ENERGY EFFICIENT RAIL TRANSIT OPERATION

Ronald W. Eash, Chicago Area Transportation Study

The paper investigates the energy consumption characteristics of modern rail rapid transit. The paper shows the variation in energy consumption caused by different operating policies and design characteristics of the rail transit mode, and points out the energy economies of improved design and operation. Five variables are analyzed using a rail transit performance computer model that simulates the performance of a rail transit train whose operating characteristics are specified by the program user. The simulated train runs over a track segment established by the user and a performance log of train speed and acceleration along the track segment plus the rate of energy consumption and cumulative energy used are output by the train performance program. The analysis indicates that of the variables studied, the most promising ways of reducing rail transit energy consumption are to include a coasting phase with reduced maximum speeds in the train's performance cycle and to adjust the track vertical profile.

A number of recent studies have attempted to compare the energy consumption of modes and evaluate their relative energy efficiency. For the most part, this work depends on gross average estimates of the energy consumed for a given output such as passenger, ton, or vehicle kilometers (vehicle miles). This acceptance of gross estimates of modal energy consumption has hidden the variation in energy usage due to design and operation of a mode, and the potential energy economies of improved design and operation.

This paper looks at the energy consumption characteristics of modern rail rapid transit. There are at least two reasons to seek energy efficient designs for rail rapid transit systems. First, rail systems are long lived so that even minor inefficiencies in vehicle and track design cause the accumulation of much wasted energy over these long periods of time. A second reason is that a number of new rail rapid transit systems are planned and they should be designed with energy efficiency in mind. In this paper the energy consumption of a rail rapid transit state of the art vehicle is investigated subject to changes in five design and operational variables: length of train, distance between stations, maximum speed permitted between stations, track profile, and train braking policy of the operating agency.

The analysis makes use of a rail transit performance model developed at the University of Pennsylvania by the author. This rail transit train performance program will accept the track profile, vehicle operating characteristics, and braking policies as program inputs and produce a time-distance computation. The program also calculates the rate of vehicle energy consumption in kilowatt-minutes. Since distances between stopping points and train lengths for rapid transit are not large, the program is economical to use and a number of different track profiles and input parameters can be quickly compared.

Characteristics of the Simulated Rail Transit Train

Physical Characteristics

The vehicle used in the simulation program is basically the Bay Area Rapid Transit vehicle (1). Each car has seats for 72 passengers. A normal passenger load for a car is 120 persons, and 216 persons is the crush load. In the simulation an empty car weight of 27.2 metric tons (30.0 tons) was used. The average car weight for a loaded car was taken as 38.1 metric tons (42.0 tons). Maximum acceleration and deceleration rates were held to 5.0 KPHPS (3.1 MPHPS), and the change in acceleration or braking (jerk) was kept to 3.2 KPHPSPS (2.0 MPHPSPS). Both parameters are determined by passenger comfort and safety rather than actual train performance limits (2). Maximum train speed was restricted to 129 KPH (80 MPH). The simulated train is powered by a 1000 volt D. C. source.

Motive Power and Braking

The maximum tractive effort delivered by the train's motors as a function of speed was computed in the simulation from general motor characteristics supplied to the program. With the vehicle weights noted earlier, a maximum tractive effort of 57,000 newtons (13,000 pounds) per car is allowed at low speeds without exceeding the acceleration limit. This tractive effort is less than the maximum tractive effort permitted by the adhesion between wheel and rail in reasonable condition.

Electric traction motors can produce output far in excess of their hourly rated power, the power that can be produced by the motor continuously for one hour without overheating. Since traction motors in transit operations are not run continuously, they can dissipate heat while they are idling during coasting, braking, and station stops. Thus, the motors can be run at overheating levels during acceleration of the train when the highest power output is required. Comparison of computed tractive effort curves with actual tractive effort plots for the BART system indicated that traction motors are commonly run at 140% to 160% of the hourly power rating.

Four traction motors per car, each rated at 104 kilowatts were used in the simulated train. Total kilowatts generated per car at maximum power is then:

$$KW_{max/car} = 1.50KW_{motor}(\text{Motors/Car}). \quad (1)$$

Maximum tractive effort in newtons per car as a function of speed can be computed by:

$$TE_{max/car} = \frac{3600KW_{max/car}EFF_{gear}}{v}. \quad (2)$$

Where v is the speed and EFF_{gear} is the efficiency of the gears between the motors and the wheels which varies between 80% and 95%, with the lower values at higher speeds. Figure 1 compares the reported maximum tractive effort curve for the BART car (1,3) against the computed maximum tractive effort curve used for the simulated car.

