to bus operations is especially important in front of bus terminals at LRT stations. These off-street locations have a large number of bus movements on and off major arterial roads, and traffic signals with bus priority measures will be used in some cases.

The Transit Control Center will have direct contact with the bus fleet. In the first stage of development, this monitoring and supervision will be based on voice communication. It will, therefore, be limited to the most logical locations, such as LRT-bus transfer stations. Radio communication will also be used to minimize disruptions in service caused by breakdowns or other incidents. Since there is a connection to the overall TMS, corrective measures can then be taken in areas not under the Transit Control Center's jurisdiction. More advanced monitoring and supervision options, including digital radio transmission of such data as bus location and passenger volumes, will be evaluated and may be incorporated into the system.

CONCLUSIONS

Introduction of LRT in Edmonton would have been difficult if costs had not been kept within a reasonable range. Keeping the costs down required a certain amount of compromise between minimum and maximum operational requirements. These trade-offs tax the management abilities of LRT. Its control system and the TMS together, however, provide sufficient tools to guarantee satisfactory standards of operational safety and the desired regularity of service, both of which are necessary for any transit operation. Moreover, by integrating transportation modes, this combined system offers several additional features that can improve the overall transit performance in northeast Edmonton. The design of the system and the negotiations leading to integration of its individual portions were not easy. It appears at this stage, however, that operational problems have been effectively solved because of the streetcarlike features of LRT and the flexibility of the TMS.

The TMS provides an opportunity to closely monitor the operation of all components of the LRT line. The data supplied by the system will be evaluated and assessed regularly. Operating experience will be the base for making adjustments to the system and to the design of future phases of both LRT and TMS.

Since the accepted transportation philosophy in Edmonton concentrates on full utilization of available facilities before new ones are built, the control of transportation operations will become even more important as new LRT lines are introduced. It is realized, of course, that in the future more complex and in some cases more capital-intensive solutions may be required. Notwithstanding the introduction of more complex methods and technology, it is a certainty that the effective management of transportation resources will be the key to resolving Edmonton's urban transportation problems.

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Light-Rail Transit Signaling

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This paper presents considerations regarding conventional signal systems that should be helpful to people planning a light-rail system. Attention is first directed to establishing the need for a signal system, including a discussion of its advantages and disadvantages on the basis of the technical, operational, economic, labor, and regulatory elements involved. A definition of conventional signal systems is provided, and the various types of systems are explained on the basis of their capabilities. Safety and failure modes are addressed as the key issues in any signal-system design. To illustrate the importance of all these factors, a comprehensive description of the new San Francisco Municipal Railway's subway signal system is presented, and conclusions are then drawn as to the general design concepts required for other future light-rail systems.

Any transit planner, regardless of his or her particular area of interest, is confronted by many questions in considering light-rail transit (LRT): Is a signal system necessary? If so, what type of signal system will meet the need? What kind of equipment should the signal system employ? What systems are available, and what are their relative merits? This paper will address these questions.

Whether to install a signal system on an LRT facility is a very important issue and involves a trade-off between economy on one hand and safety and efficiency on the other hand. A signal system adds to the initial cost of a facility, increases maintenance expense, and presents operational and administrative problems. From the standpoints of both safety and uninterrupted service, a poorly maintained signal system is worse than no signal system, and a competent maintenance force must be recruited, trained, and maintained by the operating authority. In the case of small signal systems, it is necessary to train and keep a larger force of people familiar with the signal system than is actually necessary to carry the work load; qualified people will thus be available at all times and the force will not be completely depleted by resignations, retirements, sickness, vacations, and so on. Ordinarily, training is part of the construction contract, and the original trainees train others as vacancies occur and are filled. Every signal system must have its set of operating rules to govern employees, both the car operators and others. The employees must be capable of understanding the rules and be willing to abide by them; this fact may force a change in hiring practices and involve special measures to enforce compliance with the rules. It may even involve changes in labor contracts to permit the discharge of employees who violate the operating rules.

