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A Survey and Analysis of Energy Intensity Estimates for Urban Transportation Modes

Author
Chomitz, Kenneth M.

Publication Date
1978-12-01

UCI-ITS-WP-78-14

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Kenneth M. Chomitz

School of Social Sciences and
Institute of Transportation Studies
University of California, Irvine

December 1978

Institute of Transportation Studies
University of California, Irvine
Irvine, CA 92697-3600, U.S.A.
http://www.its.uci.edu

The research in this paper was supported by Oak Ridge National Laboratory, Oak Ridge, Tennessee, under contract #ORNL-19-55435V. The author is grateful to ORNL and ITS for support, both financial and otherwise: special thanks are due to Charles Lave, School of Social Sciences and Lyn Long, Institute of Transportation Studies.

ABSTRACT

The current interest in energy conservation has resulted in a spate of divergent estimates of the energy intensiveness (EI) of urban transit modes. This paper critically reviews the methodologies and data sources employed by these estimates. It is shown that a very small repertory of sources and methodologies underlie the EI estimates, and that variance among them is primarily attributable to contradictory load factor assumptions. EI estimates for bus and rail transit are developed, and the inadequacies of automobile data are discussed. Buses are shown to be more efficient than rail transit, and it is shown that light rail's energy advantage over heavy rail lies in construction, not operation.

GLOSSARY

APTA -- American Public Transit Association

BART -- Bay Area Rapid Transit

Btu -- British thermal unit

CM - car-miles

EI -- energy intensity; in this report, always in Btu/passenger-mile, rounded to nearest 50.

FHWA -- Federal Highway Administration

ICC -- Interstate Commerce Commission

KWHe -- kilowatt-hours of electricity (delivered or consumed)

LF -- load factor: vehicle occupancy, expressed either in number of people/vehicle or in passenger-miles/seat-mile

LRV -- light rail vehicle

MBTA -- Massachusetts Bay Transportation Authority

NPTS -- Nationwide Personal Transportation Study

NTS -- National Travel Survey

NTranS -- 1974 National Transportation Study

NYCTA -- New York City Transit Authority

PATCO -- Port Authority Transit Corporation of Pennsylvania and New Jersey

PATH -- Port Authority Trans-Hudson Corporation

PM -- passenger-miles

SEPTA -- Southeastern Pennsylvania Transportation Authority

SM - seat-miles

SRI -- Stanford Research Institute

VMT -- vehicle-miles travelled; for rail, refers to car-miles or coach-miles

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Note on conversion factors:

The following equivalences are used throughout --

1 KWHe = 11373 Btu
1 gallon gasoline = 125000 Btu
1 gallon diesel = 138700 Btu
1 gallon propane = 91600 Btu

INTRODUCTION

During the past few years, researchers have devoted considerable effort to estimating the energy intensiveness of various transportation modes. As a result, a plethora of energy intensity (EI) values, often widely divergent, has been published. This report, which focuses on principal modes of urban passenger transportation, reviews some of the standard methodologies and data sources employed by EI researchers in an attempt to reconcile, or at least explain, the varying results. The principal conclusions are as follows:

--- The variety of EI estimates is misleading, in that much of the literature consists of secondary reports which reproduce a much smaller number of primary analyses.

--- The primary analyses rely on a limited repertoire of methodologies and a very small set of data sources.

--- Variance between EI estimates is primarily attributable to contradictory assumptions about vehicle occupancy. However, consistency in energy/vehicle-mile estimates tends to indicate parallel methods of analysis rather than mutually confirming independent approaches.

--- There are no reliable estimates of average urban automotive EI.

--- Buses are substantially more energy efficient than rail transit: A) traditional heavy rail systems use about 24% more operating energy than buses; B) modern heavy rail systems use about 100% more operating energy than buses; C) modern light rail transit seems to have about the same operating energy characteristics as modern heavy rail transit, i.e., it has no operating energy advantage.

Scope and Outline of Report

This report concentrates on aggregate statistical measures of EI rather than disaggregate engineering analyses. Following a brief exposition of definitional problems relating to EI, reviews of five urban transportation modes are presented. Each review describes the scope and reliability of source data, methods used to calculate vehicle fuel economy and load factor, and previous results. In some cases where new or expanded data have become available, this paper presents new EI estimates. Finally, an appendix describes a much-overlooked source, the 1974 National Transportation Study, and uses it to derive estimates of peak hour and weekday average load factors.

ENERGY INTENSITY - PROBLEMS OF DEFINITION

Energy intensity may be ambiguously defined as (energy input)/(transportation output). Ambiguity results unless the boundaries of the energy supply and the transportation system are precisely delineated. Different boundaries may be chosen to serve different analytic purposes. A recent Senate report (Congressional Budget Office, 1977) presents an excellent hierarchical framework of EI definition. A modification of that schema is shown in Table 1.