Braking effort versus speed for a rail rapid transit car is much simpler to compute than tractive effort. The train is braked by two braking systems, dynamic braking and train friction brakes. Dynamic braking is accomplished by turning the traction motors into electric generators to produce a current which is dissipated as heat through a bank of resistors, or returned to the line source in regenerative braking. With adequate resistance, a dynamic braking effort greater than the amount permitted by the maximum braking rate is possible except at low speeds. When dynamic braking fades, train friction brakes are blended with the dynamic brakes to maintain the braking rate. The BART car's dynamic braking curve (1,3) as it was incorporated into the program is shown in Figure 2.

Figure 1. Simulated and BART Tractive Effort

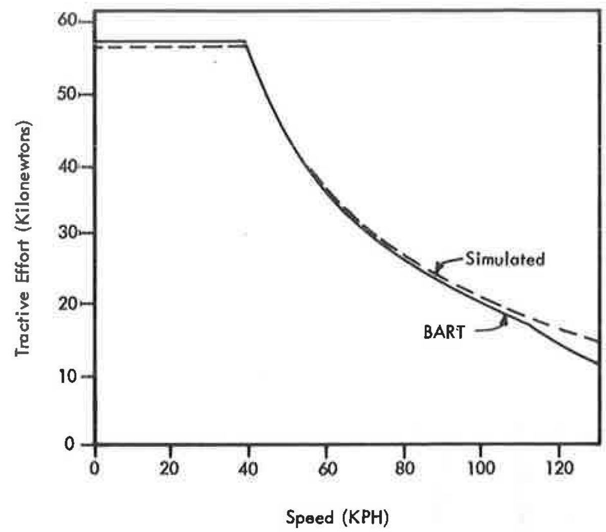
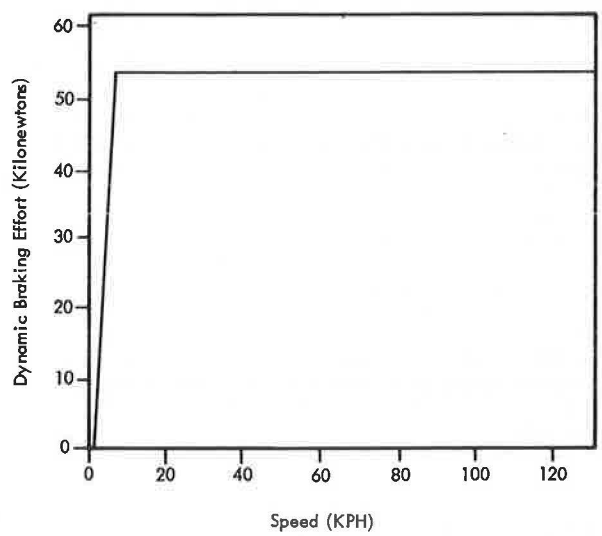


Figure 2. BART Dynamic Braking Effort



Note: 1 Kilonewton = 225 Lbs. 1 KPH = 0.62 MPH.

Train Resistance

In the train performance simulation, resistance to motion comes from two sources: grades and the train's inherent resistance. Resistance on grades is calculated by multiplying train weight times the tangent of the grade. The second component of train resistance, inherent train resistance, is calculated from the Davis Equation, used to compute the inherent resistance to motion of conventional rail transit vehicles (2,4,5,6,7).

To determine inherent train resistance in newtons, the Davis Equation equals:

$$F = 0.65 + \frac{129}{w} + k_1 v + \frac{k_2 A v^2}{W}. \quad (3)$$

where F = newtons of resistance per kilonewton of car weight.
w = car weight per axle in kilonewtons.
W = total car weight in kilonewtons.
v = speed in kilometers per hour.
A = area of a car's cross section in square meters.

In this version of the Davis Equation, an average value for k_1 is 0.009, while for k_2 an average value for a leading car equals 0.030. For trailing cars, an average value of k_2 is 0.0063. However, both k_1 and k_2 depend on car characteristics.

