CR-137911

SUBURB-TO-SUBURB INTERCITY TRAVEL: ENERGY, TIME AND DOLLAR EXPENDITURES*

Margaret Fulton Fels

Center for Environmental Studies
and Transportation Program
Department of Civil Engineering
Princeton University

(NASA-CR-137911) SUBURB-TO-SUBURB INTERCITY TRAVEL: ENERGY, TIME AND DOLLAR EXPENDITURES (Princeton Univ.) 70 p HC $4.50 CSCL 13F

N76-29064

Unclas
G3/85 47245

June 1976

NASA NSG 2037
Transportation Report #76-TR-10

*Supported in part by NASA-AMES Research Center, Moffett Field, California

FOREWARD

The author gratefully acknowledges the assistance of Shari Glassman, who devotedly analyzed timetables, maps and a myriad of data, and Ian Harrington, who as part of a National Science Foundation summer grant carefully evaluated the energy and emissions characteristics of aircraft and other travel modes. In addition, Alfred Mascy and co-workers at NASA Ames offered helpful advice in answer to numerous questions concerning aircraft manufacture and operation.

This paper represents a preliminary report of work which is continuing. The data are rich; the conclusions are difficult to draw. Our analysis will benefit from time and constructive comments from readers.

TABLE OF CONTENTS

TABLE OF CONTENTS (Cont.)

SUMMARY

When a person travels from his home in a suburb of one city to some destination near or in another city, he may drive his personal automobile the entire length of the trip, or alternatively take an airplane, train or bus. The latter modes connect between terminals in the two cities: additional travel on both ends of the trip, involving perhaps several other modes, is required to take the traveler from his origin to his destination.

The total costs of the trip must reflect the modes linking the terminals to the ends of the trip, as well as the dominant cost of travel between terminals. Where an energy comparison of travel modes necessarily represents travel between terminals only, this analysis is an attempt to examine the effect of adding suburb-to-terminal and terminal-to-suburb travel, to estimate the energy consumed in entire trips. The total energy costs are compared with total travel times, and dollar costs to the traveler.

To carry out the analysis, trips between origins in seven suburbs of Newark, New Jersey and destinations in two Washington, D.C. suburbs are analyzed:

origin suburbs (in New Jersey, near Newark)	destination suburbs (in Maryland, near Washington, D.C.)
Bernardsville	
Clifton	Bethesda
Maplewood	
Allenhurst	
Linden	Rockville
Morristown	
Princeton	

The above suburbs were selected to represent a wide range of economic, and thereby travel, characteristics.

A total of 248 specific feasible trips comprise the sample. Each trip was followed, by map and timetable, to clock exact travel distances and times by each of the modes used.

In the analysis, trips were classified according to the MAIN mode used, for the bulk of the trip between Newark and Washington. Five MAIN modes were studied: AUTO, AIR, METROliner, conventional RAIL and BUS. The link modes, connecting a terminal to each end of the trip, include auto, bus, rail and walking. From a detailed energy analysis of manufacture as well as operation contributions, and an assumed occupany level for each mode, the energy consumption per passenger-mile for the MAIN and link modes are estimated as summarized in Table S1.

Table S1

ASSUMED VALUES FOR ENERGY CONSUMED PER PASSENGER-MILE (ϵ_{pm})

	Urban Modes				Intercity(MAIN) modes				
	auto	bus	rail	walk	AUTO	BUS	RAIL	METRO	AIR
ϵ_{pm} *	2.6	1.1	0.32	0.063	1.5	0.26	0.32	0.66	2.9
assumed load factor	23%	20%	57%	-	27%	65%	57%	56%	46%

*Energy units in kilowatt hours (kwh) per passenger-mile.

More details are found in Tables 3 and 4 of the report, as well as its Appendix.

For each trip type, the average energy, time and dollar costs are plotted as shown in summary form in Figure S1. (More detailed data concerning individual trips are shown in Figures 4, 5 and 6 in the report). Energy and time appear inversely correlated, in the way that energy and dollar costs are correlated. In general the more energy-intensive and dollar-costly trips (in increasing order: bus, rail, Metroliner, auto and air) are less time-consuming. A more detailed look at the results indicates considerable overlap among trip types, and several exceptions and unexpected findings are discussed in the report.

It is unrealistic to assume that the average traveler chooses how he travels on the basis of low energy consumption. More likely, he estimates the total amount of money the trip will cost him, with travel time folded in. To combine time and dollar costs, two approaches are attempted.

First, individual trips (or trip types) are compared on the basis of money saved per extra hour spent in travel. Table 6 and Table 8 in the report present results, respectively, for specific and average trips. The analysis places METRO trips in a favorable light. (Additional conclusions are stated in the report.)

To compare the total perceived (dollar) costs with energy costs, the second approach "adds" dollar and time expenditures together to reflect the value a traveler places on his own time. Where placing no dollar value on a traveler's time yields the anticipated ranking of MAIN modes (BUS and RAIL, METRO, AUTO, AIR, in order of increasing dollar costs), a high value for the traveler's time produces a totally new, unexpected ordering, and leaves BUS trips as the most "expensive" (see Figure 7). The results are discussed in the report.

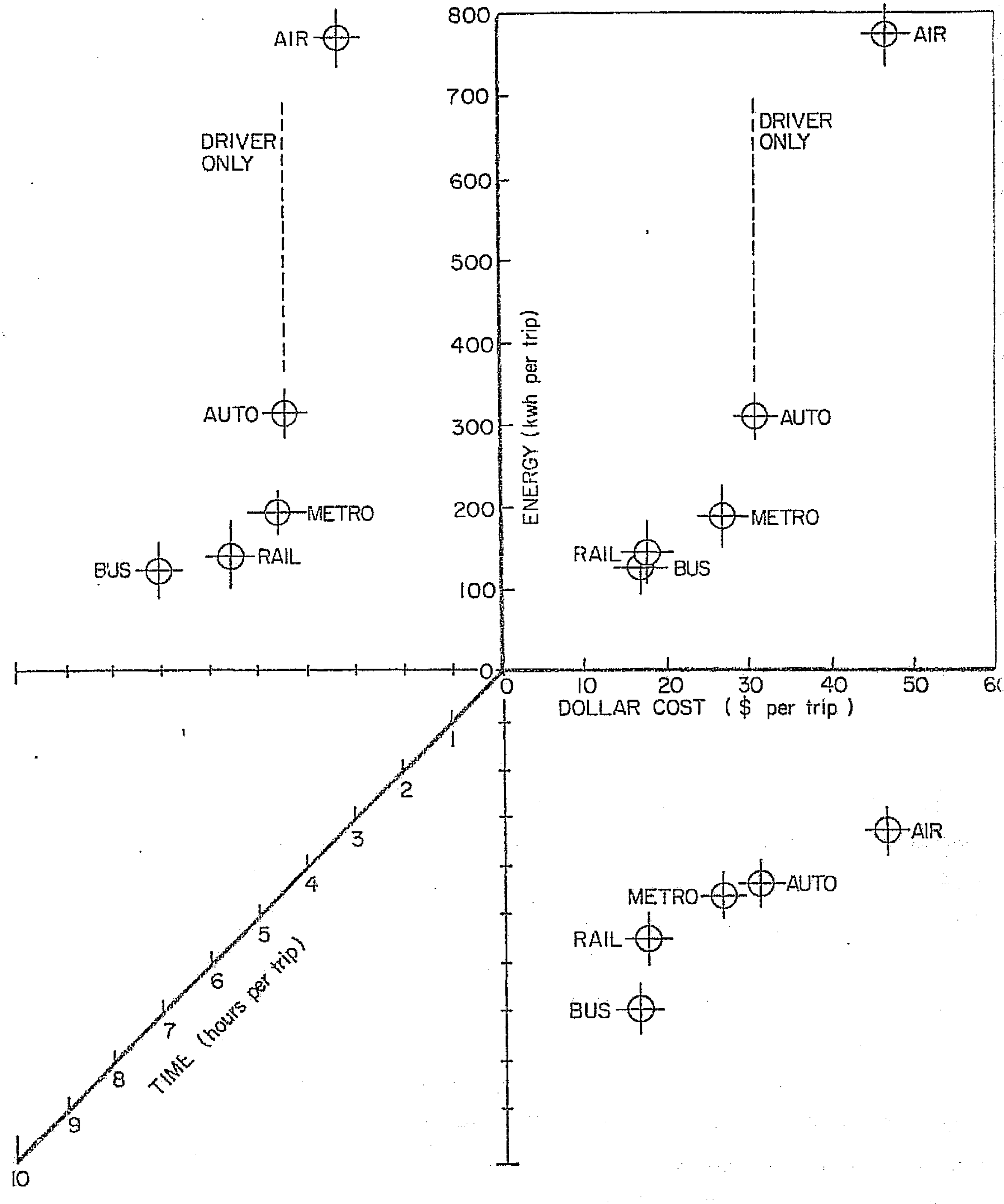


FIGURE S1. ENERGY VS. TIME VS. DOLLAR EXPENDITURES FOR AVERAGE TRIP

Circles for each MAIN mode correspond to average values for all trips by that MAIN mode (cross lines indicate standard deviations).

A. CHOICE OF TRIPS COMPRISING STUDY.

A resident of Clifton, New Jersey can reasonably travel to Rockville, Maryland in at least 27 different ways. How does the energy consumed depend on the modes chosen? The traveler's decision is rooted in anticipated dollar expenses: the fare and his perception of the value of his own time. How do the energy costs compare with the time and dollars spent in travel?

While it is well known that travel by bus or rail consumes considerably less energy but more time than auto or air travel, such conclusions are traditionally based on terminal-to-terminal analyses, involving only single modes of travel. Unless he uses the auto, however, our Clifton resident will use at least three separate modes in his trip to Rockville: one (or more) to transport him from home to the appropriate terminal in Newark, perhaps a 15-mile trip; the mode (bus, rail or air) involved in the 225-mile terminal-to-terminal trip between cities; and the final mode(s) from the Washington terminal to his destination, perhaps another 15 miles in travel. In this case, the suburb-to-city or city-to-suburb travel adds 15% to the city-to-city distance. The energy addition could be proportionately higher, because of the extensive use of the auto to link suburb to city. In addition to time spent in travel, appreciable waiting times are required to connect between modes.

For our laboratory area we chose the New York-to-Washington corridor. Five alternative main modes exist for these trips:* auto, air, bus, conventional electric rail and the Metroliner which we take to be representative of newer, faster rail systems between many U.S. city pairs. For a realistic

---

*A travel mode (auto, bus, etc.) is distinct from a trip which we define as a set of modes whose combination links a specified origin and destination.

data base, hundreds of specific trips between suburbs in the Newark-New York (origin) area and suburbs in the Washington, D.C. (destination) area were analyzed for the energy consumed, in the travel between cities (terminal-to-terminal) and total origin-to-destination travel for each trip. In addition, total time spend in travel and waiting, and the dollar cost to the traveler were estimated.*

For each main mode connecting a terminal in the origin city with a terminal in the destination city, any number of ways exist to get to or from the terminal: auto all the way to the terminal, for example, or several modes combined (e.g., walk to a busstop, bus to city bus terminal, and taxi to rail terminal). In addition, "auto" can represent private auto with parking charges, rent-a-car, taxi, Kiss-n-Ride (involving double mileage), or Park-n-Ride where available. The choice of trips proceeded from an analysis of what specific trips are currently available (i.e., how an individual could travel from the origin to the destination in question), combined with some judgment concerning what trips are likely to be taken.

The set of suburbs was chosen to cover a wide range of distances from the center cities between which the intercity travel is based. On the supposition that the choice of travel modes depends to some extent on income,** the communities are intended to represent a variety of economic

---

*The original intent of this work was to include pollution "costs" as well as energy, time and dollar expenditures. Without further work, the results are inconclusive, and will not be included in this paper.

**A more specific rule of thumb (not used quantitatively here) might be: the level of income correlates in increasing order with use of bus, conventional rail, Metroliner, auto and air - we will discuss this later in light of the results of the study.

characteristics as well as travel alternatives. The set consists of seven suburbs in the Newark-New York area and two suburbs near Washington, D. C. To simplify the analysis and to avoid uninstructive complications resulting from possible use of three major airports in the New York area, all suburbs in the first set lie in New Jersey (and are therefore served by Newark International Airport). The travel envisioned is from a home in one of the New Jersey suburbs to a place of business, or to a relative's or friend's home in the Washington area.

The New Jersey suburbs are described in Table 1. Clifton, as a middle-income large suburb ten miles* north of Newark, offers a wide range of bus and rail links to downtown Newark or New York; bus or rail travel to Washington might proceed through New York because of a direct rail line to Hoboken. Maplewood is an affluent community 5 miles west of Newark, while Linden, seven miles south of Newark, has a larger representation from lower income families. Farther away, 20 miles to the west, is Bernardsville, which is a low density, predominately upper middle class community. A few miles north of Bernardsville is Morristown, a larger community with a wider range of income groups. All of these communities have a rail link (and in most cases bus links) with Newark, so that non-auto travel to Washington is feasible. On the New Jersey shore, some 35 miles southeast of Newark, is Allenhurst, chosen for its lack of direct routes to Washington. The seventh New Jersey suburb, coincident with the location of the study, is Princeton, which lies near the travel

*Distances given here are as-the-crow-flies. Subsequent distances, for the purpose of analysis, are for actual travel distances.

Table 1

POPULATION CHARACTERISTICS OF
NEW JERSEY SUBURBS IN STUDY

Suburb	population	population density (1000 persons per square mile)	direction miles from Newark	median family income	percent of households with income above $15,000	auto ownership: percent of households owning no auto	auto ownership: percent of households with 2 or more autos
Bernardsville	6,700	0.5	20 W	$16,000	54%	6%	59
Clifton	82,000	7.4	10 N	12,000	37	12	43
Maplewood	25,000	6.2	5 W	14,000	50	9	47
Allenhurst	1,200	3.1	35 SE	20,000	15	2	71
Linden	41,000	3.7	7 S	9,700	25	13	37
Morristown	18,000	6.1	16 NW	11,000	30	21	30
Princeton	26,000	1.4	40 S	18,000	56	12	43

Sources: References 1 and 2.

line between Newark and Washington; this is a community considerably south of Newark, so that travel to Washington by air involves considerable back-tracking.*

The Washington suburbs are both in Maryland. Bethesda, a close-in suburb only 2 miles from Washington city limits and approximately 8 miles from downtown Washington, contains commercial establishments attracting business trips (National Institute of Health, for example) as well as residential areas. Rockville, a suburb farther out, is 9 miles from the city limits; equidistant (18 miles) from both Washington airports, it offers a rail link to the central city.

