Chapter 3

AUTOMATIC TRAIN CONTROL

Train control is the process by which the movement of rail rapid transit vehicles is regulated for the purposes of safety and efficiency. The process is carried out by a combination of elements-some men, some machines—located on the train, along the track, in stations, and at remote central facilities. These elements interact to form a command and control system with four major functions:

. Train Protection	prevention of collisions and derailments,
. Train Operation	control of train movement and stopping at stations,
● Train Supervision	direction of train movement in relation to schedule,
. Communication	interchange of information among the elements of the system.

The train control system is analogous to the sensory organs and central nervous system of the human body. It senses and processes information, makes decisions, and transmits commands. Also as in the human body, the execution of commands is not a function of the train control system but of other parts specialized for that purpose. For example, the train control system may sense train speed, determine that it should be increased, provide an appropriate command signal to the motors, and monitor to see that the desired result is achieved. The means by which a speed change is effected, however, are not part of the train control system. All the equipment for getting electric power to the wayside, bringing it into the train, converting it to mechanical energy, and providing tractive effort is external to the train control system. Similarly, the equipment to select a route for a particular train and transmit commands to aline switches accordingly are within the train control system, but the parts of the trackwork that actually move (the switch points) are not elements of the train control system.

TRAIN CONTROL SYSTEM FUNCTIONS

Presented below is a description of the specific functions performed by a train control system and of the way in which functional elements interact. These functional relationships are also illustrated by the diagram in figure 1. Since the purpose is only to provide the reader with a general background for understanding the nature of train control, the definitions presented here are brief and nontechnical.[8]

Train Protection

Train protection is a family of functions whose purpose is to assure the safety of train movement by preventing collisions and derailments.[9] rain protection functions and requirements override all other control system functions either through equipment design or, in a completely manual mode, by rules and procedures. The functions that make up train protection are:

Train detection—monitoring of the track to determine the presence and location of trains;

Train separation-assuring that trains on the same track maintain a safe following distance to prevent collisions;

Route interlocking—preventing trains on crossing, merging, or branching routes from making conflicting (unsafe) moves that would cause a collision or derailment;

Overspeed protection—assuring that train speed remains at or below the commanded or posted civil speed limit[10] as to prevent collisions resulting from going too fast to stop within the available distance and to prevent derailments due to excessive speed on curves or through switches;

Train and track surveillance-observing conditions on and in the vicinity of the track ahead of the train and monitoring safety-related conditions on board the train.

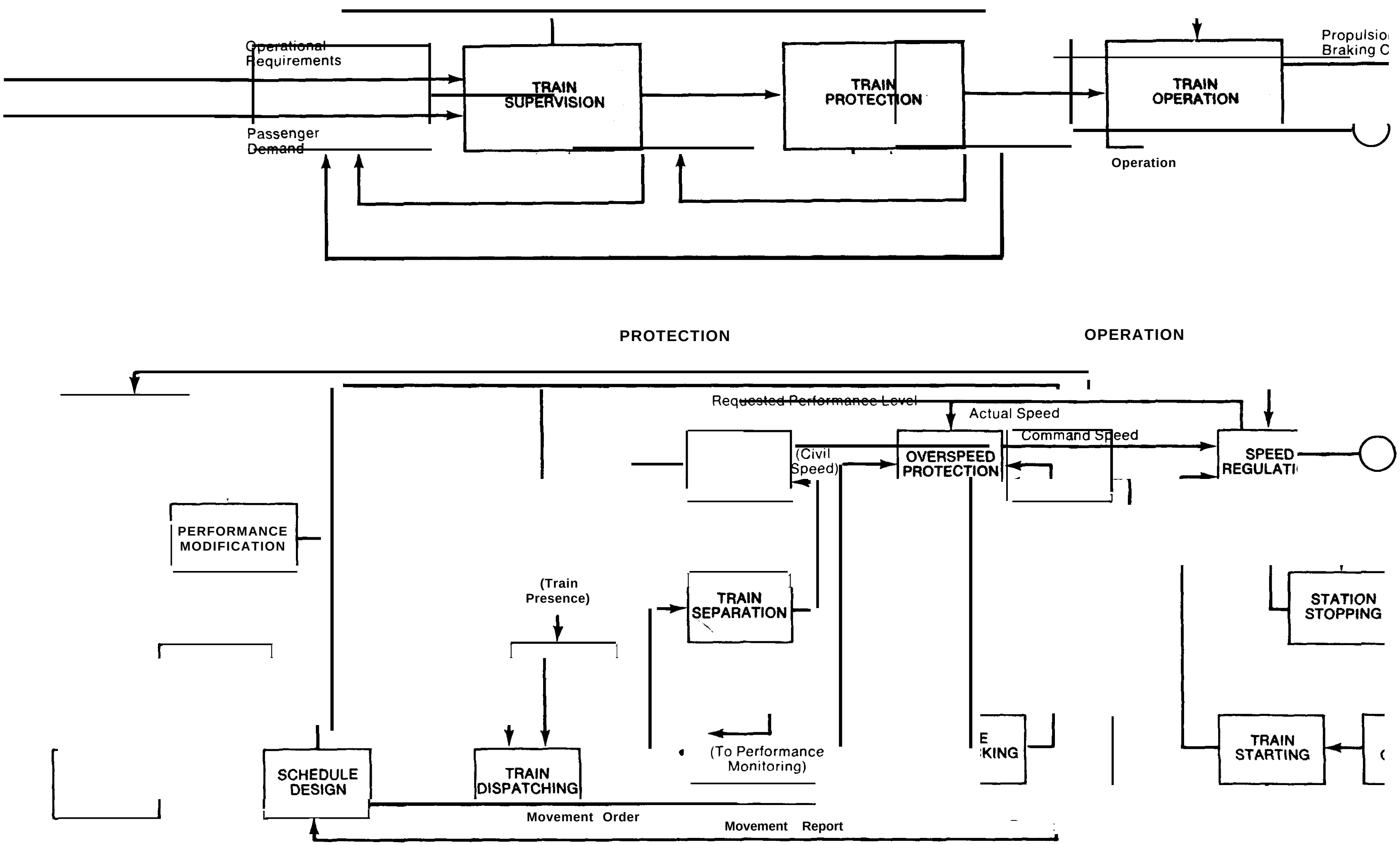
Train Operation

Train operation consists of those functions necessary to move the train and to stop it at stations

F. For more detailed technical descriptions of train control system functions and technology, see appendices A and B.

[9]There is no universally accepted terminology and scheme of definitions for train control system functions within the transit industry. The terms and classification employed here are based on several sources and represent the best of current usage.

[10]A glossary of train control and rail rapid transit terms is provided in appendix D.



" To simplify the diagram, the functions of Alarmlng and Recordkeepinq are not shown

FIGURE 1.—Train (

to board and discharge passengers. Train movement, as controlled by train operation functions, is under the direction of train supervisory functions and always within the constraints of train protection functions. Train operation involves the following:

Speed regulation-controlling train speed, within the constraints of overspeed protection, to make the run according to schedule;[11]

Station stopping—bringing the train to a stop within some specified area in a station;

Door control--opening of doors in stations to permit passengers to enter or leave the train and closing of doors when the train is ready to start;[12]

Train starting—initiating train departure from a station after the doors are closed (and provided the train protection system permits it),[13]

Train Supervision

Train supervision involves monitoring the movement of individual trains in relation to schedule and route assignments and overseeing the general disposition of vehicles and flow of traffic for the system as a whole. The train supervision system may thus be thought of as making strategic decisions which the train operation system carries out tactically, In addition, train supervision includes certain information processing and recording activities not directly concerned with train safety and movement but necessary to the general scheme of operations. Train supervision functions are:

Schedule design and implementation—preparing a plan of service in light of expected demand, available equipment, and environmental conditions and issuing a schedule to implement the plan;

Route assignment and control--selecting and assigning routes to be followed by trains (and rerouting as necessary);

Train dispatching-controlling train departures from terminals or waypoints in accordance with the schedule;

Performance monitoring—following the progress of trains against the schedule by obtaining periodic updates of train identity, location, and destination;

Performance modification—adjusting movement commands and revising the schedule in response to train, traffic, and environmental conditions.

Alarms and malfunction recording-alerting to malfunctions, breakdowns, or problems, and recording their time, location, and nature;

Recordkeeping —maintaining operational logs and records for business and payroll purposes, for scheduling maintenance, for ordering supplies and equipment, and for computing technical statistics.

Communication

The communication system is the means by which the information needed to carry out all other train control functions is transmitted and exchanged.[14] This information may take any of several forms-voice, visual, auditory, and digital

[11]Speed regulation involves more than matching actual to command speed. It also includes control of acceleration, jerk limiting (controlling the rate of change of acceleration), slip-slide control (correction of wheel spinning during acceleration and skidding during braking), and flare-out (gradual relaxation of braking effort as the train comes to a stop). Flare-out is considered by some transit engineers to be a subsidiary function of speed regulation, and hence part of the train control system. Acceleration control, jerk limiting, and slip-slide control are regarded by transit engineers to be propulsion and braking system functions, but they are mentioned here because of their relationship to the train control functions of speed regulation and station stopping.

[12]The mechanisms that actually open and close doors are not part of the train control system, but the signals to actuate these mechanisms and the interlocks to assure that doors are closed before starting and that they remain closed while the train is in motion are generated within the train control system. Because of the safety implications of door control, some transit engineers consider it to be a part of train protection.

[13]Train starting is sometimes classified as part of the door control function. It is separated here for two reasons: (1) in some automated systems, door control is automatic while train starting is retained as a manual function; (2) in manual systems, the door control and train starting functions are often assigned to different persons.

[14]On the function diagram in figure 1, communication functions are indicated by the lines connecting the boxes which represent train protection, operation, and supervision functions,

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or analog electrical signals.[15] Unlike other train control functions, which involve information processing and decisionmaking, communication is largely a facilitative process-serving to convey information but without producing any unique functional outcomes of and by itself. For this reason, the categorization given below indicates not functions as such but major classes of information that must flow throughout the system in order for other train control functions to take place:

- Train protection—information necessary to locate individual trains, to assure their safe separation, to prevent overspeed, and to control movement at route interlockings;[16]
- Command and status—information on the operational state of the system, command signals to control train and switch movement, and feedback to determine the response of system elements to command inputs;[16]
- Emergency—information on the nature and location of emergency events and summons for help to elements within the transit system or to outside agencies (e.g., fire, police, medical, and rescue);
- Passenger service—information relating to train service and system operation for the purpose of assisting passengers using transit facilities;
- Maintenance—information needed to plan or conduct preventive and corrective maintenance;
- Business operations--operational information used to maintain a record of (and to plan for) work force allocation, vehicle utilization, procurement of supplies and equipment, operating expenses, and system patronage.

[15] Some transit engineers limit the definition of communication to verbal or visual communication (radio, telephone, TV, and the like). Machine-to-machine communications, since they tend to be very specialized, are considered part of the function which they serve. This seems to be unnecessarily restrictive and makes an artificial distinction between information exchange by human operators and other forms of information exchange involved in operating the system (i.e., man to machine or machine to machine). The definition offered here is generic and embraces all types of information flow, regardless of how effected.

[16] Customarily, this part of the communication system is completely separate from the network used for other types of information and is considered to be an integral part of the train protection system.

AUTOMATION

At one time or another, all of the train control functions listed above have been performed by human operators, and many still are, even in the most technologically advanced transit systems. Theoretically, any of these functions could also be performed by automatic devices, and more and more have, in fact, been assigned to machines over the years, Before examining the technology by which train control automation has been achieved, it is first necessary to consider what is meant by automation and to clarify the terminology used in this report.