Traction Motor Current Consumption

With the forces of resistance and tractive effort or braking effort acting on the train computed, the acceleration-braking and speed profiles can be simulated. To determine the energy consumed by the train following this performance profile, the current consumption of the traction motors must be estimated. In a D. C. series motor, the following proportionality exists between tractive effort and motor current (8).

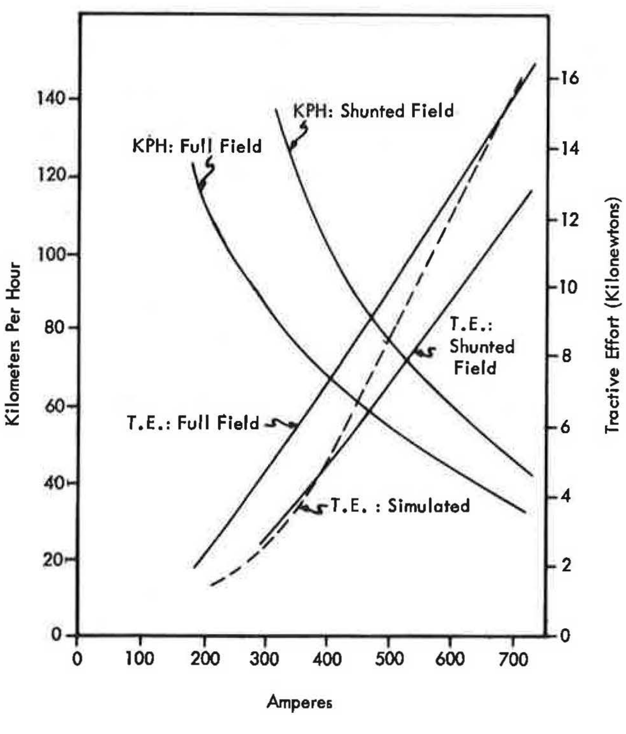
$$I_{motor} = k\sqrt{TE_{car}} \tag{4}$$

To obtain a point with known current and tractive effort to solve for k, it is first assumed that the maximum voltage across a motor is known, and that this maximum voltage equals the motor voltage at the car's maximum speed. The tractive effort at the maximum speed and power output at maximum speed are also known. Substituting this power and motor voltage into the equation relating power, motor current, and voltage determines the minimum current through the motor at the minimum tractive effort. Therefore:

$$I_{motor} = I_{motor}^{min}\sqrt{\frac{TE_{car}}{TE_{car}^{min}}}. \tag{5}$$

In operating the simulated train, it is assumed that all car motors are in series over the range of speed when maximum tractive effort is available. This is in the speed range of 0 to 30-40 KPH (20-25 MPH). Past this speed the simulation assumes that the motors are circuited in parallel. A comparison of the simulated motor operation with actual motor operation is shown in Figure 3, which plots the tractive effort versus motor current curve for a Westinghouse 1463-B traction motor (1), the motor used in the BART car, against the tractive effort versus current curve in the simulation.

Figure 3. Simulated and Actual Motor Operation



Note: 1 KPH = 0.62 MPH. 1 Kilonewton = 225 Lbs.

Simulated and Measured Train Performance

Speed and Acceleration

It was highly desirable that the output from a simulation be compared against measured performance of a rail transit vehicle. This proved difficult to do because accurate performance data is rarely published. Finally, the simulation was compared against train performance data developed and published during the preliminary testing and evaluation of the BART propulsion system (3).

However, this could not be a straightforward comparison. The most important difference between the test data and simulation output is that the test propulsion system does not exactly match the propulsion system in the final BART vehicle. The test traction motor features lower current consumption at every level of tractive effort than the BART Westinghouse 1463-B motor. The geometry of the test track and its vertical alignment is also different from the simulated track segment. A third problem is that the test car was not completely equal in weight or configuration to the final BART design.

Figure 4 compares the simulated train acceleration and speed against test data. Simulated and reported performance are quite close over the first 150 meters (500 feet) of operation. After this distance, the higher simulated acceleration takes effect and the simulated and test speeds diverge rapidly.