Within the boundaries of reasonable judgment, all trips between these fourteen pairs of Newark and Washington suburbs were analyzed in terms of the energy and time expended. For each trip, the cost to the traveler was estimated, both in terms of out-of-pocket costs and value of the traveler's time spent in travel.

Each trip consists of a main mode (auto, bus, conventional rail, Metroliner or air) and link modes (auto, bus, rail or walk) to connect the traveler from home (the origin, in one of 7 New Jersey suburbs) to the terminal for the main mode, in the Newark area, or connect him from the main mode's Washington terminal to his destination (in one of 2 Washington suburbs). Trips involving one, three or a maximum of four links (including the main mode) were considered. Walking from a bus to rail station was considered a link, while walking at the beginning or end of the trip, from home to the local bus or rail terminal, for example, was not counted as one of the four links. (Walking consumes nearly negligible energy). In addition, while it is obvious that travel from home to a local terminal

*A local airport services Princeton-to-Washington trips, with generally smaller planes than those used in Newark-to-Washington flights. For consistency of analysis, all air trips considered here will originate from the Newark airport.

might involve a short auto trip, this small increment was neglected for the 258-mile trips considered here. If two links are by the same mode (city bus connecting to intercity bus, for example), they are counted as two separate links with waiting time between.

The only single-link trip is AUTO, where a private automobile is used for the entire trip. Letting capital letters denote the main mode, with RAIL for conventional rail and METRO for Metroliner, a three-link trip by rail might be auto-RAIL-auto, auto-RAIL-rail, bus-RAIL-auto, etc. A four-link trip involves a double link at one end, such as rail-bus-RAIL-bus, or bus-bus-AIR-auto.

With this set of ground rules, hundreds of possible trips exist between any origin-destination pair. The following assumptions are among those used to cut the number down to a manageable set of likely, as well as physically possible, trips:

1) With a rare exception, auto used at either end connects to the MAIN-mode terminal (i.e., auto-METRO-auto is more likely than auto-bus-METRO-auto).
2) Auto link between origin suburb and Newark airport or rail station is private auto, with parking charges.
3) Auto link between any two city terminals is by taxi (e.g., between bus and rail stations in Newark).
4) Auto link to Metropark (Metroliner station) is Park-n-Ride (free).
5) Link from Washington airport to destination suburbs is by Rent-a-Car auto (air traveler is apt to be "in a hurry").
6) Auto link from Washington METRO is by taxi.
7) Auto link from Washington BUS or RAIL terminal to suburbs is by Kiss-n-Ride.
8) AIR traveler to Bethesda uses National Airport, while both National and Dulles Airports serve Rockville.
9) For the more affluent New Jersey suburbs, BUS travel to Washington is less likely than travel by the other MAIN modes.

For all origin-destination pairs, locations of terminals, detailed routes and timetables were analyzed, so that all trips studied represent actual trips currently taken.

Table 2 shows the trips chosen for this analysis. A possible choice between two terminals (Newark or Metropark, for use of METRO;* or the availability of two airports for AIR trips to Rockville) is indicated by an asterisk. The resulting sample set includes 248 trips.

Before proceeding to our analysis of specific trips, the energy characteristics of individual modes are summarized,in Section B. For each mode, energy requirements to manufacture the vehicles and guideway are considered along with the usual operation energy contributions. Details are presented in the Appendix.

The largest BUS representation is in the Clifton trips. We start our discussion of the energy-time-dollar costs with a detailed analysis of trips between Clifton and Rockville: Section C. Other specific trips are discussed briefly in Section D. With preliminary results in hand, we examine our results averaged over all origin-destination pairs, in Section E. The salient results, comparing energy, time and dollar costs, are shown in Figures 4, 5 and 6. Tentative conclusions are drawn by assigning a dollar value to the traveler's time. Future directions for this study are suggested in Section F.

---

*Conventional rail trains do not stop at Metropark.

Table 2

SUBURB-TO-SUBURB TRIPS INCLUDED IN STUDY, BY MODE COMBINATION

Origin - Destination (In New Jersey) (In Maryland)	AUTO	auto-BUS-auto	auto-BUS-bus	bus-BUS-auto, or bus-walk-BUS-auto	bus-BUS-bus, or bus-walk-BUS-bus	auto-bus-BUS-auto	auto-bus-BUS-bus	rail-bus-BUS-auto	rail-bus-BUS-bus
Clifton to Rockville	X	X	X	X X	X X			X	X
Bernardsville to Rockville	X								
Maplewood to Rockville	X	X	X	X	X				
Allenhurst to Rockville	X					X	X		
Linden to Rockville	X	X	X	X	X				
Morristown to Rockville	X								
Princeton to Rockville	X								
Clifton to Bethesda	X	X	X	X X	X X			X	X
Bernardsville to Bethesda	X								
Maplewood to Bethesda	X	X	X	X	X				
Allenhurst to Bethesda	X					X	X		
Linden to Bethesda	X	X	X	X	X				
Morristown to Bethesda	X								
Princeton to Bethesda	X								

Origin - Destination (In New Jersey) (In Maryland)	auto-RAIL-auto	auto-RAIL-rail	bus-RAIL-auto	bus-RAIL-rail	rail-RAIL-auto	rail-RAIL-rail	rail-auto-RAIL-auto	rail-auto-RAIL-rail	rail-bus-RAIL-auto	rail-bus-RAIL-rail	rail-rail-RAIL-auto	rail-rail-RAIL-rail
Clifton to Rockville	X	X	X	X							X	X
Bernardsville to Rockville	X	X					X	X	X	X		
Maplewood to Rockville	X	X	X	X			X	X	X	X		
Allenhurst to Rockville	X	X			X	X						
Linden to Rockville	X	X	X	X	X	X						
Morristown to Rockville	X	X	X	X					X	X		
Princeton to Rockville	*	*	X	X	X	X						
Clifton to Bethesda	X		X								X	
Bernardsville to Bethesda	X						X		X			
Maplewood to Bethesda	X		X				X		X			
Allenhurst to Bethesda	X				X							
Linden to Bethesda	X		X		X							
Morristown to Bethesda	X		X						X			
Princeton to Bethesda	*		X		X							

Origin - Destination (In New Jersey) (In Maryland)	auto-METRO-auto	auto-METRO-rail	bus-METRO-auto	bus-METRO-rail	rail-METRO-auto	rail-METRO-rail	rail-auto-METRO-auto	rail-auto-METRO-rail	rail-bus-METRO-auto	rail-bus-METRO-rail	rail-rail-METRO-auto	rail-rail-METRO-rail
Clifton to Rockville	X	X	X	X							X	X
Bernardsville to Rockville	*	*					X	X	X	X		
Maplewood to Rockville	*	*	X	X			X	X	X	X		
Allenhurst to Rockville	*	*			X	X						
Linden to Rockville	*	*	*	*	X	X						
Morristown to Rockville	X	X	X	X					X	X		
Princeton to Rockville	X	X	X	X								
Clifton to Bethesda	X		X								X	
Bernardsville to Bethesda	*						X		X			
Maplewood to Bethesda	*		X				X		X			
Allenhurst to Bethesda	*				X							
Linden to Bethesda	*		*		X							
Morristown to Bethesda	X		X						X			
Princeton to Bethesda	X		X									

Origin - Destination (In New Jersey) (In Maryland)	auto-AIR-auto	bus-AIR-auto	bus-auto-AIR-auto, or auto-bus-AIR-auto	rail-auto-AIR-auto	bus-bus-AIR-auto	rail-bus-AIR-auto
Clifton to Rockville	*		*		*	
Bernardsville to Rockville	*			*		
Maplewood to Rockville	*	*		*		
Allenhurst to Rockville	*		*	*		*
Linden to Rockville	*	*		*		*
Morristown to Rockville	*			*		
Princeton to Rockville	*					
Clifton to Bethesda	X		X		X	
Bernardsville to Bethesda	X			X		
Maplewood to Bethesda	X	X		X		
Allenhurst to Bethesda	X		X	X		X
Linden to Bethesda	X	X		X		X
Morristown to Bethesda	X			X		
Princeton to Bethesda	X					

Asterisk denotes two trips, via different terminals; capital letters in mode combination denote main mode used in trip (other modes indicated are links to main mode)

Total # of trips: Rockville - 157
Bethesda - 91
Total - 248

B. ENERGY CHARACTERISTICS OF TRAVEL MODES USED IN INTERCITY TRAVEL

Driving a 3600-pound automobile which averages 14 mpg and carries 2.2 persons is equivalent in energy terms (per passenger-mile) to driving a 2000-pound (25 mpg) car with 1.24 persons or, if we can hypothesize an overall efficiency improvement of 15%, a car carrying only the driver can maintain a comparable efficiency, if, at 1800 pounds it averages 32 mpg. In an energy comparison of trips, the average occupancy of the vehicles used is as important a consideration as the vehicles' energy efficiency (i.e., energy per vehicle-mile). The results presented in this study can be translated into equivalent situations such as these.

Table 3 summarizes the energy consumption for each of the urban and intercity (i.e., MAIN) modes considered.* The energy per passenger-mile (ϵ_{pm}) is estimated from the energy consumed per vehicle-mile (ϵ_{vm}) divided by the assumed average occupancy levels (p), as shown in the table. For the auto used as a link to MAIN modes, a lower occupancy (and lower mileage of 12.3 mpg) is assumed. The average occupancy for urban modes in general corresponds to national averages, while values of p for the MAIN modes were obtained from major carriers serving the New York-to-Washington routes.

The energy per vehicle-mile estimate includes the operating energy requirements (ϵ_o), plus the energy consumed in the manufacture of the vehicles (M_v) and guideways (M_g) amortized over their respective lifetimes (L_v and L_g). Evaluation of the energy consumed to manufacture a vehicle, for example, involves tracing the manufacture process back to the mining of the ores from which the metals were refined, and estimating the energy contribution at each step. The evaluation of the energy required in the

*Energy units used are thermal kilowatt-hours (kwh) where 1 kwh is equivalent to 3413 BTU. For the electrical modes, energy consumption represents energy resources used, by taking into account the efficiency of electricity generation.

Table 3

ENERGY-PER-MILE DATA FOR

URBAN AND INTERCITY MODES

	ϵ_{vm} (kwh per vehicle-mile)	p (average number of passengers per vehicle)	s (seats per vehicle)	ϵ_{pm} (kwh per passenger-mile
Urban Modes:				
auto	3.6	1.4	6	2.6
bus	9.0	8.0	40	1.1
rail	13.2	41.0	72	0.32
walk	0.063	1.0	1	0.063
Intercity (MAIN) Modes:				
AUTO	3.2	2.2	6	1.5
BUS	7.4	28.4	44	0.26
RAIL(conventional)	13.2	41.0	72	0.32
METROliner	26.4	40.0	72	0.66
AIR	147.	49.9	109	2.9

manufacture of a 67-ton passenger aircraft was carried out as part of this project. Figure 1 shows schematically the steps, and corresponding energy contributions involved. The total approaches 6 million kwh, enough to propel the aircraft 16,000 miles.

Individual manufacture contributions, for each MAIN mode, are summarized in Table 4. (Their derivation is described in the Appendix). These contributions are "added" to the operation energy consumption (ϵ_o), by the following formula:

$$\epsilon_{vm} = \epsilon_o + M_v/L_v + M_g/L_g \quad , \qquad (1)$$

to yield the energy consumed per vehicle-mile (ϵ_{vm}) shown in Table 3 for each mode.

On a terminal-to-terminal, or energy-per-passenger-mile, comparison of the MAIN modes, it is clear that BUS and conventional RAIL consume only half the energy of METRO which in turn is twice as efficient as AUTO. By far the least efficient mode is AIR.* How does the energy comparison change when we include the incremental energy due to travel from the traveler's home to, say, the Newark terminal, and travel from the Washington terminal to his destination? To answer this question, we turn our attention to specific trips, between Clifton, New Jersey, and Rockville, Maryland.

*As indicated in the Appendix, energy values for AIR represent an average of the aircraft used for Newark-to-National flights, in a short-haul flight pattern. Energy results for Newark-to-Dulles flights are considerably higher because of the use of less efficient aircraft and lower occupancy levels.

