Assessment of Energy and Petroleum Consumption of Different Transportation Modes in the Buffalo Area

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This analysis evaluates the results of a local rail vehicle performance model. Line-haul travel calculations, operating energy consumption, and total energy consumption, especially of petroleum energy, are calculated for an example situation in Buffalo, New York. The energy impacts that result from the implementation of a carpool and express bus system are also included. The comparison of these results with energy estimates by using average values indicates that the variance in urban rail system performance is too large for generalizations at the national level. A second reason for the promotion of local energy studies is the need to develop criteria to calculate the petroleum consumption of modes that do not burn petroleum products directly. The results of this study demonstrate that a light rail system in the example city will save energy; however, due to the relatively small demand, the net energy and petroleum savings are rather small. Recent trends toward the purchase of foreign-manufactured light rail vehicles have a negative impact on energy savings.

The energy-saving capabilities of various urban transportation modes has been an intensely studied subject area throughout the 1970s. Much of the data collection and discussion has pertained to local evaluations of energy strategies. However, a substantial amount of discussion has come from the aggregation of local energy and system performance information for the purpose of evaluating conservation measures in a different or at a higher spatial unit. For example, in order for federal officials to evaluate the effectiveness of national energy policies, especially with regard to various approaches to encourage individuals to switch to more energy-efficient modes, the collection and summation of local information was undertaken. This process of collecting local information for the purpose of evaluating energy-conserving strategies is referred to in this paper as the aggregate approach.

There are three major objectives of this study:

1. To develop a local energy model to be used as one component of a much larger transportation system performance model (special consideration for including direct and indirect energy considerations is an essential requirement),
2. To assess the difference between this locally developed energy model with that of the aggregate approach (this will aid in the validation of the developed procedures as well as refine differences in the two approaches), and
3. To conduct a sensitivity analysis on the major variables that affect rail energy consumption in order to determine the effects of rail design and operating decisions on rail operating energy consumption, as well as to demonstrate the benefits generated from a locally developed, policy-sensitive modeling system.

Six modes are included in this local energy model: automobile, carpool, local bus, express bus, light rail, and heavy rail. From information that will be discussed later in this paper, several modes are set to default values due to the lack of variability in operating performance at the aggregate level. Therefore, emphasis in this study is on methods for evaluating the impact of rail modes. This results from the observation that aggregate methods ignore the variation in urban rail system data.

The following analysis addresses four areas that pertain to rail vehicle performance at the local level:

1. Line-haul travel time;
2. Operating energy consumption;
3. Total energy consumption, especially that of petroleum energy; and
4. An example application of the generated methodology in Buffalo, New York.

PROBLEM DEFINITION

This investigation into the energy dilemma of the United States is required in order to establish appropriate criteria for the evaluation of energy aspects of various transportation modes. Some controversy about the efficiency of the rail mode stems from various definitions of the energy problem.

It is generally accepted that the current energy supply is dwindling and the demand for energy is increasing. The existence of price controls on energy has meant that the demand for energy has not adjusted to supply. This gap between supply and demand is widening every year. The following statistics demonstrate that the energy problem is particularly acute for petroleum energy:

1. The United States produced 81 percent of its energy needs in 1976 (1), but
2. The United States produced only 49 percent of its petroleum-derived energy needs in that year (1).

Since a large share of petroleum is imported, emphasis on solutions that reduce petroleum consumption should be one of our major objectives.

The activity system most vulnerable to a petroleum shortfall is that of transportation. The following statements demonstrate transportation's role in the petroleum energy problem:

1. Transportation is run on 96 percent petroleum (2);
2. Transportation uses 60 percent of all petroleum in this country (3);
3. Urban passenger transportation, the largest petroleum-consuming group, uses approximately 25 percent of the petroleum in the United States (3); and
4. Less than 1 percent of the energy used in transportation is converted from coal, which is an abundant domestic energy resource (4).

All indications are that the relationship between urban passenger transportation and petroleum use will intensify if current patterns continue. This is substantiated by recent projections from analyses into the petroleum-consumption problem:

1. Vehicle miles of travel, the number of automobiles, passenger miles, and the number of automobile drivers will continue to increase at a substantial rate (5);
2. The supply of foreign oil may decrease to all importing nations and greatly affect both the amount and the price of petroleum; and

3. Current energy regulation in the United States is thought to have a far less petroleum-conserving impact than had previously been thought (6).

