becoming more and more popular for controlling and monitoring the power supply system. Remote control and measurement are carried out by using standard, proven telemetering components. By adding specific components, the problem of the automatization of the traction power supply can be solved. Integrated circuits provide a high level of dependability, high transmission speed, simple expansion, and simple programming. The signals, commands, and measurements to be transmitted are coded into impulses that are transmitted over a single pair of wires. The receiver then decodes these impulses.

The central control can be simplified by using mosaic block systems in which the push buttons, control switches, pilot lights, and so on are inserted. Mosaic boards have the advantage that future changes of the network can be incorporated very easily. Although the mosaic technique maximizes the number of control functions that can fit in a small space, some regional control centers require a control board that would be too long for efficient operation. Large control rooms and long control panels debase the overview and reaction time. Such large regional control centers have selective graphic displays and use computers. The network is represented on the mosaic display board to give a general overview. The illumination of the mosaic board, which depicts the actual switching conditions, is governed by a process computer. The complete and detailed display of stations or network sections (as selected by the operator) is shown on the graphic display board (Figures 17 and 18). The switch to be operated is located on the graphic display and can then be switched by a single push button. If a faulty operational signal has been given, the process computer will so indicate in written form, giving the correct operating instructions. All signals and operations will be recorded; this permits accurate reconstruction of the situation in case this is needed.

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Technology and Economics of Regeneration for Light-Rail Applications

Norman Vutz, Louis T. Klauder and Associates, Philadelphia

Regeneration is one method of recycling a vehicle's surplus kinetic energy during braking. Regeneration is recuperative braking in which the recycled energy goes back to the vehicles' power supply system for use by other vehicles. Several propulsion systems that use regenerative braking have been applied and operated on direct-current electrified rail systems. The fundamental limitations on effectiveness that are beyond the propulsion designer's control are considered. The performance of an alternating-current induction motor system with an inverter and a direct-current series motor system with a chopper are explored to illustrate the present state of technology. Comparison is made with two other types of recuperative braking—flywheel energy storage and height changes in the route profile. The inefficiency of the former and the difficulty of construction of the latter are noted. The industry's present interest in regeneration is questioned since it would have minimal economic impact but require complex propulsion hardware and extra maintenance costs.

Regenerative braking is one method of recycling a vehicle's surplus kinetic energy during deceleration. It is recuperative braking in which the recycled energy goes back to the supply system for use by other vehicles. In transit operation, acceleration and deceleration are the predominant vehicle activities. Because of this, the duty cycle that determines the required rating of a vehicle's propulsion system and brake system equipment depends primarily on the acceleration and deceleration needs for that vehicle. For example, on the Norristown Line of the Southeastern Pennsylvania Transportation Authority (SEPTA) local cars go through 21 acceleration-deceleration cycles in a 26-min run that covers 20.9 km (13 miles). That averages out to just more than 74 s/cycle. Of this, approximately 50 to 55 s are spent accelerating and decelerating, which leaves from 19 to 24 s for coasting and station dwells.

The propulsion and brake equipment on these cars is from an era when the virtues of simplicity and serviceability were considered as well as the costs of power. The motors and motor controls have only one task, i.e., accelerating the car. The friction brake has only one task, i.e., decelerating the car. When these cars were built in the early 1930s, it was not practical to usefully recover the energy wasted in braking. Energy costs were important then, as is indicated by the aerodynamic body shape and the attention given to light weight in the vehicle design. For an interesting history of these cars, one may refer to Chapter 7 of The Red Arrow (1). Some trolley coaches were equipped with special compound field motors that provided limited regenerative braking at higher speeds by means of motor field control (2).

Subsequent developments in motors and motor controls have produced vehicles that have dynamic braking (properly called rheostatic braking) that lessens the duty and wear on the friction brake system. In dynamic or rheostatic braking, the drive motors function as generators during deceleration, but all the resulting electrical braking energy is wasted as heat in the braking resistors. The use of rheostatic braking does not provide any savings in the vehicle's energy consumption.

DEVELOPMENT OF REGENERATIVE BRAKING

Although there is a long history of attempts to develop

regenerative braking for start-stop rail transit service, the costs always exceeded the savings. The recent development of solid-state power control systems that use thyristors (silicon-controlled rectifiers) makes it practical to return a portion of the electrical braking energy back to the supply system for use by other vehicles. Several regenerative chopper systems and one inverter system that has alternating-current motors (Figure 1), all of which use thyristors, have been placed in actual transit service. The practicality of using thyristors for power control in conjunction with regenerative braking has been demonstrated in the narrow context of the individual light-rail vehicle (LRV). Not enough attention has been paid to how the regenerated energy flows back through the wayside supply network (the line receptivity) or to the effects of the moving substations that vehicles can become while they are decelerating.

There is an upper limit to the energy that can be recovered by means of regenerative braking that is independent of both line receptivity and the characteristics of the propulsion system. This limit is a consequence of the rolling losses of the vehicle; these are relatively low for rail vehicles, but they are not negligible. The importance of rolling losses can be illustrated by considering the ratio shown below.

maximum vehicle energy recovery factor = (maximum car kinetic energy - braking rolling losses) ÷ (maximum car kinetic energy + acceleration and cruise rolling losses)

In this ratio, the numerator is the net braking energy available for return to the line at the propulsion motor shafts, and the denominator is the gross propulsion energy drawn from the line at the propulsion motor shafts. In other words, the numerator is the maximum possible

Figure 1. Power flow diagram of LRV with inverter.

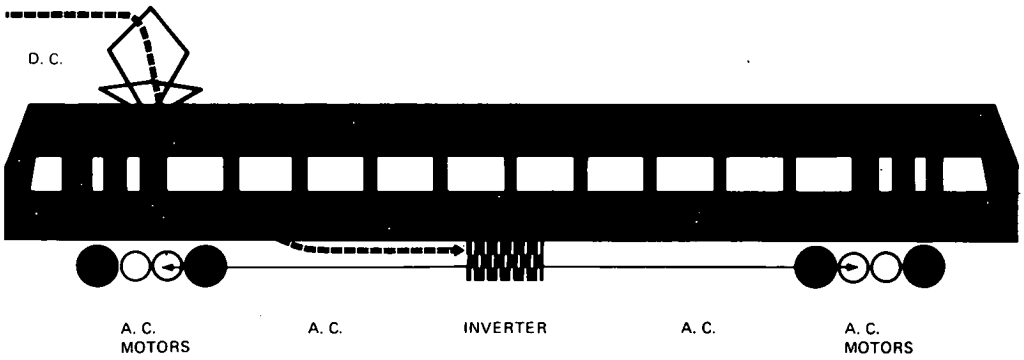
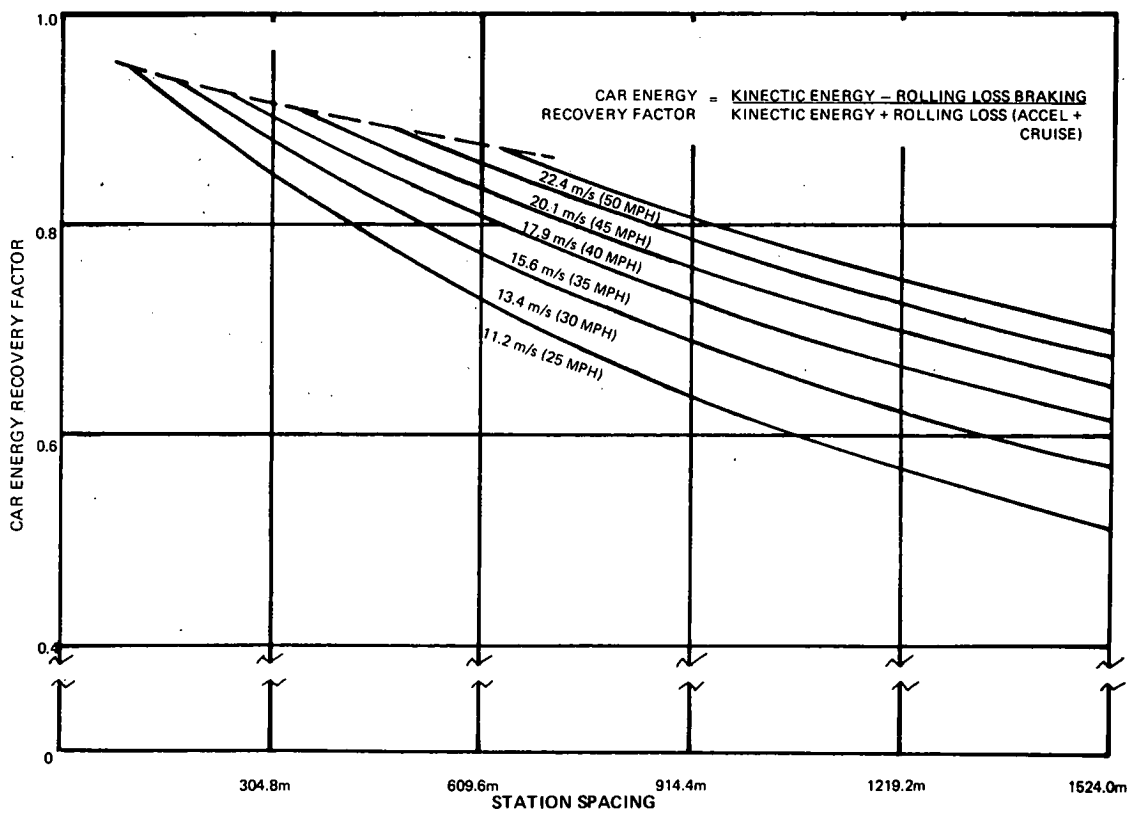