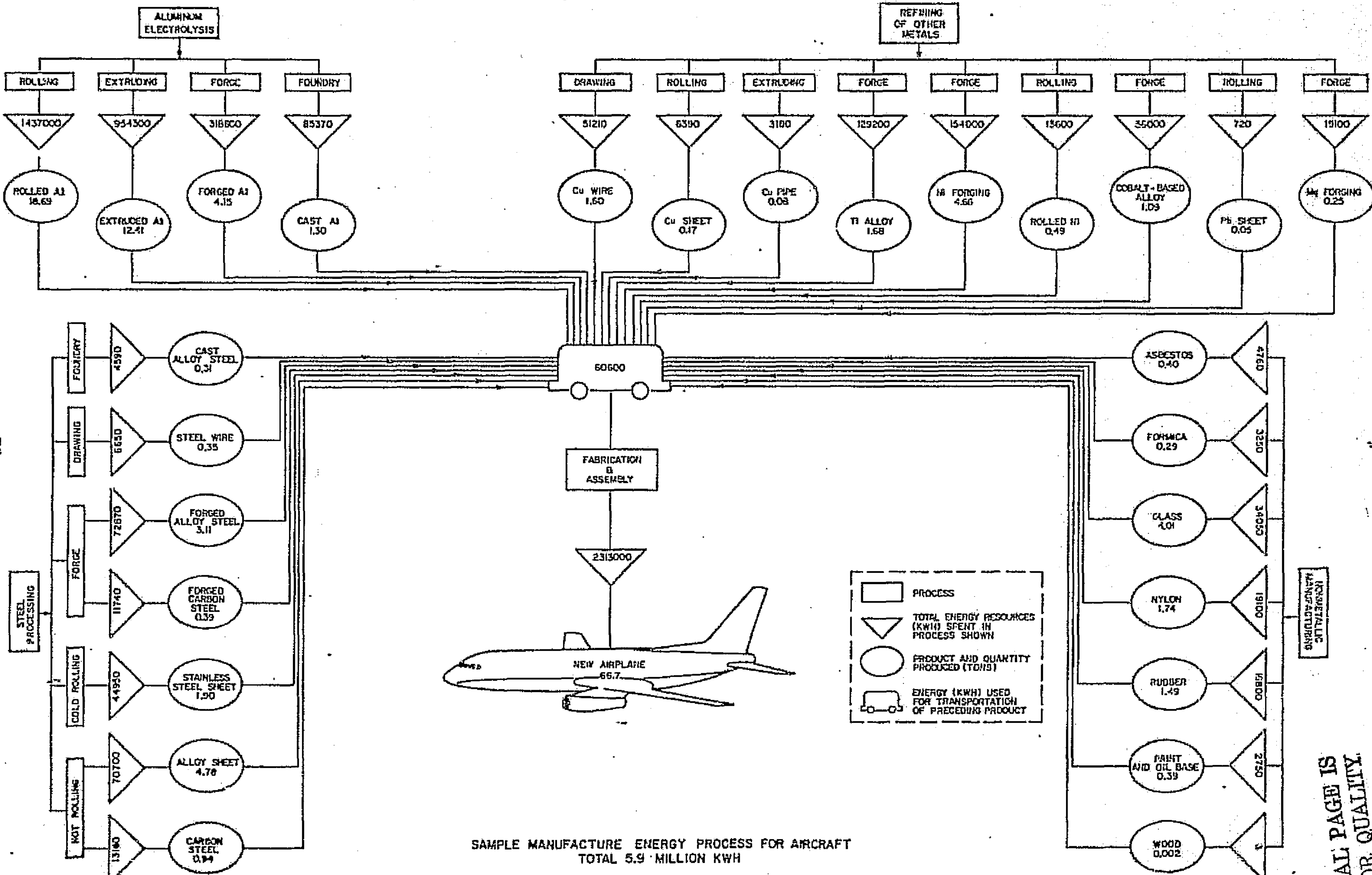


Figure 1: ENERGY AND MATERIAL MAP OF THE MANUFACTURE OF ONE NEW AIRCRAFT FROM PRIMARY MATERIALS. For each manufacture process, material quantity and resulting energy usage are shown, to correspond with a 67-ton Boeing passenger aircraft. Individual energy contributions add to 5.9 million kwh.

Table 4

MANUFACTURE ENERGY REQUIREMENTS FOR MAIN MODES[1]

	M_v [2] (kwh per vehicle)	L_v (vehicle-miles)	Mg (kwh per mile)	Lg (vehicles)
AUTO	38,600	0.1 million	4.6 million	160.million
BUS	300,000	1.million	4.6 million	54.million
RAIL[3] (METRO)	2,000,000	3.million	5.0 million	35.million
AIR	5,900,000	10.million	58.million	330.million

[1] Each link mode (e.g., auto) is assumed to have manufacture energy costs similar to its corresponding MAIN mode (AUTO). Table A1 in the Appendix provides the needed detail.

[2] M_v and Mg are the energy requirements for the manufacture of the vehicle and guideway, respectively, and L_v and Lg are the corresponding lifetimes.

[3] Independent analyses of METROliner and conventional RAIL cars give strikingly similar values for M_v; see Table A2 in the Appendix.

C. CLIFTON-TO-ROCKVILLE TRIPS

A person traveling by AUTO from Clifton, New Jersey to Rockville, Maryland will travel a distance of approximately 225 miles. This was the minimum travel distance for the 27 trips studied between these two suburbs. The trip will take him 4 hours and 30 minutes, and with tolls and operating auto expenses it will cost him nearly $34.* If he drives a 3600-pound car which for this trip averages 14 mpg, the energy consumed would be 725 kwh.(kilowatt hours). Were he to take a passenger, the energy per person-trip would be only 363 kwh. Using the national average of 2.2 persons per auto (which includes recreational trips)[4], the result becomes 330 kwh per person-trip; the higher average occupancy will be adopted for AUTO trips in this study, with reference to driver-only energy consumption.

Consider first, the traveler who uses an automobile on both ends of the trip. If he is in a hurry he might travel by AIR. Driving 16.5 miles to Newark airport (incurring $3.50 in parking charges for the day), he might take a plane to National airport, and rent a car for the 21-mile trip to Rockville. The resulting energy consumption is 790 kwh: the auto links add 14% to the energy consumed in flight, so that, in this case, nearly all the energy consumption is attributable to the MAIN mode. To use the Metroliner, he would drive 14 miles to the Newark Penn

*Cost estimates for the automobile are based on the average 13.5¢ per mile, which includes gasoline, insurance and registration fees, wear and tear, maintenance and the capital cost amortized over 100,000 miles.[3]

Railroad Station, (for which he would pay $7.00 in parking charges for the day), take METRO 215 miles to Washington, and then a taxi 18 miles from the Washington's Union Station to Rockville. The resulting energy consumed is 225 kwh, representing a 63% increment over the METRO energy consumption.

Had he taken RAIL, the auto travel is nearly the same with Kiss-n-Ride at the destination end, the total energy consumed is 200 kwh, or almost three times the RAIL energy. Energy consumption for a BUS trip is similar: 185 kwh, slightly over three times the BUS energy.

The energy results for these trips, designated as auto-MAIN-auto, are summarized in Table 5. Although highest for the AIR trip, the energy consumption is only 9% higher than it is for the traveler driving himself by AUTO. With an additional passenger (or a considerably more efficient, smaller automobile), the AUTO energy is only 47% higher than the METRO energy (rather than 220% higher for the driver-only AUTO). Although the terminal-to-terminal energy consumed per vehicle-mile for METRO is twice that for RAIL (see Table 3), the total energy consumption for the auto-METRO-auto trip is only 13% higher than the auto-RAIL-auto trip. (This is because the auto links add so significantly to the METRO and even moreso to the RAIL energy). Eight percent lower than the RAIL trip, the auto-BUS-auto trip is the lowest energy-consumer of this type. The maximum disparity, between the AIR and BUS trips, is a factor of 4.3.

An alternative is to fly from Newark to the Dulles airport, which is farther outside of Washington, but also 21 miles from Rockville. The fare is the same, and with an increased flight distance of 20 miles the travel time is only 15 minutes longer; thus it is a choice a traveler well might make. Probably unbeknown to him, the resulting energy consumption

Table 5

TRIPS BETWEEN CLIFTON AND ROCKVILLE WITH

AUTO LINKS AT BOTH ENDS

	distance traveled	energy consumed per trip	MAIN mode terminal-to-terminal energy consumption (% of total)	travel time per trip	dollar cost per person-trip
AUTO (driver only)	226 miles	725 kwh	100%	4.5 hours	$34.
AUTO (national average occupancy)	226	330	100%	4.5	$15.
auto-AIR-auto	272	790	88	2.7	$ 48.
auto-METRO-auto	247	225	63	4.0	$ 33.
auto-RAIL-auto	265	200	35	4.9	$ 22
auto-BUS-auto	276	185	32	6.1	$ 21.

is, by our estimates, astonishingly high: 2450 kwh for the trip, or three times the energy consumed via National. Part of this increase is due to the use of aircraft better suited to longer range trips: Newark-to-Dulles is often only one leg of a longer trip. The main increase is due to the considerably lower load factor: 25%, vs 46% for Newark-to-National trips (See Appendix). Since AIR trips via National are probably more representative of short-range AIR trips, and the Dulles results imply a bias against AIR, we have chosen to exclude the AIR via Dulles trips from our sample. Thus from hereon in, AIR results represent travel via National airport.

Returning now to the trips described in Table 5, what are the time and dollar expenditures associated with them? In terms of dollars, AIR is the most expensive ($48, including AIR fare, auto operating and parking expenses from Clifton to the Newark airport, and Rent-a-Car from National airport to Rockville). Since the AIR traveler is probably in a hurry how much time does he actually save? And how much does it cost him? The flight time is less than an hour. The time spent in auto travel at both ends adds another hour. A conservative estimate of 45 minutes total waiting time at Newark airport for the plane and at National for the Rent-a-Car brings the total time spent to 2.7 hours. As is evident in Table 5, this is the least time-consuming of the auto-MAIN-auto trips. For example, auto-METRO-auto takes an additional 1.3 hours -- but costs $15 less. The traveler's time must, in some sense, be "worth" more than $11.50 per hour to render the AIR trip preferable over METRO.

As a measure of whether a traveler would choose one way of travel (i.e., mode combination) over another, we have computed the ratio of the dollar cost difference and the travel time difference, between pairs of trips* listed in Table 5. More exactly, if C_L and T_L represent respectively the dollar and time (hour) costs of trip L, then we define the "time value" V_{LM} between trips L and M as the following ratio:

$$V_{LM} = - \frac{C_L - C_M}{T_L - T_M} . \tag{2}$$

In general (with one exception noted below), the less time-consuming trips cost the traveler more, i.e., V_{LM} is positive. If trip L costs more than trip M, then trip L is preferable to trip M (i.e. the excess cost is "worth it") if the traveler values his time more than V_{LM} dollars per hour. Thus, the time value for AIR vs. METRO compared above becomes $11.50. On this basis, the lower the value of V_{LM}, the more attractive the choice of trip L over trip M becomes.

Table 6 shows the resulting time values V_{LM} for the auto-MAIN-auto trips presented in Table 5. Continuing with our comparison of AIR vs. other MAIN modes, the value for V_{LM} is nearly the same for AIR vs. RAIL as it is for AIR vs METRO : the added cost of AIR vs. RAIL is considerably more than it is for AIR vs. METRO, but the time savings is greater by approximately the same factor.

Much closer to realistic time values are AIR vs. AUTO (driver only) and AIR vs. BUS. If a person values his time at more than $8 an hour, he would choose AIR instead of driving his AUTO or riding a BUS. (If the traveler, like many, underestimates the waiting time involved in AIR

---

*This measure is intended to reflect a traveler's perception of the value of his own time, and not necessarily his earning power.

Table 6

COMPARISON OF auto-MAIN-auto TRIPS ON BASIS OF DOLLAR VALUE TRAVELER PLACES ON HIS OWN TIME: ATTRACTIVENESS OF TRIP L OVER TRIP M INCREASES AS V_{LM} DECREASES

Trip L auto-MAIN-auto		M auto-MAIN-auto		V_{LM}[1]
AIR	is preferable to	METRO	if traveler's time is worthmore than	$11.50 per hour
AIR	"	AUTO[2]	"	7.80 per hour
AIR	"	RAIL	"	11.80 per hour
AIR	"	BUS	"	7.90 per hour
AUTO	"	METRO	"	——[3]
AUTO	"	RAIL	"	$30.00
AUTO	"	BUS	"	8.10
RAIL	"	BUS	"	2.00

[1] Time value V_{LM} is computed from dollar cost difference divided by the the difference in total travel time, between the two MAIN modes shown. (See Eq. 2) . In all cases the first trip shown costs more money (and less time) than the second.

[2] AUTO trips represent the dollar cost borne by the driver alone.

[3] AUTO (driver only) trip is both more dollar costly and more time-consuming than auto-METRO-auto .

travel, the time value V_{LM} of AIR vs AUTO could be as low as $5.40 an hour, making the choice of AIR over AUTO more attractive than it is when total travel time is considered.) On the other hand, a traveler valuing his time at less than $8.00 an hour would find travel by AIR not worth the added cost, and on this basis would find any other MAIN mode preferable.

Comparing travel by non-AIR modes, AUTO saves so little time over conventional RAIL that the added cost of $12 would not be worth it for most people (Resulting value of V_{LM} is over $30). On the opposite extreme is RAIL vs BUS: for only a single additional dollar, more than an hour can be saved.

For this set of auto-MAIN-auto trips, there is an exception to the more-time more-money hypothesis, namely for AUTO (driver only) vs. METRO. Compared with auto-METRO-auto, the AUTO is slightly ($1) more costly and consumes an additional half hour in travel time. Thus the METRO trip is preferable -- by a small margin -- on both counts. The choice between modes will be made on grounds other than economics. The fact that METRO consumes considerably less energy per person-trip unless the AUTO carries, on the average, 3.2 persons places METRO in an even more favorable position.

A glance at Table 5 tells us that, in general, the more costly, less time-consuming trips consume the most energy. Ranking the MAIN modes in the auto-MAIN-auto trips according to the maximum dollar costs, minimum travel time and maximum energy consumption the following rough order emerges: AIR, AUTO (driver only), METRO, RAIL and BUS. (AUTO with passenger falls between AIR and METRO for energy rating, but is the cheapest of all modes in dollar cost per passenger, if the cost is shared equally among the passengers.) Thus the ranking seen in Table 3 for the terminal-to-terminal energy consumption per passenger-mile ($\mathcal{E}_{pm}$) for the MAIN modes is preserved for these auto-MAIN-auto trips when total origin-to-destination energy consumption or the total dollar cost is considered, and is reversed for travel times.

