ENERGY OPTIMIZATION FOR RAIL PUBLIC TRANSIT SYSTEMS

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Energy optimization for rail public transit systems is discussed from the viewpoint of an integrated systems approach. This approach considers the interaction of all the major subsystems of a total rapid transit system rather than each subsystem independently as has often been done previously. Some of the major subsystems examined include vehicles and their major propulsion, braking and auxiliary systems, train operations, environmental control facilities, and civil and structural facilities. The major factors that may significantly affect an overall energy evaluation are identified, and the ways in which each of these factors may be controlled to effect overall maximum efficiency of energy use are discussed. Energy evaluation techniques include a new strain performance simulation computer program developed by Parsons, Brinckerhoff, Quade and Douglas, Inc., as part of a 4-year subway environment research project. This paper notes that the procedures for evaluation on a total systemwide basis are applicable for any rail transit system and can be used to extend or modify existing rail transit systems and the design of new systems.

•UNTIL fairly recently, discussing the optimization of energy in rail public transit systems would have been considered quite irrelevant. Considering the absence of new construction, the need for energy optimization might have been questioned, and, considering the many variables involved, the ability to perform a meaningful analysis would have been doubtful.

It has become clear, however, that these objections are no longer valid. The growing need for rapid and comfortable urban public transit is widely regarded as one of the outstanding technological challenges of the last half of the twentieth century. Today, more rapid transit systems are being thought about, planned, designed, or built than ever before. It has been estimated that, in cities in the United States, expenditures on new, expanded, or improved rapid transit facilities will amount to $25 to $35 billion over the next 10 to 15 years. Cities expanding existing systems or planning new systems include Atlanta, Baltimore, Boston, Buffalo, Chicago, Cleveland, Honolulu, Los Angeles, Miami, Minneapolis-St. Paul, New York, Pittsburgh, St. Louis, and Washington, D.C. In other countries, planning or construction of transit is under way in Toronto, Montreal, Mexico City, Vienna, Munich, Frankfurt, Budapest, Caracas, Hong Kong, and Sao Paulo; transit studies are being done in Singapore; Japan is planning to almost double its existing 82 miles (132 km) of rapid transit in Tokyo, Osaka, and Kobe; and Brussels, Helsinki, Turin, and Amsterdam are among the European cities planning entirely new rapid transit systems. The population growth in urban areas demands a greater frequency of rapid transit service at higher speeds. Since the increase in power to provide faster and more frequent train service varies as the square of the increase in speed, power requirements may be expected to increase at an equal rate.

EVALUATION OF ENERGY BALANCE

The need for an integrated systems approach deserves particular emphasis when requirements or problems related to a transit system energy balance are to be evaluated. Because of the transient nature of subway system characteristics, few, if any, phenomena or parameters are truly independent. Variations in design average and

maximum train speeds, for example, will have a profound effect on many aspects of a transit system. These include operation concepts, required number of trains for the system, vehicle propulsion and braking system characteristics, radii of track curvature, environmental control systems, and traction power and auxiliary power distribution systems. The energy balance for the entire transit system must therefore consider all of its physical, geometrical, operational, and physiological parameters. After an energy evaluation has been made, energy and cost trade-off evaluations can be accomplished to provide guidance on alternative system concepts.

The methodologies for performing cost trade-off evaluations are familiar to most engineers. They should consider, in their evaluations of alternatives, capital costs, operating costs, life of equipment, and the financing costs. Because of the various funding factors and the variations in their application to both the capital and operating costs of a transit system, the highest priority cost factor cannot be established in a generalized way. The planner should take into account current federal, state, and local funding options before a meaningful trade-off evaluation is made.

Before one can evaluate the energy balance that is obtained in a rapid transit system, it is necessary to understand the characteristics and behavior patterns of the various interrelated parameters. To begin, one must identify and quantify the power loads. The most important loads, of course, are those associated with train operations. They account for approximately 85 to 90 percent of the system energy demands. When one examines the most significant load contributor, the vehicle, several factors are apparent. Power required within line sections by trains for their propulsion system and air-conditioning equipment will be substantially higher in systems now under construction or being planned for the future than most present systems. The higher speed and acceleration requirements of future trains necessitate significantly higher power input and resultant power losses.