The above discussion indicates that the incorporation of additional criteria for evaluating modal energy consumption on the basis of Btus of petroleum seems justified. The following analyses assess the impact of a policy that promotes a shift from automobile to express bus, carpooling, or rail transit. Emphasis on the rail mode in this study is the result of seemingly inadequate methods to deal with rail modal efficiencies at the national (i.e., aggregate) level.

LITERATURE REVIEW

A review of several studies that pertain to approaches to calculate energy consumption, important variables to include in energy calculations, and the results or estimates of energy consumption under varying conditions are summarized in this paper (2,6-22).

There are three major outcomes of this review. First, most studies that analyzed energy demand in urban passenger transportation have measured energy intensity on the basis of Btus per passenger mile. This method does not take into consideration the type of energy used for transportation. The previously stated problem definition indicates that the energy type is also an important consideration. Therefore, the transportation alternatives should also be evaluated in those terms, which results in the measurement of energy intensity on the basis of Btus of petroleum per passenger mile.

The second point is that average values were frequently used to measure the net energy impact of a shift in mode choice. This approach does not take into consideration any effect that local areas have on mode choice or the energy consumption of various modes. Analyses that use average figures to measure the change in energy consumption are insensitive to the range and variance of energy consumed at the local level. This is especially true with regard to the rail mode.

To demonstrate the large variance in energy estimates by using aggregate methods [e.g., the Congressional Budget Office (CBO) report (8)], estimates of operating energy consumption are examined more closely. Operating energy includes the energy used in the propulsion of the vehicle plus the auxiliary energy (e.g., heating and air conditioning). This particular energy component has been selected for demonstration purposes because (a) it is the most important variable in the determination of total energy consumption, (b) it is the most important energy component to a transit agency, and (c) it is thought to have the smallest variance because of the engineering aspects that do not vary among local areas.

Operating energy consumption from local studies on six urban passenger modes was collected and compared with the results of the CBO report. The reason for a somewhat duplicate effort in collecting energy data was the omission of standard deviation information from the CBO report. Table 1 contains a comparison of the two information sources as well as some summary statistics on the data. The mean columns and the confidence interval columns demonstrate the similarity between the data. The standard deviation column, the coefficient of variation column, and the extreme error coefficient column all show that rail systems, especially light rail, have a large variance in operating energy consumption. Automobiles and local buses, on the other hand, each possess a similarity in operating energy values.

Some authors indicate potentially severe errors with the input data [e.g., Chomitz (14) and Rose (1)]; therefore, it is difficult to justify very little dispersion in the energy consumption of the automobile and local bus modes and generally a great deal of dispersion in the rail modes. There are two plausible reasons for this large dispersion in operating energy consumption values in the rail modes--measurement error in the input data as well as variance in the age, local geometrics, vehicle types, station spacing, and operating policies that vary greatly from city to city. However, for whatever reason, any definite conclusion that uses this information to demonstrate the ability of rail to save or lose energy must be questioned. What must be addressed is the adoption of a sound methodology for local areas to determine the feasibility of rail systems to save energy.

The potential petroleum savings of a rail system in an urban area depends on the type of system selected, the locality where the system is built, the layout and operation of the system, and the type of fuel used to generate the electricity for the particular rail operation in question. Therefore, under certain circumstances, a policy that promotes a mode shift will have beneficial results on energy consumption. Sometimes, however, it will be unsuccessful.

The third important result of this review is that most studies evaluate various modes at a constant point in time, usually early after the implementation of the system. For instance, modes such as rail transit accrue energy benefits over the long run when access modes have adjusted to increasing use of the new alternative. Other factors, such as land use changes, technological improvements, residential relocation, and travel-demand increases will also affect energy consumption in the long run. This phenomenon is much more difficult to measure than an evaluation at one point in time. The fact that large capital expenditures accrue benefits over time is not new; however, accurate methods to represent this phenomenon are difficult to come by, even in a cursory fashion.

There has been growing interest in transportation research for adopting a more comprehensive strategy for analyzing energy consumption. The consideration of a local perspective, the calculation of values over time, and the adoption of a petroleum-measuring

Table 1. Average operating energy estimates.