Energy Consumption

Figure 5 shows the instantaneous energy in kilowatts consumed by the test car accelerating over the first 1220 meters (4000 feet) of a run at the rate shown in Figure 4. Simulated energy consumption per car, also shown in this figure, is clearly higher than the BART test vehicle consumption on the test track. Part of this increased consumption is due to the higher current consuming motors of the simulation vehicle and part of the difference is attributable to the higher acceleration rate of the simulated train.

A major difference in energy consumption between the simulated and test vehicle can be seen in Figure 5 during the first 30 meters (100 feet) or so of acceleration. Traction motors in the BART test vehicle were permanently wired with two motors in series on each truck, but all four of the simulated vehicle motors are switched into a series circuit over the first 43 meters (140 feet) of the run. This use of series operation decreases the current consumed per car and explains the discontinuity in the simulation curve and most of the difference in energy consumption between the test car and the simulated vehicle at low speeds.

Simulation Results

Energy Consumption Versus Train Length and Distance Between Stops

The first relationship between energy consumption and rapid transit operation to be investigated using the train performance simulation program was the impact of longer trains and greater distances between stations. A total of nine simulations were run using three different train lengths and three varying distances between stops. Trains two, four, and eight cars long were simulated over distances between stations of 305, 1524, and 3048 meters (1000, 5000, and 10,000 feet). In all these

Figure 4. Simulated and Test Train Performance

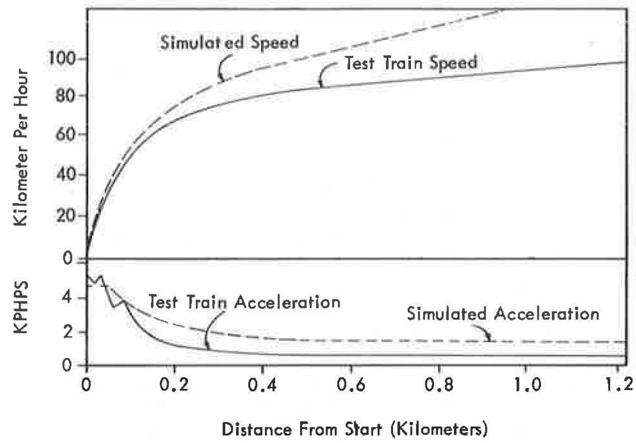
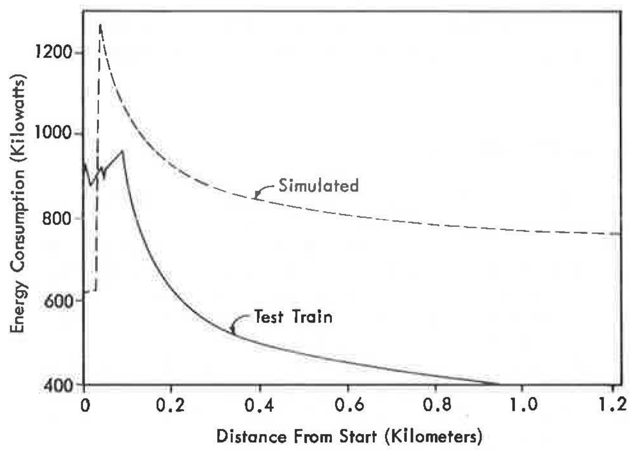


Figure 5. Simulated and Test Train Energy Consumption

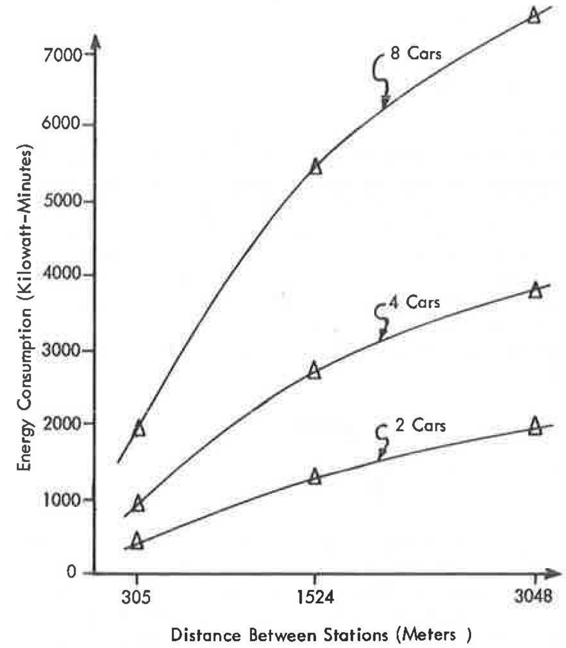


Note: 1 Kilometer = 0.62 Miles.

calculations maximum performance of the train was assumed. Maximum tractive and braking efforts, subject to maximum permissible acceleration and braking rates, were applied and the train was not permitted to coast.