Approximately 50 percent of the total vehicle energy input is dissipated in the train braking cycle. When current dynamic or friction braking systems are used, this energy loss is converted to heat. Recent studies (1) indicate that, in subway sections of rapid transit systems, the average annual energy requirements for mechanical cooling and ventilating systems necessary to maintain desirable environmental conditions can amount to as much as 50 percent of the traction energy requirements.

On-board vehicle auxiliaries, most notably the air-conditioning equipment but also the lighting systems and air compressors, are the major power loads of the vehicle. Lighting and miscellaneous power loads for the fixed facilities of a rapid transit system normally account for the remaining 10 to 15 percent of the system power demands. These power loads primarily include escalators and environmental control systems (ventilation and mechanical cooling).

An understanding of the characteristics of a vehicle, as they may interact with overall energy considerations, is appropriate. Table 1 gives various vehicle characteristics for several systems in the western hemisphere (1).

Table 1. Vehicle characteristics.

System	Cars/Train		Maximum Passengers/Car		Motors		Tare Weight (lb)	Speed (mph)	
	Minimum	Maximum	Seated	Standing	hp/Motor	Motors/Powered Car		Average	Maximum
New York	10	10	50	250	100	4	76,500	18	50
Chicago	2	8	50	75	55	4	42,700	24	55
Philadelphia	2	6	54	71	100	4	51,000	18	42
Boston	2	4	54	254	100	4	70,500	26	50
San Francisco (BART)	2	10	72	144	150	4	56,500	35	80
Toronto (TTC)	4	6	83	217	125	4	59,000	17	50
Montreal (MUCTC)	3	9	40	120	155	4	60,000	20	50
Washington, D.C. (WMATA)	2	8	81	94	175	4	70,000	35	75

Note: 1 lb = 0.45 kg. 1 mph = 1.6 km/h. 1 hp = 746 W.

The kinetic energy of the vehicle is primarily a function of its weight and operating speed ($K = mV^2$). The weight is a consequence of the physical characteristics. The weight and operating speed are generally influenced by the anticipated passenger loadings or traffic density and by other parameters such as length of the system; alignment, profile considerations, and constraints; vehicle structural design requirements; and distance between stations. Some of the major systemwide features and their range of variations are described below.

Vehicle Length and Weight

The consist (number of cars) varies as a function of system operating requirements and will generally vary from 2 to 10 cars. These requirements are usually influenced by peak versus off-peak traffic demands. Often, cars are semipermanently coupled in married pairs, which consist of two cars that share certain auxiliaries such as air compressors and communication systems. Although this provides certain economies in car construction and maintenance, the two cars may only be operated as a pair. Some systems, such as the MUCTC in Montreal, operate a three-car consist. Large transit systems may operate trains 600 ft (183 m) long or longer and use 10 or 12 cars during peak traffic periods.

Weight will vary with the size of the vehicle; however, it will also vary as a function of construction materials. Cars with aluminum bodies, for example, are generally regarded as lightweight when compared with stainless steel bodies. Vehicle tare weights for rapid transit service will generally range from 50,000 to 80,000 lb (22 680 to 36 288 kg).

Vehicle and Wheel Type

The most common type of vehicle truck is a two-axle, four-wheel type. The wheels are steel-flanged for operation on steel rails. Because of the steel wheel-steel rail noise problem in the older portions of the Paris Metro, which contains short radius curves, the French developed a pneumatic rubber-tired truck. This design concept is now in use in some parts of the Paris Metro and in the new Metros in Montreal and Mexico City. Two rubber-tired wheels are mounted on each of the two axles per truck. The wheels ride on a concrete or steel track. The trucks include horizontally mounted, rubber-tired wheels operating against sidewalls of the guideway to steer the vehicles.