Figure 2 is a generalized diagram of the process by which any train control function is accomplished. It involves receiving information about some operational state of the system and some desired state. This information must then be interpreted—for example, by comparing the two states and deriving a quantitative expression of the difference, Next, an appropriate control response to null the difference must be selected, and some specific command message to the controlled element must be formulated and transmitted. A final, and all-important, step is monitoring the results of the control action to ascertain that the desired system state or condition has been achieved. This last step, called feedback, provides an input signal to start the process all over again, thereby creating a loop that permits the control process to be continuous and adaptive.[17]

If all of the steps in the general sequence shown in Figure 2 are performed by a human operator, the process is called manual, even though manual action in the strict sense may not be involved. Thus, manual denotes a process that may include visual, auditory, and other forms of sensory perception as well as purely cognitive activities such as interpretation, weighing alternatives, and decisionmaking. The command output might be accomplished by some manual activity such as pressing a button or moving a control lever, or it might take the form of a voice command or simply a nod of the head. The essential feature of a manual process, as the term is used here, is that all the basic control steps to accomplish a function are human activities.

[17] This description overlooks the difference between closed- and open-loop control systems. For a discussion of the application of each in train control technology, see appendix B.

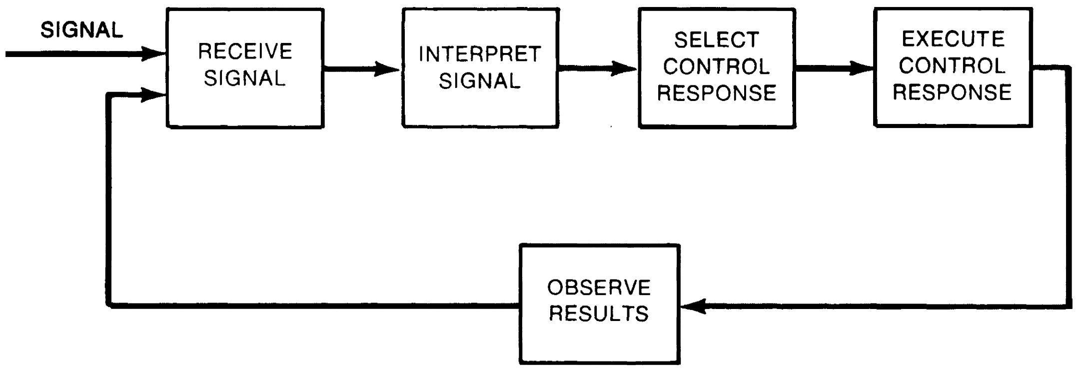


FIGURE 2.—Generalized Control Process

It is also possible for all of the steps in the control loop to be accomplished by some mechanical or electrical device. If so, the process is called automated. The device need not necessarily be complicated, nor is a computer required in order for the apparatus to process information and make a "decision." A simple junction box with a two-state logic circuit (ON or OFF) would satisfy the definition of an automated control device, provided no human actions were required to receive and interpret input signals, select and order a response, and monitor the result.

Between the extremes of purely manual control and fully automatic control, there are numerous combinations of mixed man-machine control loops. These are called semi-automated or partially automated—the terms are used synonymously to denote a process (or a system) in which there are both manual and automatic elements. Thus, automation is not to be taken in an absolute, all-or-nothing sense. The machine can be introduced by degrees into a system to perform specific functions or parts of functions. When comparing parts of a train control system or when comparing one system with another, it is therefore possible to speak of automation in comparative terms and to say that one is more or less automated than another, depending on how many specific functions are performed by machines.

For brevity, acronyms are used to describe certain areas where automation is applied in train control. ATC (automatic train control) refers generally to the use of machines to accomplish train control functions. It does not necessarily suggest a completely automated system. It can be applied to a system where certain functions or groups of functions are performed automatically while others are performed manually. ATP (automatic train protection), ATO (automatic train operation), and ATS (automatic train supervision) are used to designate major groups of functions that may be automated. For example, if a system is said to have ATP, it means that train protection is accomplished (either completely or mostly) by automatic devices without direct human involvement. If a system is described as having ATC consisting of ATP and some ATS, this indicates that train protection is assured by automatic devices and that train supervision is a mixture of manual and automatic elements. By implication, train operation in such a system would be manual.

While automation involves the substitution of machine for human control, this does not mean that the human operator is removed from the system altogether. An automated system is not always an unmanned system, even though all functions are routinely performed by machines. For instance, train protection and train operation may be completely automatic in a given transit system, but there could still be an operator or attendant on board the train to oversee equipment operation and, most importantly, to intervene in the event of failure or malfunction. This emergency and backup role is, in fact, a major type of human involvement in even the most automated train control systems, In all rail rapid transit train control systems now in operation or under development, automation is utilized only for normal modes of operation, with manual backup as the alternative for unusual conditions, breakdowns, and emergencies.

In passing, it should also be noted that automation is not synonymous with remote control, even though the two may at times go hand in hand. In train supervision, for example, many functions are accomplished manually by controllers who are physically far removed from the train and wayside. In central control facilities, the operators may never actually see the vehicles or track and yet perform all or most of the functions necessary to set up routes, dispatch trains, and monitor traffic. Conversely, automated functions are often performed locally, i.e., by devices on board the train or at a station or switch. In general, the location of the controlling element in relation to the controlled element is independent of how the functions are accomplished. However, it is also true that automation does facilitate the process of remote control, and systems with a high level of ATC tend also to employ more centralized forms of train control, especially for supervisory functions.

AUTOMATIC TRAIN CONTROL TECHNOLOGY

The automatic equipment that accomplishes train control functions is often of complex design, but the basic technology is quite simple. The purpose of this section is to provide an acquaintance with the fundamental elements of an ATC system—track circuits, signaling apparatus, train operating devices, interlocking controls, and supervisory equipment, The details of this technology and the design features of ATC equipment now in use in rail rapid transit systems are omitted here but are provided in appendices B and C.

Track Circuits

For safety and efficient operation of a transit system, it is imperative to know the locations of trains at all times. The sensing device providing this information is the track circuit, which was invented over 100 years ago and has remained essentially unchanged in principle even though extensively refined and modified in its engineering details.

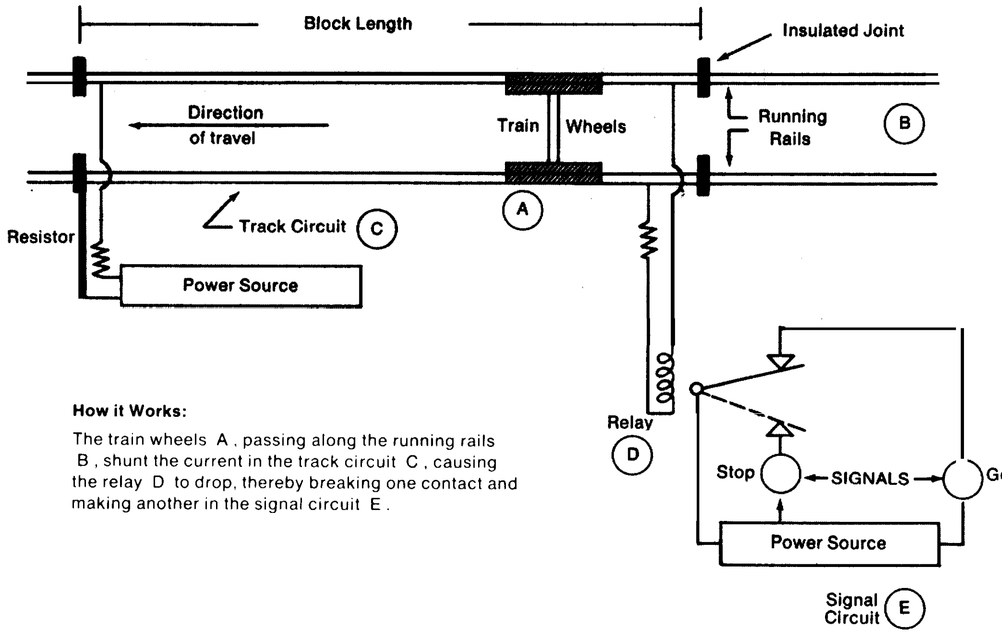


FIGURE 3.—Simple D.C. Track Circuit

The track circuit is an electrical circuit consisting of a power source, the running rails, and a signal receiver (relay).[18] The track is divided into electrically isolated segments (called blocks) by insulated joints placed at intervals in the running rails.[19] This forms a circuit with a power source connected to the rails at one end of the block and a relay at the other. The relay, in turn, forms part of a second electrical circuit which has its own independent power supply (commonly a battery) and includes a signaling device such as wayside colored lights,

When no train occupies the block, the relay is energized by the track circuit battery, causing the relay to "pick up, " i.e., a movable element (armature) is moved to and held electromagnetically in a position opposed to the force of gravity. This closes an electrical contact in the secondary signal circuit. When a train enters the block, the wheels and axles conduct electricity between the running rails, thereby short circuiting (shunting) the track circuit and reducing the current to the relay. This weakens the electromagnetic force holding up the armature, allowing it to drop under the force of gravity. This action opens the contact that was previously closed and closes a different contact in the signal circuit. The relay, therefore, acts as a switch in the secondary signal circuit and creates one electrical path when it picks up and another when it drops.

Thus, the basic principle of the track circuit is the shunting phenomenon produced by the train wheels passing along the electrically energized running rails. The presence of the train is detected in the track circuit as a reduction of electrical current, which-by means of the relay—is used to control the secondary signal circuit and operate various types of track occupancy indicators.

The track circuit is designed according to the fail-safe principle. In order for a clear (unoccupied block) indication to be given, the track circuit must be in proper working order. If one of the rails were to break, the relay would receive no current; and the armature would drop just as if a train were present. A broken electrical connection, a failure of the power source, or a burned-out relay coil would also have the same effect.

Wayside Signals

One of the earliest types of signal devices employed to control train movement, and one still widely used, is the automatic wayside block signal, It consists of a color-light signal, in appearance much like the traffic signal on city streets, located beside the track at the entrance to each block, This signal is controlled by the track circuit relay, as described above. The signal directs train movement by displaying red, yellow, or green lights (aspects) to indicate track circuit occupancy ahead,

Since it would be impractical for the train to creep ahead block by block, waiting to be sure each block is clear before entering, the wayside signals are arranged to give the operator advanced indication of speed and stopping commands. Figure 4 is an illustration of a three-block, three-aspect wayside signal system, This signaling arrangement tells the train operator the occupancy of the track three blocks ahead of the train and conveys three different movement commands (indications)—green (proceed), yellow (proceed prepared to stop at the next signal), red (stop).

In the illustration, Train A is stopped in Block 4 and Train B is approaching from the rear. Since there is a separation of at least three blocks between them, Train B receives a green aspect at the entrance to Block 1, allowing it to proceed at the maximum allowable speed. At the entrance to Block z, however, Train B receives a yellow aspect, indicating that the train operator should be prepared to stop at the next signal because there may be a train ahead. At the entrance to Block 3, Train B is commanded to stop by a red signal aspect. When Train A leaves Block 4 and moves on to Blocks 5 and 6, the signal at the entrance to Block 3 changes to yellow and then green, allowing Train B to proceed.

The wayside signaling system is made fail-safe through design and by operating rules. Dual, or sometimes triple, lamps are used to illuminate each signal aspect. Redundant power sources are sometimes provided. The ultimate safeguard, however, is

[18] Track circuits may utilize one or both running rails, may operate on direct or alternating current, and may have electromechanical relays or solid-state electronic receivers. The type described here is a double-rail dc track circuit with a relay. The other types are similar in principle and operation.

