build a grade separation for LRT. On the other hand, it requires a lot of imagination to build and operate a fast, efficient, safe, and inexpensive at-grade LRT system. To achieve optimum operation a community must be willing to sacrifice some of the conveniences of the automobile for the benefit of LRT. Most importantly, the various jurisdictions governing transportation, such as transit planning, operations, design, traffic engineering, and police, must work together in designing, operating, and maintaining the traffic-control system for an at-grade LRT system.

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Control of Light-Rail Transit Operations in Edmonton

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The first line of Edmonton's light-rail transit (LRT) system is currently being completed. The underground portion of the line in the downtown area connects to a surface portion that shares its corridor with a major railway line. Interactions between the railway, LRT, and other transportation modes have created problems in the areas of safety, roadway capacity, and regularity of service. This paper describes the approach taken in Edmonton to overcome these problems. The new transportation management system, which is in its initial stages of implementation, is a major tool in minimizing the negative impacts of LRT. The system focuses on the establishment of LRT controls that, in addition to the categoric requirements of safety, must guarantee optimum use of the LRT tunnel, which in turn depends greatly on the regularity of service on surface portions of the LRT line, and integration with other transportation modes in terms of safety, coordination of scheduling between LRT and buses, and minimization of disruption to all modes at the nine grade crossings. In general, the flexibility of LRT operations and the implementation of an integrated transportation management system has enabled cost-effective solutions to be developed.

In 1974, the city of Edmonton formally adopted a transportation philosophy that had as a basic objective an increased reliance on public transportation and the development of techniques to use more fully the capacity of the existing transportation network. This led to the development of a new transit concept plan for Edmonton and the development of a transportation management system (TMS).

The transit concept relies on the new light-rail transit (LRT) system and a restructured bus system for provision of improved public transit service. The TMS will integrate the management of all transportation resources of the city and will use advanced surveillance and monitoring techniques to provide better utilization of the transportation infrastructure. Both systems are now in a first stage of implementation. The implementation of the Northeast LRT line provided the first opportunity to apply some of the TMS features to a real-life situation.

PUBLIC TRANSIT IN EDMONTON

Public transit in Edmonton is an important component of the urban transportation system. It carries about 20 percent of all daily work trips and about 35 percent of the peak-period trips to the central area of Edmonton. During the past 15 years the proportion of central-area trips made by transit has been increasing steadily. A second major function of the transit system is the provision of transportation services for people who cannot use an automobile for travel.

An overall public transit plan for Edmonton is set out conceptually in Part 1 of the city's Transportation Plan (1). Figure 1 illustrates the general pattern of transit service proposed in this plan. A main feature of this concept is the development of transit centers in the outlying sectors of the city. Local feeder-bus routes serving the surrounding areas meet at the transit centers, and then most routes continue to the downtown area. This plan provides direct service to the downtown area, and passenger transfers between different bus routes are provided at the transit centers; this permits reasonably direct trips between outlying origins and destinations.

In the northeast sector of the city, the first LRT line is now in the last stage of construction. This facility will provide a high-capacity transit line to the downtown. The three outlying stations will serve as transit centers for LRT, buses, and private vehicles (Figure 2). At these transit centers, off-street bus stations and parking areas will be provided, along with pedestrian connections to the station. An example of a typical outlying station is shown in Figure 3. These stations will also offer transit services during special events along the corridor. Near the middle of the Northeast Line, a new stadium with a capacity of 40 000 is being built for the 1978 Commonwealth Games. Further to the northeast, the Edmonton Coliseum attracts regular audiences of more than 15 000 people. Finally, in the same neighborhood, the Northlands horse-racing track and Edmonton Exhibition Grounds draw very large daily crowds during major events, such as Klondike Days. Since all of these facilities are in developed areas, parking space is limited.

The other two stations on the Northeast Line are in the downtown area. One of these stations is a through station; the other will serve as a temporary terminus until the line is extended through the downtown.

The line is 7.2 km long; about 1.6 km are in the downtown tunnel, and 5.6 km are at grade along the Canadian National Railways (CNR) right-of-way. While this corridor provided a readily available route for LRT, it re-

quired addressing specific problems related to operational aspects of LRT and other modes, as will be discussed later. The table below examines the daily work-trip travel demand in the northeast corridor.

	1971		1981	
Mode	Number	Percent	Number	Percent
Automobile	8 656	59	10 380	55
Transit	3 860	26	5 705	31
Other	2 035	15	2 607	14
Total	14 551		18 692	

The typical travel demand for a special event at the new stadium in 1978 is expected to be handled as follows:

Mode	Number	Percent
Park-and-ride	25 000	68
LRT	4 500	12
Private automobile	3 000	8
Chartered bus	2 500	7
Other	2 000	6

A more detailed description of Edmonton's LRT system is presented by MacDonald and Bakker elsewhere in this Report.