Observations to this point have been based on trips in which the auto was used to link to and from the MAIN mode. Many other link modes are feasible for Clifton-to-Rockville trips: Table 2 indicated the 24 mode combinations chosen for this analysis. The energy-time-dollar results are shown, in bar-graph form, in Figure 2.*

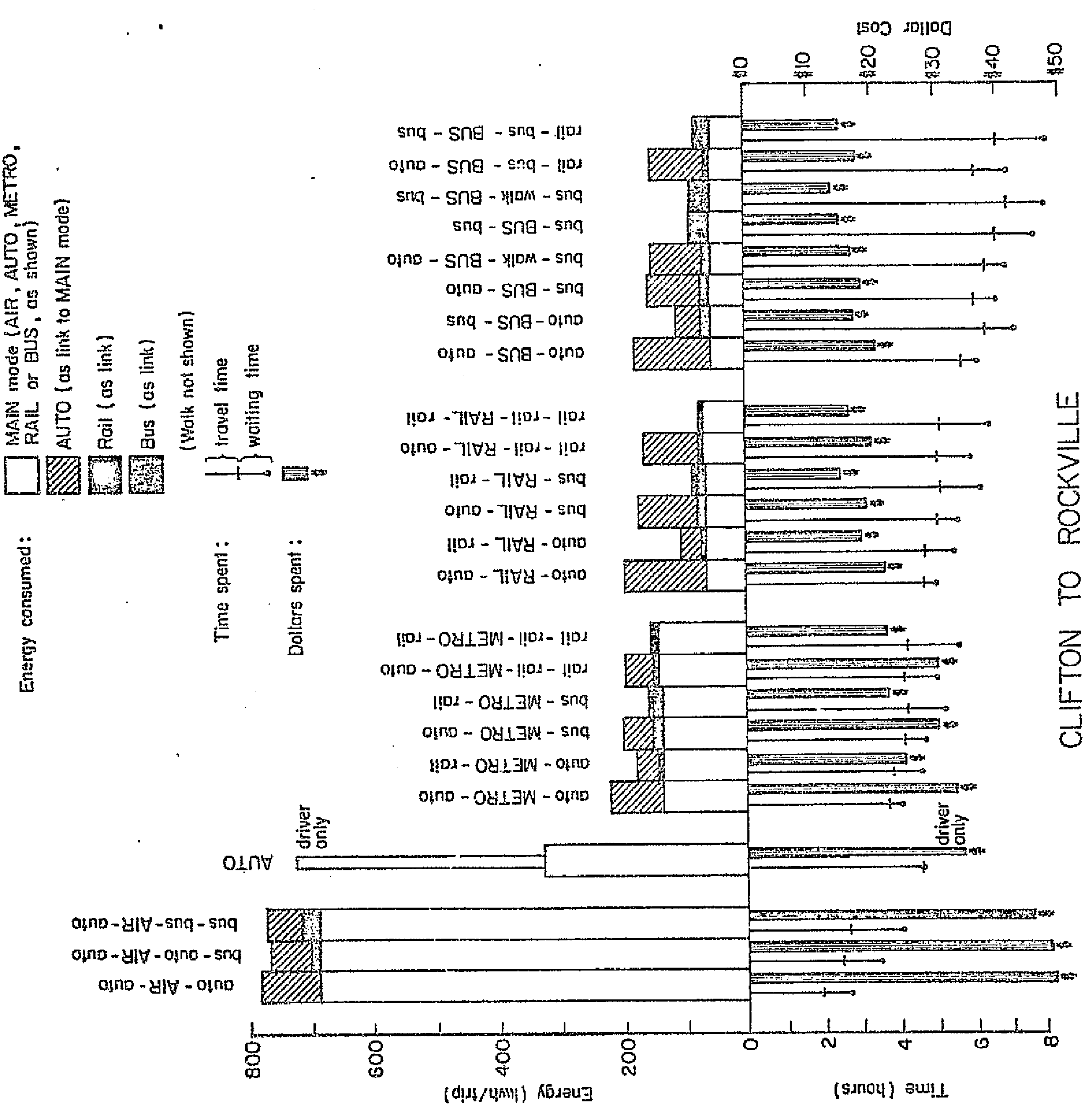
Visually we see the following pattern in energy consumption emerge: AIR and AUTO (driver only) are considerably more energy intensive than any of the METRO, RAIL and BUS trips, and unless AUTO carries 3 persons it is not competitive with the three more energy thrifty MAIN modes. As already seen, when the auto is used at both ends of the trip, the energy results for METRO, RAIL and BUS are suprisingly similar: the auto links add so significantly (by a factor of 3) to the RAIL and BUS energy contributions that the totals are not very different from the METRO total.**

The energy advantage of BUS and RAIL trips over METRO widens as the traveler relies less on the automobile to link with the MAIN mode. Because bus and rail use so much less energy than the auto does, per

---

*For reasons mentioned earlier, the AIR trips via Dulles are omitted from the graph.

**This is in part attributable to our assumption that Kiss-n-Ride, involving double auto distance, would be used to link BUS and RAIL to Rockville.



ORIGINAL PAGE IS OF POOR QUALITY

Figure 2: ENERGY, TIME AND DOLLAR EXPENDITURES FOR TRIPS BETWEEN CLIFTON AND ROCKVILLE. Total energy results are separated among individual MAIN and link modes comprising each trip; total time is divided between travel and waiting times.

passenger-mile, and because the distance traveled on link modes is, for Clifton-to-Rockville, considerably less than the MAIN mode travel distance, bus and rail add very little energy to the terminal-to-terminal, or MAIN, energy consumption.

On the bottom half of the graph, somewhat as a reflection of the energy bar graph, are shown the time and dollar costs for each trip. In general as we move from AIR to BUS results, the travel time increases while dollar costs decrease. On the (arbitrary) scales used in Figure 2, the lines depicting dollar costs are considerably larger than the corresponding time lines at the AIR end, and the situation is progressively reversed as we move through AUTO, METRO and RAIL until, at the BUS end, time lines are much longer than dollar lines.

Let's look in more detail at the different trips for the same MAIN mode. For the three AIR trips considered, the AIR energy so dominates the total energy consumption that the use of more energy-thrifty modes between Clifton and the airport causes an insignificant energy reduction. The same observation holds for dollar costs. The time added to travel to the airport by bus instead of auto, however, is significant. Since the resulting time value V_{LM} of auto-AIR-auto vs bus-bus-AIR-auto is only $2.60, a person traveling by AIR may as well use an auto on both ends of the trip.

The METRO trip energy results range from a maximum of 225 kwh (auto-METRO-auto) to a minimum of 160 kwh for rail-rail-METRO-rail.* For the latter the rail links add only 6% to the METRO energy consumption. A time-money comparison between these two trips leads to a time savings of 1.5 hours for $10.60, or, the rail-rail-METRO-rail is preferable for a person who values his time at less than $7.00 an hour.

---

*Rail from Clifton to Hoboken, change for Penn Station in New York City, METRO to Washington, and rail to Rockville. The only non-auto link from Clifton to Newark RAIL station is by bus.

The range of energy results for RAIL trips is wider: from a maximum of 200 kwh for auto-RAIL-auto to a minimum of 82 kwh for rail-rail-RAIL-rail. A similar range in energy results is seen for the BUS trips. Of all the trips studied, the lowest energy consumed is for rail-rail-RAIL-rail, with rail-bus-BUS-bus only 3 kwh higher at 85 kwh. This is to be contrasted with the largest, auto-AIR-auto, energy result which is an order of magnitude higher.

For the several trips by each main MODE (See Figure 2), the waiting time and thereby the total travel time, increases as the use of non-auto links increases. To determine to what extent these increased travel times are correlated with decreased dollar costs, we examined the sign of the time value V_{LM} for all pairs of trips in the Clifton-to-Rockville set: as we saw in Table 6, V_{LM} is generally positive, to indicate trip L as more dollar-costly but less time-consuming than trip M. Of the 276 possibly trip pairs (excluding trips via Dulles Airport), only about 35 of them have negative values of V_{LM}. And in many of these, the time difference T_L-T_M or the dollar cost difference C_L-C_M is so small as to make the sign of V_{LM} insignificant. The choice in these cases is obviously toward the cheaper (and less time-consuming) trip.

We have already noted that auto-METRO-auto costs less money and time and consumes less energy than AUTO. Similar comparisons exist for auto-RAIL-auto vs. rail-rail-METRO-rail, and auto-METRO-auto vs. bus-bus-AIR-auto, for example. On the other hand, several trip pairs show an energy decrease along with time and money increase (positive V_{LM}): auto-METRO-rail vs. AUTO, for example, where the former is more expensive and (slightly) more time-consuming, but far less energy-intensive.

In this three-dimensional analysis of energy, time and dollars spent, an unmanageable number of comparisons can be made. And conclusions from specific examples are untrustworthy. After a brief look at trips between other origins and destinations, we will examine trends seen in the average values of the data.

D. OTHER ORIGIN-DESTINATION PAIRS

The set of origins described in Table 1 represents a wide range of trip patterns and travel choices available to residents. Where Clifton is relatively close to Newark (as well as to New York City), Allenhurst, on the shore, is far from any metropolitan center. The direct distance from Allenhurst to Rockville by AUTO is 208 miles. A trip via Newark by BUS (e.g., auto-bus-BUS-auto)* can total over 300 miles, but costs the traveler considerably less (in energy as well as dollars); if he travels via Newark by AIR, the time savings overAUTO is 55 minutes (although the energy and dollar costs are considerably more), but the distance traveled is again over 300 miles.

Another difference between Allenhurst-to-Rockville and Clifton-to-Rockville trips is in the fractional increment in the energy consumption due to the modes linking to the MAIN mode. For auto-RAIL-auto trips, the auto links in the Clifton trip added 190% to the RAIL energy consumption to give a total of 200 kwh for the trip. For the longer Allenhurst trip (via Trenton) the increase was over 400%, with a total of 270 kwh for the trip. The all-rail trip for the two origins, on the other hand, show similar low energy consumption. The travel time involved for the Allenhurst trip is proportionately higher than it was for the corresponding all-rail Clifton trip, when compared with AUTO.

A suburb located almost as far from Newark is Princeton. The AUTO travel distance is 188 miles, taking 3.8 hours and consuming 275 kwh of energy. As was essentially true for the trips from Rockville, two trips take less time than the AUTO trip: auto-METRO-auto (via Trenton),

---

*No auto-BUS-auto trip was considered since a person with access to his own auto is more likely to drive to Rockville, than drive to Newark to take a BUS.

which takes 25 minutes less (costs $2.50 less) and consumes 34% less energy; and auto-AIR-auto, via Newark and National airports,* which takes almost 40 minutes less but consumes over 3 times as much energy as the AUTO trips. (The corresponding ratio for the Clifton trips was 2.4). The AIR trip is nearly twice as expensive as the AUTO trip, so that the time value V_{LM} for auto-AIR-auto vs. AUTO becomes $38. A Princeton businessman might more realistically choose between the early METRO and AIR via Newark. The resulting time savings of 15 minutes would cost him $27, putting a price tag on his time of over $125. per hour. For the Clifton trips, the corresponding AIR vs METRO value of V_{LM} was $11., for which AIR saved 1.3 hours in travel time over METRO.

If we were to look in detail at trips to Bethesda, or other trips to Rockville, we would see results similar to those shown for Clifton to Rockville in Figure 2. As indicated by the Allenhurst and Princeton trips, the magnitude of energy, time and dollars spent differ (the energy added by the modes linking with the MAIN mode is less, for example, in the Bethesda trips then in the Rockville trips) and comparison of specific trip types may give different results, but in general the trends are similar to those shown visually in Figure 2.

---

*As mentioned on p.5, it might be more realistic to consider auto-AIR-auto via a small airport near Princeton. The less likely trip, via Newark, is considered here for consistency, and to include an extreme, as the outer edge of sanity, for AIR trips. (Note that the extreme still produces a relatively fast AIR trip).

E. AVERAGE VALUES, AND STANDARD DEVIATIONS

To examine suburb-to-suburb trips without bias toward any particular type of origin or destination, we have examined the mean values of our energy, time and dollar data. For each trip type, or mode combination (e.g., auto-RAIL-auto), the data were averaged over all 14 origin-destination pairs (As shown in Table 2, a mode combination was often not feasible for many origin-destination pairs -- bus-BUS-auto, for example)*. In addition the average data for all trips of each MAIN mode type were obtained.

For each set of data for which average values were computed, the standard deviation σ was estimated according to the formula

$$\sigma = \sqrt{\sum_{i=1}^{N} \frac{(X_i - \bar{X})^2}{N}} \quad \text{for} \quad \bar{X} = \frac{\sum_{i=1}^{N} X_i}{N}, \qquad (3)$$

where $\bar{X}$ represents the mean value of the N data points $\{X_i\}$**. This serves as a measure of how widely the trip data vary among the many origin-to-destination pairs. Small values of σ are hopefully a sign that trends seen in the data are significant.

Consider, then, an "average" suburb-to-suburb trip representing the mean of the 14 origin-to-destination pairs in the study. The AUTO distance for this trip is 212 miles. (The average distance traveled for all 229 trips*** studied is 251 miles). The energy consumed is 311 kwh; the time

---

*We do not mean to imply that our set of trips is a scientifically chosen random sample of all trips in the New York-to-Washington corridor. Rather, we seek a variety of trips to span a realistic range of trip patterns for medium-range, suburb-to-suburb travel.

**The terms "mean" and "average" are used interchangeably here, as defined in Eq. (3).

***This set excludes AIR via Dulles trips, of which there were 19.

spent is 4.3 hours and the cost, $31. The most energy-thrifty trip is rail-RAIL-rail, whose average is 76 kwh; the most energy intensive is auto-AIR-auto at 800 kwh.

In a manner analagous to Figure 2, we plot, in Figure 3, the energy, time and dollar expenditures for our average suburb-to-suburb trips. Each value represents an average of all trips of that type studied.

For the energy results, the energy consumed by the MAIN mode is indicated below the total (average) energy consumption. In addition, the magnitude of the standard deviation σ is indicated by an arrow for each mean energy value, along with the number of trips (N) from which the mean values were calculated.

As is evident in Figure 3, the value of σ is in general an order of magnitude lower than the corresponding mean value. This is to be contrasted to the average (not shown) of all trip types for each origin-to-destination pair, for which σ was comparable in magnitude to the average energy value. Thus the homogeneity of the data is stronger among trips of the same mode combination between different origin and destinations, than it is among all the trips between the same origin and destination. The standard deviations for other quantities averaged (time, dollar cost, distance, etc.) showed similar behavior. Note, in addition, that the magnitude of σ is greater for all trips by any MAIN mode than it is for individual trip types by that MAIN mode. The purpose of this work is to analyze the costs of many trip types, or mode combinations, with a vareity of origin and destinations providing a range of results. The relative smallness of σ indicated in Figure 3 is hopefully a sign that trends seen in the average data for each trip type are representative of many intercity trips.