[19] Block length in rail rapid transit systems varies considerably as a function of track and traffic conditions and signal system design. Some are as short as 40 feet; others are over half a mile long,

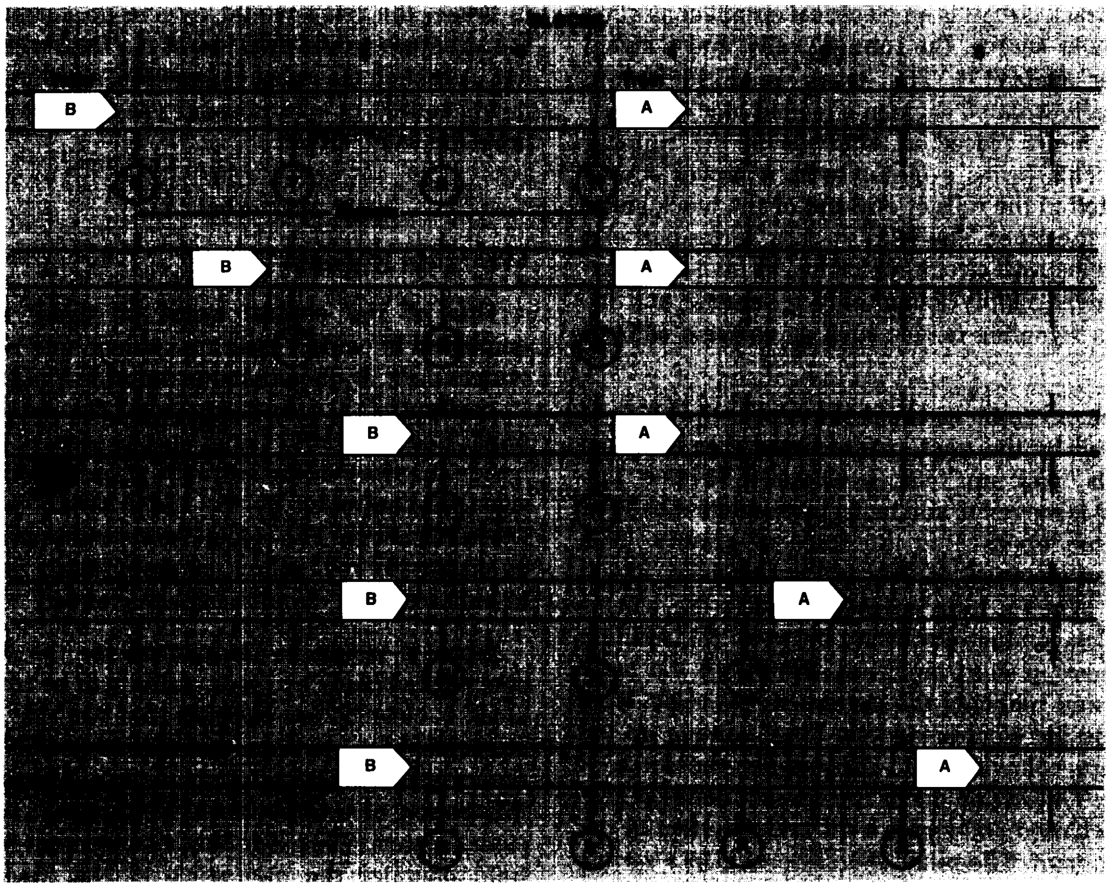


FIGURE 4.—Three-Block, Three-Aspect Wayside Signal System

procedural. A complete failure of the signal lamps or a loss of power would result in a dark (unlighted) signal, which standard operating rules require the train operator to observe as if it were a red signal.

Trip Stops

In the wayside signal system described above, safe train movement depends solely on the compliance of the operator with signal indications. To guard against error, inattention, or incapacitation of the train operator, wayside signals can be supplemented with an automatic stop-enforcing mechanism, called a trip stop.

The trip stop is a device located beside the track at each wayside signal. The type commonly used in the United States consists of a mechanical arm that is raised or lowered in response to the track occupancy detected by the track circuit. When the arm is in the raised position, it engages a triggering device on the train and actuates (trips) the emergency brake.[20] A train entering a block in violation of the wayside signal indication would thus be brought to a complete stop before colliding with the train in the next block regardless of what action the train operator took, or failed to take.

In addition to protecting against rear-end collisions, trip stops can also be used in conjunction with the track circuits and other signal appliances to provide automatic protection against overspeed. For this application, a timing device is added to the circuit controlling the trip stop. When a train enters a

[20]An alternative system employing inductive train stops is used on main-line railroads in the United States and on rail rapid transit systems abroad. The device is somewhat more complex than the mechanical trip stop, but it avoids mechanical contact between a stationary wayside element and a moving train and is less vulnerable to blockage by snow or debris. Both trip stops and inductive train stops have the inherent disadvantage of requiring strict alinement of wayside devices. Further, if either type of device is removed, the system will operate in a mode that is not fail-safe.

block, the trip stop at the entrance to the next block is in the raised position but will be lowered after a time interval corresponding to the minimum time (the maximum speed) permitted for a train to traverse the block. This arrangement is commonly used on curves, downgrades, and other such sections of track where excessive speed could cause a derailment. A variation of this scheme is commonly used at stations to allow a following train to close in on a leading train, provided the follower moves at appropriately diminishing speed as it approaches its leader.

Like track circuits and signals, the trip stop is designed to operate in a fail-safe manner. The trip is raised to the stopping position by gravity or a heavy spring and lowered by a pneumatic or electric mechanism. Thus, failure of the trip stop actuating mechanism or its source of energy will result in the trip stop being raised to the stop position.

Cab Signals

Automatic block signal systems with wayside signals and trip stops, while offering effective train protection, have certain operational disadvantages. Sometimes the signals are obscured by fog, rain, or snow. In such cases, operating rules require that the operator consider the signal as displaying its most restrictive aspect and operate the train accordingly. If the signal is actually displaying a more permissive indication, time is lost unnecessarily. A second disadvantage is that wayside signals convey commands only at the entrance to a block. The train operator must reduce speed to the maximum permitted by the signal and maintain that speed until reaching the next signal. If conditions change immediately after the train enters the block and it becomes safe to proceed at a greater speed, the train operator has no way of knowing this since the signal is behind him. Again, time is lost. With wayside block signals there is also the possibility that the operator will fail to observe the signal correctly, read the wrong signal in multiple-track territory, or forget the indication of the last signal passed. If there are trip stops, these kinds of human failure do not result in an unsafe condition, but the efficiency of train operation can be adversely affected.

One way to overcome these disadvantages is to provide signal displays within the cab of the train, This is called cab signaling, A display unit, mounted in the cab within the train operator's forward field of view, shows indicator lights similar to those of wayside signals, e.g., red, yellow, and green aspects. Cab signals can thus convey the same movement commands as wayside signals, but they do so continuously in response to the instantaneous condition of the track ahead. They can also convey precise speed commands instead of just stop-and-go information, thus providing more flexible operation and paving the way to ATO. The cab signal unit has an audible warning that sounds whenever the signal aspect becomes more restrictive and continues to sound until the operator silences it by an acknowledging device. Figure 5 is an illustration of a typical cab signal.

Transferring the display of information from the wayside to the cab involves an alternate type of track circuit technology. To operate cab signals, the current passing through the track circuit (usually a.c. is not steady, as for conventional wayside signals, but is pulsed (turned on and off) at several different repetition rates in response to track occupancy. Each pulse rate is a code to indicate allowable train speed. This pulsed d.c. energy is passed through the rails, picked up inductively by a receiver (antenna) on the train, and decoded to retrieve speed command information, This information is used to actuate the appropriate cab signal display. Because the train is continuously receiving pulses of energy, a change in the pulse rate of the coded track circuits indicating a change of conditions ahead of the train is instantaneously received by carborne equipment and displayed by cab signals regardless of where the train happens to be within a block.

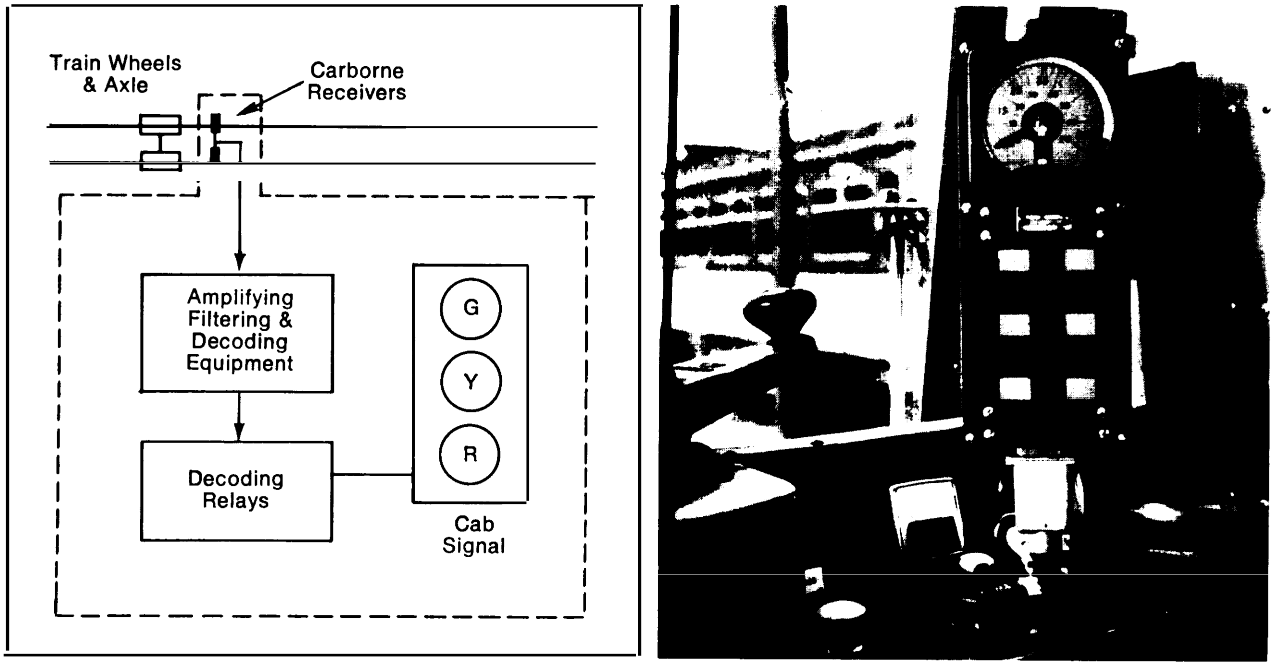
Figure 6 illustrates how cab signals control a train in a three-block, three-aspect signaling system. In this example, the code rates transmitted through the rails (expressed as pulses per minute) correspond to the following signal aspects:

180 Green (Proceed)

75 Yellow (Proceed at medium speed prepared to stop)

O Red (stop)[21]

[21]Note that O code-the absence of a code—is the most restrictive, Thus, any failure of the track circuit or the carborne receiver is a fail-safe condition since it is interpreted by the cab signal equipment as a command to stop.