Energy consumption is outlined in the left-hand column. At the top of the column is vehicle propulsion energy, which is the most narrowly construed boundary of energy input possible. Going down the column, other components of energy use are successively added, incrementally widening the scope of the energy input. The right-hand column, describing the transportation system, works in the opposite direction.Starting with the broadest interpretation of transportation output, namely, seat miles or vehicle miles offered, scope is increasingly narrowed down to door-to-door straight-line passenger miles. Thus, to unambiguously

Table 1: Defining Energy Intensity

Components of Energy Input (listed downward in increasing generality of energy system boundary)	Measures of Transportation Output (listed downward in increasing specificity of desired output measure)
Vehicle propulsion- revenue operation	Vehicle-miles or seat-miles offered
Auxiliary power-revenue operation (heating, lighting, etc.)	
Vehicle operation-nonrevenue service	Passenger route-miles
Vehicle operation-inactive service	
Power to stations, shops, other fixed facilities	Passenger straight-line miles
Energy used to construct vehicles, guideways, stations	
Energy used by subsidiary modes (feeders, distributors)	Passenger straight-line miles,
	Door-to-door

specify EI, it is necessary to pick a specific level in the right-hand column and a cutoff point in the left.

Besides enforcing consistency, the hierarchical EI scheme has the attractive feature of distinguishing between fixed and variable energy costs. Too often an average EI value is employed in policy analysis where a marginal EI value wold be more applicable, and vice versa. For instance, it is inappropriate to consider sunk energy costs such as guideway construction when evaluating potential mode shifts between existing transportation systems. However, costs do become relevant in the evaluation of wholly new transit systems.

Thus, a hierarchical scheme of EI definition allows the energy analyst a great degree of flexibility. Unfortunately there is a paucity of information about station, maintenance and construction energy costs, and about trip circuity. Therefore, this report concentrates on vehicle operating energy: energy used to propel, heat, and light vehicles in active and inactive operation.

AUTOMOBILES

Automotive EI is determined by both vehicle fuel economy and by average occupancy (load factor). Methodologically, these two aspects of EI are very distinct and will therefore be treated separately.

Auto Fuel Economy

Attempts to estimate nationwide average auto fuel economy fall into three categories:

--- those based on FHWA compilations of aggregate gasoline consumption and VMT;

--- those employing weighted averages of EPA fuel economy ratings for individual models;

--- those based on the selection of a "representative" auto.

Each of these methodologies has severe drawbacks.

FHWA Statistics

Highway Statistics, an annual publication of the Federal Highway Administration (U. S. Federal Highway Administration, 1974), presents data on gasoline consumption and on vehicle miles traveled. Its tables MF-26, "Highway use of gasoline by months," and MF-25, "Private and commercial use of special fuels by months" ('special fuels' being primarily diesel) are based on state reports of fuel tax rates and revenues. The FHWA asserts that "the highway fuel consumption data are reliable for most states, but in a few there are indications that refund claims are excessive and that gasoline allegedly used for nonhighway purposes is actually used on the highway. To the extent that this occurs, the highway consumption of motor fuel is understated." (Highway Statistics, 1974, p. 6). However, since all nonhighway fuel use (detailed in Table MF-21) accounts for only 3.3% of total fuel use, even widespread tax fraud of this sort would have little impact; the fuel consumption figures may therefore be presumed reasonably accurate. In scope, these tables cover all nonmilitary domestic fuel use. Public and private fuel is disaggregated in Table MF-21. In short, the FHWA fuel consumption data appear to be about as reliable as transportation statistics get.

Calculating total U. S. vehicle miles traveled is a formidable task. The FHWA's procedures for estimating nationwide VMT were the subject of a recent study by TERA (Transportation and Economic Research Associates, 1977). TERA's findings may be briefly summarized as follows:

1. The FHWA's role is limited to reporting VMT estimates prepared by the individual state highway departments.

2. There is no uniformity of methodology among the states. Two principal approaches are used:

   a. traffic count - By monitoring the highway system with manual or automatic counters, it is theoretically possible to establish a rate of traffic flow which, integrated over a year's time, yields annual VMT. Since the U.S. highway system is nearly four million miles long, the monitoring effort is necessarily diffuse and sporadic. States typically rely on a mixture of continuous monitoring of a few primary routes, statistical sampling, and slowly rotating coverage of all road sections over a cycle of up to a decade. The states pursue traffic count programs with varying degrees of enthusiasm.

   b. fuel consumption method - Many states, lacking the resources to undertake comprehensive traffic counts, rely on the fuel consumption method, which consists simply of multiplying an assumed average miles-per-gallon figure by fuel consumed. In many cases, the fuel economy figure was generated by dividing FHWA-reported VMT by highway fuel consumption.

Evidently the FHWA VMT figures are of dubious utility in estimating average fuel economy, since the VMT estimates merely reproduce state assumptions about fuel economy. Nor is there much reason to trust the breakdown of driving between urban and rural highways; a predominantly rural state using the fuel consumption method of estimating VMT will, for instance, err in its estimate of rural VMT by nearly as large a percentage as its assumed mpg figure differs from the actual value.

Method of Weighted Averages

Given a profile of the U.S. auto fleet and the EPA fuel economy ratings for each auto model, it is tempting to try to compute a weighted average of auto fuel economy. This approach is attractive because it seems to offer the possibility of easy annual updating with new registration and fuel economy statistics. In practice, however, there are complications.