Figure 2. Energy recovery factor for single-car SLRV.



work that can be done on the motors (acting as generators) in decelerating the car, and the denominator is the work done on the car by the motors in accelerating and running the car during a station-to-station run.

Figure 2 shows the ratio calculated for a single fully loaded standard LRV (SLRV) as a function of station spacing. The family of curves shows cruise speeds from 11.2 to 22.4 m/s (25 to 50 mph). The irrecoverable losses that result from running at constant speed between the acceleration interval and the braking inter-

Figure 3. Energy recovery factor for two-car SLRV train.

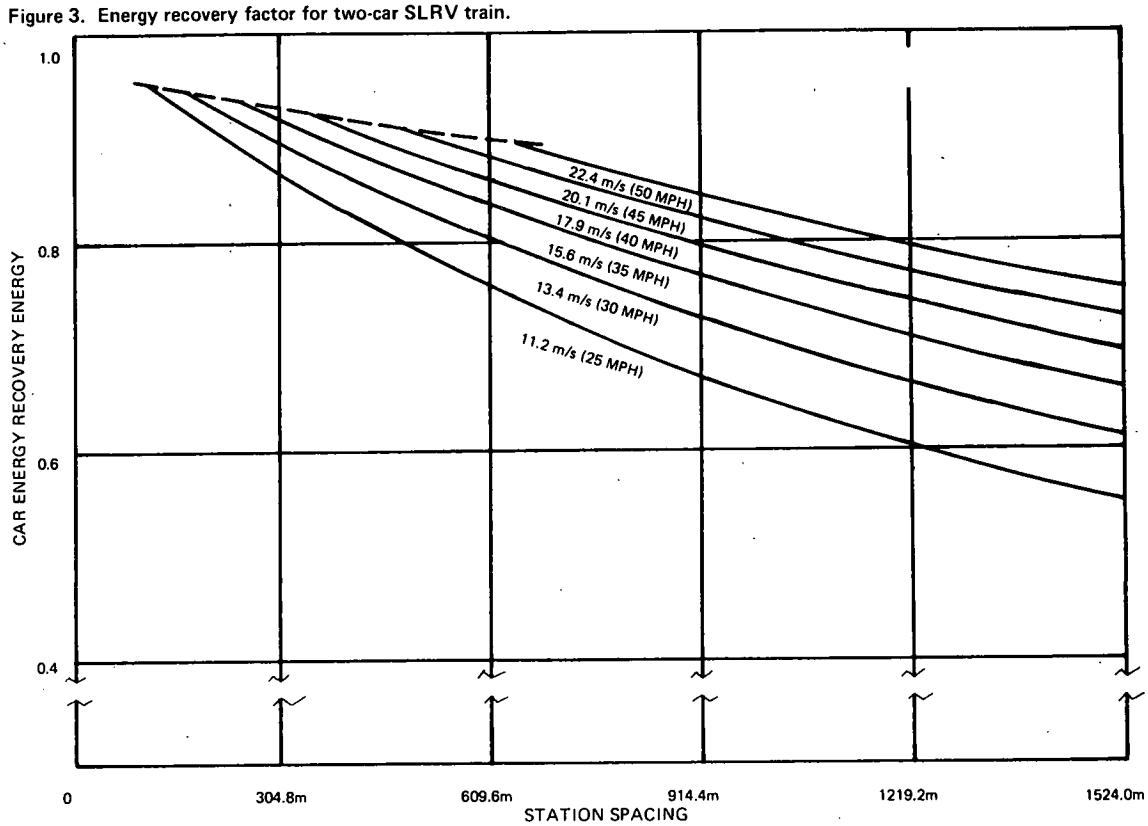
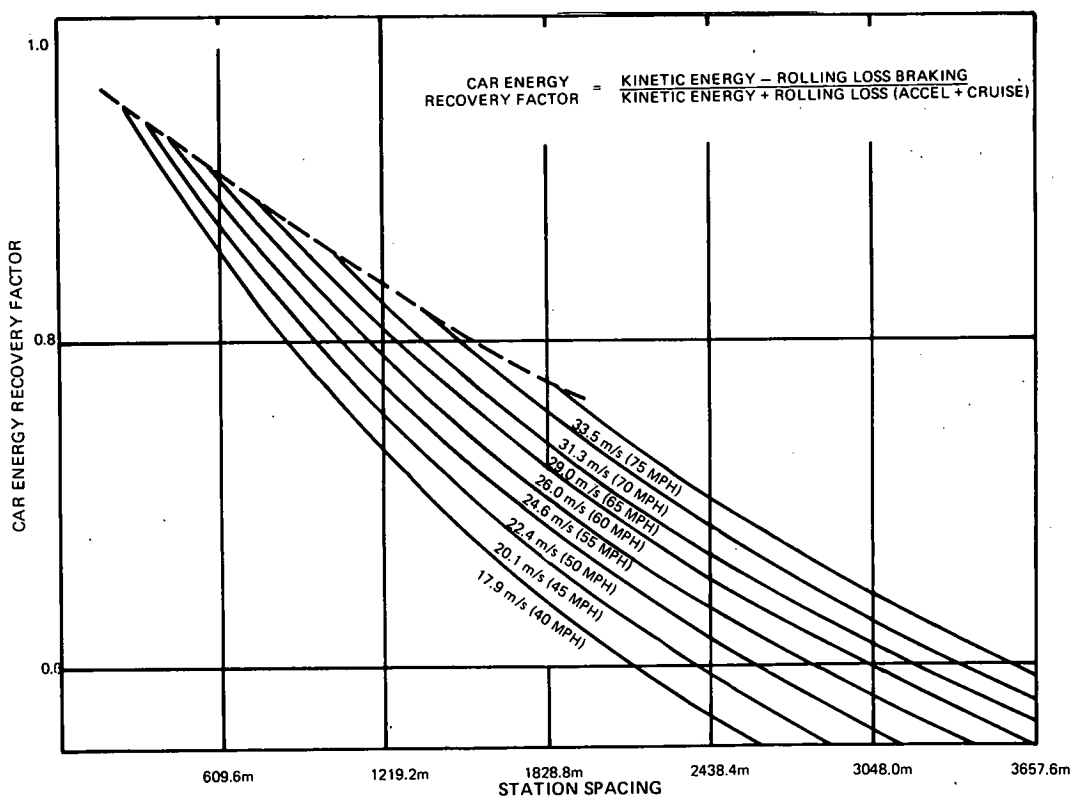


Figure 4. Energy recovery factor for two-car train in Washington, D.C.



val lower the energy recovery factor for longer station spacings.

At higher speeds, the kinetic energy of the vehicle increases more rapidly than its rolling losses. Taken together with the longer acceleration and braking distances, which shorten the steady-speed cruise distance, this causes the ratio to increase as the vehicle cruise speed increases for a given station spacing.

Figure 3 shows the ratio calculated for a fully loaded two-car SLRV train. The only difference between these results and those in Figure 2 is that the frontal area of the vehicle is less important to the rolling losses per car. Similar results are obtained for rapid transit operations; Figure 4 shows the ratio for a two-car train in the Washington, D.C., Metro system.