Mode	N	Mean Btus per Vehicle Mile ($\bar{X}$)	Mean Btus from CBO Report	Confidence Interval [$\bar{X} \pm 2(S/\sqrt{n})$]	Confidence Interval from CBO Report	SD	Coefficent of Variation (SD/$\bar{X}$)	Extreme Error Coefficient [(H - L)/L]
Automobile	9	10 400	10 800	9 500-11 300	10 400-11 000	1 170	0.11	0.19
Heavy rail, old	19	72 300	72 500	65 500-79 100	50 000-95 000	14 130	0.20	0.81
Heavy rail, new	9	87 200	90 000	72 300-102 000	70 000-110 000	19 400	0.22	1.08
Commuter rail	9	114 900	125 000	101 200-128 500	100 000-150 000	17 750	0.15	0.53
Light rail	15	79 000	75 000	65 100-92 900	50 000-100 000	25 090	0.32	1.70
Bus	11	32 100	29 500	30 200-33 900	29 900-34 000	2 760	0.09	0.33

framework represents an attempt toward a more comprehensive approach to the investigation of this problem.

STUDY METHOD AND APPLICATION RESULTS

Adoption of the CBO methodology for the previous three criticisms results in an approach that is responsive to local needs, in accord with an appropriate problem definition, and comprehensive in specification. An additional variable is included to take into consideration not only the additional trips of the new mode but also additional trips that are generated by the forfeited mode (e.g., additional trips from automobiles left at home). This method inputs local values for each variable instead of national averages. A set of default aggregate values is included in the absence of a local value. The variables are listed below.

Program Energy (Increased Energy Use Due to Changes in Demand)

1. Source of new patronage,
2. Additional trips generated by the new mode, and
3. Additional trips generated by the forfeited mode.

Modal Energy

Line-Haul Energy

1. Propulsion energy per vehicle mile,
2. Auxiliary energy per vehicle mile,
3. Construction energy per vehicle mile,
4. Vehicle manufacturing energy per vehicle mile,
5. Station and maintenance energy per vehicle mile,
6. Average number of passengers (passenger miles per vehicle mile), and
7. Percentage of petroleum in 1-5.

Access-Circuity Variables

1. Mode of access,
2. Fraction of trip devoted to access, and
3. Circuity.

The input data used for the rail mode partly come from the other portions of the transportation planning model but mostly from what is often called the work (i.e., force through distance) methodology (15, 16, 18, 22). A simplified derivation of this approach demonstrates the relationship between force and resistance as well as the resulting travel time and energy consumption. Propulsion force of a rail vehicle can be defined as follows:

$$M \leqslant \mathrm{MIN}\left\{[1584 \cdot (\mathrm{TD} + 6.8)], [3471 \cdot \mathrm{K3} \cdot (\mathrm{Y/V})]\right\} \quad (1)$$

where

M = propulsion force (N),
TD = weight of the rail vehicle (t),
K3 = actual tractive effort divided by the hourly power rating (this value is calculated internally by dividing the total line-haul time by the travel time incurred in acceleration and at maximum speed),
Y = the rated kilowatt output reserved for propulsion (kW), and
V = velocity (km/h).

The acceleration of the vehicle is defined as

$$\mathrm{AC} = (\mathrm{M-R})/\mathrm{MA} \quad (2)$$

where

AC = acceleration rate (m/s^2),
R = total resistance force (e.g., flange friction or air resistance) (N), and
MA = mass ($N{-}{-}s^2/m$).

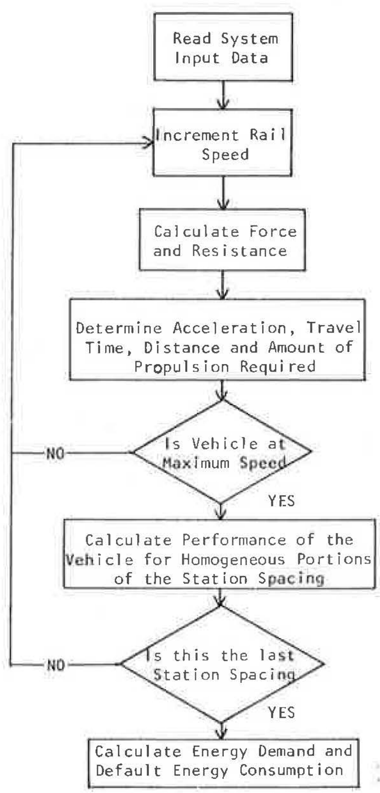
From these equations, along with the system characteristics (e.g., station spacing distance and maximum speed) one is able to determine important characteristics of rail vehicle performance. Figure 1 demonstrates this overall methodology.