Advantages claimed for the rubber-tired systems are reduced noise on short radius turns and the ability to operate on steeper grades than with flanged steel wheels. Because of the construction features and number of components of the pneumatic rubber-tired trucks, their weight and rotational inertia are significantly higher than for flanged steel-wheel trucks. In addition, the limitations of load-bearing capacity of the rubber tires result in significantly shorter car lengths than the allowable maximum for steel-wheeled cars. Another disadvantage of rubber-tired trucks is the higher rolling friction and hysteresis losses common to any rubber-tired vehicle. Collectively, these losses, together with a greater car weight per passenger, result in total system traction power requirements that may be more than 50 percent greater than for steel-wheeled vehicles per passenger carrying capability for systems with similar track profiles (2). Therefore, it should be evident to system designers that many site and system factors must be taken into account in selecting the most appropriate truck-vehicle concept.

Propulsion System

Most rapid transit system cars are driven by electric traction motors that are contained on each car. The source of energy is wayside electric power distributed through a third rail or overhead catenary wire. Contact shoes or pantographs, as appropriate, function as the power pickups for the car. The traction motors are generally mounted

within the vehicle truck and there may be one or two motors per truck, or two to four per car. Four motors up to 150 hp each per car are possible. Motors may be ac or dc, although most transit systems use dc. The motor sizes are determined as a function of car weight, design speed criteria, and design acceleration rate requirements.

Braking System

For safety considerations, most rapid transit cars have multiple braking systems. These include friction shoe or disc brakes and usually some form of electric braking. In electric braking (dynamic or regenerative), the traction motors are switched to function as generators during the braking mode. Where dynamic brakes are used, the electric energy generated by the conversion of the train's kinetic energy in bringing the vehicle to a stop is discharged to on-board resistor grids. In the process, these resistor elements are heated up to 500 or 600 F (260 or 315 C) or even higher. Thus, the braking energy is ultimately all dissipated as heat, either at the wheels as a result of the friction brakes or at the resistor grids.

One of the more recent advances in transit vehicle propulsion-braking systems is the use of a regenerative braking system. Although this system is similar to a dynamic braking system insofar as the switching of the traction motors to operate as generators is concerned, part of the generated energy is then used by on-board auxiliaries. An alternative system permits return of the electrical energy to the contact rail for possible use by other trains. Regeneration can reuse 25 percent or more of the available braking energy of trains. Since, on the average, the braking energy accounts for almost 50 percent of the total energy lost in a rapid transit system, reuse of some of that energy and resultant reductions in heat dissipation can be effected. Therefore, a regenerative braking concept is highly desirable for energy conservation. The effective use of a regenerative braking system is limited only by present technology. Further advances in compatible electrification and power control systems are necessary before the full benefits of regeneration can be realized.

Air Conditioning

Most transit agencies building new systems or replacing outmoded rolling stock are purchasing air-conditioned vehicles. Since the power required per car for air conditioning may be as much as 50 kW, the energy and heat dissipation loads of the air conditioners are significant contributors to the overall load side of the transit system energy balance. This is particularly true during hot summer months when they operate almost continuously, even when the train is stopped and no propulsion power is drawn. In addition, the weight of vehicle air conditioning adds to the overall propulsion system energy requirement.

Operational Requirements

Since the kinetic energy of a vehicle varies as the square of its speed, it is apparent that operational requirements of vehicles can significantly affect the vehicle power demands. Higher speeds for vehicles are generally desired by transit system planners because they influence the travel time of the passengers and are a factor in determining rolling stock inventory requirements. However, in downtown subway systems, relatively close spacing of stations [within 0.5 mile (0.31 km)] will limit maximum operating speeds that might be achieved, since criteria for accelerating and decelerating rates will govern the operating conditions. In some instances, close station spacing may result in a train shifting from a maximum acceleration mode to maximum deceleration mode without any operation at a steady cruising or diminishing coasting speed. Consequently, if an increase in running time of trains can be accepted (usually measured in seconds for a downtown station-to-station run), the resultant

reductions in energy demand could be significant. In many cases, the maximum cost effectiveness can be achieved where a slight increase in headways due to coasting can be tolerated without overloading the system.

Although newer systems are using semiautomatic or fully automatic train control systems, existing systems are predominantly manually controlled. In such a system, the train operator or motor person manually controls the starting, running, and stopping of the train and the opening and closing of the train doors in stations. The motor person operates the train by varying a control lever in the cab. On most systems, through a device known as a cam controller, appropriate parts of the vehicle propulsion motor circuitry are mechanically switched to accelerate, cruise, and decelerate the train.

