019	0.0013
Lindenwold Line	76-80	22	57.0	2.6	0.032	0.0015
Subway-elevated	56	28	43.6	1.6	0.025	0.0009
Park-and-ride[a]	-	-	-	3.2	-	0.0028

Note: 1 MJ = 948 Btu; 1 km = 0.62 mile.

[a] Lindenwold Line plus access and egress modes.

Table 2. Comparison of daily passenger travel to work with and without the Lindenwold Line by origin, destination, and mode.

		Passenger Kilometers With Line (000s)				Passenger Kilometers Without Line (000s)			
Destination	Origin (market area)	Auto-mobile Access	Rail Line-Haul	Bus With Rail Egress	Total	Auto-mobile	Bus	Sub-way[a]	Total
Philadelphia and Camden CBDs	Inner	7.1	53.4	-	60.5	22.6	29.6	1.3	53.5
	Middle	8.7	29.7	-	38.4	14.0	15.1	0.3	29.4
	Outer	5.8	9.1	-	14.9	6.3	4.5	0.3	11.1
Total		21.7	92.2		113.9	42.9	49.4	2.0	94.3
Pennsylvania and New Jersey suburbs	Inner	2.1	13.9	6.1	22.1	9.3	8.2	0.2	17.7
	Middle	2.6	7.6	5.3	15.5	5.6	6.1	0.2	11.9
	Outer	2.6	2.9	1.1	6.6	2.9	1.6	0.2	4.8
Total		7.3	24.4	12.5	44.2	17.9	16.0	0.5	34.4
All		29.0	116.6	12.5	158.1	60.8	65.4	2.5	128.7

Notes: 1 km = 0.62 mile.
Totals are rounded numbers; total trips = 8734.

[a] Includes automobile access and bus and subway egress.

Table 3. Comparison of daily fuel consumption with and without the Lindenwold Line.

		With Line (GJ)				Without Line (GJ)			
Destination	Origin (market area)	Auto-mobile Access	Rail Line-Haul	Bus With Rail Egress	Total	Auto-mobile	Bus	Subway[a]	Total
Philadelphia and Camden CBDs	Inner	46.3	138.4	-	184.7	131.0	46.2	5.8	183.0
	Middle	57.0	76.9	-	133.9	80.5	23.6	1.6	105.7
	Outer	37.8	23.7	-	61.5	35.8	7.1	1.4	44.3
Total		141.1	239.0		380.1	247.3	77.0	8.8	333.1
Pennsylvania and New Jersey suburbs	Inner	13.5	36.0	9.4	58.9	59.2	12.9	0.4	72.5
	Middle	16.9	19.7	8.3	44.9	35.9	9.6	0.5	46.0
	Outer	16.8	7.6	1.8	26.2	18.8	2.5	0.9	22.2
Total		47.0	63.3	19.5	129.8	113.8	24.9	1.9	140.6
All		188.1	302.3	19.5	509.9	361.1	101.9	10.7	473.7

Notes: 1 GJ = 948 000 Btu.
Totals are rounded numbers.

[a] Includes automobile access and bus and subway egress.

Table 4. Comparison of daily fuel cost with and without the Lindenwold Line.

		With Line ($)				Without Line ($)			
Destination	Origin (market area)	Auto-mobile Access	Rail Line-Haul	Bus With Rail Egress	Total	Auto-mobile	Bus	Subway[a]	Total
Philadelphia and Camden CBDs	Inner	63	78	-	141	180	38	8	226
	Middle	78	43	-	121	110	20	2	132
	Outer	52	13	-	65	48	6	2	56
Total		193	135		328	338	64	12	414
Pennsylvania and New Jersey suburbs	Inner	17	20	7	44	81	10	0	91
	Middle	24	11	6	41	48	8	1	57
	Outer	23	4	2	29	27	2	1	30
Total		64	36	15	115	156	20	2	178
All		257	171	15	443	494	84	14	592

Note: Totals are rounded numbers.

[a] Includes automobile access and bus and rail egress.

heavily on the specific type of bus operation. In this study, a bus occupancy of 15 passenger-km/bus-km was assumed for these long-haul, suburban, commuter-oriented operations. If the actual occupancy was as low as 10 passenger-km/bus-km, the increase in bus fuel consumption would be about 50 GJ (47.4 million Btu) or 10 percent of the total fuel consumption by buses without the line. In this event, fuel consumption with and without the line would be roughly equal for CBD destinations; for suburban destinations, the park-and-ride system would clearly consume less energy.