HOW IT WORKS: **Receiver coils, mounted on the train near the rails, receive pulse-coded track signals, which are decoded and used to pick up relays that energize the cab signal lamp indicating track conditions ahead.**

FIGURE 5.-Cab Signals

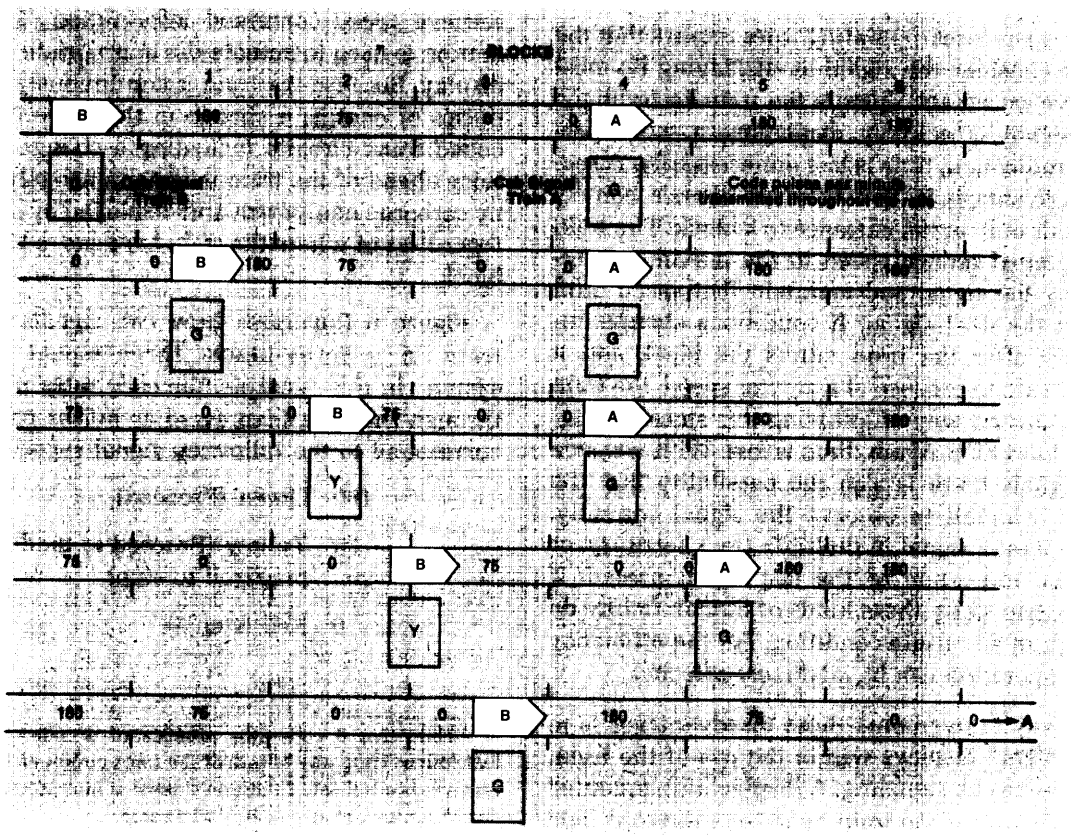


FIGURE 6.—Three-Block, Three-Aspect Cab Signal System

The situation depicted here is the same as in the illustration of wayside signals (figure 4). Train B is approaching Train A, which is completely stopped, Note that the moment Train A starts to move and clears the block, Train B receives a green signal immediately—not at the entrance to the next block, as it would with wayside signals. Note also that a O code appears in the part of the block immediately behind Train B as it moves along the track and that Train B can approach closer to Train A before being required to stop,

Speed Control

With the addition of speed sensing and brake control mechanisms, cab signals can also be used to provide automatic overspeed protection. Figure 7 is a schematic diagram of such a system. It is the same as the schematic shown in figure 5, except for the addition of speed and code rate comparison equipment and the direct connections to the propulsion and braking systems.

This arrangement allows the train operator to control speed so long as it does not exceed the commanded speed shown on the cab signal unit. If the commanded speed is exceeded or if the block speed changes to a lower value because of another train ahead, the operator receives an audible warning. The operator has a fixed time (typically 2 to 3 seconds) to initiate the required braking manually. If this is done, the brakes can be released when the commanded lower speed is reached. If not, the brakes are applied automatically and irrevocably by the ATC system, and the train is brought to a full stop before the operator can resume control. This is analogous to the overspeed control provided by wayside signals with trip stops, except that braking can be initiated anywhere within a block not just at the entrance. Another difference is that trip stops act to stop the train after an overspeed condition has occurred over a measured course, usually several hundred feet in length. Cab signals do the same, but instantaneously, thus eliminating the delay inherent in the preliminary measured course and per-

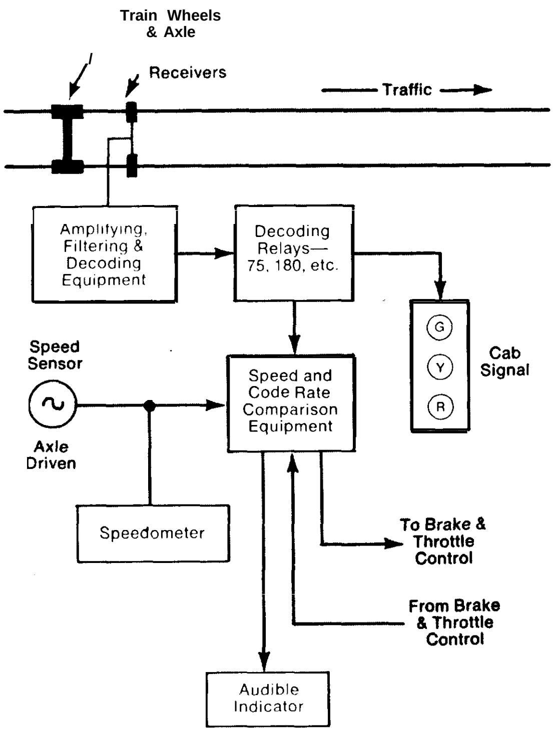


FIGURE 7.—Cab Signal System With Automatic Overspeed Protection

mit trains to follow one another more closely for a given block length.

Automatic Train Operation

Basically cab signaling provides carborne automatic train protection in the form of collision prevention. With the addition of on-board equipmerit for sensing and comparing command (allowable) and actual speed, cab signaling makes it possible to expand the train protection function to permit speed regulation. This, in turn, forms the basis for extending automation into the area of train operation.

Several forms of automatic train operation (ATO) are possible, but all have two basic features-automatic speed regulation and station stopping.

Automatic speed regulation (ASR), as the name implies, is basically a comparator circuit for matching actual speed to command speed. Speed comands received from coded track circuits are picked up by a carborne receiver, decoded, and compared to actual train speed sensed by a tachometer in the drive mechanism. Up to this point, an automatic speed regulation system is like cab signaling. The difference arises in how this comparison is used. With cab signals, the comparison is used to actuate a penalty brake application to stop the train when actual speed exceeds command speed. With ASR, the comparison is used to control the motors and brakes in an effort to minimize the difference between actual and command speed. An advisory display of speed commands and train speed may be provided for the operator. In effect, ASR removes the human operator from the control loop for running the train and provides for an essentially instantaneous and invariant response by propulsion and braking systems, without the delay of human reaction time and without the variability and possibility for misinterpretation inherent in manual train operation.

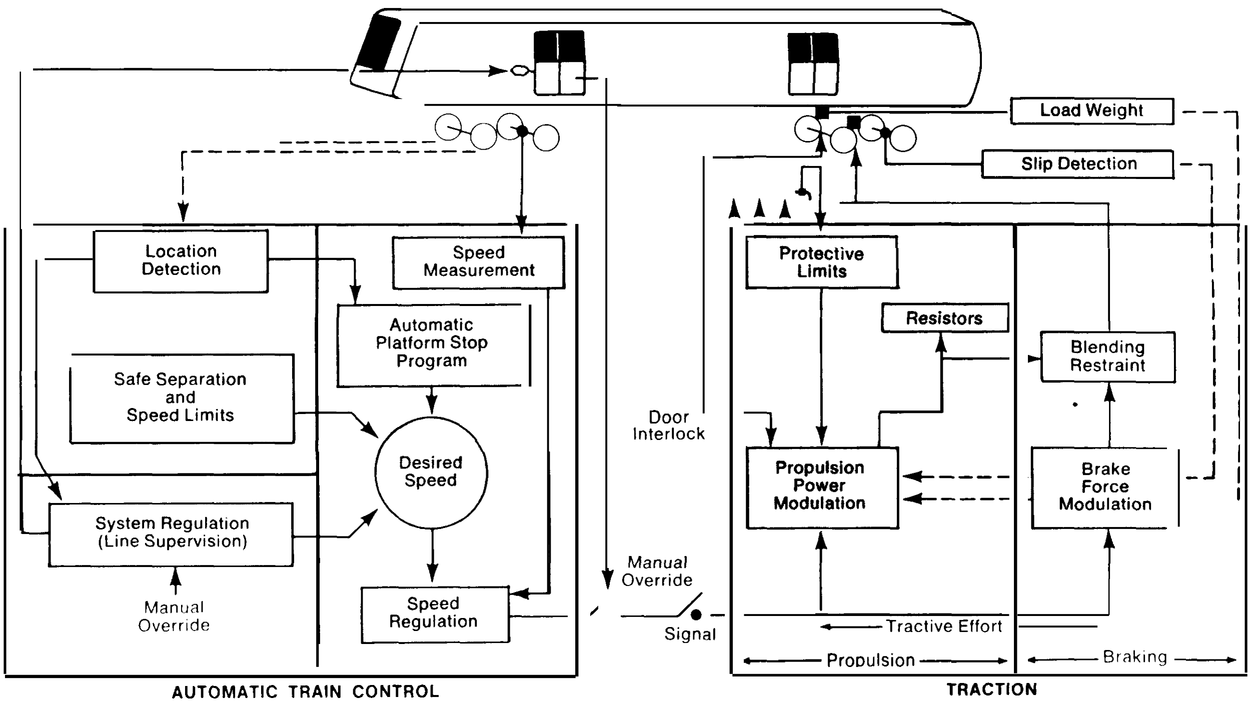
The other basic element of ATO is station stopping, which involves bringing the train to stop automatically at a predetermined location in each station. This is accomplished by special wayside control units working in cooperation with position receivers, logic circuits, and automatic speed regulation equipment on the train. One method uses wayside "triggers" spaced some distance from the station as reference points for programed stopping. The first trigger, farthest from the station, transmits a command signal that generates, on board the train, a velocity-distance profile which the train is to follow to a stop. Additional triggers, nearer the station platform, correct the generated velocity-distance profile for the effects of wheel slip and slide. The ASR system monitors the velocity-distance profile and controls the braking effort to bring the train to a stop at a predetermined point. Another method of programed stopping makes use of long wayside antenna to provide a series of position signals to a carborne control system as the train passes along its length. The carborne control system determines train position and combines this with speed and deceleration information (sensed on board the train), to produce an appropriate propulsion or braking command for the traction control system.

To this basic ATO system, other automated features may be added. Doors can be opened automatically after the train is brought to a stop in a station, This requires a circuit to actuate door opening mechanisms and appropriate safety interlocks to assure that the train is in fact stopped and at a station. Door closure may also be automated by adding a timing circuit to measure how long the doors have been open and to initiate a door closure signal automatically after a predetermined dwell time has elapsed. Train departure can also be initiated automatically by introducing another control circuit to apply propulsion power after receipt of a signal confirming that doors are closed and locked.

For each of these levels of ATO, the train operator may be provided with an advisory display to show what commands are being received and what response is being made by automatic mechanisms. The operator may also be provided with manual override controls to inhibit automatic functions or to vary automatic system operation. For example, the operator may intervene manually to adjust the stopping point, to prevent some or all doors from opening, to vary station dwell time, or to initiate or prevent departure. Figure 8 shows a functional diagram of a typical ATO system and a picture of the train operator's console.