Recent applications to new systems use chopper controls instead of cam controllers. Fundamentally, a chopper is a solid-state switching device that accomplishes similar end results as the cam controller but does this much more efficiently and smoothly by eliminating mechanical cam contactors. Chopper controls can reduce the traction power energy requirement in the acceleration mode by as much as 10 percent compared with that for cam controllers. In a chopper system, the motors do not operate at full voltage during initial acceleration, but the voltage increases as the ratio of the chopper off time to on time decreases. Because the motors do not operate at full voltage, there is a reduction in power consumption.

Since the kinetic energy of the train relates in part to its weight, the transit system planner may endeavor to specify vehicles that result in the lowest tare weight per passenger carried. Factors that the planner should consider, however, are numerous, and many decisions about the physical characteristics of the vehicle can have a significant impact on energy consumption. In general, the greater the length of a vehicle is, the lower the car weight per passenger will be. Although this would appear to be an obvious advantage, it may limit the operating flexibility for a given system (economical number of cars per train) or provide constraints on minimum track radii. These situations may require enlarged tunnels and may conflict with track routing and alignment considerations. Similarly, local topographic or right-of-way construction considerations may warrant the use of steeper grades, which may be more suitable for rubber-tired vehicles on concrete or steel guideways than for steel-wheeled vehicles on steel rails. When designers understand the characteristics of the major vehicle parameters, they will be able to evaluate the impact and interaction of those characteristics and the overall energy balance.

Track Profile

For a fixed-guideway rapid transit system, the alignment or routing of the system trackways and the locations of stations are determined by transportation planners as a function of the anticipated passenger traffic densities in the various transportation corridors.

Having established an acceptable alignment, transportation system designers then proceed to develop a track profile. Usually at this point determinations are made with regard to those segments of the system that should properly be located above, at, or below grade. Very often these determinations involve an iterative process that takes into account alternative alignments. The objective is to establish an overall system layout that best serves passenger traffic needs and that results in the most economical system construction costs. Subway, or below-grade, construction will be the most costly compared with at-grade or above-grade configurations. [In April 1974, the New York Times reported New York City construction costs of $30 million/subway mile (kilometer)]. Decisions relating to the determination of the track profile may significantly affect and interact with total energy considerations.

The development of the track profile will also consider the grade changes. Construction and other local site conditions may result in varying requirements. Vehicle characteristics will impose constraints on grades and on vertical radii of curvatures where changes in grade are necessary. Where possible, it would be desirable for

trains to travel on a downgrade when leaving a station so that it would be assisted in the accelerating mode, and this would reduce the input power requirements. Similarly, it would be desirable for trains to approach a station on a rising grade so that the braking energy requirements may be reduced. A humped track profile can result in energy conservation by using the potential energy capabilities of the trains.

Conclusions About Subsystems of Rapid Transit

Since the major contributor to the total energy load is the energy used by the vehicle, it is the characteristics of the vehicle and of the system operating concepts that should primarily be addressed to effect energy reductions. Naturally, the cost effectiveness of energy operating costs can be evaluated against amortizing the cost of capital investment. It remains for the owners of a given system, however, to ascertain the additional intangible values of energy conservation that might be achieved with still additional capital investment. In any event, unless a totally integrated transit system design approach is used, opportunities for reducing capital investments and concurrently conserving energy might not even be realized. However, the following factors may be used to achieve these goals:

1. Most transit vehicles have a service life of approximately 20 to 30 years; therefore, the decisions relative to the vehicle component characteristics will have a long-term effect in regard to energy control factors. To affect load reductions, several objectives, such as reduced weight of the vehicle and operating speed constraints, should be sought, and the most efficient propulsion systems should be obtained. Braking systems that reduce energy losses are highly desirable. Thus, from an energy viewpoint, chopper controls and regenerative braking systems with maximum line receptivity are the most desirable objectives.

2. Steeper downgrades for trains leaving a station and greater upgrades approaching the station can significantly reduce the power loads. Where grades can be made greater than those capable of being used for steel wheel-steel rail systems, the benefits may be significant enough to favor consideration of pneumatic rubber-tired vehicles.