In contrast to the expense and complications involved in a signal system are the disadvantages of operating without one. Without a signal system, full responsibility for safety rests with the car operators and their reactions to what they can see by looking ahead. Consequently, operators must limit their speed to a rate from which they can bring their cars to a stop within their range of vision. When topography or weather conditions create short sight lines, very low speeds result. Running times are also increased if cars must slow down or stop for drivers to operate track switches. For these reasons, a facility that lacks a signal system has less capacity, less operating flexibility, and probably less safety.

If, in spite of the costs and complications, it is necessary to install a signal system, a compromise must be reached between economy on one hand and, on the other hand, the need to ensure safety, attain the full potential efficiency of light-rail vehicles (LRVs), and meet both the requirements of legal responsibility and the pressures of public opinion. At this time, as in the past, the most attractive compromise is to select one of the several variations of conventional signal systems that have been in service for many years on the nation's long-haul railroads and metropolitan heavy-rail transit (HRT) facilities. The alternative choice is to assume the expense of experimenting with a newly conceived system and run the risk of operating with a patched-up one-of-a-kind system. A review of the reports presented at the 1975 Light Rail Transit Conference reveals that many of the speakers felt that the acceptance of LRT depends to a great extent on (a) keeping the costs down and (b) the development of new systems through accelerated research. Excessive cost may very well block a proposed LRT project, and there is no need to burden a project with expenditures for signal research. There are suitable systems proven in extended service immediately available that can be adapted to meet the features and operational requirements of any proposed LRT facility. These proven systems employ relay logic extensively, whereas other systems make much more use of either hard-wired, solid-state logic or computer logic and have had much shorter demonstration periods. Relay logic has some important advantages:

1. It is largely free of the bad effects of electrical transients.
2. It is easily understood, the operation can be readily determined from a circuit plan, and the operation of the component relays can be observed visually.
3. Only a few simple instruments are required to maintain relay logic and correct faults.
4. The components are rugged and, to a very great extent, free of deterioration from aging, humidity, heat, and so on.
5. Relay logic is not finely tuned; very few adjustments are necessary.

CONVENTIONAL SIGNAL SYSTEMS

1. Automatic block signal system: The track is divided into sections (blocks), and a trackside signal is located at the entrance to each block. These signals convey information to car operators concerning the presence or absence of cars in one or more (usually two) of the blocks immediately ahead. Safety depends on whether the signal system operates as intended and on whether the operators remain alert, observe the signals, and control their cars in accordance with the information conveyed by the signals. This system can be employed for two-direction operation on the same track, in which case signals are provided at each end of each block. This system does not require any car-borne signal equipment.
2. Automatic block signal system with train stop: This system reduces the degree of responsibility vested in the car operators. HRT systems generally use mechanical trip-stop arrangements in which a trackside device engages a lever on a car that passes a STOP signal and causes the brakes to be applied. Another version that has been employed by long-haul railroads consists of an electrical trackside device that inductively couples with a car-carried device and applies the brakes unless the operator manually acknowledges each restrictive signal as he or she passes it. Automatic train stop greatly reduces the hazard of an incapacitated or inattentive operator. This system requires only a moderate amount of additional car-borne equipment.
3. Cab signal system: Signals in the car operator's control cab can supplement or take the place of trackside signals and provide the car operators with signals that are not only clearly visible in all weather conditions but are also in view continuously. Cab signals advise car operators of changed conditions ahead (whether better or worse) as they occur; this enables the operator to increase or decrease speed immediately, that is, without waiting for the next trackside signal to come into view. Most cab signal systems require the car operator to manually acknowledge a restrictive cab signal indication to prevent a brake application. This also reduces the hazard of an incapacitated or inattentive operator.
4. Cab signal system with automatic speed control: This system requires the operator to take steps immediately to reduce the speed of the car when the cab signal calls for a speed lower than that at which the car is currently traveling. If this is not done, the brakes will be applied and cannot then be released until the car comes to a stop. A limit to the highest speed permitted is also imposed.
5. Automatic train operation system: This system leaves the car operator little to do except watch the operation and take control of the car in an emergency. In some but not all installations, the operators control the doors or depress a button to start a car in motion. In a fully automated system, the speed of the train is automatically controlled in accordance with conditions ahead, and the cars stop in their proper berths at stations automatically.