Regardless of how it is implemented, regenerative braking cannot recover more than the net available braking energy at the propulsion motor shafts. This imposes an upper limit on the regenerative energy savings that depends on the profile of the run. It is apparent that regenerative braking has the best potential in the frequent start-stop operation that is typical of light-rail transit systems.

When an operating property puts a few cars that have regenerative braking into service in a large fleet that does not, it crosses only the first of several hurdles to

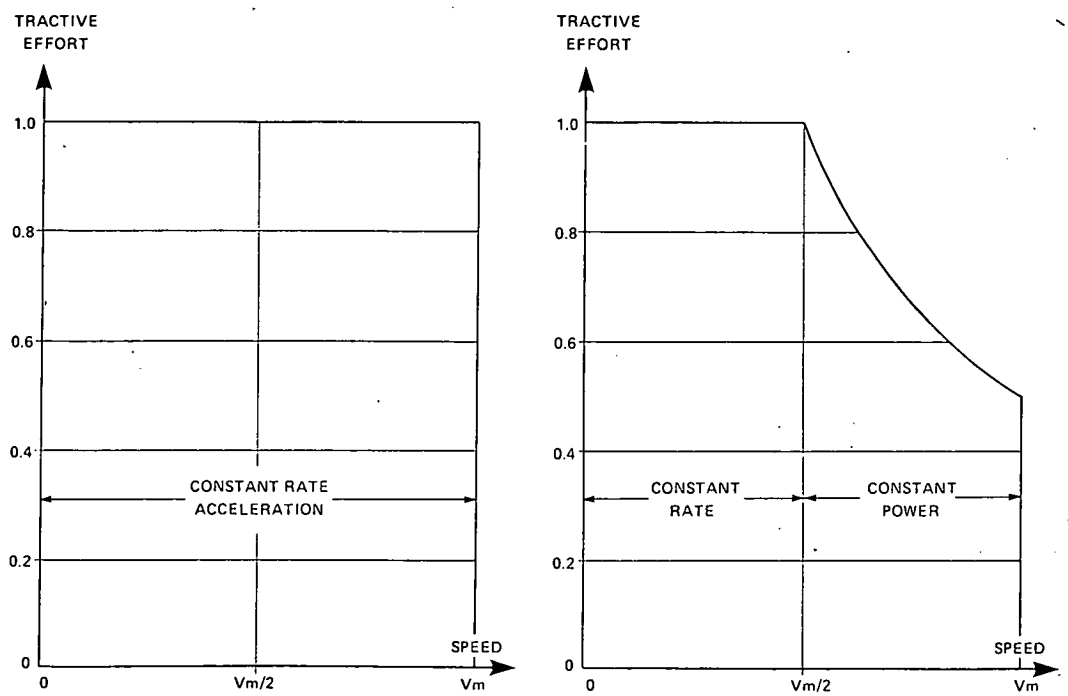


Figure 5. Comparison of acceleration at constant rate and constant power.

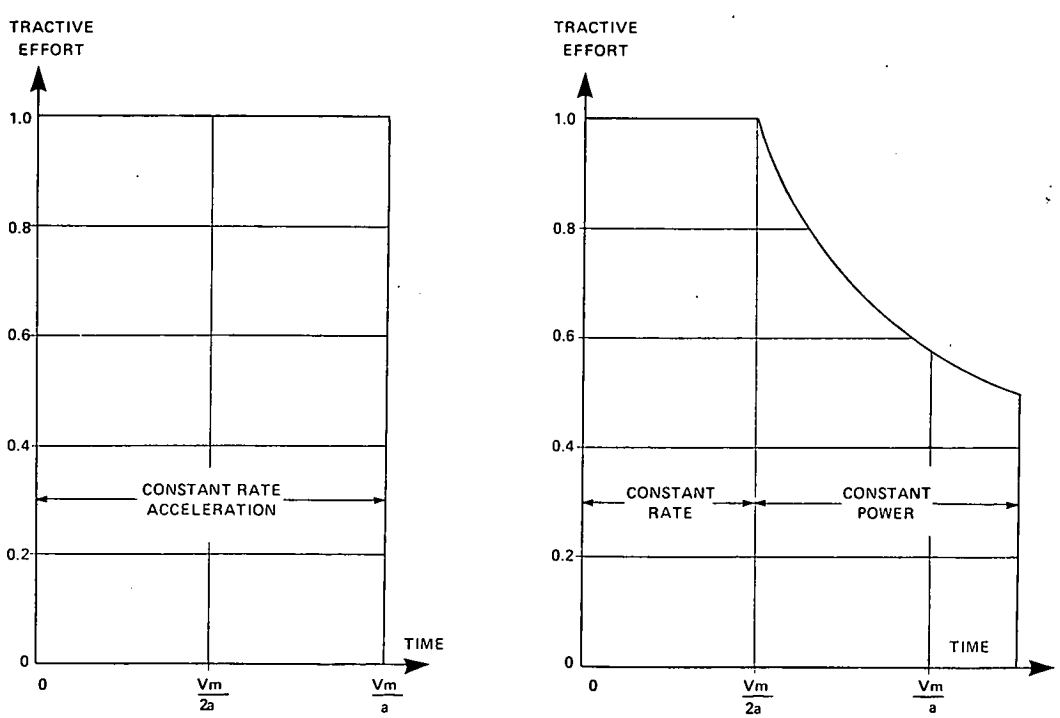


Figure 6. Comparison of acceleration histories at constant rate and at constant power.

Figure 7. Comparison of power flows for constant rate and constant power.

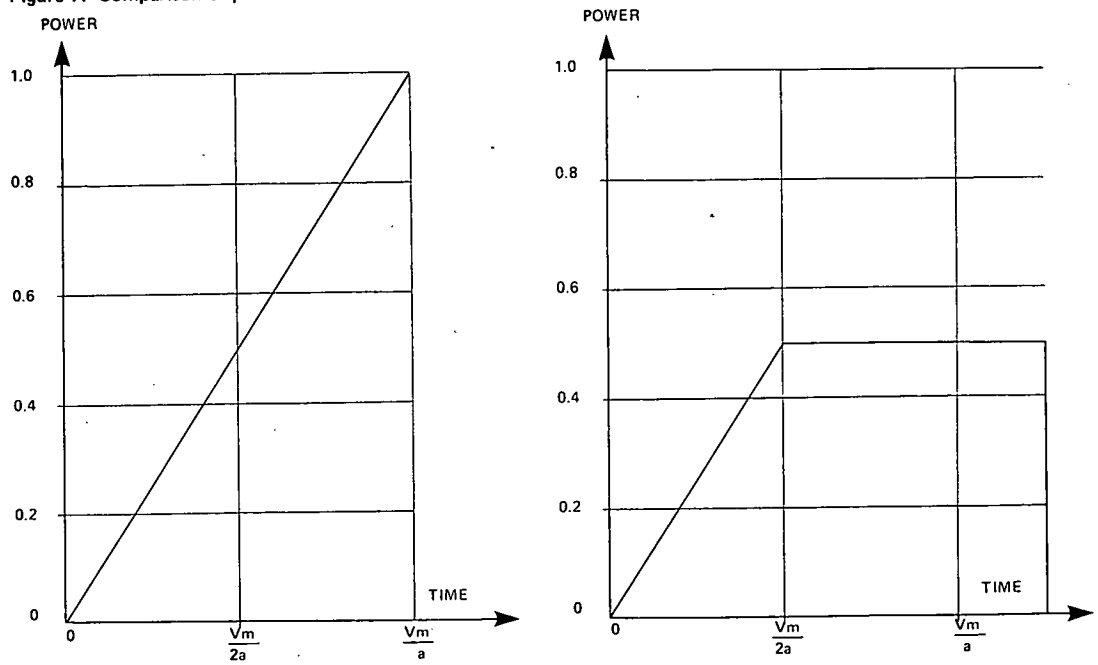
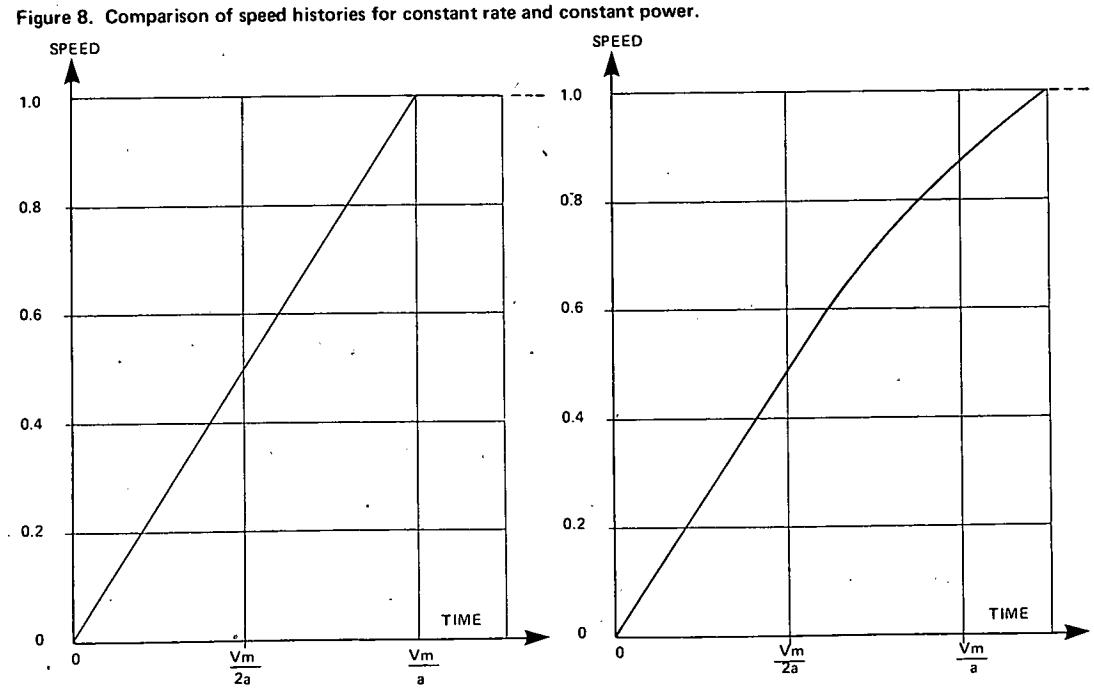