The accounts are not complete at this point, however; one should disaggregate these accounts by type of fuel. Automobiles and buses use petroleum-based fuels and therefore contribute to the nation's oil import problem. Rail uses electricity, which may be generated from oil, coal, or nuclear or water power. Oil was in fact the principal fuel used to generate electricity during the time period analyzed in this study (1970-1973). Since that time, electric utilities have converted some generating stations to coal, and some nuclear power capacity has been added.

But the matter is not so simple. The peak period of energy consumption for rail transit coincides with the peak period of electricity use: 4:00 to 6:00 p.m. Utilities often use oil or natural-gas-fired turbines to meet these late-afternoon peak demands. Therefore, truly detailed energy accounts must consider the time of day of energy consumption as well.

Another point of interest concerns the importance of automobile fuel consumption in both with and without analyses. With the Lindenwold Line, automobiles consume 37 percent of the fuel and account for 18 percent of passenger kilometers for access. Without the line, automobiles consume 76 percent of the fuel but account for only 47 percent of the passenger kilometers. Thus, the automobile is a major source of fuel consumption even with rail transit. Does this not suggest that a principal strategy for conserving petroleum may be to improve the fuel efficiency of the automobile? For example, if the overall rate of fuel consumption by automobiles were halved, then the automobile share of energy consumption would decrease to 23 percent with the Lindenwold Line and 62 percent without it. This hypothetical example is intended to illustrate that there are many strategies to reduce energy consumption and that each must be carefully evaluated.

The final comparison given in Table 4 (1) converts the passenger-kilometer estimates given in Table 2 into estimates of the cost of fuel valued at prices charged at the point of production. In terms of mean cost per trip with the Lindenwold Line, automobile access accounts for nearly $0.03/trip and rail line-haul for $0.02/trip and bus with rail egress for $0.002/trip, for a total mean cost of $0.051/trip. Thus, automobiles account for 58 percent of the cost of fuel with the line versus 18 percent of passenger kilometers and 37 percent of fuel consumption. Without the line, automobiles account for 83 percent of fuel cost versus 47 percent of passenger kilometers and 76 percent of fuel consumption.

In examining the total fuel costs given in Table 4, one is struck by how small they are. For example, the total fuel costs for the one-way daily journey to work for all persons using the Lindenwold Line in 1970 are only a few hundred dollars for nearly 9000 trips. Five cents per trip represents a tiny fraction of the total monetary and time cost of these journeys. By comparison, the mean fare in 1970 was about $0.47, or more than 20 times the cost of fuel. It is not surprising, then, that fuel costs, even if accurately perceived, play a small role in modal choice.

CONCLUSIONS AND RECOMMENDATIONS

A principal finding of this research is that the operation of a suburban rail park-and-ride system in South Jersey in 1970 generated more passenger kilometers of travel and consumed slightly more energy for the journey to work than the combination of modes that commuters formerly used. The reasons are that work trips are estimated to be somewhat longer with park-and-ride transit and that energy savings that result from diversion of automobile trips to rail are more than offset by losses from the diversion of bus trips.

This analysis is based on many approximations and averages; however, it seems unlikely that use of other reasonable parameter values would substantially change the conclusions for this case. Whether rail transit systems in other situations save or lose energy depends on the mix of modes they replace, the spatial configuration of the transportation system, and the energy consumption characteristics of the modal mix. If a substantial proportion of trips are diverted from buses, however, it seems unlikely that park-and-ride rail transit will conserve energy without major improvements in the energy efficiency of rail vehicles. Rapid transit may, however, shift the source of energy from oil to coal or nuclear power; moreover, it may be successful in reducing environmental pollution by reducing automobile and bus emissions.

In all fairness, it is not surprising that the Lindenwold Line is not highly energy efficient. It was not designed to conserve energy but to provide fast, convenient travel to the CBD by using automobile as an access mode. It serves this function very well, competing effectively with both automobile and bus modes. Indeed, the success of the line has probably reduced highway congestion somewhat on radial routes, and this may contribute to slight improvements in fuel consumption.