Line-Haul Travel Time

Accuracy in line-haul travel time calculations are important for three interdependent reasons. First, there is a trade-off between energy consumption and travel time. Second, the travel-time savings of a particular mode determine the benefits of that alternative. Rightly or wrongly, travel-time benefits in excess of 60 percent are common in studies that justify the implementation of a rail system. Third, line-haul travel time is usually a large percentage of the total travel time and, as such, is important for forecasts of rail patronage.

A popular method used to estimate line-haul travel time assumes a linear acceleration of a vehicle from zero to maximum speed. This, however, can have very serious consequences on the travel time estimates. Since the propulsion force of a rail vehicle decreases with increasing velocity (Equation 1) and resistance increases with increasing speeds, the acceleration rate will be nonlinear (Equation 2). This results in a decreasing acceleration rate with increasing speeds. Therefore, the assumption of a linear acceleration rate results in a serious underestimate

Figure 1. Methodology for obtaining local performance information for the rail mode.



of the rail line-haul travel time. In a case study application of a light rail line in Buffalo, New York, the assumption of a linear acceleration rate underestimated the travel time by 16 percent.

Operating Energy Consumption

The method selected to calculate the line-haul travel time of rail is intertwined with the method used to calculate energy consumption. The simultaneous calculation of both of these components at the local level leads to more realistic results and adds few coding requirements.

There are two potential users of the previously defined energy and travel-time model. The first class of users is the local planners. They are interested in the line-haul travel time, operating energy consumption, and energy costs that result from the performance of a rail system. The second type of users is energy policy analysts. These users are interested not only in the operation of the system but also in all other features, components, and activities that consume energy. This user group is interested in total energy consumption.

This analysis assesses the energy implications of a rail system during a typical peak period. This decision results from energy studies that conclude that regenerative braking may be feasible during this period (22).

The energy consumption of a particular rail system is affected by three interrelated decisions. The first is the type of technology and the layout of the track. For this example analysis, a light rail vehicle (LRV) and the planned right-of-way of the Buffalo system is held constant throughout the sensitivity of the rail energy model. The second decision is the selection of a rail vehicle (i.e., which manufacturer). The third decision is the operating policies of a vehicle once purchased. These decisions are obviously not as mutually exclusive as this distinction portrays.

The following investigation addresses the impacts of different LRVs and operating policies in greater detail. Table 2 lists the major input variables that pertain to different vehicles as well as the values from three internationally known LRV manufacturers, all of which meet the specifications of the operating agency.

For this portion of the study, all vehicles are simulated by using the same operating policy as defined by the local transportation agency. The maximum speed in mixed traffic is 45 km/h and 80 km/h in the tunneled portion. The acceleration and deceleration rates are 1.22 and 1.34 m/s^2, respectively. The other operating variables and the parameters that represent the attributes of the vehicle itself are listed in Table 2. These simulations are represented by 1-1, 2-1, and 3-1. All three of these simulations vary the values of the vehicle type and hold constant the values that represent the operation of the system.

Table 3 summarizes a different situation. The 1-1 vehicle is selected and its design characteristics held constant, but the values that represent the operation are allowed to vary. Alternative 1-2 is identical to 1-1 except that the acceleration and deceleration rates are reduced by 20 percent. Alternative 1-4 is also identical to 1-1 except that the acceleration and deceleration rates are increased by 20 percent. Alternative 1-3 is also identical to 1-1; however, in this alternative the vehicle contains regenerative braking. This results in an increase in vehicle weight (variable 9), auxiliary output (variable 15), and an 80 percent recovery of braking energy (variable 6) (22). In these model simulations, it is assumed that there will be priority signalization for the rail vehicle in mixed traffic and on cross streets.