Figure 8. Comparison of speed histories for constant rate and constant power.



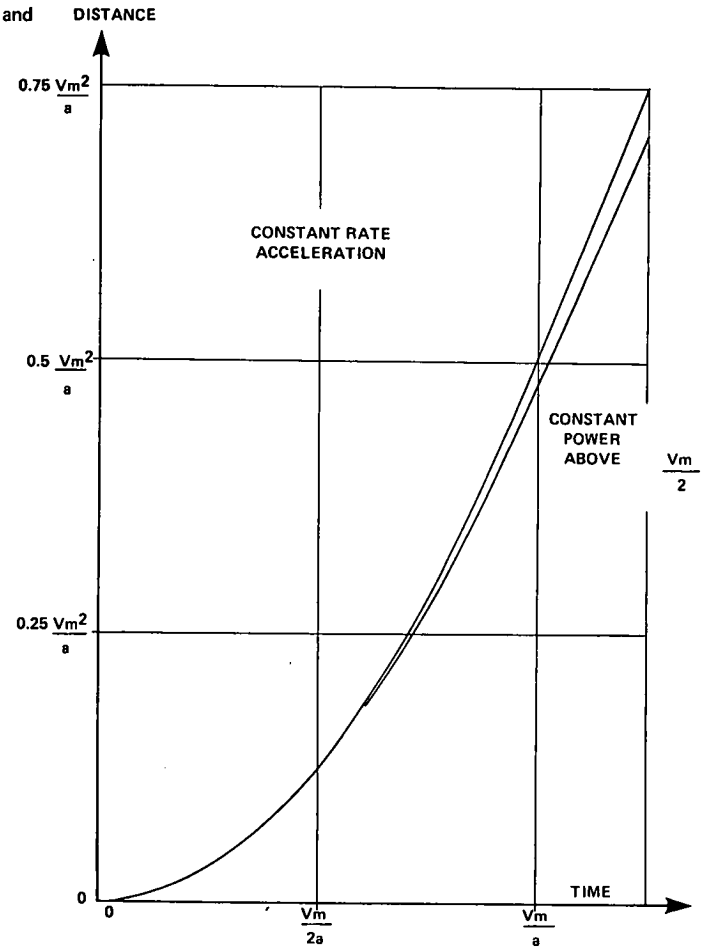
meaningful energy savings. The next hurdle, the handling of the regenerated energy when it returns to the supply, will influence the economic trade-offs entailed in configuring the braking system.

In general, full-rate vehicle deceleration is desired at much higher speeds than those at which full-rate vehicle acceleration is desired. This is a carry-over of placing much more importance on accelerating power than on the dissipation levels of braking power. The mode's requirement for full-rate acceleration only up to a relatively low base speed reflects a proper appreciation of the incremental costs of converting higher levels of propulsion power at substations and of the incremental costs of delivering higher levels of propulsion power to vehicles through third rails or overhead wires.

METHODS OF ACCELERATION

One can compare two possible ways to accelerate a vehicle to a desired speed (Vm), as is shown in Figure 5. The first, a hypothetical way, involves accelerating at a constant rate (a) up to Vm; the second, a practical way, involves accelerating at a constant rate up to half speed (Vm/2) and accelerating at a constant power level from Vm/2 to Vm. The required installed power capability for substations, trolley wire, and the vehicle's

Figure 9. Comparison of distance histories for constant rate and constant power.



propulsion system in the second case is only half that in the first case. There is only a slight reduction in performance. If rolling resistance is ignored, the two cases can be analyzed by closed-form solutions. For typical rail vehicles, the rolling resistance is small in relation to the accelerating tractive effort.

In Figure 5 the curves for the tractive effort versus speed for the two cases are shown. The lower high-speed tractive effort for the constant power (above Vm/2) will cause the car to take longer to reach maximum speed. The curves for the comparative tractive effort, or acceleration versus time, are shown in Figure 6. The time required to attain the desired speed is 25 percent longer for the car going at constant power than for the car going at a constant rate. The curves for the power or energy flow versus time for the two cars are shown in Figure 7. Note that the constant-rate car briefly draws twice the power required by the constant-power car. The area under either curve is the same, which indicates that each car ends up with the same kinetic energy and the same speed, i.e., Vm. The curves for the comparative speed versus time are shown in Figure 8. The longer time required to reach top speed looks important but, from the standpoint of covering actual distance, it is not so important. The curves for the comparative distance versus time are shown in Figure 9. The distance difference looks quite small.

To make this abstract comparison more concrete, consider an SLRV accelerating to 14.3 m/s (32 mph). The design acceleration is 1.25 m/s^2 (2.8 mph/s) up to 7.15 m/s (16 mph). In the constant-power case, this corresponds to a Vm of 14.3 m/s (32 mph) and an a of 1.25 m/s^2 (2.8 mph/s). The normalizing time unit (Vm/a) is 11.43 s. The time at which the lower performance vehicle reaches speed (5/4 × Vm/a) is 14.28 s. After 14.28 s, a lower performance (constant-power) vehicle will be only 6.7 m (22 ft) behind the higher performance (constant-rate) vehicle; both will be moving at 14.3 m/s (32 mph). The lower performance vehicle would pass a given point at most 0.47 s later than the higher performance vehicle. Doubling the installed car, line, and substation power therefore saves less than 0.5 s in reaching a speed of 14.3 m/s (32 mph). This is a small gain in comparison with the cost of doubling the peak power level of the power supply, distribution system, and propulsion system.

Similar considerations would apply in regenerative braking systems, but the braking power would flow from the vehicle's propulsion system back through the distribution system either to a receptive substation or to another vehicle. In nonregenerative braking systems, the hardware design trade-offs involve only vehicle-carried equipment. In the case of dynamic braking, the capability to withstand extra voltage that must be designed into the motors and motor controls to allow for electrical distribution and collection transients can be used to increase the level of the dynamic braking power. Transients on the order of several thousand volts are common on 600-V systems. In dynamic braking, the motors, controls, and braking resistors are not in a circuit with the current collector and therefore need not tolerate supply transients. For any given motor current, the motor speed and motor voltage are proportional to each other. Full-rate dynamic braking is thus available for current series motor and switched-resistor propulsion systems at speeds of two to three times the acceleration base

speed for only an increase in the size of the braking resistor.