A general formulation of the weighted average is as follows:

$$\text{average fuel economy (in mpg)} = \frac{\sum_{i,y} n_{iy} m_{iy} \left[r_{iy} R_{iy} + (1 - r_{iy}) U_{iy} \right]}{\sum_{i,y} n_{iy} m_{iy}}$$

where i indexes auto model (or, for less disaggregate approach, auto size/weight class)

y indexes model year or age of auto

n_{iy} is the number of registered cars of model (class) i, vintage y

m_{iy} is the corresponding average annual miles travelled

r_{iy} is the proportion of mileage driven on rural highways

R_{iy} is average rural (highway) fuel economy, mpg

U_{iy} is average urban fuel economy, mpg

The computation requires five data values for each auto type. Of these five values, the first is known or can be established; the last two are known with modest reliability for recent vintages; the other two are not known at all. The following data are all that is actually available:

$$m_y = \frac{\sum_i n_{iy} m_{iy}}{\sum_i n_{iy}} \text{, as estimated by the NPTS of 1969-70}$$

R_{iy}, U_{iy} as estimated by EPA dynamometer tests subject to correction for cold starts, winter driving, etc.

Obviously there are severe problems with using this data. First, the applicability of the EPA tests can be questioned. There is now some understanding of the relation between dynamometer measurements and actual road tests using a particular driving cycle, but the extent to which the EPA driving cycles are typical of urban and rural driving is unknown. It is for precisely this reason that empirical data on auto use would be preferable. Second, it is not known how much covariance exists between vehicle weight and miles traveled, or proportion of rural driving. Do city dwellers tend to buy smaller cars? Are larger cars driven further, on the average? Data from the NPTS might be used to answer these questions.

Method of the "Representative Car"

Given the lack of aggregate data on VMT, it is reasonable to change strategy and merely choose some "typical" auto model as a point of comparison. The method of the "representative car" seeks to go a step further and choose the auto whose fuel economy approximates the national average. It is apparent that selecting this "representative car" is equivalent to computing the weighted average detailed in the previous section; that is, impossible, given existing data. Some authors have

Table 2: Survey of Methodologies Used to Estimate Automotive Fuel Economy

Author	Methodology
Hirst (1974)	a) combined (urban + rural) mpg: from Highway Statistics: mpg_{av} = total VMT/total gals. gas consumed b) allocation between urban and rural driving: (rural mpg) = 1.4 x (urban mpg) by assumption (urban VMT) = .55 x (total VMT), based on unpublished NPTS breakdown of household auto trips by distance, defining 'urban travel' as all trips less than 20 miles plus 20% of trips 21 to 30 miles
Hirst (1973)	same as Hirst (1974) except urban VMT = .5 (total VMT)
Shapiro and Pratt, (1976)	follows Hirst (1974)
Pollard (1977)	follows Hirst (1975)
Aerospace Corp (1977)	mpg_{av} from Highway Statistics
Voorhees (1974)	mpg_{av} = 12.0, suggested by FHWA internal memo

Mascy/Paullin (1974)	theoretical (engineering) estimates for various size classes.
Boeing (1975)	intercity mpg estimate based on representative car method: a) median age intercity auto in 1974 was 1972 model b) av weight, all 1972 autos = 3700 lbs. c) therefore av. intercity auto was a 1972 model in the 3700 - 4500 lb. weight range. d) the fuel economy for cars in this range was obtained from EPA, Consumer Reports tests
Lieb (1974)	representative car method a) typical car weighs 4000 lbs. by assumption b) a weighted average was taken of EPA ratings of 4000 lb. cars, all model years.

made the mistake of equating the national average fuel economy with the fuel economy of the national median-sized car.

Auto Load Factor

Load factor, or average occupancy, is the other determinant of automotive EI. Load factor varies, of course, with trip purpose and length, geographic area, size of car, and a host of other variables. For general transportation analysis it would be useful to have estimates of average load factor for at least the following types of trips:

urban, peak hour
urban, daily average
rural and suburban, local trips
intercity (long distance) trips

<u>Urban Load Factor</u>

The literature on urban load factors includes a few studies of specific cities and two comprehensive studies.

Specific-city studies include Boyce and ITS. Boyce & al. (1975) studies journey-to-work trips originating in three sububan New Jersey counties in 1970. Data on auto occupancy, origins, and destinations from the 1970 census urban transportation planning package was used to compute a passenger-mile/vehicle mile ratio of 1.14.

The Institute for Transportation Studies has for some years conducted surveys of San Francisco-bound commuter traffic originating in the East Bay area. The surveys are disaggregate, based on screenlines at the Caldecott Tunnel and the Bay Bridge. A Fall 1977 survey yielded the following observations of vehicle occupancy:

	6:30 AM to 6:30 PM		7:30 AM to 8:00 AM (peak half-hour)	
	Westbound	Eastbound	Westbound	Eastbound
Caldecott	1.26	1.28	1.22	1.20
Bay Bridge	1.51	1.40	1.73	1.23

(Source: U.C. Berkeley, Institute for Transportation Studies, Traffic Survey Series A-49 and C-35)

The Nationwide Personal Transportation Study of 1969-70 (NPTS), sponsored by the FHWA, attempted to characterize the driving habits of the entire civilian (noninstitutional) population. Report 1 deals with auto occupancy and presents the following summary data for households located in incorporated areas:

	to and from work	all purposes
passenger-mi/VMT	1.5	2.2
occupants/trip	1.4	1.9

(Source: NPTS, Report 1, Table 1)

The PM/VMT measure is simply occupants/trip weighted by trip length. The former is skewed upwards by the high average occupancy of long trips: 2.6 occupants/trip for trips of over forty miles. Since many of these long-distance trips are undoubtably vacation or other intercity journeys, all-purpose urban load factor is more accurately estimated by the occupants/trip measure.