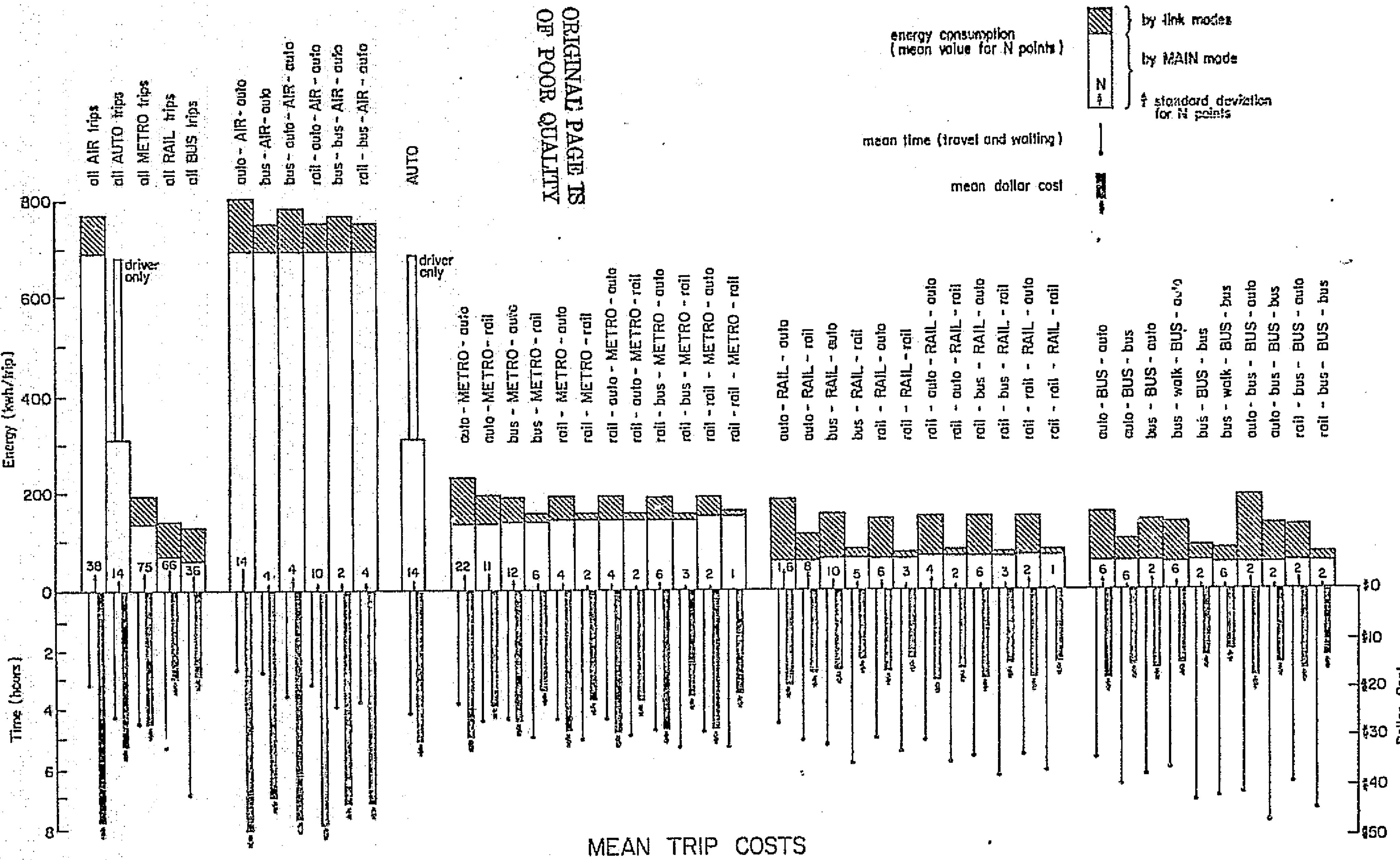


Figure 3: ENERGY, TIME AND DOLLAR EXPENDITURES FOR AVERAGE SUBURB-TO-SUBURB TRIP.
First set of bars show mean values for trips by each MAIN mode (38 AIR trips, etc.). Remaining bars show mean values for each trip type (14 auto-AIR-auto trips, etc.) Total energy results are separated into MAIN and link-mode contributions; arrow indicates the standard deviation for the N trips in sample.

A visual examination of Figure 3 indicates an expansion of the same trends we saw for the Clifton-to-Rockville trips. Dividing all trip types according to their present MAIN modes, the first set of five bars shows mean values for all trips by each MAIN mode. The anticipated result is there: in order of decreasing energy consumption, increasing time and decreasing dollar costs, the MAIN modes are ranked as follows: AIR, AUTO, METRO, RAIL and BUS.

A terminal-to-terminal energy comparison is based on energy per passenger-mile ϵ_{pm} data for the MAIN modes, of which Table 3 is a sample. We want to compare these with the average energy per passenger-mile data resulting from our origin-to-destination study, where these data, denoted E_{pm}, include the effect of modes linking to the MAIN modes, and the variation in total distance traveled as a result of different mode combinations. Values for E_{pm} will be computed from the total energy consumed for each trip type , as shown in Figure 3, divided by the total distance traveled. For our "average" suburb-to-suburb trips the minimum distance* traveled is by AUTO: 212 miles. Trips involving RAIL or METRO average 245 miles. On the average, BUS trips are longer: 265 miles. By far the longest trips are by AIR, for which the average trip distance traveled is 280 miles. Since RAIL or BUS is less energy-intensive than AUTO (on the basis of ϵ_{pm}), the added distance traveled narrows the energy gap between RAIL and AUTO, or BUS and AUTO trips. On the other hand, the fact that origin-to-destination AIR trips are so long makes them appear even more energy-intensive than they would in a terminal-to-terminal analysis.

---

*The AUTO distance was a minimum for <u>each</u> origin-destination pair, as well as for their averages.

Table 7 shows a comparison of terminal-to-terminal energy-per-passenger-mile (ϵ_{pm}) data with the average energy consumed per mile (E_{pm}) by a passenger for a complete trip between origin and destination. For a direct comparison with ϵ_{pm}, values shown for E_{pm} represent average values for <u>all</u> trips by each MAIN mod^ ·-th the range in values indicated for relevant trips.

In all cases, the maximum values result from an auto link on both ends of the trip (auto-AIR-auto, etc.) For BUS trips, the link modes increase ϵ_{pm} by as much as by a factor of 2.4 (or as little as 1.2). The increase for RAIL is similar. For METRO, the increase is a maximum factor of 1.4 while an 8% reduction is possible by the use of bus and rail for two of the two or three links. For AIR any ground transportation is less energy-intensive, but because the energy consumed in flight is so high, the resulting energy per passenger-mile, E_{pm}, is between 90% and 98% of the value shown for ϵ_{pm}. Thus the major variations are seen for the energy-thrifty modes, and the gap between BUS and AIR is narrowed by an origin-to-destination versus a terminal-to-terminal comparison.

An analagous comparison can be made with dollar costs per passenger-mile. It turns out that the cost per mile for each MAIN mode, as measured by the fare between terminals, is to a great extent independent of terminal pairs, for our study area. The variation is a factor of two: BUS costs a passenger approximately 5.5¢ per mile, RAIL costs 6¢ per mile, METRO is 9¢ per mile, and AIR is approximately 12¢ per mile (By our assumption, driver-only AUTO is the most expensive, at 13.5¢ per mile). A total trip, of course, includes the dollar cost associated with the link modes, parking charges and tolls. The resulting average dollar costs per passenger-mile, for the entire origin-to-destination trip (averaged over trip types for each MAIN mode) increase the terminal-to-terminal costs by from 1¢ to 3¢ per mile: to 6¢ per mile for all BUS trips, 7¢ per mile for RAIL, 11¢ per mile for METRO, up to 15¢ per mile for AUTO and nearly 16¢ per mile for AIR.

Table 7

TERMINAL-TO-TERMINAL VS. ORIGIN-TO-DESTINATION

ENERGY-PER-PASSENGER-MILE DATA

MAIN mode	Terminal-to-terminal ε_{pm}	Average for all trips E_{pm}	Origin-to-destination Range in values seen[2]
AIR	2.94	2.79	2.66 to 2.89
AUTO	1.46	1.46	--
METRO	0.66	0.80	0.61 to 0.95
RAIL	0.32	0.57	0.32 to 0.75
BUS	0.26	0.47	0.32 to 0.63

[1] Taken from Table 3.

[2] Values shown are mean values for trip types as shown in Figure 3.

[3] Computed from total average energy per trip divided by total (average) distance traveled.

Per-passenger-mile data do not reflect different distances traveled, between the same origin and destination by different mode combinations. We return now to the total costs per trip for the mode combinations studied. The maximum average energy seen is for auto-AIR-auto, at 800 kwh. This trip type also reflects the maximum dollar cost ($49) and minimum total travel time (2.7 hours). The minimum energy-consumer is rail-RAIL-rail at 76 kwh. Only slightly above the minimum, about 6 kwh higher, are rail-auto-RAIL-rail, rail-bus-RAIL-rail, rail-rail-RAIL-rail, and rail-bus-BUS-bus.* Thus, with one exception, the mode combinations including only bus and rail are the most energy efficient, even though the distances traveled are considerably larger than by AUTO or some other mode combinations. Since auto-AIR-auto and rail-RAIL-rail represent combinations of, respectively, the highest and lowest energy-consuming modes, the factor of ten variation, from 800 kwh to less than 80 kwh, probably represents a realistic range of results for suburb-to-suburb trips involving cities approximately 200 miles apart.

The variation for time and dollar costs is a factor of three. Where auto-AIR-auto represents the quickest (2.7 hours) but most costly ($49) trip, the cheapest trip is by bus-walk-BUS-bus for $14.00, with corresponding travel time of 7.3 hours. Similar low-cost (and time-intensive) results were seen for rail-bus-BUS-bus ($15; 7.8 hours), bus-RAIL-rail ($14.50; 6 hours) and rail-RAIL-rail ($15; 5.7 hours). Note that the energy consumption for these trips is near-minimum, so that they become the antithesis of the energy-intensive, dollar costly and time-saving auto-AIR-auto trip.

---

*In Figure 3, auto-bus-BUS-auto and auto-bus-BUS-bus results reflect trips only from Allenhurst: the anomalously high energy consumption is a result of the added travel required to get to centrally located BUS or RAIL terminals.

As is evident from Figure 3, nearly all BUS and RAIL trips, whose maximum cost is $20, are considerably less expensive than the average driver-only AUTO trip whose cost, including tolls and 13.5¢ per mile, comes to $31. Clearly if the cost is shared evenly between driver and passenger, AUTO can be as "cheap" as BUS or RAIL. In terms of time, the AUTO trip takes 4.3 hours -- considerably less than the average of 5.4 hours for all RAIL trips and 6.9 for all BUS trips, and on a par with the METRO average of 4.5 hours. As noted, AUTO is more time-consuming than AIR trips which average 3.2 hours -- for an average additional cost of $16.

In general, as we saw for the Clifton-to-Rockville trips, these time savings can be had for a price, or, savings in dollars or energy cost the traveler time. We are faced with a three-dimensional analysis: energy vs. time vs. money, where the optimal trip represents a minimum in these three variables, or some combination of them. The task is complicated by the inverse correlation between energy and time, and between dollar cost and time. As there is no intrinsic dollar value of time or energy, an objective index of the "total" cost of a trip, reflecting energy, time and dollar costs, is difficult to come by. For our purposes here, we will approximate the three-dimensional analysis by presenting the results in two-dimensional form, where we compare costs two at a time (e.g., time vs. money), with reference to the third (energy).

We start with energy vs. dollar cost: Figure 4 shows the results for our "average" suburb-to-suburb travel. For each MAIN mode, the mean energy-dollar cost is shown, with the standard deviation in energy or dollar cost indicated respectively, by a vertical or horizontal line through the mean value. In addition, the (average) result for each trip-type is shown. These values appear in clusters, according to their MAIN modes. It is evident that, for each MAIN mode, results for the

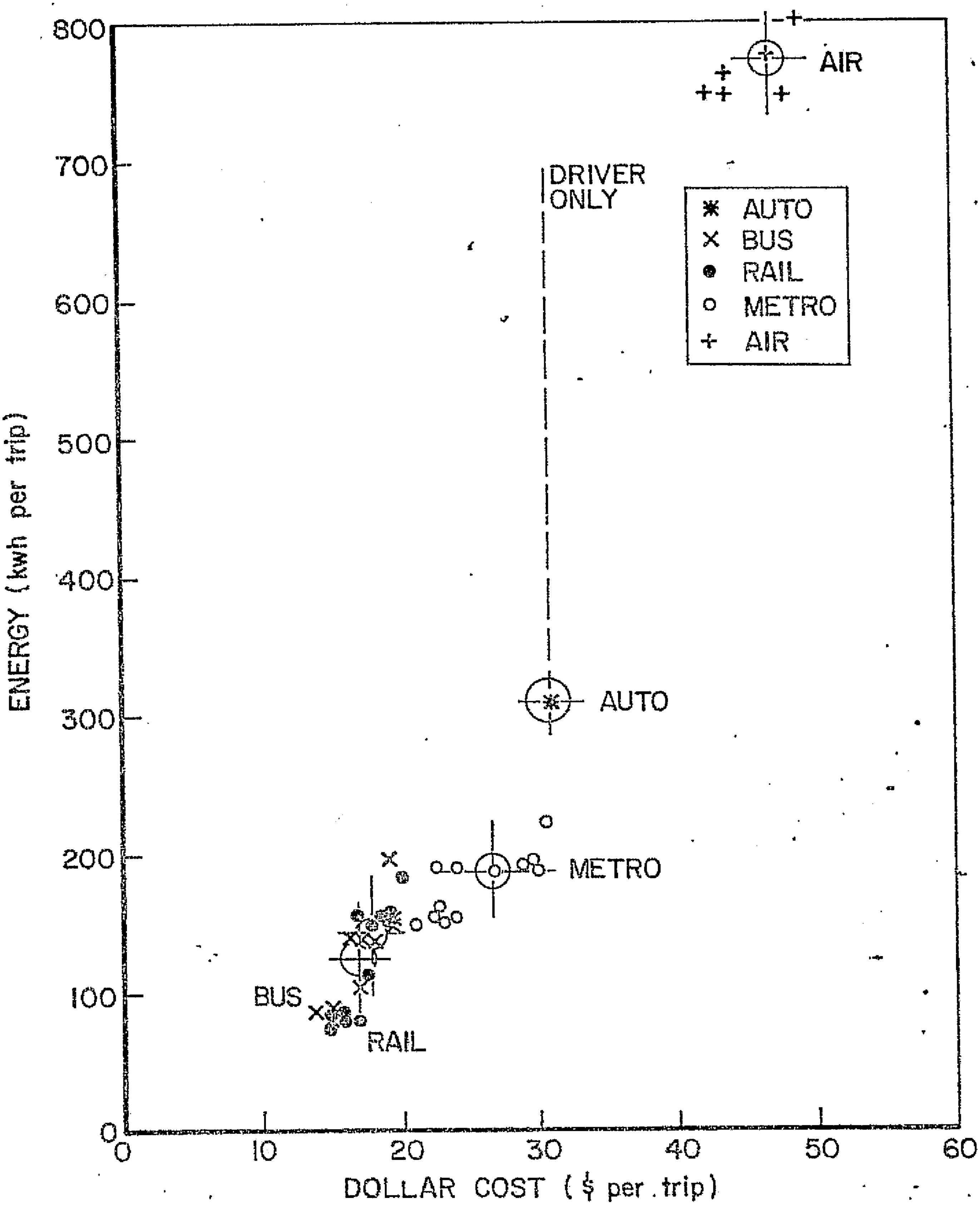


Figure 4: TOTAL ENERGY VS. TOTAL DOLLAR EXPENDITURES FOR AVERAGE TRIP. For each MAIN mode, large circle (with cross lines) indicates average value (and standard deviations) for all trips by that MAIN mode. Other parts correspond to mean values for individual trip types. (Data shown are consistent with Figure 2).

several trip types in general vary less than results for different MAIN modes. The exception is BUS and RAIL where the energy-dollar results overlap considerably: BUS trips are slightly more energy and dollar-costly than RAIL trips. METRO trips are considerably more costly in energy and dollar terms. Considerably higher --moreso in energy than in dollar terms -- is AUTO: the energy consumption is proportionately out of scale for the driver-only case. The AIR trips appear at the high-energy, high-dollar-cost end of the scale. Not only does the absolute value of these costs increase as we proceed from BUS to AIR, but their ratio increases substantially, from approximately 7 kwh per dollar for BUS, RAIL and METRO to more than twice that for AIR.