ANALYSIS OF ENERGY BALANCE DESIGN PROCESS

Overview

The analysis phase of the energy balance design process, however, is not a singular cycle of events. On the contrary, it is more of a repetitive process that continues as appropriate to the nature of the overall rapid transit system design decisions under consideration. In this iterative approach, the intensity of investigation and evaluation must be in proper relationship to the other systemwide investigations.

Given a set of input parameters and an ability to make the evaluation of the simultaneous interaction of all these parameters in a dynamic system, the engineer or planner can then ultimately determine the overall energy requirements and ascertain the system cost. What then becomes most important for the system planner is the ability to quickly estimate the total system cost variations as a function of varying some of the controllable input parameters. There could be several hundred significant alternatives resulting from the possible major variations in the controllable input parameters that would be a result of these permutations and combinations.

The preoperational computation of train velocity, acceleration, and position in a given system has long been carried out by rail transit engineers using a classical computational procedure based on track profile and alignment (grade and curvature), train weight, and propulsion system characteristics. The tedious nature of these computations eventually prompted a number of motor manufacturers and engineering consultants to create computer programs for determining train performance. Although

these computer programs vary in their ability to simulate complex operating schedules, all use a computational procedure that follows closely that used in classical hand calculation.

Subway Environment Simulation Computer Program

One of the major products of a recently completed subway environmental research project (1) was the development of a subway environment simulation (SES) computer program. The program was developed by Parsons, Brinckerhoff, Quade and Douglas, Inc. and reflects inputs from Kaiser Engineers, De Leuw Cather and Company, the Graduate Aeronautical Laboratories of the California Institute of Technology working with the Jet Propulsion Laboratories, the aerospace technology division of the Developmental Sciences, Inc., and from every operating rapid transit authority in the western hemisphere (these data were received through the offices of the Transit Development Corporation). The Urban Mass Transportation Administration provided most of the funding for the project, and the operating rapid transit agencies of the United States and Canada provided additional funding.

The research project that led to the development of the SES program came about when it was recognized that there was a long-standing need for analytical tools with which the environmental characteristics of a proposed rapid transit system subway design could be evaluated before construction. To achieve this objective, the computer program was developed to provide a dynamic simulation of the operation of multiple trains in a multiple track subway and to permit continuous readings of the air velocity, temperature, and humidity throughout any arbitrary arrangement of stations, tunnels, ventilation shafts, and fan shafts. The SES program comprises four interdependent computation sequences: a train performance subprogram, an aerodynamic subprogram, a temperature/humidity subprogram, and a heat sink subprogram. These subprograms operate simultaneously by using a mutually shared set of system descriptive parameters. The computations in the program of the aerodynamic and thermodynamic phenomena integrate the various differential equations by using a modified version of the Runge-Kutta numerical integration technique.

The new SES train performance subprogram differs from most conventional train performance programs in two important respects: (a) It has been designed specifically to accomodate accurate, continuous computations of the total heat (energy) released by trains, passengers, and ancillary equipment such as air conditioning; and (b) it permits the direct computation of the aerodynamic drag acting on each of the trains in the system by using continuously computed aerodynamic parameters (3). This is particularly important in an overall energy analysis because the aerodynamic drag on vehicles resulting from air motion relative to the trains affects the power consumption of the vehicle motors. In evaluating vehicle aerodynamic drag, conventional programs ordinarily settle for a semiempirical relationship based on train velocity and blockage ratio (the ratio of the train frontal area to that of the tunnel cross section). In practice, the aerodynamic drag on a train fluctuates continuously as it encounters variable annular airflows resulting from changes in tunnel diameter, ventilation shaft location, mechanical ventilation, and the piston-action airflow from other trains. Therefore, the continuous computation of vehicle aerodynamic drag in the SES program represents a significant advance in the state of the art.

The air velocities computed in the aerodynamic subprogram are recycled to the train performance subprogram, and there they are used to determine the airflows adjacent to the trains and provide a means to compute the vehicle aerodynamic drag. The aerodynamic drag is a function of the air velocity in the tunnel relative to the train, the train blockage ratio, tunnel wall friction, and the configuration of the cars.