Interlocking

An interlocking is an arrangement of signals and signal appliances so interconnected that functions must succeed each other in a predetermined sequence, thus permitting safe train movements along a selected route without collision or derailment. An



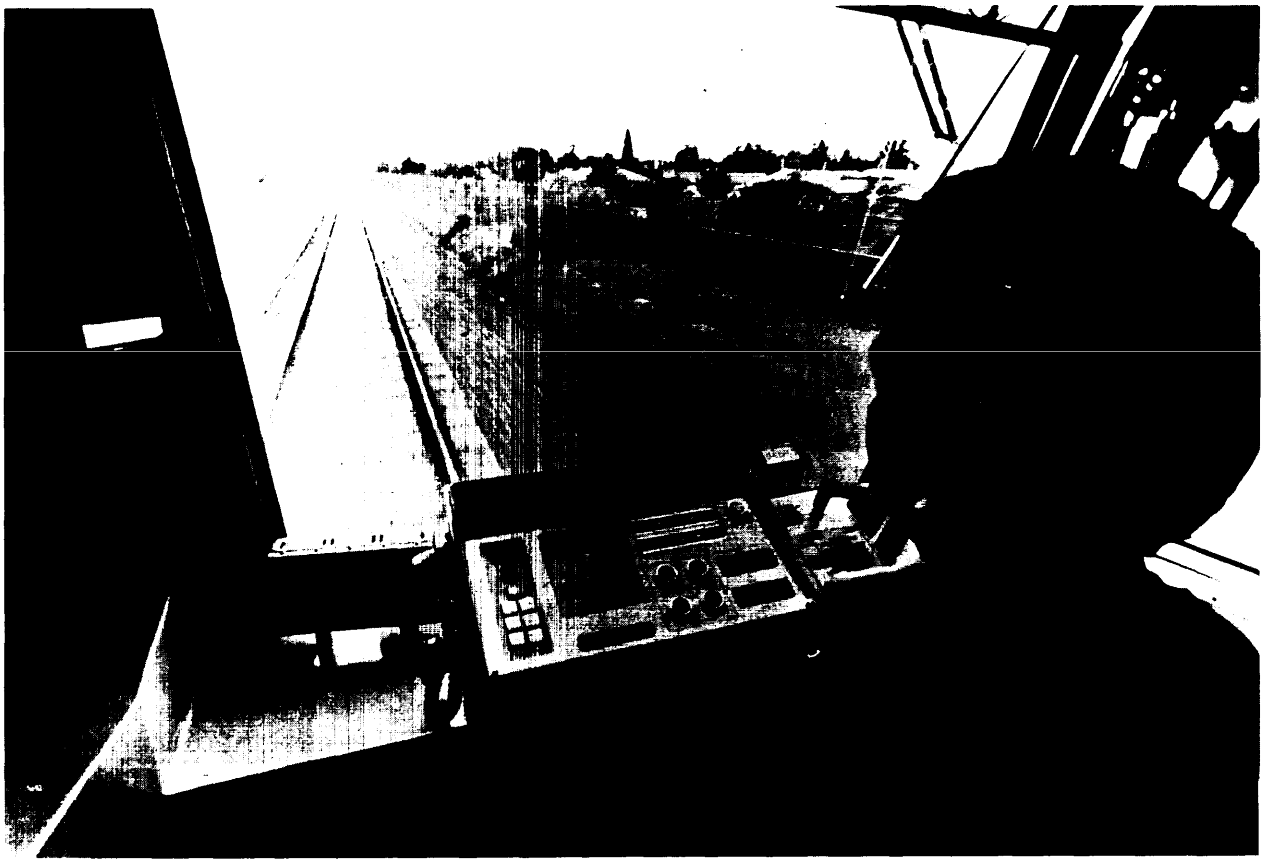


FIGURE 8.—Automatic Train Operation System

FIGURE 9.—Typical Interlocking Location

interlocking thus consists of more than just switches to allow trains to move along crossing, merging or branching routes; it is also made up of signals and control devices that automatically prevent conflicting or improper movements. Interlocking may be manually controlled or equipped with automatic devices that sort trains through branches and junctions according to desired destinations,

Several forms of automatic interlocking are in use. One of the oldest and simplest is an arrangement of hand-operated switches, each of which controls an individual signal or track turnout. The switches are mechanically or electrically interconnected such that once a particular route is selected, the switch points locked in place, and the signals cleared, no other route for a potentially conflicting move can be established until the train bound for the cleared route has safely passed, This arrangement represents a semiautomated form of movement control, Manual operation is required to select a route and move the control levers, but all else follows automatically, including inhibition of further switch movement until the train has traversed the limits of the interlocking.

A more advanced, but still not completely automated, type of interlocking is a system that permits a towerman or central supervisor to select the entrance and exit points for a train to pass through an interlocking, with the switches and signals for the appropriate route then being set up automatically by an arrangement of electrical relays, Figure 10 shows such a control panel for a system called entrance-exit route interlocking, The tower operator moves the control knobs to designate a desired route. Internal logic circuits automatically select the best available nonconflicting route, aline and lock switches, and activate the appropriate wayside signals to allowing train movement while holding other signals at stop to prevent conflicting moves. This level of automation may be characterized as automatic execution in response to manual inputs,

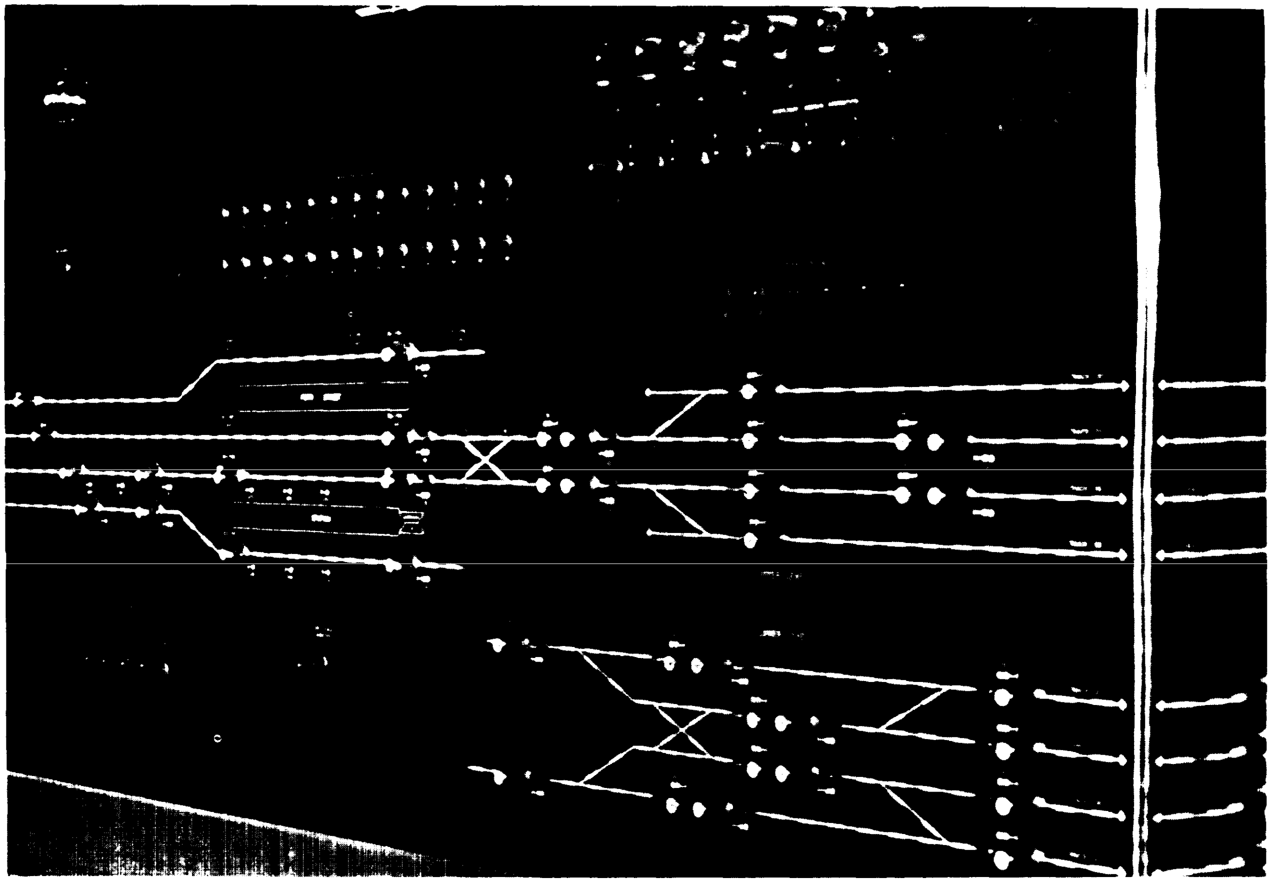


FIGURE 10.—Entrance-Exit Interlocking Control Panel

Fully automatic interlocking are also in use. In addition to track circuits, switch operation, and signal control elements, the automatic interlocking must have some device for identifying a specific train in order to create the necessary input to the logic circuits.[22] One method to identify trains is by means of wayside optical device that scans a panel on the lead car which gives destination, route, and other needed information. Another method makes use of a carborne transponder that is interrogated by a wayside device. With either technique, however, train identity becomes the substitute for manual inputs that allows trains to be sent along predetermined routes without human involvement.

[22]A rudimentary form of automatic interlocking is one that uses a simple in-out logic circuit to switch trains from one track to another. This device is commonly used at terminals and operates to switch each entering train from the inbound to the outbound track and thus does not require train identity information.

Train Supervision Equipment

Train supervision embraces a wide variety of functions. The special-purpose equipment that has been developed to perform these functions is equally varied. In a general survey of train control technology it is not possible to describe all types of automatic and semiautomatic devices that are in use. The following, therefore, is a brief catalog of some of the more important systems.

Train dispatching is concerned with the timing of train departures from terminals in accordance with the schedule of operations. In conventional transit systems this function is accomplished by preprogrammed dispatching machines that automatically ring a bell or flash a light as a signal to the train operator that it is time to leave a terminal or intermediate waypoint. In some systems, the dispatch function may be assigned to a central train control computer that transmits electric starting signals to the train in accordance with a master schedule stored in the computer memory.