Highway grade-crossing protection consists of flashing lights that warn highway traffic of approaching rail vehicles. In many cases the flashing lights are augmented by crossing gates, which provide a physical barrier to highway traffic on both sides of the tracks. Highway crossing protection is usually controlled automatically by approaching trains, but manual control may be provided either as the primary control or as a supplement to automatic control. The automatic control can effectively take care of special situations, such as avoiding delay to highway traffic when a rail car makes a station stop near a highway crossing. The train-detection system employed in conventional signal systems can be used to preempt street traffic lights either independently or in a way that coordinates the operation of street traffic lights with the operation of highway grade-crossing protection gates and flashing lights.

Interlockings are power-operated track switches protected by trackside signals whose controls of switches and signals are interlocked so that the signals cannot be displayed to authorize car movements unless the switches are properly set and so that switches cannot be operated while PROCEED signals are displayed. Interlockings can be controlled manually from local control panels, remote control panels, or push buttons located at the signals, or they can be controlled automatically by ap-

proaching cars. Conventional interlockings may have two different sections—one that is not involved with safety and one that is. The generation and transmission of commands from a central (remote) control panel, a local control panel, or an automatic route-selection or dispatching arrangement are not safety functions and, while failure of the equipment that performs these functions may interrupt service, such failures will not affect safety. Therefore, cheaper relays, multiplex techniques, and other techniques in which failure modes are unpredictable can be used. The section that executes the commands, however, is very much concerned with safety, and that section, as well as the automatic block system between interlockings, must be designed with safety as the prime consideration.

FAILURE MODES

Failure modes are an important consideration in securing safety. Most devices have two or more failure modes, and some devices can be designed to have one failure mode that occurs extremely infrequently. For instance, when it is operating normally, a relay has its prime contacts closed when its coil is energized and its prime contacts open when its coil is deenergized. Therefore, this relay has two failure modes: the prime contacts may be open when they should be closed, or they may be closed when they should be open. By designing the relay so that the prime contacts are opened by gravity (plus spring bias in some relays) and carefully avoiding anything that would impede the movement of the contacts, one failure mode (prime contacts closed when they should be open) has been rendered highly unlikely at the expense of the other failure mode. It then remains to design the circuit that supplies power to the relay coil so that there is little chance of the relay coil being energized when circumstances require that vehicle movements be restricted and to arrange the circuits controlled by the relay so that restrictions will be imposed when the prime contacts of the relay are open and removed when they are closed. The relay provides a simple example of a device that has one failure mode that is extremely rare and shows how this fact can be used to advantage in relay logic. Some electronic devices can be designed to have one very rare failure mode, but this is more difficult to achieve.

The safety sections of either a simple or a complex conventional signal system are created by assembling proven components and proven methods into a system that is adapted to fit the physical features and operating requirements of a particular facility. The failure modes of all the components must be predictable, and the circuitry must be such that the more frequent failure modes do not affect safety. This has led some people to refer to the conventional signal system as a fail-safe system. This is unfortunate, however, because no system can be entirely free from unsafe failures, and the proponents of recently conceived substitute systems often denigrate the fail-safe (conventional) system on the basis that it is obviously not 100 percent fail-safe. The conventional signal system is really a highly acceptable compromise between economy and safety that has been developed and improved through decades of extensive use. It is now the standard of safety and reliability by which all proposed substitute systems must be judged. It is interesting to note that the evolution that has made conventional signal-system components extremely safe has, coincidentally, made them very reliable.