For a purely regenerative system, the provision of full-rate high-speed braking is not a simple matter. The high levels of braking power must be converted and controlled in the presence of line transients. Theoretically, a mirror image of constant-power operation above some intermediate speed for acceleration should provide a valid model for deceleration. Though the distance penalty would be small for constant-power braking from full speed to half speed and constant-rate braking below half speed, the vehicle operator or train control system would be required to make stopping decisions earlier in time and farther back from the desired stopping point. This is not an attractive prospect in the context of operation in dense traffic. If both full-rate high-speed braking and regeneration are desired, the system designer must be willing to consider:

1. Overdesign of the propulsion system for braking duty,
2. A friction-brake supplement at high speed, or
3. Combined regenerative and dynamic braking.

In the case of the Cleveland Transit System (CTS) Airporters, which have inverters and brushless induction motor drive, early track testing showed that the propulsion system could handle full-rate braking at high speeds. This was a case of overdesign of the propulsion system to accommodate the braking duty. On the new chopper-equipped Montreal Metro cars and the Toronto Transit Commission's H-5 cars, a friction-brake supplement will be used. The Presidents' Conference Committee (PCC) cars in the Hague and Rio de Janiero and the 10 chopper test cars for Chicago provide combined regenerative and dynamic braking by the addition of a modest amount of power circuitry. In the case of the Chicago cars, the power-control chopper automatically wastes, in resistors on board the vehicle, any braking power that cannot be instantly accepted by the supply.

OTHER MEANS OF RECUPERATIVE BRAKING

There are other means of recycling braking energy that are not constrained by power supply and distribution factors. These may be thought of as recuperative braking rather than regenerative braking. The recovered braking energy can be stored during a deceleration for subsequent use by the same vehicle during the next acceleration. The energy can be stored in flywheels (kinetic), in batteries (chemical), or by means of height changes in the route alignment (potential). The dissipation of braking energy can also be used to augment seasonal car heating requirements.

The storage of energy in flywheels has been used on several New York City Transit Authority (NYCTA) test cars. On-board flywheel energy storage requires the use of two propulsion mechanisms—one to drive the vehicle and one to drive the flywheel. On the NYCTA cars, the flywheel storage system added approximately 5158 kg (11 000 lb), 16 percent, to the weight of the empty car. By using direct-current motors with separately controlled field excitation, it is possible to simplify the electric power control apparatus so that no choppers are needed. The interplay of car speed and flywheel speed and separate field control of the two propulsion systems provides the necessary controllability. It is only a coincidence that flywheel energy systems have been developed at the same time as choppers. Flywheel systems could have been developed much earlier. The Advanced Concept Train (ACT-1) cars now under development will use the flywheel storage approach without choppers.

The operational advantages of car-carried flywheel energy storage are that recuperative braking is independent of line conditions and that there is enough stored energy to permit limping into a station if there is a third-rail power outage. The disadvantages are the heavy weight of the propulsion hardware, the hazards of large amounts of mechanically stored energy, the low efficiency of multiple energy conversions, and the steady running energy loss of the flywheel unit.

In order to keep the variations in flywheel speed reasonable, the total stored flywheel energy is currently designed to be twice the vehicle's maximum energy. The kinetic energy of a vehicle at a speed of 22.4 m/s (50 mph) is great—enough to lift the car about 25.6 m (84 ft)—and the flywheels can store twice that amount of energy. A mechanical failure in the shaft, bearings, or gearing may trigger the uncontrolled release of the stored energy.

Energy losses arise in recuperative braking by means of flywheels because the energy must undergo four electromechanical conversions to make a round trip. For a typical single-conversion efficiency rating of 85 percent, the round-trip efficiency would be limited to 52 percent. For an optimistic 90 percent single-conversion efficiency, the round-trip efficiency would be limited to 66 percent.

There is a steady running loss of 22.4 kW (30 hp) for each unit of the ACT-1 storage system. The total stored kinetic energy is 16.3 MJ (12 000 000 ft·lbf), half of which is useful energy for the system. If the flywheel's process of running down is considered as exponential decay, the decay constant is the rate of loss divided by the stored energy or 0.001 375/s. The estimated time for a flywheel unit to coast down to its half-energy state (i.e., that in which it has no useful stored energy) is about 8 min. This is comparable to the terminal layover times allowed for schedule make-up—about 9.7 km (6 miles) of express running at 22.4 m/s (50 mph). Another flywheel loss is that incurred between the time energy is stored during deceleration and the time it is subsequently used during acceleration. Taking 1 min as the combined deceleration, dwell, and acceleration time, the flywheel will lose an estimated 8 percent of its total energy or 16 percent of its useful energy. The 16 percent loss yields 84 percent storage efficiency on top of the estimated 52 percent energy-conversion efficiency previously mentioned, a net of about 44 percent overall propulsion-system efficiency in recuperative braking. The steady constant running loss of the flywheel while the vehicle moves at constant speed will further detract from the overall energy efficiency, even though the flywheel serves no useful storage function during this time.

The disadvantages of weight and safety hazards in vehicle-carried flywheels could be avoided by locating the energy-storage flywheel on the wayside within a properly protected structure at each station. However, if the station spacing is closer than the train spacing, this will result in a greater amount of installed machinery, and each individual machine will be used less frequently and less economically.

Battery-energy storage has not been tried for regenerative braking in transit. The weight, size, and maintenance of large-capacity batteries have been the major problems.

Gravitational storage through height changes is the simplest means to provide recuperative braking at station stops. It imposes constraints on alignment and civil engineering works that are sometimes hard to accommodate. D. T. Catling (3) analyzed the operational aspects of gravity recuperation in a system of hump sta-

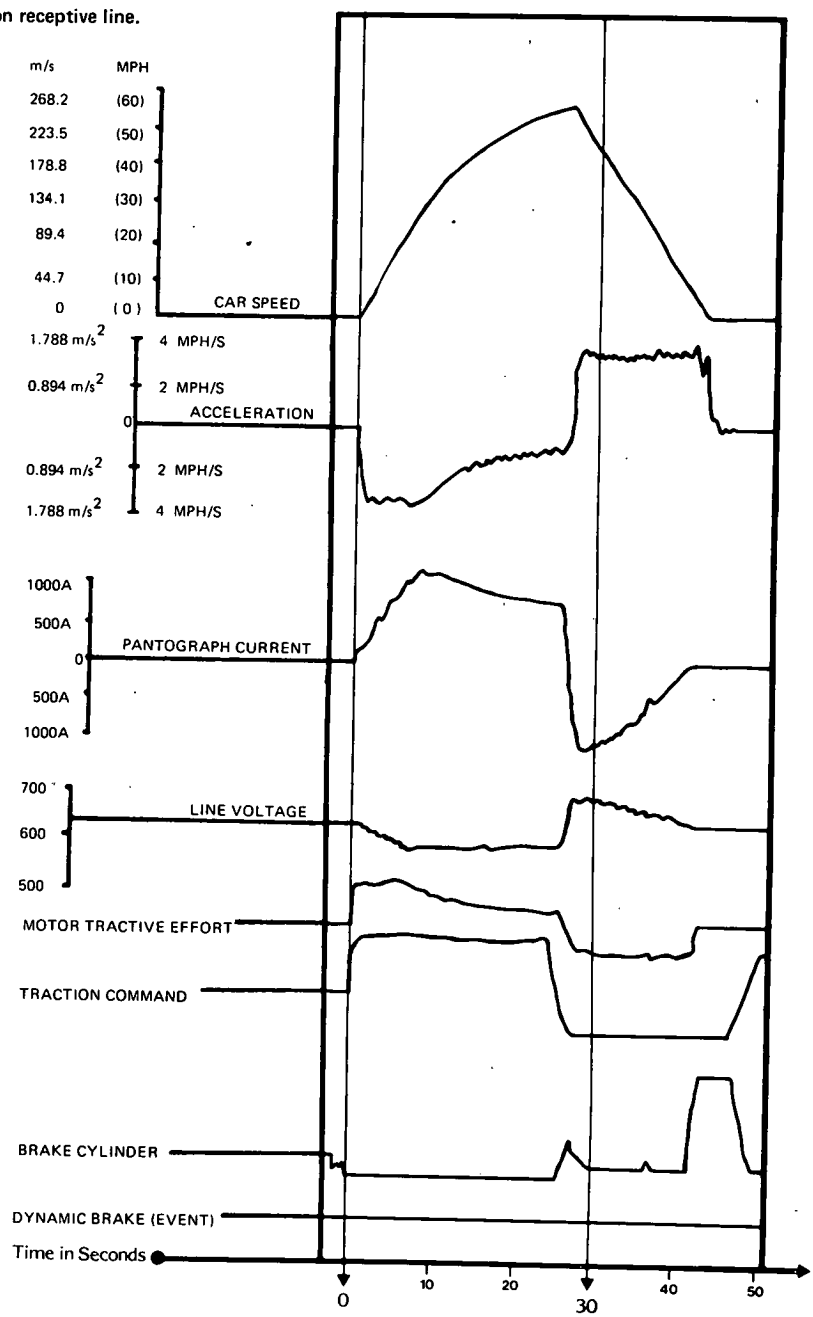
tions. Practical limitations, such as starting trains with some nonpowered cars on the upgrade approaching a station, limited grade considered to 2 percent. With this modest grade, a drop of 7.62 m (25 ft) resulted in increasing the schedule speed enough to eliminate one train and provide a 14 percent saving in each train's energy consumption for a 32-km (20-mile) 20-station service with a 2-min headway. The concept is attractive for its simplicity, and its implementation need not be systemwide. The trade-off between the value of anticipated energy savings and extra route construction costs can be analyzed only on a site-specific case-by-case basis. The Montreal Metro and some NYCTA lines have hump stations. Occasionally a proposal for a ballistic trajectory transit system reemerges.