Results of these simulations are plotted in Figure 6. It should be noted that the simulated energy consumption is only for propulsion of the train and does not include energy used for auxiliary equipment such as air conditioning. This figure shows the energy consumed by the train in kilowatt-minutes as a function of train length and distance between stops. Energy consumption rises almost proportionally with the number of cars in the train because all cars are powered and contribute about equally to the tractive effort moving the train. But more importantly, the energy consumption is increasing at a decreasing rate with the distance travelled between stations. At shorter station spacings, the high energy consumption during the initial accelerating portion of the run is a larger portion of the energy consumed for the whole run than it is at longer distances between stations.

Figure 6. Train Energy Consumption, Train Length, and Station Spacing



Note: 1 Meter = 3.28 Feet.

Table 1 further emphasizes this latter point by contrasting average energy consumption rates. In this table, the average energy per car kilometer (car mile) is compared for the simulations of Figure 6. This comparison reveals that the 1524 meter (5000 feet) station spacing is almost 75% more efficient than spacing stations only 305 meters (1000 feet) apart. Extending the distance between stations to 3048 meters (10,000 feet) continues this trend, and this spacing is about 45% more efficient than the 1524 meter (5000 feet) station spacing. Average energy consumed per car kilometer (car mile) at 305 meters (1000 feet) travel distances is almost 2.5 times the consumption rate when stations are 3048 meters (10,000 feet) apart.

There are only slight economies in longer trains. Because the lead car encounters more resistance than a trailing car, the resistance of each car added to a train is slightly less than the average resistance per car in the train. But this factor is negligible at very short station spacings when the train does not attain a high speed. Energy savings per car kilometer (car mile) on the

Table 1. Average Energy Consumption in Kilowatt-Hours per Car Kilometer

Station Spacing (meters)	Train Length in Cars 2	4	8
305	11.26	11.22	11.20
1524	6.50	6.47	6.41
3048	4.72	4.51	4.44

Note: 1 Kilometer = 0.62 Miles.
1 Meter = 3.28 Feet.

order of 1% to 2% for each added car are achieved at the 3048 meter (10,000 feet) station spacing distance.

Energy Consumption and Speed Attained Between Stops

The transit performance simulation program was applied to determine the impact of different maximum speeds on energy consumption. A four car train was simulated over different lengths of track at four different maximum speeds. The train was first limited to a maximum speed of 32.2 KPH (20 MPH), then its maximum speed was increased in 32.2 KPH (20 MPH) increments to the maximum permitted speed of 128.7 KPH (80 MPH).

In Table 2, average energy consumption rates per car kilometer (car mile) are again shown. For a trip between two stations 3048 meters (10,000 feet) apart, it requires 3.6 times as much energy to achieve a top speed of 128.7 KPH (80 MPH) than to run at a maximum speed of 32.2 KPH (20 MPH). Over this same length of track, an increase in speed from 32.2 KPH (20 MPH) to 64.4 KPH (40 MPH) requires slightly more than twice as much energy per car kilometer (car mile).

Train Energy Consumption and Track Profile

The simulation program was used to see how much influence the track profile might have upon energy consumption. Simulations were again run for the three station spacings used earlier, but the track profile was depressed between stations. In these runs, the track profile was symetrical on either side of a point midway between the two stations. This meant that the track profile faced by a train was the same regardless of direction of travel. The logic behind this assumption is that most transit designs are for two adjacent tracks, one in each direction, and that the adjacent track profiles could not widely differ without considerable added construction expense for tunneling and elevated structures.

The simulation track profile consisted of a downgrade starting at the station, a level section of track, and then an upgrade into the station. Grades were set so that all train braking would occur on the upgrade. It did not seem desirable to have the train accelerating or holding speed while on an upgrade. Grades of 2% and 4% were used for the track profile, and parabolic curves connected the tangent sections of the vertical profile.