A second NPTS is currently in the final stages of data collection. Data processing is expected to begin during summer, 1978.

Summarizing urban load factor estimates:

	work trips or peak hour (both directions)	daily av.
Boyce & al		
(Phila. area commuters, 1970)	1.14	---

ITS Bay Bridge		
(S.F. area commuters),	NA	1.3-1.5
NPTS	1.4	1.9
(all U.S. households, 1970)		
in incorporated areas		
National Transportation Study		
(all SMSA's, 1971)	1.3	1.5

Adopting an overall peak hour estimate of 1.3 or 1.4 people/auto would not be inconsistent with the specific-city studies.

It is not so easy to reconcile the disparate estimates of average daily occupancy. The NPTS estimate, although high, is the most authoritative.

Rural and Intercity Load Factors

It is important to distinguish between local traffic generated in rural areas and long-distance traffic which passes through rural areas. The two kinds of traffic are likely to have very different load factor characteristics. The distinction is important because intercity auto travel competes with other transport modes, while there is generally no substitute for the auto in local rural travel.

The NPTS is the only study which deals with rural traffic, and it shows virtually the same average load in unincorporated areas as in incorporated places. Average occupants/trip was 2.0, and this averaged out to 2.2 passenger-miles/vehicle-mile (NPTS, Report 1, Table 1).

For intercity or long-distance travel, the NPTS reports an average occupancy of 2.6 for all trips of over 40 miles (Report 1, Table 4).

An Alan M. Voorhees & Associates study (Voorhees, 1971) sampled auto occupancy between major cities in the Northeast Corridor. Results for 64 origin-destination pairs were obtained. Aside from an anomalous value of 4.0 for Trenton-Wilmington traffic, average load factors ranged from 1.23 to 2.67.

The National Travel Survey, part of the 1972 Census of Transportation, would appear to be a promising data source on trips of over 100 miles. Unfortunately its household-based sample systematically underestimates auto occupancy by failing to tally travelers who accompanied, but did not share a household with, the respondents. At most, the 1972 Survey allows us to put a lower bound of 2.07 on long-distance auto occuancy. It is to be hoped that the 1977 National Travel Survey--first release scheduled March 1978--will permit the unbiased calculation of load factors. Meanwhile the NPTS estimate appears to be the most reliable available: it counts all passenger; it counts both short and long trips; and unlike the city-specific studies, it does represent total national travel.

TRANSIT BUSES

Energy intensity is codetermined by vehicle-miles/gallon and load factor. We examine each separately.

Vehicle-miles per Gallon

The standard statistical source for both VMT and fuel consumption is APTA (American Public Transit Association). APTA surveys its members annually and publishes data for individual systems in its Transit Operating Report.

APTA also published estimates of aggregate energy consumption statistics in the Transit Fact Book. The aggregate estimates are based on the responses of about 125 systems, representing approximately 75% of total VMT. Fuel consumption for the missing systems is estimated on the basis of number of buses owned, with differential adjustments based on the service area population (John Neff, APTA, personal communication).

The APTA data is not perfectly reliable. A UMTA study reports (UMTA, 1977):

> the data's main limitations lie in the basic structure of the reporting elements, a lack of conformity by data suppliers to the (APTA reporting) system with regard to data submissions. In other words, the APTA system does not provide the scope, uniformity, consistency, and accuracy that would be desirable for current and future requirements (U.S. UMTA, 1977, p. 1-4).

Project FARE, developed by UMTA in association with APTA, aims at providing a consistent base of information about transit operations. But until FARE is fully implemented, the APTA data is the best available.

In scope, the APTA data is meant to cover all U.S. transit systems, public and private. Excluded are school buses, jitneys, sight-seeing buses, and intercity buses. VMT includes all passenger-vehicle miles, revenue and nonrevenue (APTA, 1977a, pp. 76-77). Fuel consumption is not precisely defined and has probably not been interpreted consistently.

Calculating BTU/VMT is straightforward, given the APTA data:

	gallons x 10^6			VMT x 10^6	
year	gasoline	diesel	propane		BTU/VMT
1971	29.4	256.8	26.5	1375.5	30300
1975	5.017	365.06	2.56	1526.0	33700

(Source: fuel and VMT, APTA, 1977a, pp. 30, 40. Conversions: gasoline @ 125000 BTU/gal, diesel @ 138700 BTU/gal, propane @ 91600 BTU/gal.)

It is of interest to compare these results with the engineering estimates presented in Mascy & Paullin (1974): 3.6 to 4.0 mpg, depending on load, for a 50-seat diesel bus. This corresponds to 34500 to 38500 BTU/VM, somewhat higher than the estimates derived above. The disparity could be due to errors in the APTA data, or the Mascy/Paullin paper may posit a bus with air conditioning.

APTA is unable to disaggregate vehicle-miles and energy consumption by fuel type or bus size.