The energy vs. time picture, in Figure 5, is a near-mirror image of Figure 4. Energy and time appear inversely correlated in the way that energy and dollar costs were correlated. Here RAIL and BUS trips are more separate, and BUS trips in general are more time-consuming than RAIL even though their dollar costs are similar. In general, Figure 5 shows decreased travel time resulting in increased expenditure of energy Ranking MAIN modes in the order of increasing energy consumption: BUS, RAIL, METRO, AUTO and AIR, the order is preserved to a surprising degree for increasing dollar costs and decreasing travel times.

Now we look at travel time and dollar costs, or time vs. money: the two criteria a traveler is apt to use in choosing the way to travel between two points. Figure 6 contains the results, showing the inverse correlation we anticipated. In general, BUS trips consume considerably more time than do RAIL trips without being much cheaper: as is evident from Figures 3 or 4, the relatively minor energy savings perhaps does not warrant the added travel time. Compared with the other MAIN modes,

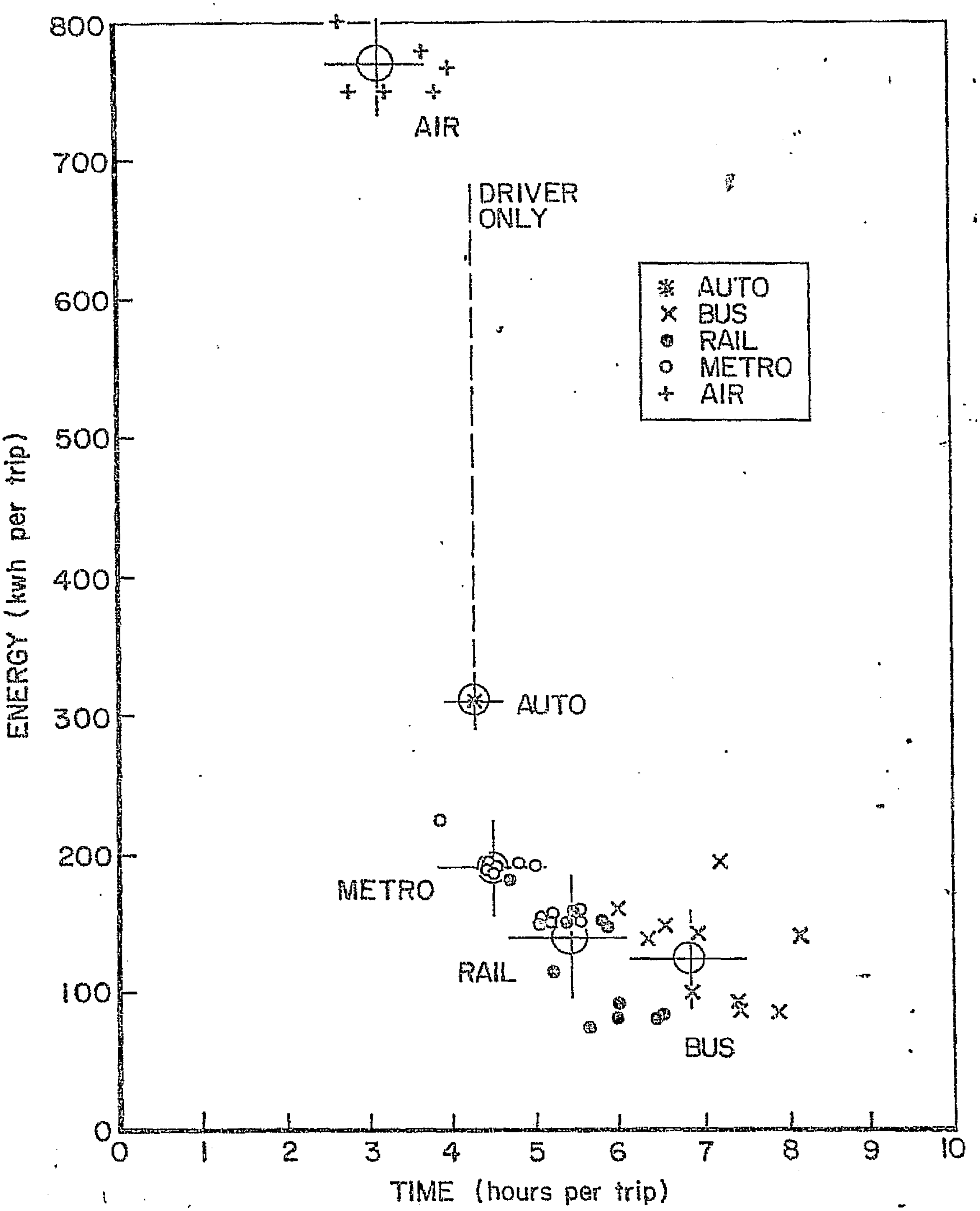


Figure 5 : TOTAL ENERGY VS. TOTAL TRAVEL TIME EXPENDITURES FOR AVERAGE TRIP. (See Figure 4 for explanation).

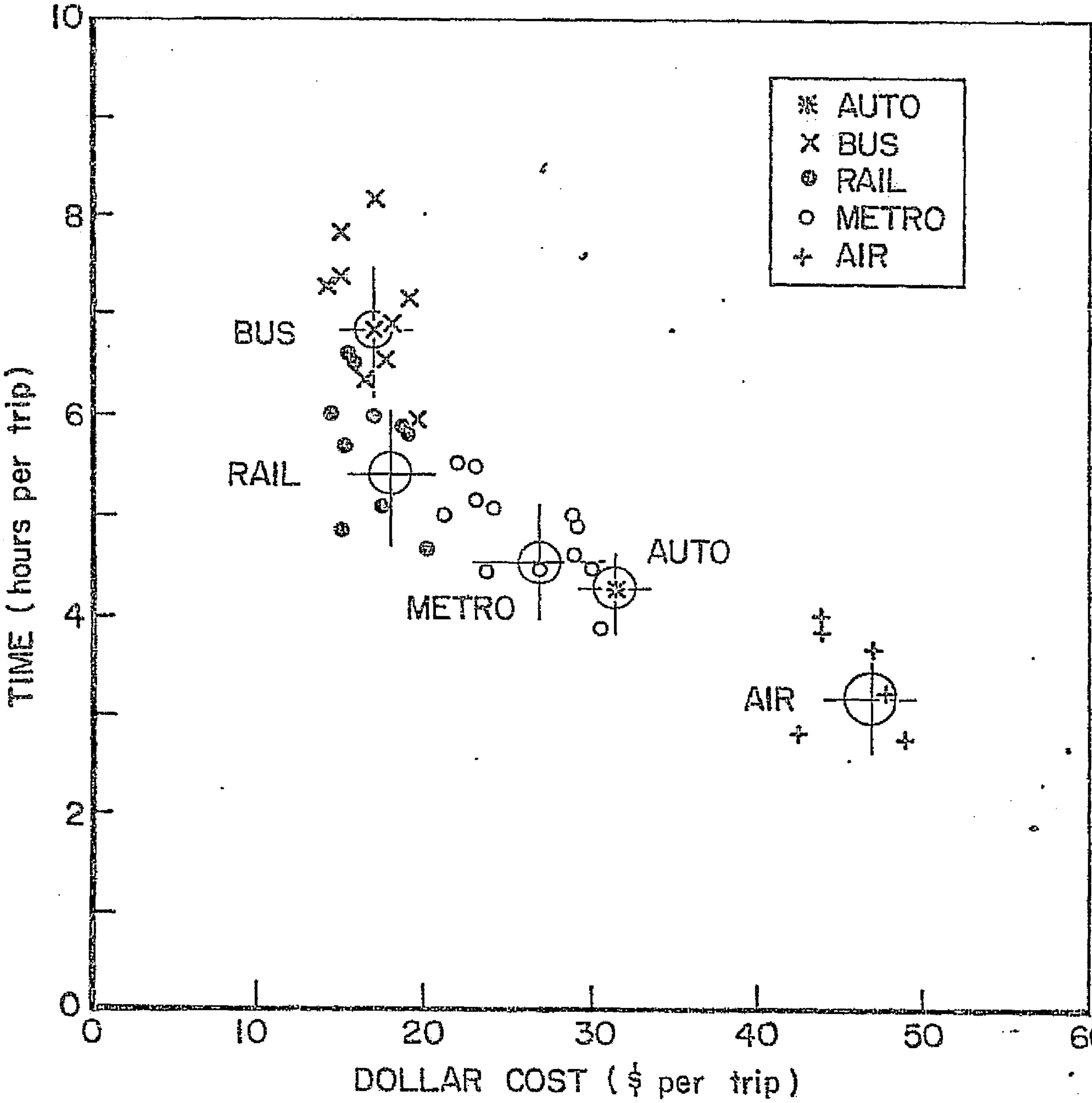


Figure 6: TOTAL TRAVEL TIME VS. TOTAL DOLLAR EXPENDITURES FOR AVERAGE TRIP. (See Figure 4 for explanation).

AIR trips are considerably more expensive, as well as time saving. To examine this in more detail, we return to the "time value" index V_{LM} discussed previously for specific Clifton-to-Rockville trips.

Again defining V_{LM} as the negative ratio of the dollar cost difference to difference in total travel time (See Eq. 2), we assume that trip L is worth the added dollar cost if the traveler values his time more than V_{LM} dollars per hour. Using the mean values shown in Figure 6, we shall compare the average trip by one MAIN mode with the average by another (AIR vs. AUTO, for example).

Results are shown in Table 8. To combine the energy results with the time-money comparison, we show corresponding values of added energy costs A_{LM}, given by the difference in average energy consumption for trips by MAIN modes L and M. As we saw in Figure 3 the more expensive trip generally consumes more energy. Thus, if L is more expensive than M, we see generally positive results for V_{LM} and A_{LM}.

In our sample, AIR trips are the quickest but the most expensive. On the average, AUTO costs $16 less but takes 1.1 hours longer: the AIR trip is worth the added expense for the traveler whose time value is greater than $14 per hour. Should a traveler choose AUTO on this basis, he might save several hundred kwh of energy, depending on whether he drives alone or not.*

RAIL costs $30 less than AIR, but because the added time is over 2 hours, the time value is similar to the AIR vs. AUTO comparison. Note the substantial (nearly 700 kwh) energy savings of RAIL over AIR.

---

*We emphasize the non-random nature of our sample. How representative of other 200-mile trips our sample is needs further exploration.

Table 8

COMPARISON OF AVERAGE SUBURB-TO-SUBURB TRIPS ON BASIS OF DOLLAR VALUE TRAVELER PLACES ON HIS OWN TIME: THE LOWER THE VALUE OF V_{LM}, THE MORE LIKELY THE TRAVELER WILL CHOOSE L OVER M

	L		M		V_{LM} [1]		A_{LM} [2]
On the average:	AIR[3]	is preferable to	AUTO	if traveler's time is worth more than	$14. per hour	Added energy cost	90 to 460 kwh
	"	"	METRO	"	$15.	"	580
	"	"	RAIL	"	$13.	"	630
	"	"	BUS	"	$ 8.	"	650
	AUTO	"	METRO	"	$49.	"	120 to 490
	"	"	RAIL	"	$12.	"	170 to 540
	"	"	BUS	"	$ 6.	"	190 to 560
	METRO	""	RAIL	"	$11.	"	50
	"	"	BUS	"	$ 4.	"	70
	RAIL	"	BUS	"	$ 1.	"	15

[1] Time value V_{LM} is computed from Equation 2. In 11 cases, trips by MAIN mode L, on the average, cost more money and less time than those by MAIN mode M.

[2] A_{LM} represents the average energy consumption for trips by MAIN mode L minus average energy consumption for trips by M. Range shown for data involving AUTO indicates different occupancy levels.

[3] Each MAIN mode shown represents the average of all trips by that MAIN mode.

The comparison with the lowest time value is RAIL vs BUS: RAIL costs, on the average, only $1.10 more but saves 1.5 hours. The added energy cost is very small (15 kwh), so that for the trips studied, RAIL appears in a good light when compared with BUS.

A comparison of AUTO and METRO is interesting. The time value V_{LM} of $19. represents a small increment in dollar cost of $4. and an insignificant time savings of 13 minutes. The energy savings can be substantial if compared with driver-only AUTO. These results represent average values for all METRO trips examined.