Other factors, however, that are beyond the scope of this study may be working to offset these congestion-related savings. For example, the existence of the rail rapid transit line has probably enabled some households to relocate their residences outward from the city center, which results in longer work trips and therefore higher energy consumption per trip. Given the dependence of the line on automobile access, it has tendencies toward dispersing suburban development similar to those often associated with radial freeways.

Although the conclusions of this study for the Lindenwold case seem fairly robust, much should and can be done to improve energy accounts for other systems and to evaluate proposed systems. Four types of improvements that should be pursued are described below.

Vehicle Kilometers of Travel

For areas where detailed highway and transit network models are available, calculation of over-the-road vehicle distances is well within the present capability of urban transportation models. The method of choice for such calculations is the equilibrium trip assignment model in the Urban Transportation Planning System (8,9). This model ensures that behavioral route choice assumptions are met. An assignment approach to calculating vehicle kilometers for automobiles and buses could generate highway speeds as a by-product and thus permit use of speed-specific fuel consumption rates.

Choice of Mode

Normally, survey information is not available to allocate transit system users to former modes. In evaluating a proposed system, such information must be based on models of modal choice behavior. Recent developments in combined modal choice and trip assignment models should be useful in estimating the diversion from existing modes to a proposed new mode in this situation.

Average Occupancy of Public Transportation Modes

Another area of considerable uncertainty is the average occupancy of each mode (passenger kilometers per vehicle kilometer). Few data exist on the average occupancy of public transportation modes. Some careful survey and modeling work on this problem would be useful.

Fuel Consumption by Vehicle and Fuel Type and Average Speed

Rates of fuel consumption that are more detailed than the overall averages applied in this study should be used. However, little is known about what type of disaggregation would be most useful other than that by weight of vehicle and size of engine (weight- and engine-specific rates are useless for evaluation studies since it would be impractical to predict automobile use by such specific classes of vehicles). What types of disaggregation should be undertaken? Highway speed, type of fuel (gasoline, diesel, oil, coal, or nuclear power) and general type of vehicle (automobile, local bus, van, or express bus) would seem to be likely candidates.

Research Needs

If energy conservation is to be given serious consideration as an objective in the evaluation of urban transportation plans, additional research on improved methods and measures of the types briefly suggested above is necessary. Changes in energy consumption in urban transportation associated with new capital investments or management strategies may be subtle and not intuitively predictable. It is hoped that carefully performed analyses and case studies of existing and proposed systems will be conducted so that investment and operating decisions are based on valid and realistic estimates of energy consumption.

ACKNOWLEDGMENTS

We appreciate the support provided for this research by the Federal Energy Administration. The paper does not necessarily reflect the views, opinions, or policies of the Federal Energy Administration or any other agency of the federal government.

We are grateful for the use of the computing facilities provided by the University of Pennsylvania, where this research was performed.

REFERENCES

1. D. E. Boyce, K. Nguyen, T. Noyelle, and K. Webb. Impact of a Suburban Rapid Transit Line on Fuel Consumption and Cost for the Journey-to-Work. Federal Energy Administration, Rept. FEA/D-77/023, 1975.
2. D. E. Boyce and G. Desfor. Impact of Suburban Rapid Transit Station Location, Fare and Parking Availability on Users' Station Choice Behavior. Office of the Secretary, U.S. Department of Transportation, 1974.
3. D. E. Boyce, W. B. Allen, and F. Tang. Impact of Rapid Transit on Residential-Property Sales Prices. In Space, Location and Regional Development (M. Chatterji, ed.), Pion Limited, London, 1976, pp. 145-153.
4. D. E. Boyce and H. Rosen. Locational Choice and Travel Behavior of Commercial and Government Offices in Suburban Rapid Transit Station Areas. U.S. Department of Energy, 1977.
5. 1970 Census Transportation Planning Package—Summary Tape Technical Documentation. U.S. Bureau of the Census, 1972.
6. T. Zakaria. Analysis of 1970 Census Work Trips in the Delaware Valley Region. Delaware Valley Regional Planning Commission, Philadelphia, 1974.
7. Urban Transportation and Energy: The Potential Savings of Different Modes. Congressional Budget Office, 1977.
8. M. Florian and S. Nguyen. An Application and Validation of Equilibrium Trip Assignment Methods. Transportation Science, Vol. 10, 1976, pp. 374-390.
9. M. Florian. A Traffic Equilibrium Model of Travel by Car and Public Transit Modes. Transportation Science, Vol. 11, 1977, pp. 166-179.