REGENERATIVE BRAKING WITH AN INVERTER

Regenerative braking is recuperative braking in which the recycled energy goes back to the supply for use by other vehicles. The inverter-equipped CTS Airporters exhibited the performance shown in Figure 10 on a receptive line. This chart segment shows an acceleration to 22.4 m/s (50 mph) and an immediate deceleration to stop. The inverter drew supply current while accelerating and returned supply current while braking. While it was drawing supply current, the line voltage dropped and, while it was returning supply current, the line voltage increased. Since the response of the friction brake was slightly faster than that of the inverter at the power-to-brake transition, one notes a slight, brief rise in brake cylinder pressure.

The CTS Airporters performed as shown in Figure 11 on a nonreceptive line. These cars carried one-step

Figure 10. Performance of inverter on receptive line.



contractor-controlled resistors that artificially loaded the line to make it receptive. For the case shown, the car was accelerated to 26.8 m/s (60 mph), cruised briefly, and then braked to a stop. The speed and acceleration traces show this. The inverter current trace shows the usual acceleration behavior, which is followed by a short reduced-current cruise interval and finally a swing toward regeneration during deceleration. The line voltage shows some droop during acceleration and a significant rise at the start of braking. This voltage rise triggered the closing of the dynamic brake's resistor contactor, which diverted some of the regenerated current. The friction brake was bleeding off simultaneously; this caused the inverter-regenerated current to increase in order to maintain constant deceleration. Near the end of the stop, the regenerated current was insufficient to offset the dynamic brake's resistor current, and some line power was consumed at the end of the stop. This was a very crude first attempt at addressing the question of receptivity.

A user's view of the CTS inverter and alternating-current motor system was presented by R. T. Bretz in 1973 (4).

REGENERATIVE BRAKING WITH A CHOPPER

The use of choppers and direct-current series motors makes it possible to continuously blend regenerative and dynamic braking so that the line will be fed all available braking current up to its limit of instantaneous receptivity and only surplus braking energy will be wasted in a car-carried dynamic brake resistor. In a system that uses a chopper and direct-current motor propulsion, this can be achieved by adding a thyristor and dynamic brake resistor in the chopper power circuit as shown in Figure 12. The other contactor-staged brake resistor shown at the bottom allows for full-rate braking at high speed. Circuit operation is illustrated in Figures 13 and 14. In Figure 13 the chopper is on, and the loop current is increasing; the motor-generated voltage is imposed across the smoothing inductor and the optional high-

Figure 11. Performance of inverter on nonreceptive line.

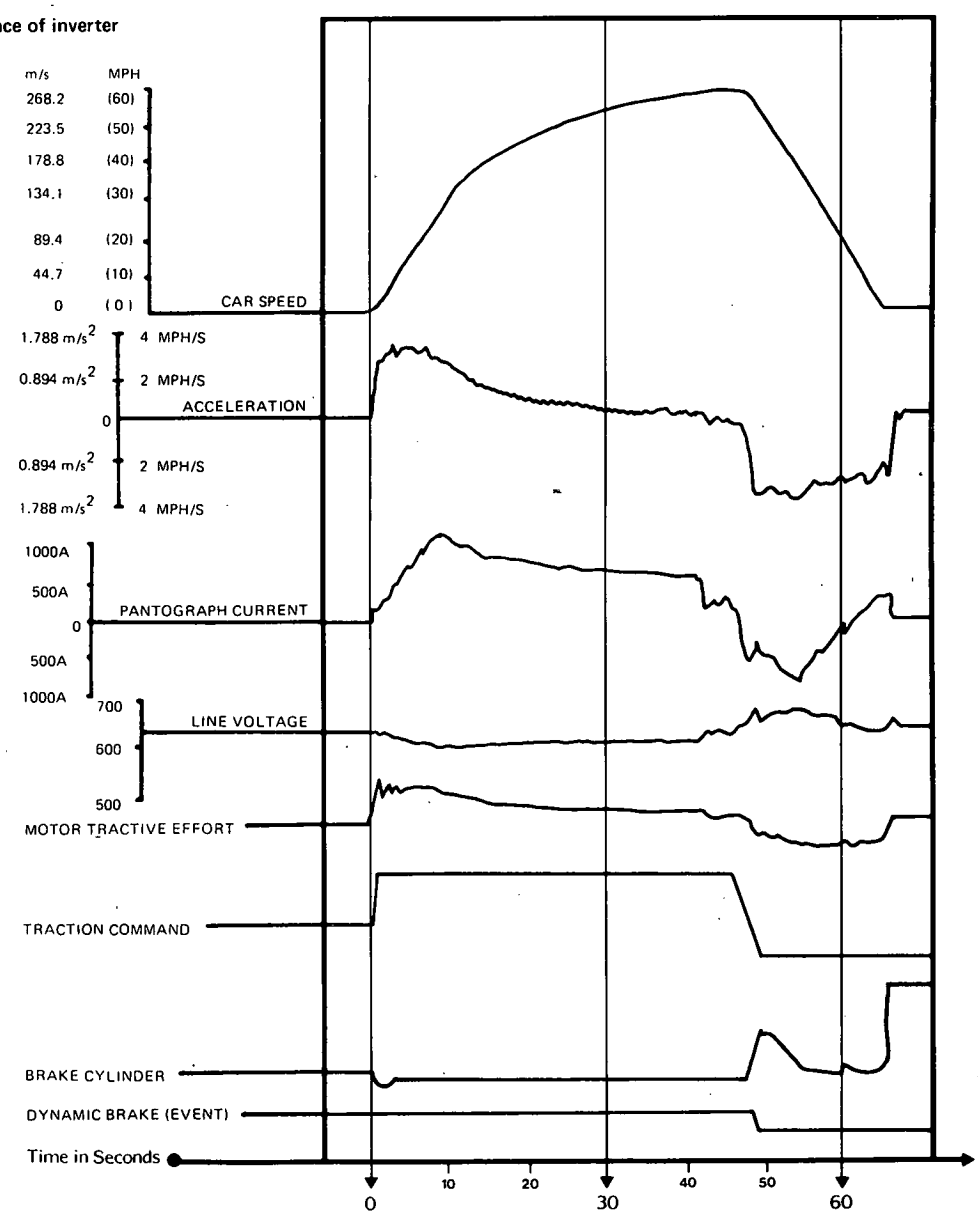


Figure 12. Chopper power circuit for regenerative braking.