If a conventional signal system includes some type of remote or centralized control of interlockings, the link between the control console and the interlockings may employ electronic devices, and the maintenance of this link may require the services of an electronic technician. On the other hand, the safety portion of a conventional signal system does not require the services of this type of technician. A person needs only a slight familiarity with the elements of electricity and a little patience to understand the relay logic and the rather simple components used in conventional signal systems. While the circuitry for a large interlocking can be very intricate, there are no truth tables, no formulas, no equations, and no complex theories involved. Even the circuit plans by which the approved components are assembled into a system can be prepared by people who have no other specialized training, provided they are familiar with the standard principles and practices of conventional signaling, which are nothing more than the lessons learned through decades of experience.

ADVANTAGES AND DISADVANTAGES

The advantages of a conventional signal system include the following.

1. It has all the advantages of relay logic mentioned above except, of course, in those portions where relay logic is not used.
2. If the electronic components included in the system can be considered black boxes that have specific outputs corresponding to specific inputs and represented on the circuit plans as empty squares, then the design is relatively straightforward, and the operation can be easily understood by people without training in electronics or other specialized fields.
3. The standard components of conventional signal systems have been perfected by long use, and the suppliers have continued to supply replacement components and repair parts for long periods.
4. The components are small and easily rearranged in different configurations when this is necessary to adjust the signal system to altered operational features, an increase in patronage, or an enlarged service area.
5. The components are distributed over the facility; that is, there is no large component or large concentration of components in which trouble will shut down or endanger the entire facility. The things that provide safety are located in the area they protect and transmission problems are largely avoided by keeping communication lines short.
6. Long experience has developed a fine balance between economy and safety in regard to details of how standard components are combined into a system to fit a particular facility.
7. Long experience has produced an accurate understanding of how much preventive maintenance is required to keep a conventional signal system operating safely.

There are some problems connected with conventional signal systems, including the following.

1. Most knowledgeable engineers, technicians, and mechanics are employed by signal-supply companies, railroads, or HRT systems in which they have learned the business from their predecessors. It is therefore difficult to recruit experienced people.
2. There are very few contracting firms that have signal experience.
3. Signaling appears so simple from the outside, like street traffic signals, that firms looking for jobs or anxious to diversify may enter into signal contracts they are ill fitted to carry out.
4. All signal work (design, installation, and maintenance) requires painstaking adherence to accepted principles and practices, but not everyone has the needed patience.

5. There is very little literature available on this subject. The signal-supply companies publish information regarding their products and the Communication and Signal Section of the Association of American Railroads has published considerable material, but none of this material is of much use to a person who does not already have a grounding in signaling.

6. The railroad industry has never recognized a need to compile statistics on railroad signal-system performance.

The fixed portion of a signal system for an LRT facility, either single or double track, should not cost more than $187 500/route km ($300 000/route mile), including impedance bonds, power supply, and all other signal costs, except system-length conduit runs or duct lines. Car-borne cab signal equipment may cost $10 000/car; automatic speed control may cost $1500/car. These are very rough average figures, and they are quoted here only to present a very general idea of signal costs, which are affected by many variables, including the fact that unit costs are higher for small quantities than for larger quantities.

SAN FRANCISCO'S SIGNAL SYSTEM

A conventional signal system is now being installed on the Market Street underground portion of the San Francisco Municipal Railway (Muni). It will include cab signals, automatic speed control, and five small interlockings. There will be no trackside signals except at the interlockings. It will be a double-track system in which both tracks are signaled for movements in both directions, but cars will normally move on the right-hand track only, and the interlocking signals will clear automatically for all normal car movements including normal turnback movements. At two locations where it is necessary to determine the identity of cars in order to set up the correct interlocking route automatically, that information will be fed to the signal system by an independent and separate destination-sign system to be described later. If the interlocking route automatically selected is not the correct route, the operator of a car may stop the car at the interlocking signal and correct the route selection by reaching through the window of the cab and depressing trackside push buttons.