Load Factor and Passenger Miles

There are two methods of estimating passenger miles. One method assumes an average load factor and multiplies by VMT. The other assumes an average trip length and multiplies by the number of passengers.

These methods can be applied at either an aggregate or disaggregate level. The only comprehensive set of disaggregate estimates available is contained in the National Transportation Study of 1974. This study, based on a survey of state transportation departments, presents estimates of passenger miles by mode for each SMSA. Despite its shortcomings, the National Transportation Study (NTranS) data contains the best available guesses about passenger-miles, load factor, and average trip length. The NTranS is consistent with APTA with regard to VMT and total pasengers:

Calendar Year 1971

	NTranS	APTA
million VMT	1368.8	1375.5
million passenger trips (total or unlinked)	4285	4699

(Sources: U.S. DOT, 1976, Tables SD-6, SD-15; APTA, 1977a, pp. 26, 30.)

It is therefore reasonable to compare APTA fuel consumption data and NTranS passenger-mile data to generate an EI estimate:

Calendar Year 1971

Energy consumption = 41.721×10^{12} Btu

Passenger-miles = 16858×10^{6}

EI = 2500 Btu/PM

(Sources: pass-mi: USDOT, 1976, table SD-23; energy consumption, calculated from data and conversion factors, preceding table.

Table 3: Other Estimates of Bus EI

For comparison, here are three alternate estimates of aggregate bus energy intensity. Hirst's estimate, for 1970, is based on unpublished APTA estimates of passenger-miles. The other two estimates have been recomputed using the authors' methodologies, but employing APTA data for 1971 to facilitate comparison with this paper's estimate. The disparities are therefore entirely attributable to the different assumptions about load factor (or, equivalently, average trip length).

Author	Methodology/sources
Pollard, 1977	PM = (av LF) x (total VMT)
	LF = 12 PM/VMT, suggested by FHWA, unpublished memo
(data for 1971)	VMT = 1375.5×10^6, from APTA
	PM = 16.5×10^9
	Fuel consumption = 41.7×10^{12} Btu*; from APTA
	EI = 2550
Lieb, 1974	PM = (av. trip length) x (no. of revenue rides)
(data for 1971)	av. trip length = 4.0 mi., by assumption
	no. of revenue rides = 3734.8×10^6, from APTA
	PM = 14.9×10^9
	Fuel consumption = 41.7×10^{12} Btu*, from APTA
	EI = 2800
Hirst, 1973	PM = 13×10^9, from unpublished APTA data
(data for 1971)	Fuel consumption = 45.0×10^{12} Btu*, from APTA
	EI = 3450

All APTA data faom Transit Fact Book '76-'77 (APTA, 1977a)

*Fuel consumption data:

	millions of gallons		
year	gasoline	diesel	propane
1970	37.2	270.6	31.0
1971	29.4	256.8	26.5

Conversions (Btu/gallon): gasoline, 125000; diesel, 138700; propane, 91600.

HEAVY RAIL

Aggregate Estimates

Several attempts have been made to estimate the average energy intensity of all ten US heavy rail systems combined (see table 6). All are ultimately based on the energy consumption statistics published by APTA in the Transit Fact Book. The APTA statistics are comprehensive but flawed. First, APTA no longer splits out light rail and trolley coach energy consumption, because the combined heavy/light rail systems do not do a good job of this in their own internal accounting. Second, the systems have not interpreted "electricity used to operate vehicles" in a consistent fashion. Some systems have reported total energy consumption, including station heating and lighting; others have reported traction energy only. These inconsistencies become evident when comparing data reported in APTA's Transit Operating Report 1975 with detailed analyses presented by Stanford Research Institute (1977), Boyce (1975), Smith (n.d.), and Fels (1977). Using these sources in conjunction it is possible to separate traction energy from station and other energy for six systems which together account for 95.2% of heavy rail VMT (based on the Transit Fact Book.) These calculations are performed and documented in Table 4. In addition, SRI has made or obtained a 'best guess' of average trip length on each system and derived passenger mile estimates. These are also presented in Table 4.

Averaging over all six systems, we have the following:

Traction Energy Only	Total Energy
.227 KWHe/PM = 2600 BTU/PM	.280 KWHe/PM = 3100 Btu/PM
5.56 KWHe/VMT = 63250 BTU/VMT	6.81 KWHe/VMT = 77450 Btu/VMT

Table 4: Heavy Rail Data Aggregation

SYSTEM	REVENUE VMT	PM (millions)	ENERGY Consumption (million KWHe) total	traction	NOTES
Chicago	49.127	1078	260.152	228.90 (DC)	18.2 x 10^6 lost in AC-DC conversion
New York	302.80	7543	2048.8	1679.3	
PATH	10.657	184	63.575	55.94	SRI lists 7.63 x 10^6 KWHe to "auxiliaries"; Smith and Fels make it clear that this is actually for fixed installation, and it is therefore excluded from traction energy
PATCO	4.193	94.52	40.526	34.04	Traction desired from total energy applying Boyce's ratio of .84
BART	21.456	467 (Fels)	219 (Fels)	155.49 (Fels)	
SEPTA (Heavy rail)	14.560	418.9	111.856	71.406	Energy consumption derivation by SRI, somewhat muddled
TOTAL	402.80	9786	2745	2226	

Sources: VMT: APTA (1976b)
PM: / Energy: {SRI (1977) except BART: Fels (1977)
Boyce (1975 and Smith (n.d.) used (respectively) for PATCO and Path traction energy

Traction energy includes all energy drawn by cars: propulsion, heating, air-conditioning, lighting, in active service or on standby. For the most part, available data does not specify whether the traction energy reported refers to DC or AC electricity use. Because of conversion losses, about five percent more current is purchased as AC than is actually used in DC form. It is assumed here that the systems have reported DC usage.