Table 4 contains a summary of these six alternatives. The energy consumption varies greatly from vehicle to vehicle. Vehicle 1-1 has a total operating-energy consumption of 8.05 kW•h/vehicle mile and vehicle 2-1 exhibits an estimate of 11.22 kW•h/vehicle mile. The travel time difference among the vehicles tested is less than 40 s for the 6.22-mile length of the system.

In this example application, the Btus of petroleum per vehicle mile are comparable to that of a city bus. The articulated light rail car has a capacity that is three times larger than that of a bus and, in this case, an average speed that is approximately twice as great. The difference in energy consumption for the three operating policies is minimal. For regenerative braking, it seems clear that the energy saved in reduced propulsion energy is lost in increased auxiliary energy. The three latter alternatives, which vary the operating variables, all contain energy costs of $0.32/vehicle mile (i.e., assuming a rate of $0.04/kW•h).

The two most important variables that affect energy consumption, from the perspective of the local planner, are categorized in the earliest decisions in the hierarchy of decisions that affect the performance of a rail vehicle. The station spacing and the vehicle type purchased are by far the most important decisions because they affect not only the energy consumption but also the overall performance of the system. Variation in the vehicle

Table 2. Input variables to energy model by vehicle type.

Input Variables		Manufacturer[a]		
No.	Definition	1-1	2-1	3-1
8	N = number of axles per car	6	6	6
9	TD = weight of car (t)	31.4	39.1	39.0
10	ACC = maximum acceleration (m/s^2)	1.22	1.22	1.22
11	K3 = tractive effort/hourly power[b]	1.744	1.826	1.805
12	DC = deceleration rate (m/s^2)	1.34	1.34	1.34
14	Y = propulsion output (kW)	247	435	335
15	YA = auxiliary output (kW)	35	35	35
19	Petroleum used in generation (%)	28	28	28

[a]In 1-1, the first number indicates the manufacturer, and the second number refers to the system options used. In this table, the same system options are used for all three vehicle types.

[b]Calibrated from energy model.

Table 3. Input variables to energy model by operating policy.

Input Variables		Operation[a]		
No.	Definition	1-2	1-3	1-4
6	K5 = percentage of regenerated braking	0.0	0.8	0.0
9	TD = weight of car (t)	31.4	32.3	31.4
10	ACC = maximum acceleration (m/s^2)	0.98	1.22	1.48
11	K3 = tractive effort/hourly power[b]	1.82	1.62	1.69
12	DC = deceleration rate (m/s^2)	1.07	1.34	1.61
15	TA = auxiliary output (kW)	35	83	35

[a]The first number indicates the manufacturer, and the second number refers to the system options used.

[b]Calibrated from energy model.

Table 4. Operating energy summary statistics.

Performance Summary	Vehicle[a] 1-1	2-1	3-1	Operation[a] 1-2	1-3	1-4
Travel time in one direction (min)	17.1	16.7	16.9	17.7	17.2	16.7
Energy consumption (kW·h/vehicle mile)						
Propulsion	6.48	9.68	8.46	6.42	4.09	6.51
Auxiliary	1.57	1.54	1.56	1.63	3.76	1.54
Total	8.05	11.22	10.02	8.05	7.85	8.05
Btus per vehicle mile	91 700	127 500	114 000	91 700	89 300	91 700
Btus of petroleum per vehicle mile	15 700	35 700	31 900	25 700	25 000	25 700
Energy costs ($/vehicle mile)	0.32	0.45	0.40	0.32	0.32	0.32

[a]The first number indicates the manufacturer, and the second number refers to the system options used.

Table 5. Comparison of program energy savings for Buffalo in 1985.