Route assignment and control is a train supervisory function that is allied to the train protection function of route interlocking. Route control is a strategic function, consisting of selecting routes for trains and transmitting the orders to wayside points, where the orders are implemented tactically by interlocking equipment. In conventional transit systems, route assignment and control is performed locally, either manually or automatically, With remotely controlled route interlocking, however, it becomes operationally practical to place the strategic and tactical management of routing in a computer. The programing to accomplish this is relatively simple and straightforward, and a computer is ideally suited to handle what is an essentially repetitious task with a limited number of alternative courses of action. The safety aspects of route interlocking are assured not by central computer control, but locally by conventional interlocking equipment at the wayside,

Performance monitoring involves comparing the overall movement of traffic with the schedule and taking action to smooth out irregularities of traffic flow. In most transit systems this function is carried out by central control personnel aided by automatic display devices. One such device is a pen recorder that marks a moving paper graph to record the passage of trains past check points, Each spike on the graph indicates the presence of a train, as detected by the track circuits, at some time and place along the route. A train supervisor, by checking this graph against the schedule, can monitor the progress of all trains operating on line and detect delays or queuing up of trains, (Figure 18, page 36 shows such a device,)

Another form of performance monitoring aid is the model board (figure 11), which is a schematic representation of the track plan of the transit system with indicator lights to denote track circuit occupancy and, hence, the position of each train on the line, This is the functional equivalent of the pengraph recorder, but in a more pictorial form of display. Another type of model board used in newer transit systems has, in addition to the master track plan, small cathode ray tube displays that permit individual supervisors to obtain more detailed or expanded views of selected track sections or to call up special-purpose presentations of data,

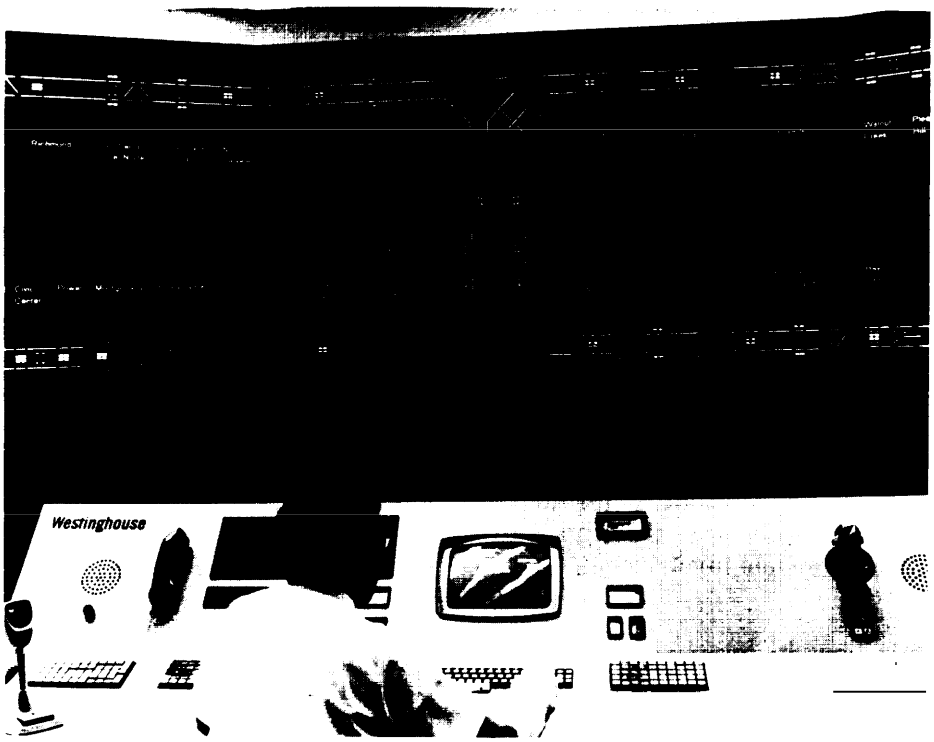


FIGURE Il.—Model Board and Train Control Console

Pengraphs, model boards, and the like are not fully automatic supervisory devices. The human operator is still needed to interpret the display and to formulate orders to individual trains. In the most advanced systems routine performance monitoring is assigned to computers, which keep a continuous watch on traffic movement and automatically calculate and transmit performance commands to trains. Man, in this circumstance, acts in a completely different supervisory capacity. He does not monitor and regulate traffic. Instead, he supervises machines which, in turn, monitor and regulate traffic.

There are two general types of action that can be taken to smooth out irregularities in traffic flow. Both are accomplished in response to commands from central control. One is to hold a train in a station for a time longer or shorter than the scheduled dwell time or, in extreme cases, to direct a train to bypass a station in order to close up a gap. The other method is to alter the speed of the train between stations. This latter method is called performance level modification and takes the form of a proportional reduction of train speed below the speed normally allowed in each block. In systems supervised by a central computer and with automatic train operation, performance level modification is accomplished without human intervention. The required reduction is calculated by the central computer and automatically transmitted to stations or other critical locations, where the signals are picked up by carborne ATO equipment that modifies the response to the normal speed commands transmitted by the coded track circuits. These systems may also include provisions for manual inputs and displays at central control or on the train, but the normal mode of operation is automatic.

A WALK THROUGH A TRANSIT SYSTEM

To place ATC in perspective, it maybe helpful to make a brief tour of the facilities of a transit system, pointing out the type and location of the equipment that carries out train control functions.

Station

The passenger's first point of contact with a transit system is the station. The most prominent features-vending and fare collection facilities (possibly automated), escalators and elevators, heating and air conditioning, and platform amenities—have nothing to do with train control. There may also be public address systems and video or audio surveillance equipment for fare collection and platforms. These are not, strictly speaking, part of the train control facility even though they maybe connected to the central control facility and monitored by central supervisory personnel, About the only direct manifestations of ATC are the automated train departure and destination signs or loudspeakers found in some transit systems. These public announcement devices are connected to the ATC system and use information inputs derived from track circuits and train identification equipment, There may be an ATC equipment room in the station, but it is out of sight and locked. Its presence is usually unknown to passengers.

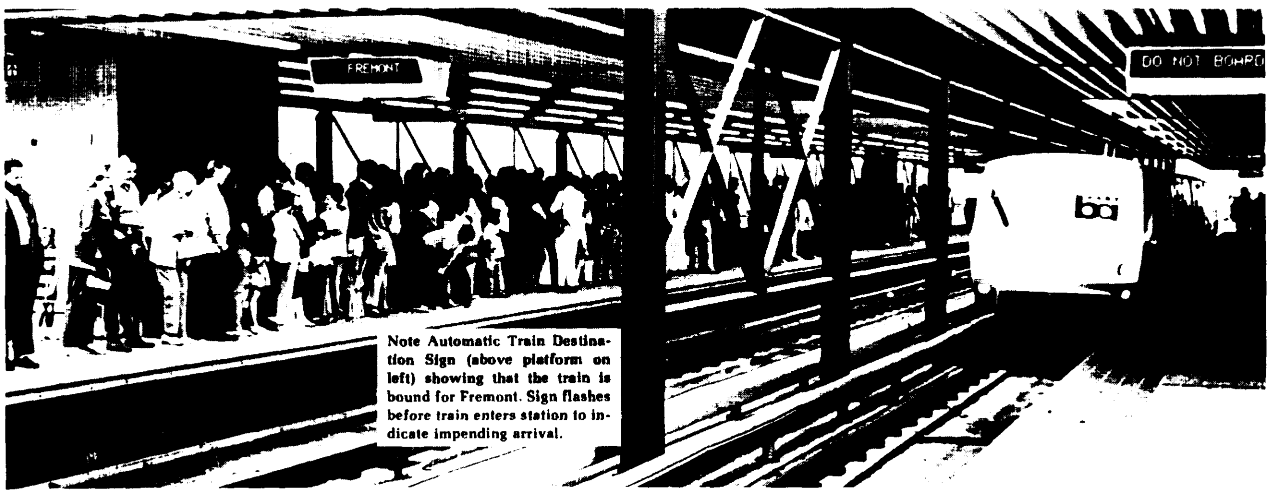


FIGURE 12.—General View of Rail Rapid Transit Station

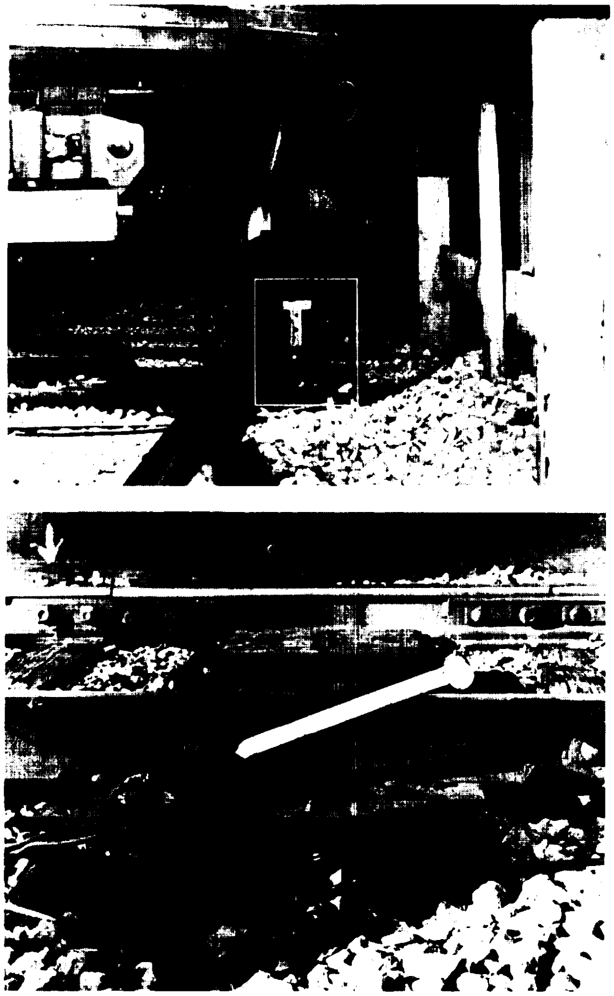


FIGURE 13.—Trip Stop

Wayside

An observant passenger might notice two wayside features that can be seen from the station platform. Looking down the tracks in the direction of train movement, there are wayside signal lights that change aspect from time to time. Often, just beyond the downstream end of the platform and alongside the rail, there is a trip stop which can be seen to raise behind a train that has just left the station and later lower as the train recedes.

Moving out along the tracks, other wayside elements can be found. The track circuits themselves are not plainly visible since they are largely in wayside housings. However, at intervals there are small flat equipment cases situated between the rails and connected to them by electrical wiring. These are the impedance bonds that isolate the track into blocks. At the ends of the blocks, there are small boxes, containing relays, with electrical connections from the track circuits to the signaling apparatus,

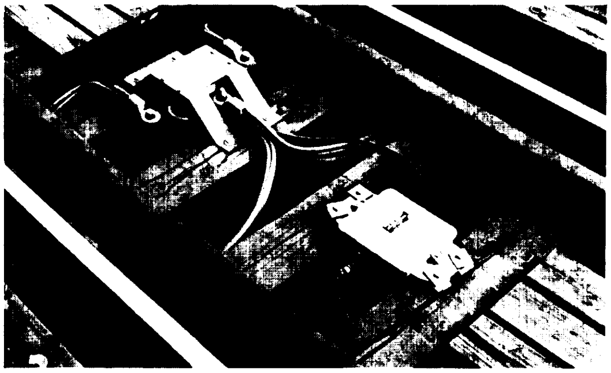


FIGURE 14,—Track Circuit Wiring

Other signal equipment is contained in small cases placed at intervals along the right-of-way. There are also telephones or other communication equipment and antennas or transmitters used for precision station stopping, train identification, or performance level modification, In certain locations, ATC apparatus and other trackside equipment may be housed in small sheds to protect the equipment from the weather and to facilitate maintenance by wayside workers.

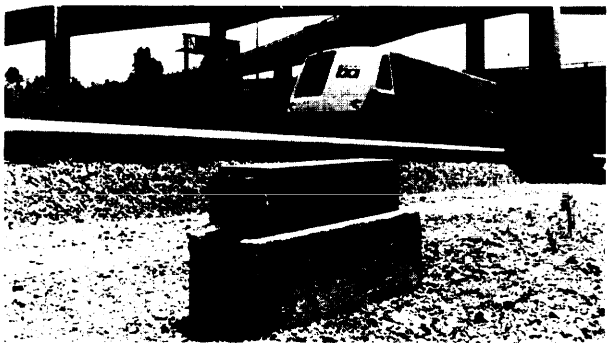


FIGURE 15.—Wayside Equipment Case (contains multiplex equipment for transmitting information between trains and station control rooms)

At junctions and crossovers there is switch apparatus, the most visible parts of which are the switch points, frogs, levers, and motive equipment, This is the wayside equipment, known as a switch machine, that performs the function of interlocking for train protection,

FIGURE 16.—Track Apparatus at an Interlocking

By far the largest part of the equipment, facilities, and structures along the right-of-way—trackage, tunnels, bridges, the third rail, and power distribution equipment-are not related to train control. Nevertheless, the wayside is where the bulk of the ATC equipment in a transit system is located. The proportion varies as a function of the level of automation, but generally about 80 percent or more of all train control equipment is not on the train but along the wayside and in central control facilities.