Total energy includes traction energy; energy used by stations shops and offices; energy used to heat rails and ventilate tunnels; and AC to DC conversion losses.

Vehicle -miles are revenue car-miles. Nonrevenue car-miles are a small fraction of total car-miles for those systems which distinguish between the two; most systems do not report nonrevenue car-miles.

Heat rates - This paper uses a standard conversion of 1 KWHe = 11373 Btu. According to SRI, the appropriate heat rate for Con Ed which supplies NYCTA is 13680 Btu/KWHe (Stanford Research Institute, 1977, p. 78.). Allowance for this would increase the overall EI values by 15%.

The overall average EI values presented above are somewhat misleading and must be used with great caution. These averages reflect the efficient performance of the New York subways, which account for the bulk of heavy-rail passenger-miles travelled. Modern heavy-rail systems tend to use more energy-intensive vehicles in less heavily-populated regions, resulting in much higher EI's. A disaggregate approach to heavy-rail EI is therefore desirable.

HEAVY RAIL - INDIVIDUAL SYSTEM ESTIMATES

There is a great deal of diversity among heavy rail systems. Detailed energy profiles of three systems have been prepared by Margaret Fels whose results are shown below.

Table 5: Energy Consumption of Three Heavy Rail Systems

	BART	PATCO	PATH
Car-miles (millions)	23.4	4.2	11
Passenger-miles (millions)	467	92	183
Total energy consumed (million KWHe)	219	40	69
% traction	71	85.5	89
% station	24	12.5	5
% maintenance	5	2	6
KWHe/car-mile -total energy	9.4	9.5	6.4
KWHe/car-mile -traction	6.6	8.1	5.6
EI--total BTU/passenger-mile	5350	4950	4300
EI--traction BTU/passenger-mile	3800	4200	3800

(Source: the first seven rows of the above table are taken from Fels (1977), p. 18, and were used to derive the bottom three rows. Fel's figures are based on the systems' billing records for energy, and the systems' own estimates of car-miles and passenger-mies).

For PATCO and PATH, almost all of the traction energy is used in active operation of the vehicles. By contrast, BART's policy of keeping all cars "hot" (i.e., idling) at all times results in a substantial component of energy devoted to inactive operation. Fels estimated that BART cars consumed only 3.7 KWHe/car-mile in active operation but used 26 KWHe/car-hours in inactive hours of service, fully 46% of traction energy consumption is incurred by inactive operation. As BART expands service hours and increases car utilization, the proportion of inactive operation will decrease, probably resulting in thriftier energy intensities.

Table 6: Other Rail Transit Estimates

Following are alternate estimates of aggregate electric transit EI. Hirst's estimate is for 1970; the other two authors' methodologies have been applied to 1975 data. In all three cases, EI has been readjusted to reflect a conversion of 11373 Btu/KWHe. N.B. these figures are for the total U.S. rail system: heavy rail + light rail + trolley coach.

Author	Methodology/sources
Pollard, 1977 (data for 1975)	PM = (total passenger rides) x (av trip length) av trip length = 8.0 miles, by assumption no of passenger rides (includes nonrevenue and transfer passengers) = 1869×10^6 from APTA PM = 15.0×10^9 Energy consumption = 2646×10^6 KWHe = 3.0×10^{13} Btu EI = 2000 Btu/PM
Lieb, 1974 (data for 1975)	for each mode, PM = (revenue passenger rides) x (av trip length)

mode	av trip, mi	rev. pass. rides (millions)
heavy rail	6.5	1387.8
light rail	2.75	94.0
trolley coach	2.5	56.0

(trip lengths by assumption; passenger rides from APTA)

PM = 9419×10^6

Energy consumption = 2646×10^6 KWHe = 3.0×10^{13} Btu

EI = 3200 Btu/PM

Hirst, 1973 (data for 1970)	PM = 7.2×10^9, unpublished reference
	Energy consumption = 2561×10^6 KWHe = 2.9×10^{13} Btu, from APTA
	EI = 4050

All APTA data from APTA, 1977a.

*Recomputed using conversion of 11373 Btu/KWHe. Hirst estimate recomputed using energy consumption figure for 1970 as reported in 1976-77 Transit Fact Book.

LIGHT RAIL VEHICLES

Operating data on light rail vehicles is scarce. APTA reported aggregate U.S. light rail energy consumption until 1973. During that year light rail operations were reported to have consumed 140 million KWHe in the production of 31.2 million car-miles, for an average of 4.5 KWHe/car-mile. APTA has discontinued estimating aggregate light rail energy consumption because of problems with data reliability. The problem lies mainly with the MBTA's inability to account separately for light and heavy rail components of energy use. The MBTA generates a large fraction of total U.S. LRV (light rail vehicle) VMT, so no meaningful average can be made without it.