Table 3 shows the results from these simulations of a train running over a depressed track profile. Over a run of 1524 meters (5000 feet) an energy saving of around 16% is possible with a profile incorporating 4% grades. This saving of energy is reduced slightly when the train makes a longer run between stations. The 3048 meter (10,000 feet) simulation shows an energy consumption reduction of less than 14% when 4% grades are used in the track profile. The table also indicates that the energy consumption is nearly proportional to the amount of grade used in the profile even though the length of track on grade changes only slightly due to the increased lengths of vertical curves.

Energy Consumption and Braking Policy

The final aspect of rail transit characteristics to be investigated is the operating agency's braking policy. Allowing a train to coast for some distance before applying the brakes will affect the energy consumption of the train. Two simulations of a four car train running 3048 meters (10,000 feet) between stations were completed to test the energy conserving value of coasting before braking. In the first simulation, the train reached top speed then coasted to 112.7 KPH (70 MPH) before applying brakes to come to a stop. The second simulation was similar except that the train coasted to 96.6 KPH (60 MPH) before applying brakes.

Table 4 summarizes the results of these two simulations incorporating coasting and compares them against the maximum performance simulation over the same distance. The results are quite interesting since considerable energy savings occur when the train coasts, with only a small increase in travel time between the two stations. Especially interesting is how long a train can coast on level track without losing too much speed. In the simulation with the longest length of coast, energy consumption is 40% less than in the maximum performance run.

However, these figures somewhat overstate the energy conserving value of the coasting phase. Even with 3048 meters (10,000 feet) between stations, the train was unable to reach its maximum speed before entering the coasting phase of its performance cycle. Thus, a certain fraction of the energy savings cited in Table 4 is attributable to the limited maximum speed reached in the simulations. A glance at Table 2 indicates that approximately 0.6 kilowatt-hours of the 2.10 kilowatt-hours per car kilometer (1 kilowatt-hour of the 3.39 kilowatt-hours per car mile) saved by coasting to 96.6 KPH (60 MPH) is due to the lower maximum speed reached in the simulation.

Table 2. Average Energy Consumption for a Four Car Train versus Maximum Speed in Kilowatt-Hours per Car Kilometer

Station Spacing	Maximum Speed (KPH)			
(meters)	32.2	64.4	96.6	128.7
305	2.91	8.86		
1524	1.62	3.65	5.31	
3048	1.46	3.01	3.87	5.19

Note: 1 Kilometer = 0.62 Miles.
1 Meter = 3.28 Feet.

Table 3. Energy Consumption for a Four Car Train versus Track Profile in Kilowatt-Minutes

Station Spacing	Percent Grade in Profile		
(meters)	0%	2%	4%
305	945	901	
1524	2724	2527	2290
3048	3799	3531	3283

Note: 1 Meter = 3.28 Feet.

Conclusions

The most important concept brought out by the train performance simulations is the strong dependence of energy consumption upon the operation of the rail transit vehicle and the design of the

Table 4. The Impact of Different Coasting Policies

Item	Coasting Policy		
	No Coast	1500 Meter Coast	2000 Meter Coast
1. Speed Range of Coast		127 KPH-113 KPH	114 KPH-97 KPH
2. Total Energy Used	3799 KW-Minutes	2755 KW-Minutes	2259 KW-Minutes
3. Energy Used per Car Kilometer	5.19 KW-Hour	3.77 KW-Hour	3.09 KW-Hour
4. Travel Time	117 Seconds	120 Seconds	128 Seconds

Note: 1 Meter = 3.28 Feet. 1 KPH = 0.62 MPH.

track profile. An energy efficient rail transit design and operation would use only about one-half the energy of less efficient designs and operations. Considering the limitations imposed on train size and station spacing by capacity and service requirements, the last two factors discussed in the paper appear to have the most potential for improving energy consumption in rail transit. These two factors are: incorporating a coasting phase in the performance cycle between stations, and adjusting the track profile.

Of these two factors, incorporating a coasting cycle is clearly of greater importance than changing the track profile for energy conservation. A policy of coasting can be easily implemented without capital investment, and coasting between stations generally causes a slight reduction in the maximum speed attained between stations, which also promotes energy efficiency.