Central Control

Supervisory control of the system may be exercised in a central control room equipped with model boards, communication, equipment, system monitoring apparatus, and individual supervisor's

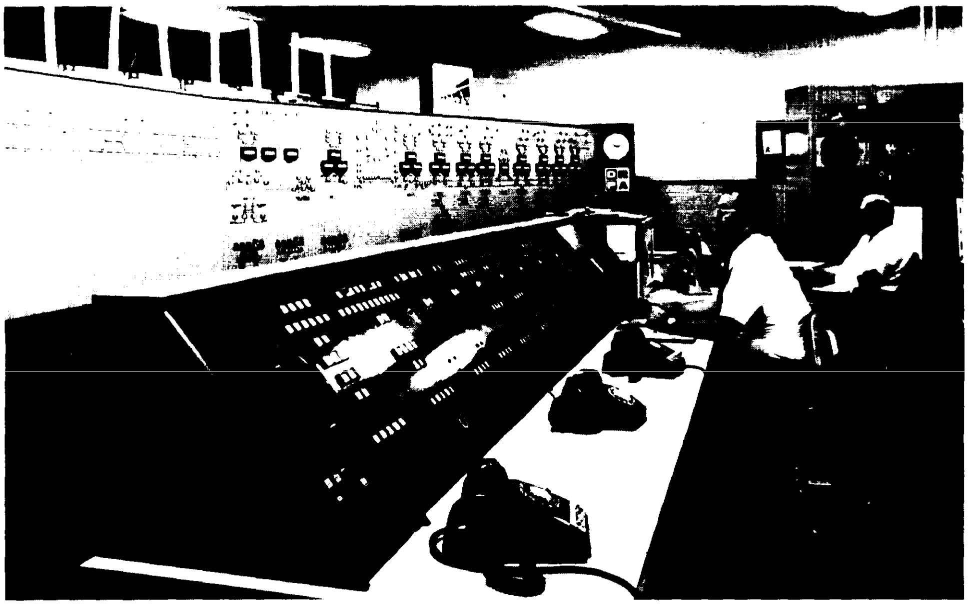


FIGURE 17.-Central Train Control Facility

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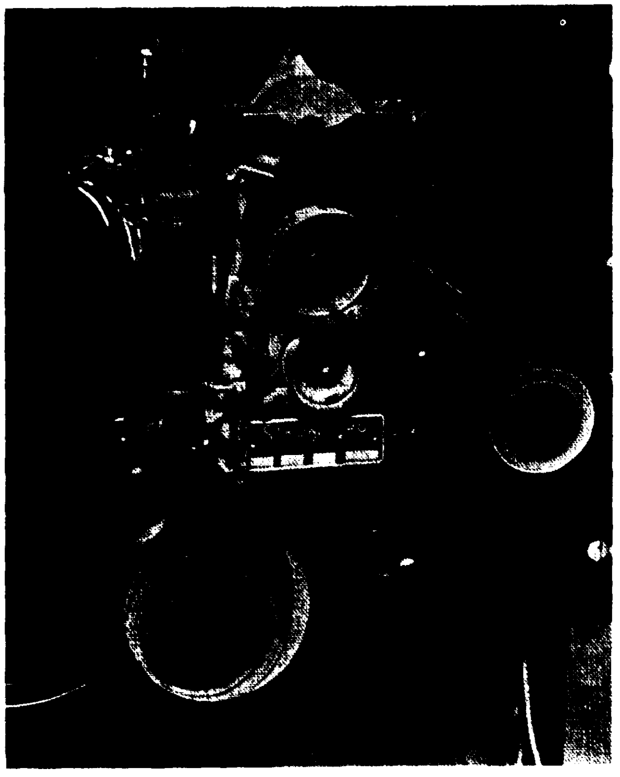

FIGURE 18.—Two Views of a Central Control Facility with Electromechanical Equipment

left-a clock-driven paper tape device for dispatching trains

above-pengraph device for monitoring train movement

consoles. If the system has ATS, the computers and other data processing equipment are also located in the central control building, which often houses administrative and training facilities as well.

Not all transit systems have a single centralized control facility. Some disperse control and supervision to outlying towers, situated at major interlocking along the routes. Figure 19 is a photograph of such a local control tower.

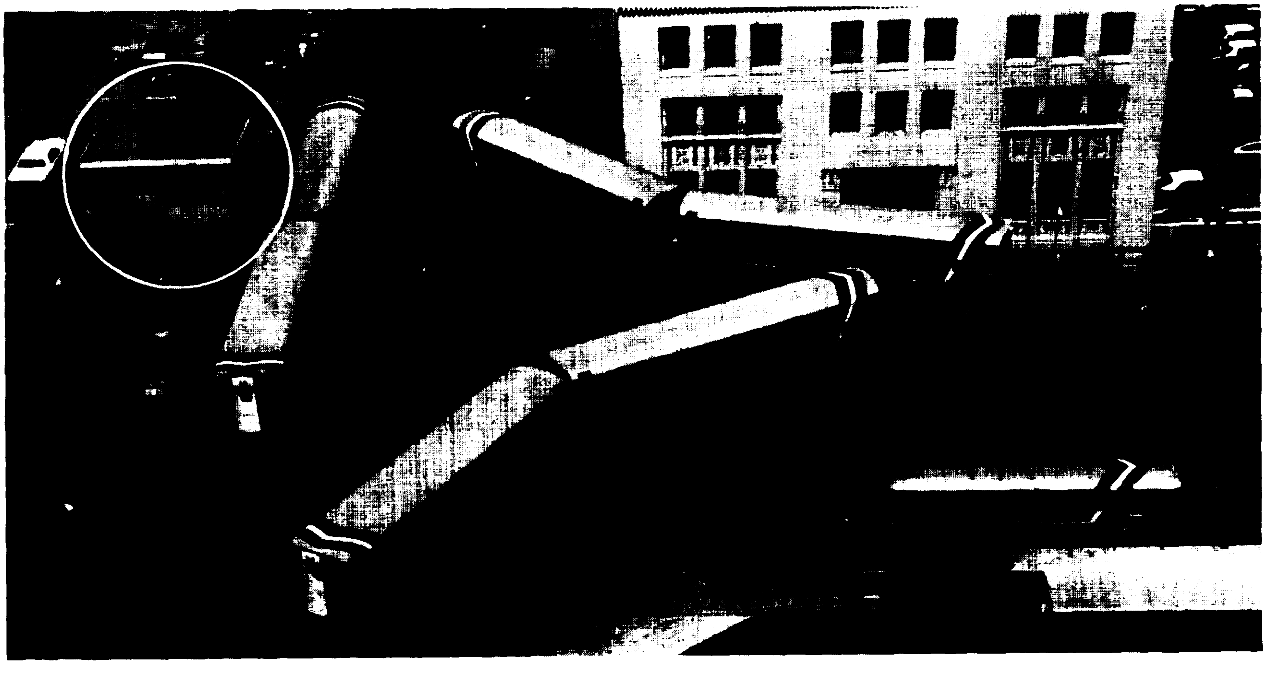

FIGURE 19.—Tower for Local Control of Interlocking

Vehicles

Most of the ATC equipment on transit vehicles is carried in equipment cases under the body or in the train operator's cab. About the only features distinguishable from outside the train are a receiver coil mounted on the lead car to pick up coded track circuit signals (figure 20) and—for systems with optical scanners-small identification panels mounted on the side of each car.

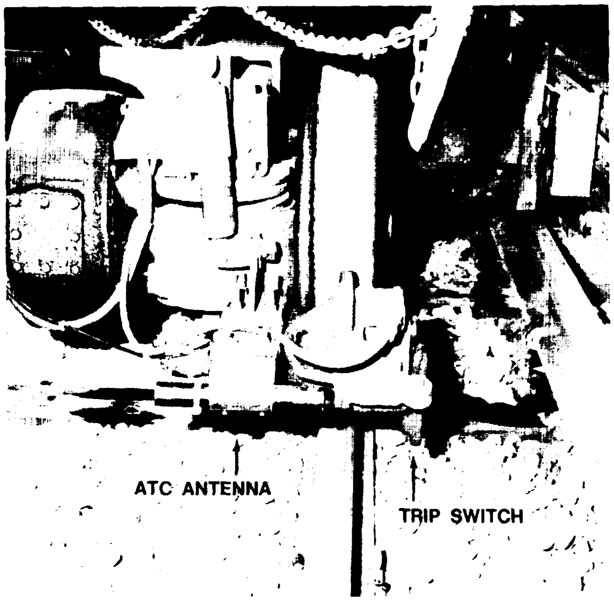

FIGURE 20.—Carborne Receiver Coil for Coded Track Circuit Signals

The operator's cab contains the displays and controls necessary to operate the train or to monitor the functions of ATC equipment. The amount and sophistication of this equipment varies greatly—ranging from very simple and utilitarian apparatus in manually operated systems to highly complex consoles in the newest and most automated systems, The console typically includes propulsion and brake controls, a speedometer and command speed indicator, lighted placards indicating the operating state of automatic elements, warning lights, pushbuttons or control knobs to make data inputs or to select various operating modes, a train phone or radio for communicating with central supervisors, a passenger address microphone, and a deadman control to prevent the train from operating in case the operator is inattentive or incapacitated.

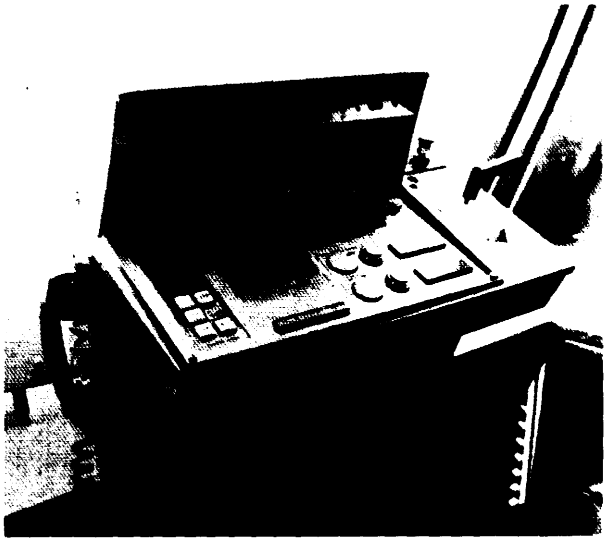

FIGURE 21.—Train Operator's Console for System with ATO

Yards and Shops

A large part of the important activity of a transit system does not occur in revenue service on the main lines, but in the yards and shops, These facilities, though seldom seen by the riding public, contribute greatly to the quality and level of service that the transit system offers.

The yards are usually located near terminals and consist of a vast complex of tracks for storing vehicles and making up trains to be operated on the lines. Even in systems with the most advanced levels of automation, train operation in yards is under manual control. Train sorting and classification is also an essentially manual operation, although some systems have a limited amount of automatic switching in the yards, principally to and from revenue tracks.

Car shops and maintenance facilities are usually located within the yard complex. The shops contain facilities for light and heavy maintenance, component repair, car washing, and checkout of vehicles before they are dispatched back into service,

The maintenance facility may also include a test track and special test equipment to qualify vehicles and components for acceptance or to carry out trials of equipment modifications.