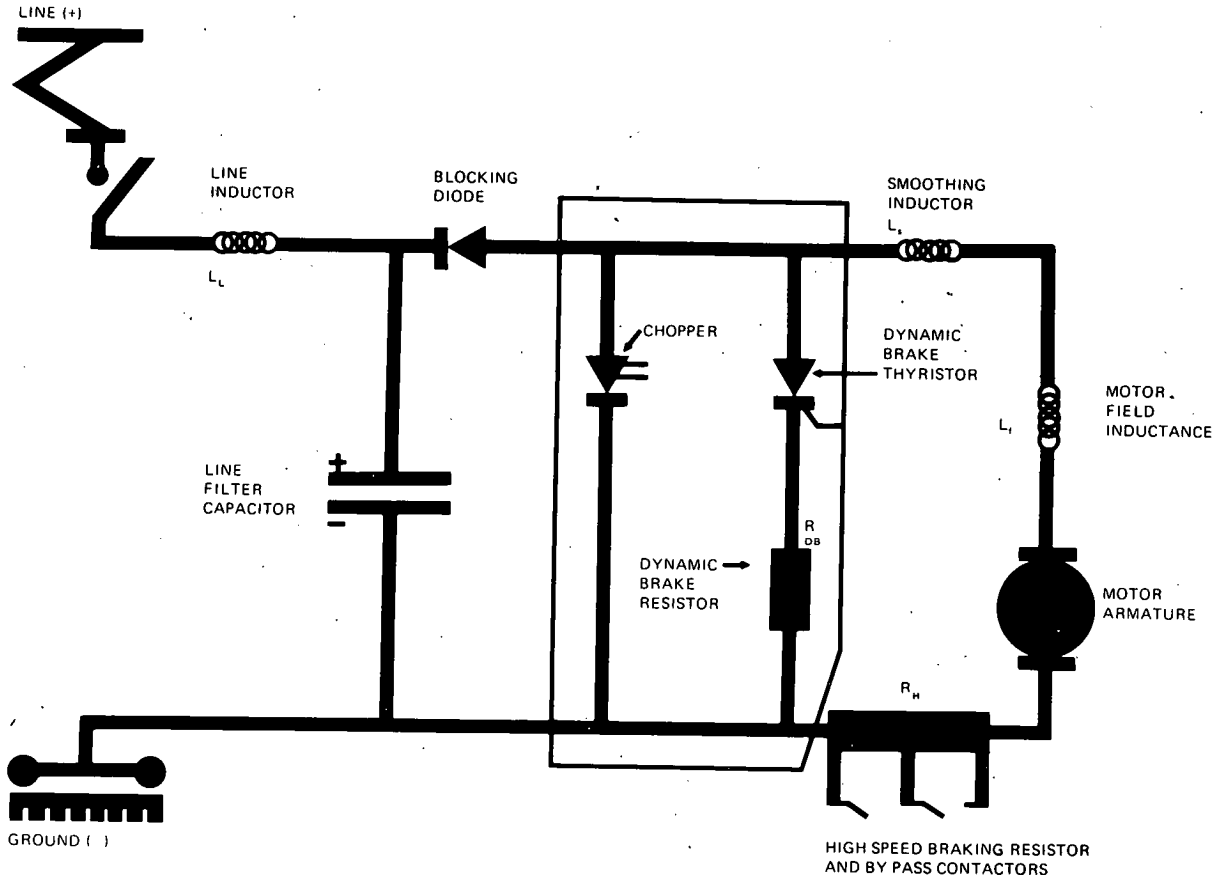


Figure 13. Buildup in the loop current.

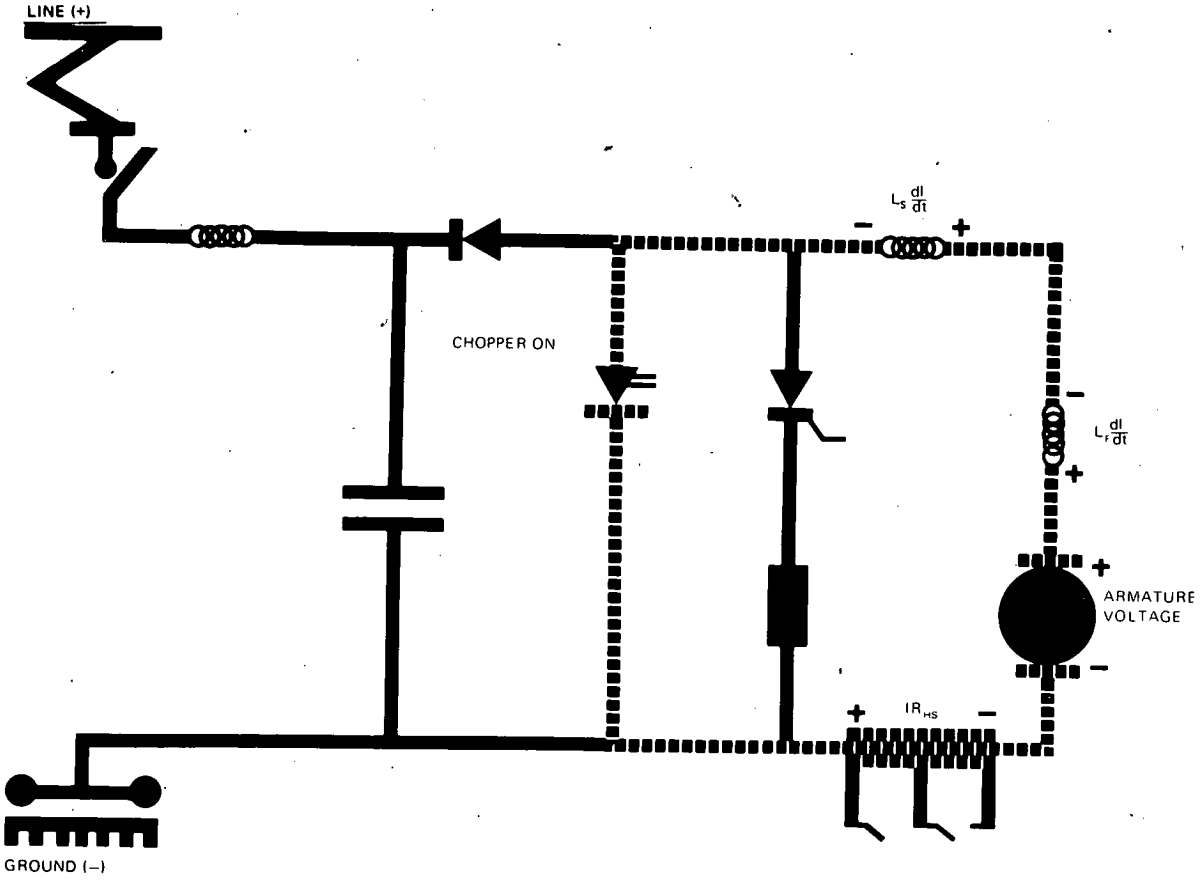
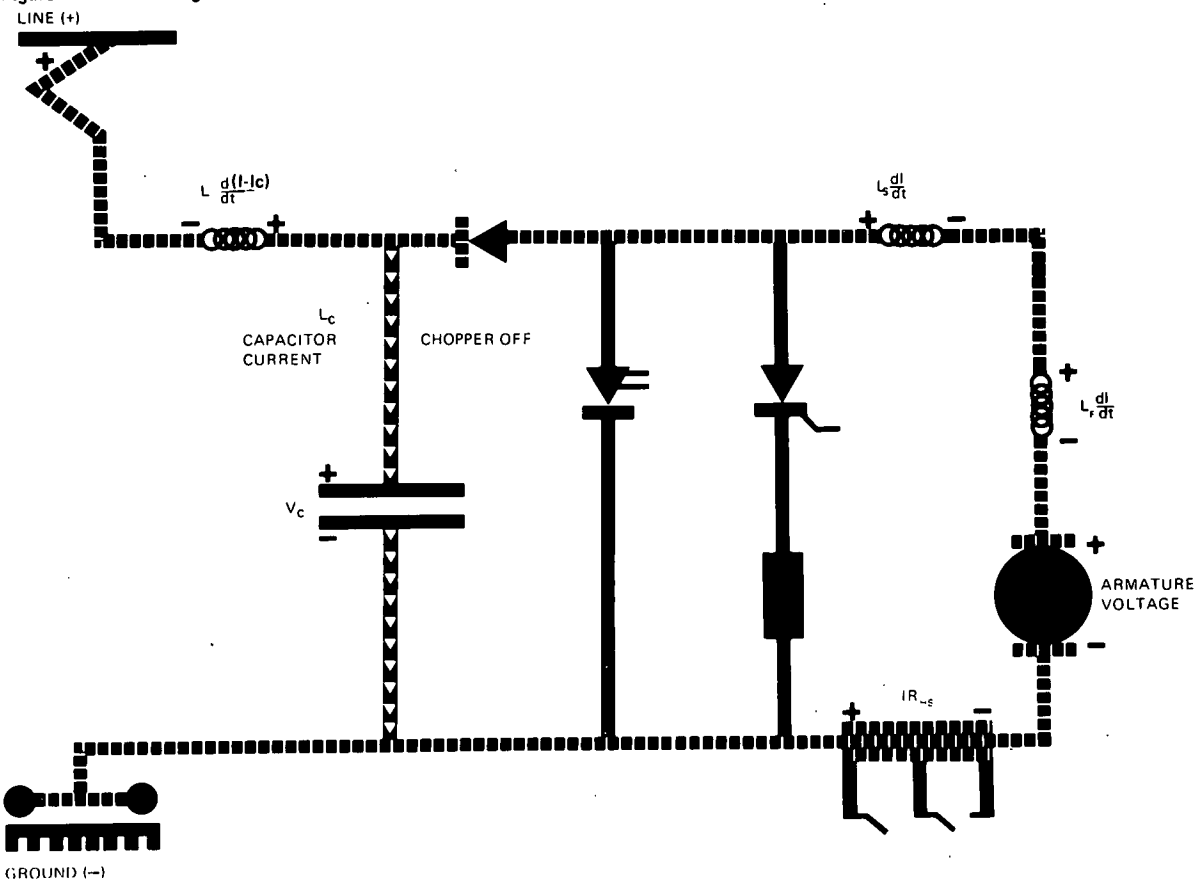