The trend toward high performance rail transit vehicles has caused an increase in the energy consumption of the mode. A reported average figure of 3.3 kilowatt-hours per car kilometer (5.3 kilowatt-hours per car mile) used in recent U.M.T.A. analyses (9) is too low for new high performance equipment. This figure is probably too low even when a conscious effort is made to promote energy conservation in this new equipment's operation.

The importance of energy conservation in justifying new transportation system management type improvements should not be overlooked. When electricity costs are rising to \$0.04 to \$0.05 per kilowatt-hour for rapid transit operations, it is clear that savings in energy costs can rapidly accumulate. Thé advantages of automatic train control for insuring an energy efficient coasting phase in the train performance cycle are obvious, and a portion of the cost of this equipment should be justified through the resulting energy cost savings.

Improvement of poor track alignment is another case where some of the cost of the improvement is covered by the improved energy efficiency of the rail transit operation. In these two situations, and in similar problems in the evaluation and planning of rail transit improvements, the analyst must be aware of how alternative designs and operations impact energy consumption.

Acknowledgements

The simulation program, initial computer runs, and a first draft of this paper were prepared while the author was at the University of Pennsylvania. The support and advise of Professor Vukan R. Vuchic of the University of Pennsylvania in the preparation of this paper is gratefully acknowledged. In addition, the author wishes to note that his time at the University was supported by the Transportation Research and Education Fellowship Program of the Federal Highway Administration.

References

1. BART Prototype Car Development Program. Bay Area Rapid Transit District. Vol. 1: Program Synopsis, Vol. 2: Program Details, 1973.
2. Robert G. Hennes and Martin I. Ekse. Fundamentals of Transportation Engineering. McGraw-Hill Book Company, Inc., New York, 1955.
3. Rapid Transit Propulsion Systems. Bay Area Rapid Transit District Demonstration Project. Technical Report No. 4, 1968.
4. Thomas McGean. Urban Transportation Technology. Lexington Books, Lexington, Mass., 1975.
5. William W. Hay. An Introduction to Transportation Engineering. John Wiley and Sons, Inc., New York, 1961.
6. William W. Hay. Railroad Engineering. John Wiley and Sons, Inc., New York, 1953.
7. American Railway Signaling Principles and Practices. Association of American Railroads. Chapter 3: Principles and Economies of Signaling, 1955.
8. D. W. Hinde and M. Hinde. Electric Traction Systems and Equipment. Pergamon Press, Oxford, England, 1968.
9. Characteristics of Urban Transportation Systems: A Handbook for Transportation Planners. Urban Mass Transportation Administration, 1977.

Discussion

David R. Phelps, General Electric Company

Optimizing the energy consumption of a rail transit system consistent with operational, physical, and civil constraints is an important issue in the design of new systems and operation of existing systems. Mr. Eash's paper addresses the alternative strategies and design features in a useful manner, and his results are instructive.

It is unfortunate that the validity of Mr. Eash's comparative results is clouded by the serious errors in certain portions of his analysis. Mr. Eash has correctly highlighted several strategies and design considerations capable of significantly reducing the energy consumption of a rail transit system. However, his results are useful only in a qualitative sense; the quantitative, numerical results are derived from a simulation which, regretable, is inconsistent with the true physics of transit railcar propulsion systems.

At the outset, Mr. Eash leaves unexplained the discrepancy between his simulation and the BART data. Investigation of his analysis shows several probable sources of the discrepancy. Taking his analysis in the order of presentation, his train resistance equations were examined. Converting the usual form in English units to metric yielded two coefficients with values different from Mr. Eash: k_1 - 0.014 (rather than 0.009) and k_2 = 0.044 (leading car, rather than 0.030). Unfortunately, Mr. Eash does not give the simulated train length for his Figures 4 and 5. The test data cited is for a single car.

Further review of Mr. Eash's analysis showed a significant shortcoming in the presentation of design parameters of D.C. traction motors. Contrary to his statement, in such motors magnetic flux is not a "linear function of the current through the motor." Because of saturation effects, it is decidedly non-linear. Reference to his Figure 3 shows that his simulation thus becomes greatly in error in that it understates the current required to produce the required tractive effort. In addition, Mr. Eash, although unclear on this point, appears to have ignored field weakening and to have used, in effect, a (erroneous) "Shunted Field" curve throughout.