Perhaps a more realistic comparison is between AUTO and auto-METRO-auto (As Table 2 showed, both trip types were included for all origin-destination pairs). For this comparison the time value V_{LM} is negative: AUTO costs almost $1 more and takes nearly one-half hour longer. In addition, the energy consumed for the AUTO trips is nearly 500 kwh more per person-trip if the driver travels alone, and 2 passengers (i.e., AUTO occupancy of 3) are required before the energy consumption for AUTO and auto-METRO-auto becomes comparable. This is one of the rare cases where one trip type costs less in dollar, time and energy terms: similar results were seen for specific AUTO and auto-METRO-auto trips between Clifton and Rockville, as noted, and for essentially all other origin-destination pairs in the study. With the criteria used here, then, auto-METRO-auto appears unequivocably preferable to AUTO for medium-range intercity trips.

This result prompted a search among all pairs of trips, for any in which one trip is uniformly more costly than the other, in time, dollar and energy terms. We looked first at the average values for each trip type, and then at specific trips between origin and destination.

From the total of 42 trip types (or, mode combinations) studied here, a comparison of over 800 pairs is possible. For the average values, less than one-tenth of the possible pairs show greater time, dollar and energy costs for one trip type over another: as already mentioned, the trip type costing more in dollars typically consumes more energy and less time.

Of the exceptions the following pattern emerged: on the average, many RAIL trips are cheaper in all three ways then many BUS trips: auto-RAIL-auto vs. auto-BUS-auto, for example. The three specific origin-destination pairs for which both of these trip types are options show the same pattern: each specific auto-RAIL-auto trip consumes less energy, money and time than the auto-BUS-auto trip between the same origin and destination. Similarly, specific results uphold the trends of the average results for all BUS vs. RAIL comparisons. In this light, RAIL trips appear preferable to BUS trips, even, as it turns out, when the BUS trip relies more on the auto (e.g, auto-BUS-bus vs. bus-RAIL-rail).

A terminal-to-terminal comparison of RAIL and BUS would show RAIL as less time-consuming but more energy-costly (Dollar costs are similar, at approximately 6¢ per mile). The change indicated by a consideration of origin-to-destination trips, wherein RAIL appears favorable to BUS on all counts, of course depends on current practice of BUS trips: location of terminals and frequency of service (as well as our subjective judgment that a BUS traveler might be reluctant to pay for a taxi to his destination).

A look at average values for METRO and RAIL trips leads to a deceptively similar conclusion, that RAIL trips may be preferable to METRO trips. For example, on the average rail-METRO-auto trips cost more money, time and energy than rail-RAIL-auto trips. But any traveler knows that between the same origin and destination, which are linked to the same terminals for RAIL or METRO, the METRO trip takes less time and costs more money (as well as energy) than the comparable trip. The four specific trips for which rail-METRO-auto and rail-RAIL-auto are both options show higher dollar, energy costs but lower time for the METRO trip. In the several other cases where on the basis of average values RAIL appears favorable to METRO, specific trips usually contradict this trend, so that RAIL is preferable in some way(s)and METRO in other(s).

Possibly we should restrict our comparisons of trips by different MAIN modes to trips with similar links on both ends. Except for those mentioned: AUTO vs. auto-METRO-auto, auto-BUS-auto vs. auto-RAIL-auto, auto-BUS-auto vs. rail-auto-RAIL-auto, (and rail-METRO-auto vs. rail-RAIL-auto, for which specific results do not uphold the average), all comparisons yield one trip more costly on only two of the three counts (e.g. money, energy but not time).

A few cases exist for which the more energy--intensive trip costs less time and money* (e.g., bus-RAIL-auto vs. rail-bus-BUS-auto). These comparisons show a time-money incentive to use more energy. A change in fare structure might shift the incentive to the more energy-thrifty mode combination.

*In previous notation, V_{LM} is negative when A_{LM} is positive.

Our analysis thus far has placed no dollar value on the actual time spent in travel, but only on the additional time spent due to one type of trip versus another. An alternative approach is to examine the total dollar cost of a trip, to reflect the out-of-pocket costs and in addition any earnings lost from spending time in travel. This new approach of course, depends on the validity of the "time equals money" hypothesis, which is at best subject to criticism.

Let v represent the value of an hour of a traveler's time, as measured perhaps by his earning power. If the trip's fare (or, in the case of AUTO, operating and toll expenses) is C and the time expended in hours is T, then the <u>total</u> dollar cost reflecting both time and dollar expenditures becomes

$$D(v) = C + Tv \quad . \tag{4}$$

Note that D(O) corresponds to the dollar costs presented previously, in Figures 2,3,4 and 6. We have seen that BUS and RAIL trips are comparable in dollar costs. With increasing values of v, BUS diverges, and by v =\$10 per hour, BUS trips on the average are 20% higher than RAIL trips.

In order to compare the MAIN modes on the basis of the total cost estimate D(v), D and T were averaged over all origin-destination pairs, for each trip type, to obtain average total costs D(v) as a function of v. The resulting range in values for each MAIN mode is shown in Figure 7. At the lower end of the scale (v=o), representing out-of-pocket expenditures, BUS and RAIL trips are equally inexpensive. The cheapest METRO trip costs not much more than the most expensive BUS or RAIL trip, but in general METRO is considerably more expensive. AUTO overlaps with the upper part of the METRO scale. AIR is far above the other MAIN modes, by approximately a factor of two.

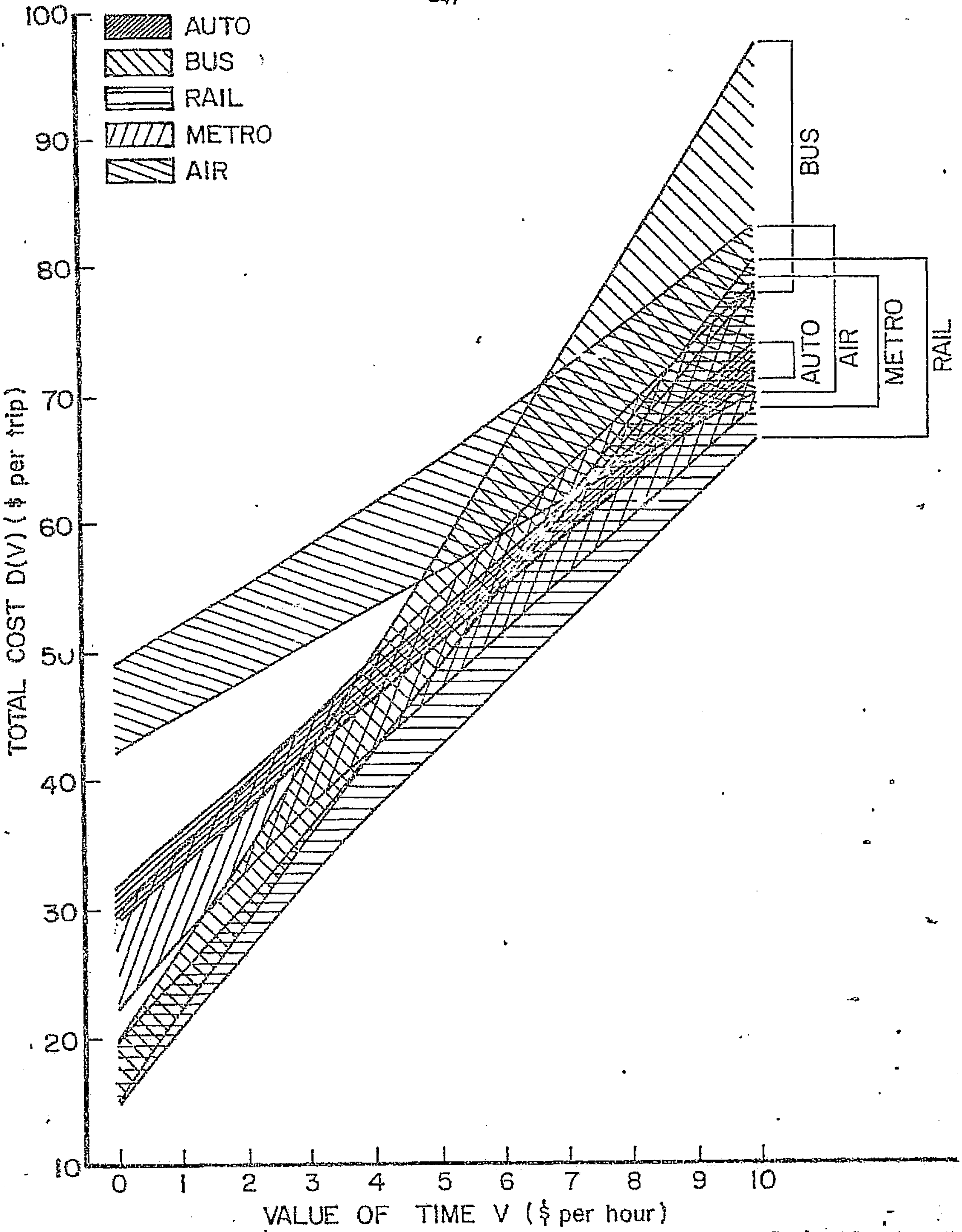


Figure 7: TOTAL DOLLAR COST D(v) FOR AVERAGE SUBURB-TO-SUBURB TRIP. Cost includes out-of-pocket expenditures C (corresponding to dollar costs shown in Figures 3, 4 and 6) and value v placed on passenger's time T, where D(v)=C+Tv. For each MAIN mode, the range of (average) results obtained for each trip type is shown.

As v increases, RAIL remains as the less expensive mode. BUS diverges, with the upper end of its range being far above trips by any other mode (auto-bus-BUS-bus, from Allenhurst, produced the maximum value for D($10.), of nearly $100). A great deal of overlap appears among AIR, METRO and RAIL (as well as BUS) trips as v increases, while AUTO becomes less expensive than most trips. It is interesting that dollar costs for AIR can compare favorably with the other modes if a traveler values his time as "expensive".

If we were to examine the results for each trip type within the range shown for the parent MAIN modes, several patterns emerge. For any MAIN mode, auto-MAIN-auto, of all trip types studied, is the most expensive at v=o. By v=10, the same (average) trip becomes the cheapest because of the travel time saved at both ends of the trip. In general trips involving one or more auto links, when compared with other trips using the same MAIN mode, are more expensive in terms of direct costs (i.e., v=o), but become relatively cheap for the traveler who places a high value on his own time.

The reverse is in general true: at v=o, for any MAIN mode the cheapest trip type is one which uses non-auto links (e.g., bus-RAIL-rail trips average the lowest fare of all RAIL trips studied), and at v=10 the most expensive again is usually one--not necessarily the same one--with bus and rail links at both ends (rail-bus-RAIL-rail for RAIL trips). Thus auto links tend to increase the dollar (as well as energy) costs of a trip, but without the waiting and other additional travel times associated with other link modes, auto use can reduce total dollar costs -- on the time-equals-money hypothesis.

We have observed that low-cost trips are generally energy-thrifty

(Figure 4). This, combined with Figures 6 and 8, implies that the traveler who places little value on his own time is likely to choose an energy-thrifty trip, while the traveler at the other end of the scale (with v = $10 per hour) will rely on energy-intensive travel. Where energy conservation is the goal, market incentives should be aimed at the traveler with "earning power", to divert him from the fastest, most energy-intensive modes, or, equivalently, to improve the service characteristics of the energy-thrifty modes, so that the overall trip times can compete with the minimum travel times offered by the other more energy-intensive modes.

F. CONCLUDING REMARKS

We have examined time-money-energy costs associated with specific and "average" trips between Newark and Washington suburbs. The reader may at this point wonder whether any traveler couldn't draw the same conclusions drawn so laboriously here: it is common knowledge, for example, that AIR travel can be faster but is more dollar-and energy-costly than a similar trip by BUS. This work has attempted to put a quantitative grasp on these conclusions, to ascertain to what extent one type of trip is more or less costly than another, when energy, time and dollar costs are included, for all segments of the trip connecting its origin with its destination.

Substantial data have been generated in the course of this work. With the hundreds of trips analyzed, any number of specific comparisons are possible, with generalizable conclusions more difficult to draw. The data will continue to be reworked; other indices will hopefully be devised for comparing trips on this multi-dimensional, energy-time-dollar basis, with the ultimate aim of presenting concise conclusions of use in intercity travel policy.

Eventually, additional costs associated with emissions and noise should be added to complete the <u>total</u> cost analysis of intercity trips. Preliminary data have been generated concerning hydrocarbon, carbon monoxide and nitrogen oxide emissions as well as area "disturbed" by noise. Presentation of this part of the study awaits more reliable basic emissions and noise data for some of the modes, and, perhaps more important, an objective way of comparing one type of emission with another, or noise generated by one mode with noise from another.

Ultimately, the generalizability of the results should be tested. Once a methodology is developed by which one can draw concise conclusions, it will hopefully be applied to trips between other suburb pairs in the New York-to-Washington corridor and other areas in the U.S.

APPENDIX. ENERGY CONSUMPTION PER VEHICLE-MILE BY MODES USED IN INTERCITY TRAVEL

Table 3 contained the energy-per-passenger-mile (ϵ_{pm}) data assumed throughout the analysis. These estimates were based on energy consumption per vehicle-mile (ϵ_{vm}) and the average occupancy level (p passengers per vehicle):

$$\epsilon_{pm} = \epsilon_{vm} / p . \tag{A1}$$

The quantity ϵ_{vm} is calculated from the operating energy requirements, per vehicle-mile (ϵ_o), plus the energy consumed in the manufacture of the vehicles (M_v) and guideways (M_g) amortized over their respective lifetimes (L_v and L_g):*

$$\epsilon_{vm} = \epsilon_o + M_v/L_v + M_g/L_g . \tag{A2}$$

Table A1 contains the values of the data needed to evaluate ϵ_{vm} and ϵ_{pm}. In addition, seating capacity S of each vehicle is listed. Results are shown for each of the modes used in the intercity trips analyzed here: MAIN modes AUTO, BUS, conventional RAIL, METRO-liner and AIR; link modes auto, bus, rail and walk. The derivation of these data is described in the following. A general discussion of the manufacture energy requirements precedes a description of the operating energy requirements, which is arranged by mode.

A. MANUFACTURE ENERGY REQUIREMENTS

The manufacture energy requirements for bus and auto were derived in reference 5. With similar methodology, the calculation for conventional rail, the Metroliner and the airplane was part of this work. Evaluation of M_v requires a detailed analysis of the material content of the vehicle: this was based on specific manufacturer specifications and, in addition, <u>Census of Manufactures</u> data.[6]

---

*Reference 5 contains a description of this methodology.