As noted earlier, the computation of aerodynamic drag is an essential component of the subway simulation because this factor determines both the air resistance trains must overcome to accelerate and the amount of energy imparted by the moving trains to the surrounding air. In general, the drag experienced by a train in a single-track tunnel increases as train speed increases and decreases as the frequency of train

operation (shorter headway) decreases.

The train performance subprogram can be operated independently to evaluate the comparative performance of transit vehicles or propulsion motors by suppressing the computation and printing of environmentally related information. The airflows and air velocities of the aerodynamic subprogram would still be computed because these data would be necessary to compute aerodynamic drag for the train performance sub-program.

The most important train-related energy release to the system occurs during the vehicle braking cycle. For a train using a dynamic braking system, the speed reduc-tion of the vehicles is brought about by using the motors as generators to produce electrical power. This power frequently is dissipated to a grid of undercar resistors. The rate at which energy is dissipated is approximately equal to the net rate of the decrease in kinetic and potential energy of the braking train. The SES program com-putes this energy loss directly from vehicle deceleration rates, velocities, and total mass. Some of the braking energy is absorbed by friction brakes and by friction, windage, and bearing losses of the wheels and generators.

The SES program has been validated by field tests conducted on the rapid transit systems in the San Francisco Bay area, Chicago, and Montreal. It is currently being widely used in numerous environmental systems analyses for various rapid transit systems. Its extension to overall transit system energy optimization studies is now under consideration.

CONCLUSIONS

Examining energy problems leads to a consideration of all the major components of a rapid transit system, such as the vehicles, the fixed facilities, and the environmental control systems in the subway stations and line sections through which a transit system operates. As the various transit system specialists, including planners, engineers, architects, and others, investigate the interfaces between the energy problems and the various component subsystems of which a rapid transit system is composed, significant areas may be identified where overall optimizations of cost of construction and opera-tion can be achieved.

To optimize construction costs, the transit system specialists must first recognize those elements for which alternatives are available. Various combinations of train lengths, headways, and speeds, for example, may satisfy the same traffic demands and yet have significantly different operating energy requirements. Conventional cost estimating techniques for both capital and operating costs may be developed after the trade-off alternatives have been established. The decisions relating to these alternatives are normally made in the early phases of planning a new subway system or extension to an existing system. Such decisions may have a profound effect on the overall energy requirements.

The importance of an overall integrated systems approach in the design of rapid transit systems cannot be overremphasized, if true optimization of energy use is to be achieved. The optimization of the vehicle itself or of the operating conditions of the system may be contrary to the achievement of energy conservation objectives. In a recent design study for a new downtown subway rapid transit system, the operating conditions established in the relatively closely spaced stations [approximately 2500 ft (762 m) apart] would have resulted in trains accelerating from one station and having to initiate a braking cycle when they approached the next station while they were still in an accelerating mode with the throttle wide open. From an operating design viewpoint, this ensured the fastest run time for a train from terminal to terminal. In addition, it minimized the total number of trains required for the system to meet the peak rush hour passenger traffic demands. Consequently, the operating system was thought to have been optimized.

An examination of this operating plan in the interest of reducing the environmental cooling load resulted in a cruising or coasting operating mode being introduced between each accelerating and braking cycle for each station-to-station run. As a result, the

total station-to-station run times were each increased by several seconds. The total travel time from terminal to terminal was increased by approximately 5 percent. Two additional trains had to be purchased (at about $1 million each) to satisfy the peak rush hour traffic demands. However, the following were accomplished:

1. Traction energy requirements were reduced by 25 percent,
2. Capacity and operating energy requirements for environmental control equipment were substantially reduced, and
3. Capital cost savings for the systemwide environmental control equipment and facilities were approximately equal to twice the purchasing cost of the two additional trains.

Application of energy optimization analyses to total rapid transit systems designs may be rewarding in conserving energy and total system costs. Engineers now have all the tools and data normally required to perform these energy optimization analyses. It remains for energy engineers to apply their imagination and ingenuity in collaboration with all the other members of the transit system design team, such as the planners, vehicle designers, power engineers, environmental engineers, civil and structural engineers, and subsystem hardware component designers and fabricators, to create the optimum system design.

ACKNOWLEDGMENT

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