Mr. Eash is fortunate that the BART car characteristics uniquely comply with his assumptions regarding motor voltage, tractive effort, and power output versus speed. It is unclear that he appreciates that his assumptions, other than for motor voltage, would have been invalid for many other D.C. transit cars.

In addition to the problems with his motor simulation, Mr. Eash then proceeds to miss the point that his curve (Figure 3) is a 2S2P curve, rendering false his assumption that "all car motors are in series" during the constant tractive effort phase. Finally, Mr. Eash seems not to have simulated a current-speed curve (c.f. Figure 3, his report), which might further have highlighted the problem.

All of the above shortcomings are unfortunate because of the ease with which they could have been avoided. With reference once more to the solid line portions of his Figure 3, one may enter the diagram at the desired tractive effort (14.25 KN) to find the intersection with the Full Field T.E. curve (about 670 amperes). This current (and T.E.) can be maintained up to the speed (the "corner point") where the amperes intersect the Full Field "KPH" curve (about 40 KPH). In a switched resistor system using a 4S start, the line current would equal the motor current up to about half the corner point speed. After transition to 2S2P, line current would be double the motor current. (Sometimes a 4S characteristic is also supplied by the motor manufacturer.)

In a chopper situation such as BART, line current is ideally zero at standstill, ramping to twice motor current at the corner point. Chopper losses modify the ideal shape, but the shape of the bottom of Figure 4 looks in error in the early stages for the Test Train.

Referring once more to Figure 3, the propulsion system may undergo field shunting/weakening at constant armature current, or the accelerating rate may be held up by going to higher armature current. In either case, the tractive effort - Shunted Field T. E. intersection determines the current - KPH: Shunted Field intersection. Beyond this point the car is running on the Shunted Field motor characteristic for Amperes - T.E. and Amperes - KPH. Usually the volts per motor have been constant since crossing the current - KPH: Full Field curve; in the case of BART, volts per motor do rise to a maximum at top speed.

The above level of detail is given to indicate that Mr. Eash made his task more difficult than need be. His qualitative results are valid in the relative numbers he computes, but his numerical results rest on an incorrect analysis.

Closure

Mr. Phelps comments are quite informative on the operation of traction motors and it is gratifying to see that this paper has sparked comment from a manufacturer. The dissemination of reliable vehicle design data through this type of discussion can only improve the research of academic and government analysts in the rail transit field.

In light of his discussion comments, two general points about the work described in the paper should be emphasized. First, no attempt was made to totally reproduce the BART vehicle in the simulation computer program. Secondly, simulated motor characteristics are derived from the theoretical performance of D.C. motors in transit operation as opposed to the option of having a unique motor design built into the program. The resulting rail transit performance described in the paper should then be viewed as representative of modern rail transit performance, and not a strict recreation of BART's performance.

The simulation requires some vehicle attributes which could not be obtained from published data on the BART vehicle, and average and estimated vehicle parameters had to be used. Parameters in this category include: actual motor power as a function of hourly rating, the efficiency of gears in the trucks, and axle loadings. Average values were also used for the Davis Equation constants. The constants used were carefully checked against their English unit equivalents, but these constants are vehicle dependent and can differ by the amount noted by Mr. Phelps depending on the source cited.

With regard to the development of the traction motor performance relationships used in the paper, they are derived and discussed in the closure reference (10). The saturation effect which tends to hold magnetic flux constant is ignored in an elementary analysis of D.C. motor performance. Also, the relationships used in the paper are for a series wound D.C. motor, traditionally the most widely used type of motor in transportation vehicle applications. Based on the comparison with the BART motor, these relationships apparently provide results representative of actual transit motor performance.

Finally, some questions are raised in the discussion about the motor circuitry used in the simulation. It is true that BART's traction motors are permanently wired in a two-series-two parallel configuration, but operating a four series motor configuration in the eraly stage of the performance cycle then switching to two-series-two parallel operation is a common design practice. In any case, there is little impact on performance cycle energy consumption since the four motors in series configuration is in effect during only a small portion of the performance cycle.

Reference

10. Thomas McGean. Urban Transportation Technology. Lexington Books, Lexington, Mass., 1975. pp. 163-174.