Mode	Estimated Yearly Passenger Demand (million passenger miles)	CBO Results (Btus/passenger mile)	Local Energy Model: Btus per Passenger Mile	Local Energy Model: Btus of Petroleum per Passenger Mile
Carpool	6578[a]	4895	4060	4060
Express bus	219[b]	3591	2743	2743
Light rail	61[c]	85	620	2448
Heavy rail[d]	61	-928	686	2343

[a]This figure is for automobile travel; a small percentage of this value is for carpool demand.
[b]This figure is for local bus travel; a small percentage of this value is for express bus demand.
[c]Estimated by the Niagara Frontier Transportation Authority.
[d]This is a crude approximation of the energy consumption of the heavy rail mode; the existing right-of-way in Buffalo could not handle a heavy rail vehicle for the entire length of the rail right-of-way.

operation has a minimal impact on energy consumption except in very rare cases (e.g., electric motors on rail vehicles are run continuously when vehicles are in nonservice operation). Lack of priority signalization for rail vehicles in mixed operation is one possible exception to the proposed notion that operating decisions have little impact on operating energy consumption; however, this question can really be categorized within the domain of station spacing.

Other energy-saving strategies seem to have little impact on light rail operations. Ideas to save energy by using a coasting phase cannot be applied in situations where spacing between stations is small. Adjustment of track profile as an energy-saving measure often conflicts with the minimization of construction costs, especially in drilling operations. Regenerative braking systems often substitute increased auxiliary energy for lower propulsion energy consumption.

Total Energy Consumption

Program energy savings take into consideration all factors that affect total energy consumption and thus determine the net energy savings from the implementation of a particular mode. Therefore, this section addresses the amount of energy saved by the implementation of a particular mode. Three important factors affect the range in program energy values for the light rail mode:

1. Weight of the vehicle,
2. Kilowatt output of the motors for propulsion, and
3. Average number of passengers per vehicle (this value is determined for an average loading over the entire workday).

Due to recent developments in the domestic manufacturing of LRVs and taking into consideration the often overestimated travel demand, a moderately patronized and relatively heavy LRV is felt to accurately portray the circumstances that are ahead for the Buffalo rail system. A saving of 2450 Btus of petroleum/passenger mile results in an annual conservation of about 1 million gal of fuel/year. This is a considerable saving; however, it is certainly not the panacea to our petroleum problem.

The program energy savings from the implementation of a carpool, express bus, light rail, or heavy rail system are listed in Table 5. This table contains the results of the local approach as well as the results that would have been obtained from using the CBO report. The CBO results indicate the energy saved in Btus per passenger mile. The local energy model contains both the Btus per passenger mile and the Btus of petroleum per passenger mile. The explicit petroleum consideration is one of the advantages of using a local energy model.

This table measures the net energy savings of the implementation of one of these previously mentioned modes. For example, the CBO states that the implementation of a light rail system will save very little energy--just 85 Btus/passenger mile. The results of the test application for Buffalo indicate that a light rail system will save 620 Btus/passenger mile and 2448 Btus of petroleum/passenger mile. These results seem to clearly indicate the usefulness of the local energy approach. The additional flexibility, without rigorous data preparation, makes the local planning effort more responsive to local concerns.

The cost of construction for the light rail system in Buffalo will approach $0.5 billion for the 6.22 operating miles. If the benefits of a rail system rest heavily on the energy (or, more specifically, petroleum) savings, then the rail mode is an expensive means to use for the reduction of our petroleum dependence.

SUMMARY

The results of this study emphasize the need to address the modal energy intensity of rail systems at the local level. Due to variability in the physical components and patronage levels, a decentralized perspective is required. This approach adds to the flexibility in evaluating locally generated, policy-sensitive alternatives. A summary of the main findings follows.

Due to the petroleum problem in the United States, the establishment of petroleum measuring criteria (with local petroleum values) aids in the evaluation of modes that do not directly use petroleum-based fuels.

Operating energy consumption of new light rail and heavy rail systems is higher than the values adopted from national averages. This is due to the increased size of these vehicles, especially foreign-manufactured articulated light rail cars.

A light rail system in Buffalo, New York, will save energy; however, it will have a small overall energy impact in the region. Station spacing and rail vehicle type greatly affect the operating energy consumption of rail vehicles at the local level. Operating policies that affect rail speed have much less impact. Regenerative braking on the vehicle tested in this example city does not produce an appreciable saving in operating energy.

Urban areas that contain electric generating plants with high percentages of petroleum as fuel sources need to address the petroleum performance of their particular system in much more detail.

The aggregation of local studies into national market segments, defined by the age of the system, vehicle manufacturer, geographic area, or size of the particular study region should aid in the evaluation of national energy-conserving strategies on local areas.

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