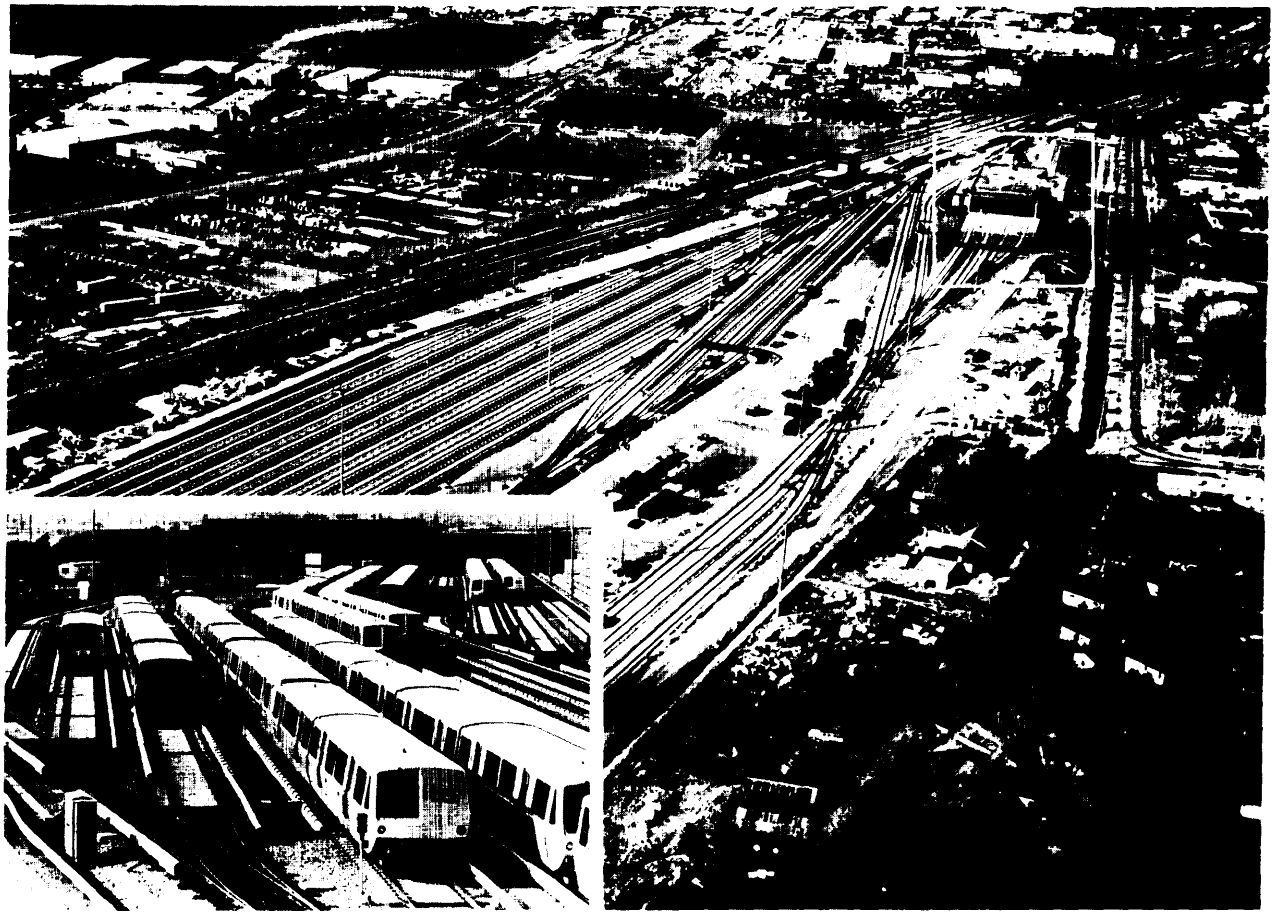

FIGURE 22.—Aerial View of Rail Rapid Transit Yard and Maintenance Facility

FIGURE 23.—Rail Rapid Transit Car Maintenance Shop

LEVELS OF AUTOMATION

It was suggested earlier that train control automation can be viewed as a continuum. At one extreme, all functions are performed by human operators; at the other, all are performed by machines. The transit systems now in operation or under development in this country lie at various points between these extremes, with their relative positions corresponding roughly to the age of the system. The older systems generally have the lowest levels of automation—primarily ATP with some ATS. The newer systems have ATP and ATO and more extensive ATS, None are completely automated.

Historically, the conversion from manual to automatic train control in rail rapid transit has been incremental and has followed a more or less common course for all systems. These major technological stops along the road to automation are outlined briefly below and summarized in table 1.

TABLE I.—Levels of Automation

LEVEL	CHARACTERISTICS	EXAMPLE
Essentially Manual	Train protection by rules and procedures Train operation manual (with or without the aid of advisory wayside signals) Train supervision by towermen and/or central dispatched	CTA (Ravenswood and Evanston Lines)
Wayside **Signal Protection**	Wayside block signals with trip stops for train separation and overspeed protection Train operation manual Supervision manual with some automation of dispatching and route interlocking	NYCTA
Carborne Train Protection	Cab signals and equipment-enforced train protection Train operation manual Supervision as above	CTA
Automatic Train Operation	Automatic Train Protection as above Train operation either completely automatic or with manual door operation and train starting Train supervision as above	PATCO
Automatic Train Supervision	ATP and ATO as above Train supervision automatic (or mostly so) under central computer control	BART
Unmanned Operation	ATP, ATO, ATS as above No on-board operator System manned only by small number of central control personnel	AIRTRANS
Full Automation	ATP, ATO, ATS as above, with automatic, not manual backups for each Skeleton force at central control Yard operation automated	None

Essentially Manual

At this level, train protection, operation, and supervision are carried out by train operators and towermen or central supervisors with little or no aid from automatic equipment. Trains are protected and operated either by rules and procedures alone or with the aid of advisory wayside signals. There are no automatic stop-enforcing mechanisms either on the wayside or on board the train. Train dispatching is carried out by personnel at terminals or at control towers along the routes, using either a written schedule or timing devices that act as prompters to signal train departure. Route assignment and interlocking control are accomplished by manually activated equipment that may have some automatic safety features but are entirely controlled by human operators. Communications are by means of visual signals (lights, hand signals, posted civil speeds, etc.) or by telephone from stations and towers to central control.

Many of the older transit systems in this country began operation at the manual level, but they have since advanced to more automated forms of train control. One of the last vestiges of a purely manual system is on the Ravenswood and Evanston lines of the Chicago Transit Authority, which as late as 1975 operated without any automatic block signal protection,

Wayside Train Protection

Wayside signals with trip stops form the basis for automatic train protection, by assuring separation of following trains and preventing conflicting moves at interlocking. Incorporation of timing devices with the trip stops also provides equipment-enforced overspeed prevention. While train protection thus becomes automatic, train operation is still completely manual. Train supervision also remains an essentially manual activity, although track circuits and signals used primarily for train protection do permit some automation of route interlocking and dispatching—usually in the form of semi-automatic devices (i. e., manually activated but automatically operating).

All transit systems in the United States have at least this level of automation. The most notable example of an entire system with enforced wayside signaling is the New York City Transit Authority. Portions of the Chicago, Boston, and Cleveland systems and all of the Philadelphia (SEPTA) system also employ this form of automatic train protection.

Carborne Train Protection

Cab signaling, using coded track circuits and automatic carborne stopping and speed limit enforcement, represents the same level of ATP as wayside signals with trip stops. To this extent, this level of automation is equivalent to the preceding. Generally, however, cab signaling is considered a higher level of automation since it also provides some automatic aids to train operation—principally automatic and continuous display of speed information to assist the operator in running the train and stopping at stations. Other aspects of train operation are still essentially manual. Cab signaling does not necessarily lead to any increase in the automation of supervisory function nor is it accompanied by any change in the communications systems.

This level and form of automation is generalIy regarded as the minimum for a new transit system, and most of the older transit systems either have converted or plan to convert to cab-signaled ATP.

Automatic Train Operation

The major advantage of cab signaling over wayside signaling is that bringing the speed command on board the train also permits evolution to automatic train operation. All of the information needed to operate the train automatically is either inherent in the cab signal system or readily available through modular additions. At this level, the human is removed from the speed control, station stopping, door control, or starting loops--or any combination of them. The human no longer functions as an operator but as an overseer of carborne control systems.

Along with ATO, there is often (but not necessarily) an increase in the level of automation of train supervisory functions. ATS functions that are sometimes considered operationally desirable to implement at the time ATO is installed include automatic dispatching, route assignment, and performance level modification.

The two newest transit systems in this country—Bay Area Rapid Transit and the Port Authority Transit Corporation—both have ATO. The new systems under development in Washington, Atlanta, and Baltimore will also have it.

Automatic Train Supervision

Train supervision functions (except for dispatching and route control) are among the last to be automated. To be effective and operationally practical, ATS usually can be introduced only when there is a high level of automation in the areas of ATP and ATO.[23] Automatic train supervision also requires a rather complex and sophisticated communication network, not only for voice messages but also for the interchange of large quantities of data among automatic system elements on a real-time basis. The distinguishing feature of ATS, however, is the use of a central computer (or computers) to process and handle data, make decisions, and formulate instructions.

The Bay Area Rapid Transit system was the first rail rapid transit system to make extensive use of ATS. The new Washington, Atlanta, and Baltimore systems will also have highly automated train supervision based on computer control. While there are some differences among them in the type and amount of control vested in ATS computers, these four stand apart from all other transit systems in this country in the extent to which automation technology is applied to train supervision.

Unmanned Operation

At all the levels of automation described previously, there is at least one operator on board each train and some supervisory personnel in central control. While these people are not part of the normal control loop, they do exercise important functions as overseers of automatic equipment and back-ups in case of failure or emergency; A more advanced form of automation is one where the trains are unmanned, with all ATP and ATO functions performed by automatic devices. The few remaining human operators in the system are at central control, but even these personnel may be reduced in number as more supervisory tasks are allocated to machines.

No rail rapid transit system in the United States, or anywhere in the world, is now operating at this level of automation. The technology to do this, however, is available; and it has been applied in various people-mover systems, such as the Morgantown Personnel Rapid Transit (PRT) and several airport transportation systems. A notable example of an unmanned airport transit system is AIRTRANS at the Dallas-Fort Worth Airport, where small unmanned transit vehicles circulate on fixed guideways over a complex of interconnecting routes. The entire system is operated and supervised from a central location by a few persons aided by a train control computer,

Full Automation

Complete removal of man from control of transit system operation-even removing him from the central control point—is probably not technically feasible or desirable, For safety and continuity of operation, it will always be necessary to have someone to monitor the system and intervene to restore operations or assist passengers in an emergency. The number of such supervisors would be only a handful, however, and it is doubtful that they could ever conduct normal operations manually as a backup to automatic systems.

Such a “fully automatic” transit would require an extremely sophisticated and costly ATC system, which would include ATP, ATO, and ATS for normal modes of operation and—most important—automatic back-ups of these mechanisms for contingencies and emergency states, The communication network would also have to be highly sophisticated, providing not only voluminous real-time interchange among automatic components but also extensive two-way voice links between passengers and the supervisory cadre. Another requirement of such a system would be automatic operation, switching, and assembly of trains in yards. The technology for automatic yard operation is available today in rudimentary form in automated freight classification yards, but it would need to be refined extensively before application to a rail rapid transit system,

[23] Even with ATP and ATO, ATS is not truly necessary until the demands imposed by the complexity of the route structure and the required level of service outstrip the capacity for effective real-time supervision by manual methods. ATS may also become necessary when the load in peak periods approaches 100 percent of system capacity.