Lacking a useful aggregate average, there is no alternative but to use the operating statistics of individual systems, or to rely on engineering estimates. Of the six remaining light-rail systems, three are described in APTA, 1977b:

Table 7: Light Rail Energy Consumption

City/system	Energy consumed KWHe x 10^6	Car-miles x 10^6	KWHe/car-miles (derived)
Cleveland RTA	4.5	1.04	4.33
Newark TNJ	2.84	.58	4.92
PHILA, Red Arrow	14.0	1.55	9.03
The following is described in SRI, 1977:			
Pittsburgh PAT	15.1	2.10	7.21

Unfortunately it is not clear whether the energy consumption reported for these four systems was total energy or traction energy.

The high energy-per-car-mile value for Philadelphia's Red Arrow line may be due to heavier-than-average cars. The Red Arrow cars range in weight from 21000 to 60000 lbs., while Cleveland's cars all fall within the 36 to 42 thousand pound range (SRI).

SRI also reports estimates of passenger-miles. Using these estimates to compute energy intensities, we have:

Table 8: Light Rail EI

system	energy consumption (million KWHe)	PM (millions)	EI (BTU/PM)
Cleveland	4.5	27.5	1850
Red Arrow	14.0	27.6	5750
TNJ	2.84	5.3*	6100

*Based on average trip length of 2.2 miles--(SRI, 1977)--and 2408000 passengers--(APTA, 1977b).

From the energy analyst's viewpoint, Cleveland is a "showcase" system. Its very success in achieving a high average load factor makes it inappropriate as a guidelines for the typical energy intensity of light rail operations. On the other hand, the poor showing of TNJ and Red Arrow--twice the EI of old heavy rail systems--are not necessarily representative either.

However it must be borne in mind that the above data refer almost exclusively to cars of 1940's vintages and older. The new generation of light rail vehicles, more sturdily constructed than their predecessors and equipped with air conditioning, are likely to be more energy intensive than current equipment. Tests of the new Boeing LRV in Boston yield an average value at 9.52 KWH/car-mile for combined data subway-surface run (Diamant, 1976, and Boeing Co., personal communication).

Thus if the existing cars on the three systems mentioned above were replaced by the new Boeing LRV cars, while continuing the former load factors, then the new EI's would be 4050, 11100, and 6400 respectively.

The main point of interest here is that the new generation of light rail systems will have EI's in the range of 4000 to 10000 Btu/PM, which is higher than the comparable EI for new heavy rail systems of about 4000 Btu/PM. Thus the energy savings associated with light rail lie in the lower construction energy, not in lower operating energy.

COMMUTER RAIL

APTA recognized fifteen commuter railroads at the end of 1976 (APTA, 1977a, p. 46). According to the National Transportation Study, the commuter rail system produced 128.6 million VMT and 5787 million passenger miles in 1971 (USDOT, 1976, tables SD-6, SD-23).

Energy consumption by commuter railroads is not regularly published. The ICC Bureau of Accounts requires each railroad annually to report on fuel consumption by motive power units. This information is contained in schedule 571 of the R-1 reports. These reports are open-filed in Washington; copies are available upon special request to ICC's Fees and Services Branch.

SRI's energy analysis of commuter rail operations is largely based on the R-1 reports. It would be possible to aggregate this data and attempt an overall average EI figure. However, Walbridge (1974) demonstrates that an important component of energy consumption is not reflected in locomotive fuel consumption alone. A substantial amount of electricity is used to keep coaches and locomotives "hot" during the winter. The results of Walbridge's detailed analysis of three Chicago commuter roads are worth reproducing as guideline examples of commuter rail energy intensity:

Table 9: Commuter Rail EI

	Northwestern	Burlington Northern	Milwaukee Road
Fuel consumption, gals, diesel/train-mi	3.3	4.3	2.9
Total "traction" energy incl. deadheading, electric standby, equivalent gals. diesel/train-mile	3.8	4.5	3.3
Btu/coach-mile ($x\ 10^5$)	1.1	1.3	1.5
av seats/coach	159	134-146	152
PM/seat-mi	29	42-46	41
EI (Btu/PM)	2400	2100	2400

(Notes: Walbridge's raw data is directly from the railroads. Walbridge uses a conversion factor of 10000 BTU/PM; reconversion to the 11373 factor used in this report would not make a difference at the two-significant-figure level Walbridge employs.)

Note that these estimates do not include energy used for stations and maintenance.

Other estimates--The only aggregate estimate located was that of Pollard (1977). Pollard's energy consumption figures were obtained from personal communications with the ICC. His passenger-mile figure is the residual after intercity rail passenger miles (from ICC, Transport Statistics in the United States) are deducted from total rail passenger miles (from Association of American Railroads, Statistics of Railroads of Class I in the United States.

Pollard's data is as follows:

	1972	1975
BTU x 10^9	20	15
Passenger-miles (billions)	5.380	5.778
EI (BTU/PM)	3638	2537

If this data is accurate, commuter rail systems increased service between 1972 and 1975 while reducing energy consumption 25%.