At the downtown terminal the tracks are stub ended. Arriving inbound cars will be automatically routed to whichever station track is vacant or, if both are vacant, to the left-hand track as viewed from the front of inbound cars. Outbound cars beginning their outbound trip will be routed to the normal outbound (right-hand) track automatically after the operator has indicated his or her readiness to depart by reaching through the cab window and depressing a trackside push button. There are two portals; one that is 8.8 km (5.5 miles) from the downtown terminal is used by three surface lines. Two turnouts in the main tracks about 4 km (2.5 miles) from the downtown terminal lead to the other portal, which is used by two other surface lines. Cars being placed in service or being taken out of service will move directly from one portal to the other without traveling to the downtown terminal. These cars will stop, reverse their direction and cross over at an interlocking approximately 3.2 km (2 miles) from the downtown terminal. Such movements are considered normal; that is, the track switches will be positioned and the signals cleared automatically in advance of each movement.

Each interlocking is provided with a local control panel in the local relay room. The interlocking at the downtown terminal has an additional control panel located on the station platform. None of these control panels will be staffed in normal circumstances, but they provide the means for changing over from automatic to manual control at will. In addition, there will be at each interlocking signal a set of push buttons that can be actuated by the operator of a car stopped at the signal. By reaching through the window of the cab, the operator can select any one of the several routes available to that car or cancel a previous route selection. It will not be necessary to make use of these push buttons in normal circumstances.

The cab signals display three aspects: 10 MPH [16 km/h], 27 MPH [43 km/h], and 50 MPH [80 km/h]; the automatic speed control enforces these speeds by requiring positive action by the operator to avoid a penalty stop when the actual speed exceeds the speed indicated by the cab signal by more than 3.2 km/h (2 mph). The cab signals are cut in automatically on all cars of a train when that train enters a portal and cut out automatically when a train leaves a portal. The automatic speed control enforces a top speed limit of 80 km/h—actually 83 km/h (52 mph)—regardless of whether the cab signals are cut in or cut out. The cab signals or the automatic speed control can be cut in or cut out manually by breaking a seal and operating a switch in the electric locker.

Interlocking signals will display stop aspects and aspects authorizing a car to proceed in accordance with cab signal indication. The operator of a car that does not have cab signals or whose cab signals are out of order and stopped at an interlocking signal will be able to change a "proceed in accordance with cab signal indication" aspect to a "track clear to next signal" aspect (when conditions permit) by reaching through the cab window and depressing a push button. All PROCEED aspects will include information concerning whether the interlocking route is straight.

The Muni signal system will include electronic amplifiers and demodulators on the cars and electronic demodulators as part of the train-detection system, but it is primarily a relay logic system.

A central computer will track the cars and control the display of destination signs at each of the nine stations. The operator of each signal car or the operator of the lead car of each train will be required to describe his or her car or train before entering a portal and before beginning an outbound trip. This will be done by means of input devices connected to the computer that can be reached from the cab. As indicated above, the destination-sign system will feed train-identity information to the signal system at two locations; otherwise, the signal and destination-sign systems are entirely independent.

The selection of the system being installed was dictated by cost considerations and current patronage, and it is expected that this system will suffice for many years. However, if conditions change, the system can readily be upgraded as needed without any major loss of the original capital investment. For example, centralized control can be conveniently added, and an automatic car-identification arrangement can be easily substituted for the present manual computer inputs. In fact, the wayside and car-carried equipment could be augmented to provide full automatic train operation in the subway if that becomes desirable.

OBJECTIONS TO CONVENTIONAL SYSTEMS

Proponents of actual or proposed systems to supersede conventional signal systems often advance objections to the conventional systems, including the following.

1. Relay logic is old-fashioned and out of date, and

relays require more space and consume more power than electronic devices.

This is true. There is nothing new or novel about relay logic, and relays do require more space and use more power than electronic devices. However, the space and power requirements of relays are not large, and the savings that can be made by substituting electronic devices is therefore limited.

2. Conventional signal systems are designed to stop vehicles when component failure occurs.

This is true, but it is entirely justified by the alternatives. No matter how serious an interruption to service may be, allowing a car to proceed when it may not be safe for it to proceed is more serious. If a component failure must cause neither a false PROCEED signal nor a stop, then redundant systems must be provided. As will be explained later, redundant systems are very expensive.