Figure 14. Flow of regenerative current.



speed brake resistor. Electrical energy is being transferred from the motor to storage in the inductor and to optional waste in the high-speed brake resistor. In Figure 14, the chopper has been turned off and the current is spilling over to the line filter via the blocking diode. The combination of motor-generated voltage and smoothing inductor voltage produces a flow of current against the line voltage and the voltage drop in the optional high-speed resistor. The flow of current against the line voltage constitutes useful regeneration. The flow of current against the drop in the optional resistor constitutes energy waste.

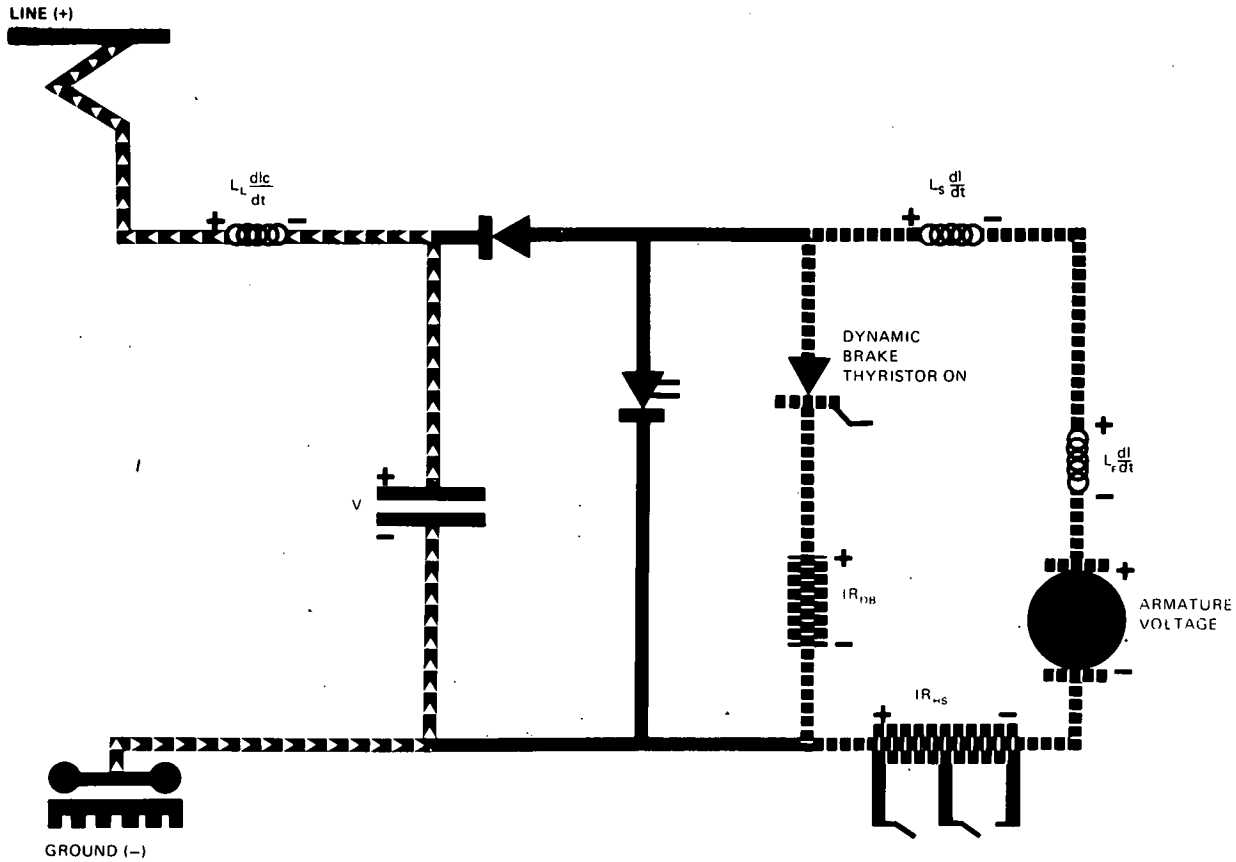
If the line is not receptive, much of the regenerated current will flow into the filter capacitor, which will cause its voltage to rise above a sensing level. When high filter-capacitor voltage is sensed, the dynamic brake thyristor is turned on and the current is diverted to the dynamic brake resistor as shown in Figure 15. A combination of motor-generated voltage and inductor voltage drives the loop current through the dynamic brake resistor and the optional high-speed braking resistor. After the current decays, the chopper is turned on and the whole process is repeated. Thus, once during each chopper cycle (approximately 200 to 400 times/s), the portion of braking energy returned and the portion of braking energy wasted are adjusted so that they do not exceed the maximum allowable line voltage under varying conditions of partial receptivity or nonreceptivity. This type of circuit has been implemented and is used successfully on many chopper-equipped rail cars.

ECONOMICS OF REGENERATION

What are the economics of regeneration? Numerous claims are being made about the amount of energy that can be saved. Most of these claims are for savings in propulsion energy only, and these reductions will not be realized on a properties' electric meters because the car auxiliary and lay-up loads are not reduced by regeneration. Regeneration can help reduce the peak-hour demand and the associated utility demand charge. For a 33.7-Mg (72 000-lb) vehicle traveling at 22.4 m/s (50 mph), each stop involves 16 MJ (12 000 000 ft·lbf) of kinetic energy. At 21.6 cents/MJ (6 cents/kW·h), this is about 27 cents worth of electricity. Since only about half the energy can be recovered, the value to an operating property would be on the order of 15 cents/vehicle stop.

Another way to look at regenerative braking is to consider the trade-off between the daily power required by an electronic cooling blower for a solid-state system and the number of stops per day needed to recover a compensating amount of energy. A 7.46-kW (10-hp) blower running 24 h/d will consume 644 MJ (475 000 000 ft·lbf) of energy. At the rate of 8.1 MJ (6 000 000 ft·lbf) of recoverable energy per stop, a vehicle with regenerative braking would have to make 79 stops at 22.4 m/s (50 mph) just to offset its blower consumption. At an average speed of 8.94 m/s (20 mph) and 1 stop/mile, it would require 4 h of car operation to reach the point at which the savings in regenerated energy offsets the added blower consumption. The fact that several properties that are exposed to severe winters (e.g., Cleveland and Boston) do not believe that the recovery of dynamic brake heat in season is worth the maintenance expense of a ventilating air-flow deflector indicates that traction energy costs are less important than maintenance costs. Regeneration may be a fad that will be of

Figure 15. Flow of dynamic brake current.



little importance to present-day transit operations if it adds to maintenance costs.

It is obvious that there are problems in vehicle energy economics at present. The fact that the ACT-1 development program is proceeding with a propulsion system that suffers a steady 22.4-kW (30-hp) flywheel running loss and with an air comfort system that requires a steady 59.7-kW (80-hp) shaft power input indicates that total vehicle energy is not all that important. If there is a constant 82.1-kW (110-hp) parasitic load on each vehicle, regenerative power savings look very small.

In summary, serious efforts to reduce transit energy consumption should take into account the simple expedients of seasonal recovery of dynamic braking heat, skip-stop and request-stop operation, local and express scheduling, and reductions in car lay-up time with auxiliaries running. These measures can provide immediate savings without recourse to complex propulsion technology and exposure to its attendant risks and expenses.

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