THE 1974 TRANSPORTATION STUDY

The Urban Data Supplement to the 1974 National Transportation Report is a potentially valuable source of information about the urban transportation system. This section describes the 1974 National Transportation Study, upon which the Urban Data Supplement was based, discusses its reliability, and presents some averages for load factor and trip length derived from this data.

The 1974 National Transportation Study--not to be confused with the 1972 National Travel Survey--was a D.O.T. attempt to assemble a comprehensive picture of the nation's transportation system and plans as of the beginning of 1972. To that end, D.O.T. surveyed the state transportation departments, who in turn polled local agencies, for their best estimates of the extent and nature of transportation services and facilities. Since there was no provision for a massive data-gathering effort, the state and local agencies generally relied on existing estimates, and there was no uniformity of estimating methodologies. The required data elements were, however, very precisely specified, so the reporting categories, at least, were consistent. The National Transportation Study therefore represents a compilation of the most detailed and best-informed estimates of such elusive data as load factors, average trip lengths, and passenger-miles travelled.

The Urban Data Supplement presents data for each of 241 urbanized areas. These urbanized areas are a generalization of the Census SMSA's modified to include all areas expected to be urbanized by 1990. All data describing annual flows--costs, vehicle miles, etc.--is for calendar year 1971.

The data falls under five categories: capital costs; annual operating costs; physical facilities and equipment; demand and supply; performance indicators; social and environmental impacts. Of particular relevance to this report are data describing vehicle-miles, passenger miles, and seat-miles, for the peak hour, the average weekday, and for the entire year.

Using this data, we derived averages, over all urbanized areas, for auto occupancy and for modal load factors. The following values resulted:

Table 10: Load Factors by Mode

Mode	Peak Hour	Av weekday
Auto occupancy	1.27	1.50
Rail transit, PM/SM	.70	.50
Bus, PM/SM	.35	.24
Commuter rail, PM/SM	.58	.41

Definitions:

peak hour - the hour in which there is heaviest patronage, includes both directions
average weekday - daily average, Monday through Friday
passenger miles - sum of all trip lengths for all passengers
seat-miles - for vehicles in revenue service, excludes deadheading
auto occupancy - excludes children 5 years and younger - defined as occupancy weighted by VMT
(definitions from USDOT, 1974, Vol. 1)

Derivations: (VMT = vehicle miles travelled; PM = passenger miles; SM = seat miles; OCC = no. of occupants; D = av weekday; P = peak hour; all sums are over the 241 urbanized areas, excluding missing or questionable data).

$$\text{auto occupancy, av weekday} = \frac{\Sigma(VMT_D \times OCC_D)}{\Sigma VMT_D}$$

$$\text{Auto occupancy, peak hour} = \frac{\Sigma(VMT_D \times OCC_P)}{\Sigma VMT_D}$$ (VMT_P was not available)

PM/SM, peak hour (bus, rail transit, commuter rail)

$$= \frac{\Sigma\left[SM_P \times (PM/SM)_P\right]}{\Sigma SM_P}$$

PM/SM av weekday (bus, rail transit, commuter rail)

$$= \frac{\Sigma\left[SM_D \times (PM/SM)_D\right]}{\Sigma SM_D}$$

Sources: Data was taken from the Urban Data Supplement, as follows: SM: tables D-9, D-10, D-11; PM/SM: tables E-4, E-5, E-6; auto VMT: table D-1; auto occupancy: table E-3.

How reliable are these values? The figures for average weekday auto occupancy and average weekday rail transit PM/SM are suspiciously round. In fact they are round to the third decimal place, which would seem to indicate that the states' raw data adjusted to average to these presumably predetermined values. However, according to the Department of Transportation, no such adjustments were made (George Wiggers, DOT, personal communication). We must therefore attribute the "roundness" of the averages to a combination of chance and a tendency on the part of the respondents to choose round numbers.

But even if these figures have not been juggled, they are not uniformly believable. Despite the influence of New York, .5 seems high for an average rail transit load factor. Further examination of the data reveals that Chicago has reported a peak hour load factor of .48, an average weekday load factor of .74, and an average annual load factor of .77; this bespeaks an unexpectedly high, and counterintuitively patterned, intensity of use.

The averages for bus and commuter rail modes are more reasonable. It is suggested that these may be used, with caution, in discussing typical peak and daily load factors.

CONCLUSIONS

In summary, it appears the variety of EI estimates is misleading. Much of the literature consists of secondary reports which reproduce a far smaller number of primary analyses. These primary analyses themselves rely on a limited repertory of methodologies and a very small set of data sources. Variance among EI estimates is primarily attributable to contradictory assumptions about vehicle occupancy. However, consistency in energy/vehicle-mile estimates tends to indicate parallel methods of analysis rather than mutually confirming independent approaches.

The best evidence available indicates that buses are substantially more energy-efficient than heavy rail transit; existing rail transit systems consume an average of 24% more operating energy per passenger mile than buses. Modern heavy rail systems consume approximately 100% more energy per passenger mile than buses, not even taking into consideration the huge construction costs (for which, see Lave, 1978). Light rail systems, on limited evidence, seem to have no advantage over heavy rail in operating energy-efficiency, but there may be some savings in construction costs. From the point of view of energy efficiency, bus is the preferred transit mode.

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