3. Conventional signal systems depend on appropriate human performance for safety.

As was explained in the descriptions of the various forms of conventional signal systems, the cheaper forms depend on appropriate human performance to a greater degree than do the more sophisticated forms. Thus, a reduction in dependence on human performance entails increased cost, and the complete elimination of vulnerability to human error entails very great cost. A typical cab signal and automatic speed control system requires dependence on the car operator in two situations. When it is approaching another car or a stop-interlocking signal, a car is automatically restricted to a low speed, such as 16 km/h (10 mph), but the operator is responsible for bringing the car to a stop. When a car is stopped by the failure of a signal, the car operator may obtain oral permission to override or cut out the devices that prevent the car from moving and then operate the car with no restrictions other than the usual operating rules. To eliminate the dependence on operators to bring a car to a stop after its speed has been reduced automatically but still permit closing up in stations and other areas, it is necessary to establish very short blocks and to control the speed of cars in very small increments. Although this can be done, the cost is high. To eliminate standby manual operation as a means of moving cars after a component in a signal system has failed, it is necessary to provide standby or redundant signal and automatic speed control systems to prevent a component failure from bringing operations to a stop. In this connection, it is important to note that simple duplication does not suffice. When duplicate systems produce conflicting outputs, e.g., GO from one and STOP from the other, it is difficult to determine which system is in error; a minimum of three redundant systems is thus required to minimize delays resulting from failures in a system that does not have standby manual operation. The cost of a signal system that neither requires nor permits human intervention would be prohibitive for any but the most highly congested facility.

Most proposed replacements for conventional signal systems are electronic—either hard-wired solid-state or digital computer systems. It is claimed that simple hard-wired solid-state devices like those currently employed in the safety portion of conventional signal systems can be designed to have predictable failure modes. However, systems able to handle more complicated logic can be made safe only by resorting to redundancy, closed-loop arrangements, or other expensive techniques. These techniques increase both the cost and the number of components that may fail. Designers of electronic signal systems must guard against the temptation to compromise safety in order to keep costs down and the temptation to avoid the increased exposure to component failure in redundant systems by accepting a GO from either system instead of requiring a GO from both systems before permitting a car movement.

The first application of electronics to the safety portion of a signal system took place in 1923 in connection with the original cab signal system. Since that time, electronics has been used extensively in the nonsafety portions of conventional signal systems, and there has been a limited use of electronics in the safety portions: amplifiers and decoders in car-borne cab signal equipment, decoders with coded track circuits, high-frequency track circuits, overlay track circuits, motion detectors, and so on. More general use of electronics in signal systems has been retarded by the difficulties and the expense involved in producing electronic devices or systems that have predictable failure modes. Safe and reliable electronic signal systems will be available eventually, but they will be available first in a form more suited to HRT than to LRT. This is because their high cost will be justified only by the demands of highly patronized and highly congested systems in which the need for full automation, high speeds, small headways, no interruptions, automatic dispatching, automatic adjustment of schedules when trains fall behind schedule, and so on is urgent. At the present time, the electronic devices used in the safety portion of conventional signal systems are used principally to drive relays, the contacts of which are then used in the conventional relay logic.

CONCLUSION

In this paper I have tried to present some facts and ideas about signal systems that will be helpful to people planning an LRT facility. Most important among these are that a signal system should not be installed unless its proper maintenance is assured and that the distinction between the section of the signal system that is not involved with safety and the section that is so involved should not be overlooked. Safety must be the prime consideration, and it must not be entrusted to unproven equipment or methods. If for some reason an exotic arrangement for generating and transmitting commands must be installed, it should be ensured that the commands will be executed by a time-proven system of the type generally referred to as fail-safe. The type and form of the signal system selected should be those that are best suited to the needs of the facility; the temptation to be ultramodern or to build a showpiece should be resisted.