Table A1

ENERGY REQUIREMENTS FOR MODES USED IN INTERCITY TRAVEL

	Link Modes				MAIN Modes					
	Auto	Bus	Rail	Walk	AUTO	BUS	RAIL	METRO	AIR via National	AIR via Dulles
S (seats per vehicle)	6	40	72	1	6	44	72	72	109	89
p (passengers per vehicle)	1.4	8.0	41	1	2.2	28.4	41	40	50	22
M_v (million kwh per vehicle)[1]	0.039	0.30	2.0	-	0.039	0.28	2.0	2.1	3.4	4.2
L_v (million vehicle-miles)	0.1	1	3	-	0.1	1	3	3	10	10
M_g (million kwh per mile)	4.6	4.6	5.0	-	4.6	4.6	5.0	5.0	58	58
L_g (million vehicles)	160	54	35	-	160	54	35	35	330	330
ϵ_o (kwh per vehicle-mile)	3.19	8.66	12.4	0.063	2.80	7.03	12.4	25.6	146	202
ϵ_{vm} (kwh per vehicle-mile)[2]	3.61	9.03	13.2	0.063	3.22	7.42	13.2	26.4	147	203
ϵ_{sm} (kwh per seat-mile)	0.60	0.23	0.18	0.063	0.54	0.17	0.18	0.37	1.3	2.3
ϵ_{pm} (kwh per passenger-mile)	2.58	1.13	0.32	0.063	1.46	0.26	0.32	0.66	2.9	9.2

Legend:

- S: vehicle capacity
- p: average occupancy (including driver for auto)
- M_v: energy required to manufacture vehicle
- L_v: lifetime of vehicle
- M_g: energy required to construct lane-mile of guideway
- L_g: guideway lifetime
- ϵ_o: operating energy consumption per vehicle mile
- ϵ_{vm}: total energy consumption per vehicle mile including operation and manufacture (Eq. A2)
- $\epsilon_{sm} = \epsilon_{vm}/s$: energy consumed per seat-mile
- $\epsilon_{pm} = \epsilon_{vm}/p$: energy consumed per passenger-mile

[1] Breakdown of manufacture energy contributions for vehicles appears in Table A2.

[2] Energy per vehicle-mile, including operation and manufacture contributions, is computed from

$$\epsilon_{vm} = \epsilon_o + M_v/L_v + M_g/L_g \quad \text{(Eq. A2)}.$$

The greatest effort was expended in the calculation of the energy required to manufacture an aircraft. A 67-ton Boeing passenger aircraft was used as a prototype, and values of M_v for other aircraft used in the Newark-to-Washington route were scaled up or down according to weight. The material analysis, based on a Boeing publication,[7] was generously supplied by Joseph Anderson at NASA Ames.[8] The resulting energy consumption, totaling nearly 6 million kwh, appeared schematically in Figure 1 on page 12. The fabrication and assembly, from Census of Manufactures data, accounts for 30 percent of the total.

Table A2 shows a breakdown of the manufacture energy M_v for the auto, bus, rail, and Metroliner, as well as for the 67-ton aircraft. In general the average energy consumed per ton is between 20,000 and 30,000 kwh per ton. For the aircraft it is considerably higher, because of the high proportion of aluminum (the production of which costs over 60,000 kwh per ton) as well as the proportionately high fabrication energy.

The average vehicle lifetimes L_v for the auto, bus and rail modes are taken from Reference 5. The estimate shown for AIR is consistent with vehicle life of 40,000 flight hours[9] and, for one-hour flights between New York and Washington, an overall average speed of 250 miles per hour.

The guideway contribution, M_g/L_g, is sufficiently small to warrant a very rough analysis. For rail and Metroliner, we adopted estimates used previously for urban rapid transit (reference 5), and for air a 1000-foot runway was assumed to be constructed with specifications, on a per square foot basis, similar to U.S. Interstate (again, reference 5), with an added 4 inches of Portland concrete.[9] The corresponding runway lifetime was derived from the equivalent of a 90-second headway for 12 hours per day, over a 15-year period, amortized over half of the 225-mile route.

Table A2

ENERGY REQUIREMENTS FOR THE MANUFACTURE OF AN
AUTOMOBILE, BUS, CONVENTIONAL RAIL AND METROLINER CARS, AND AIRCRAFT

	Auto[1]	Bus[2]	Conventional rail[3]	Metroliner[4]	Aircraft[5]
Vehicle Weight (tons)	1.8	10.0	78.6	82.9	66.7
Energy Contributions (kwh):					
manufacture of metallic materials	26,890	208,000	1.64×10^6	1.72×10^6	3.43×10^6
manufacture of other materials	1,210	11,800	0.07	0.07	0.08
fabrication of parts and assembly of the vehicle	9,600	74,400	0.21	0.26	2.31
transportation of materials	900	5,800	0.04	0.04	0.06
Total energy to manufacture vehicle (kwh)	38,600	300,000	1.96×10^6	2.08×10^6	5.88×10^6
Average manufacture energy per ton	21,400	30,000	24,900	25,100	88,100

1. Corresponds to automobile assumed for link and MAIN modes.
2. Corresponds to intercity BUS used as MAIN mode; bus used as link was assumed to be slightly smaller.
3. Corresponds to locomotive-hauled Congressional car; estimate includes energy contribution from manufacture of locomotive. Value shown was used for rail link and MAIN mode RAIL.
4. Used for METRO.
5. Based on Boeing 67 ton 130 - passenger aircraft.

B. OPERATING ENERGY REQUIREMENTS

AUTO, auto

The energy required to operate an automobile one mile, ϵ_o, is computed from the energy equivalent of one gallon of gasoline (39.2 kwh, including refining)[5], divided by the average miles per gallon. For urban auto (used as link), we assumed 12.3 mpg,[10] while for intercity AUTO, which combines highway with some stop-and-go driving, a higher value, 14 mpg, was assumed. The latter is quite close to the 1970 national average.[11]

BUS, bus

The diesel fuel used by buses represents 43.3 kwh per gallon, including refining.[5] The value of ϵ_o for link bus was based on the average 5.05 miles per gallon for a local New Jersey bus company,[10] while the average for intercity BUS between New York and Washington is higher, at 6.16 miles per gallon.[12]

RAIL, rail

By estimates of Penn Central engineers, conventional New York to Washington trains use 3.30 kwh of electrical energy per car-mile.[13] When fuel steam heating for electric locomotives and diesel fuel for switching engines are included, as implied by financial estimates, the energy consumption becomes 3.77 kwh/car-mile. The generation, transmission and distribution of 1kwh of electricity requires the consumption of over 3 kwh of energy resources. Assuming an overall end-use efficiency of 30.5%[5], the operating energy consumed for RAIL becomes 12.4 kwh per car-mile. For want of better data -- promised but not forthcoming from a large rail company in Northern New Jersey - the same value of ϵ_o was adopted for link rail.

In general better estimates are needed concerning energy consumption by all types of rail: how much energy is consumed, and for what phase of the operation.

METRO

Again from Penn Central estimates, the electrical energy consumed by METROliner is considerably more: 7.81 kwh per car-mile, or 25.6 kwh of energy resources per car-mile. As Table A2 indicates, this cannot be explained by excess weight of Metroliner cars. Apparently the discrepancy between METRO and RAIL energy consumption is due more to the difference in travel speed: by their design Metroliner trains operate optimally at higher speeds, but must decelerate and accelerate frequently in response to the out-of-date, winding track. Again, we recommend further research in this area.

AIR

Energy usage is very dependent upon the type of aircraft used. The distribution of flights and average flight times, as of June 15, 1974,[14] between Newark and Washington airports, are shown at the top of Table A3. The average values of ε_o were estimated from weighted averages of energy consumption results obtained for each aircraft type.

Our goal was to estimate ε_o, for each aircraft type, for any flight path and distance or time of flight. Relying on Calspan data[15] for the taxi, takeoff, climbout and approach modes,* and on NREC estimates[16] for the cruise mode, we obtained fuel consumption estimates for relevant engine types (JT8D for the 727's and DC9; JT9D for the 707, and T56-A15 Turboprop for FH227). As the tests were carried out at ground level, the results were adjusted for the lower fuel consumption rates at high altitude using engine manufacturer estimates.[17] The assumed times spent in each mode correspond to U.S. EPA cycle times: 25 minutes for taxi-idle (total

---

*These laboratory data were primarily obtained for emissions testing, for the U.S. Environmental Protection Agency. The cruise mode was excluded from their tests. We used their data to obtain emissions (HC, CO and NO_x) as well as fuel consumption estimates.

Table A3

ENERGY CONSUMPTION BY AIRCRAFT USED IN NEWARK-TO-WASHINGTON FLIGHTS

	Newark to National (235 airplane-miles)			Newark to Dulles (255 airplane-miles)		
	727-100	727-200	DC9-30	707-120	727-100	FH227
Distribution of flights, as of June 1974	33.1%	22.5%	19.7%	9.9%	4.9%	9.9%
Total flight time (minutes)	55	56	55	71	72	76
Fuel consumption (gallons)[1] for individual flight modes:						
taxi[2]	169.	169.	112.	217.	169.	65.
takeoff	45.	45.	30.	75.	45.	6.
climbout	94.	94.	63.	155.	94.	20.
cruise	601.	635.	405.	1913.	1043.	109.
approach	82.	82.	55.	130.	82.	20.
Total fuel (gallons) consumed for trip[3]	991.	1025.	665.	2491.	1433.	219.
e_o: energy (kwh) per airplane-mile	158.	164.	106.	367.	211.	34.
Operating energy (kwh) per seat-mile	1.7	1.2	1.1	2.8	2.2	0.75

[1] Energy equivalence of jet fuel (JP4) was assumed to be 37.6 kwh/gallon for all aircraft except the FH227, which uses a different fuel with higher energy content (39.4, including refining). (Reference 19)

[2] EPA cycle times are assumed: 25 minutes total for taxi - idle at both ends of the trip; 0.7 minutes in takeoff, 2.2 minutes in climbout, 4.0 minutes in approach, and the remaining time in the cruise mode (Times for FH227 are slightly different; see text.)

[3] Contributions may not add to total due to individual rounding.

for both ends of trip), 0.7 minutes in takeoff, 2.2 minutes in climbout, 4.0 minutes in approach, and the remaining time in the cruise mode (for FH227, times were slightly different: 0.5 minutes for takeoff, 2.5 for climbout and 4.5 for approach).[15,18]

The resulting energy consumption estimates, for each aircraft type by flight mode, appear in Table A3. The variation among aircraft types is enormous. For flights to Dulles, the energy consumption for the 707 trip is an order of magnitude higher than for the FH227. Even on a seat-mile basis, where the lower capacity of the FH227 is included, a factor-of-three discrepancy exists in the same direction. Newark to Dulles trips are frequently part of a longer flight, to which the 707 is better suited in energy terms. It should be noted that these figures do not reflect recent improvements in aircraft energy efficiency, which have occurred in response to the "energy crisis": perhaps this inefficiency of the 707 is exaggerated in present terms.

The turboprop FH227, on the other hand, looks extremely efficient for trips in the 200 to 250-mile range. The reason it is used for only a small portion of the trips is apparently because its flight path is considerably lower than it is for, albeit less efficient, small jets.

It is clear from this analysis that the choice of aircraft to a great extent determines the overall energy consumed between two air terminals. In this sense we should talk about a shift to more efficient aircraft -- a measure in the control of flight operators and government agencies -- in the same way as we speak of a shift to bus or rail-- which is ultimately controlled by the individual. This shift to more efficient aircraft is perhaps as important an energy-saving measure as the, probably more difficult, goal of increased average occupancy.

References

1. Matthew Edelman et al., "Northern New Jersey Station Notebook", Transportation Program Report #74/TR/15, Princeton University, October 1974.

2. Census Tracts, Trenton, N.J. SMSA, 1970, Bureau of the Census, U.S. Department of Commerce (Final Report PHC(1)-217).

3. "Energy Statistics" (A Supplement to "Summary of National Transportation Statistics"), U.S. Department of Transportation Report #DOT-TSC-OST-73-34, September 1973, p. 59.

4. Nationwide Personal Transportation Study, Report #1, "Automobile Occupancy," U.S. DOT/FHA, April 1972, p. 16.

5. M.F. Fels. "Comparative Energy Costs of Urban Transportation Systems," Transportation Research, an International Journal 9, p. 297 (1975).

6. 1967 Census of Manufactures, U.S. Department of Commerce, Bureau of the Census, Washington, DC, 1971.

7. Boeing Company Commercial Airplane Division, Report #D6-23204 TN, Renton, Washington.

8. Joseph L. Anderson, NASA Ames Research Center, Unpublished Analysis of Aircraft Component Weights, 1974.

9. Alfred Mascy, NASA Ames Research Center (private communication), 1974.

10. M.F. Fels, and M.J. Munson, "Energy Thrift in Urban Transportation: Options for the Future," in Energy Conservation Papers (ed., R. Williams), Ballinger Publishing Co., Cambridge, Mass., 1975.

11. Highway Statistics 1970, U.S. Department of Transportation and Federal Highway Administation, Washington, D.C. 1970.

12. R.B. Gibson, Director of Transportation, Greyhound Lines, Inc. (Eastern Division, (private communication), 1974.

13. "Fully Allocated Cost of Rail Passenger Service between New York and Washington, Phase II. Metroliner and Conventional Passenger Trains During 1970", Peat, Marwick, Mitchell and Co. (PB 202-049), July 1971.

14. Official Airlines Guide, North American Edition, a Reuben H. Donnelley Publication, Oak Brook, Ill., June 15, 1974.

15. L. Bogdan and H.T. McAdams, "Analysis of Aircraft Emission Measurements," Calspan Report #NA-5007-K-1, October 1971.

16. "The Potential Impact of Aircraft Emission upon Air Quality", Northern Research Engineering Corporation, U.S. EPA Report # APTD-1085, December 1971.

17. The Jet Engine Publication, Rolls Royce Ltd., Reference J.S.D. 1302, 1973.

18. V.J. Sarli, Pratt and Whitney Aircraft Corporation, East Hartford, Conn. (private communication), 1974.

19. James J. Mutch, "Transporation Energy Use in the U.S.: A Statistical History, 1955-71", Rand Corporation R-1391-NSF, December 1973.