Figure 1. Principal features of the Edmonton transit plan.

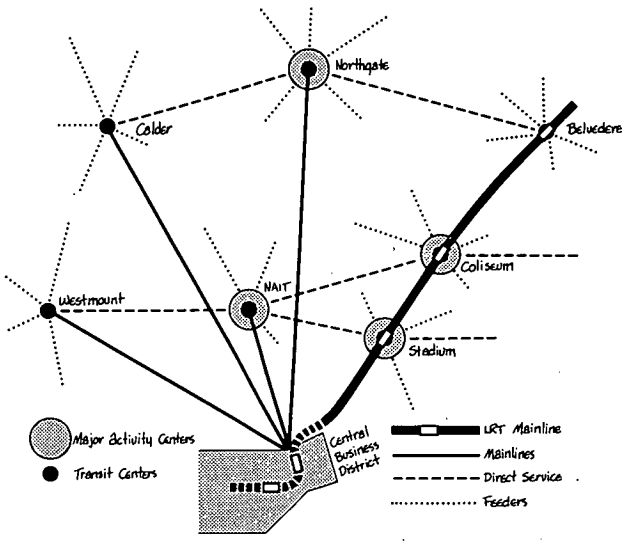
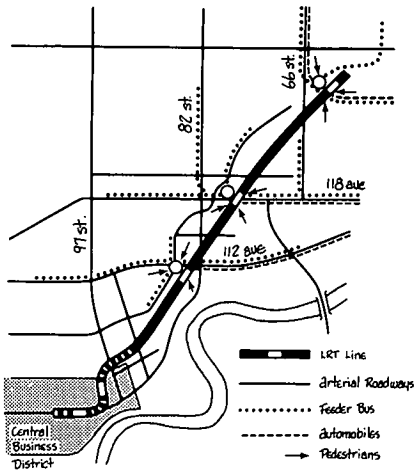


Figure 2. Interactions among transportation modes in northeast Edmonton.



TRANSPORTATION MANAGEMENT SYSTEM

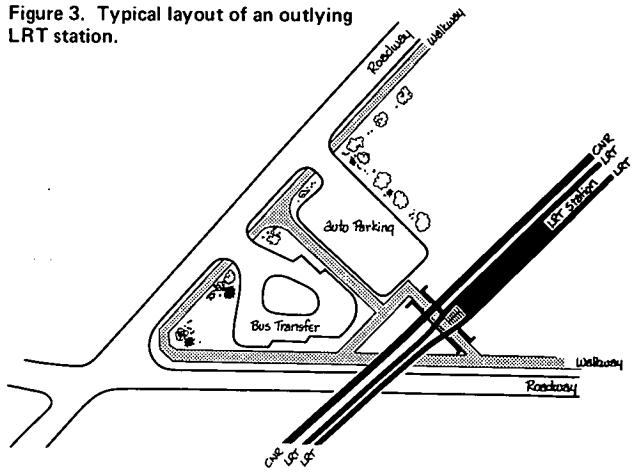
In 1977 the city of Edmonton completed a study that detailed a 10-year implementation plan for a TMS (2). This study encompassed all city agencies involved in the provision of transportation services. The study's objective was to identify measures that were available to maintain and to improve the operation of the transportation infrastructure. The objectives of individual agencies were identified and used as the basis for the definition of the overall system requirements. Improved services, dissemination of public information, and a better data base for planning and management purposes were the main TMS objectives related to the transit system. The major goals of the traffic operations group are increased safety, maintenance of acceptable levels of service in the downtown, and increased network efficiency. The police, on the other hand, are concerned with surveillance of various areas, control of special or emergency events, and the ability to monitor signal performance. The remaining goals were related to the activities of the fire department and to the maintenance and planning bodies.

Formulation of goals provided the basis for definition of the functional attributes of the system. The study identified a number of system characteristics related to transit, such as ability to integrate traffic and transit strategies and tactics, ability to accommodate both repetitive and unpredictable events, ability to monitor and analyze network performance in real time, ability to maintain a management and planning data base, ability to communicate with and supervise transit units in service, and rapid provision of information on performance of networks to both the system management group and the general public.

The various agencies connected with the Transportation Management Center agreed to place it under the control of the City Traffic Engineer. The center will perform two vital functions. One will be the provision of overall control of the street network operation of all transportation modes falling within its jurisdiction. The other will be the provision of information exchange mechanisms and integrating mechanisms between participating agencies, schematically illustrated in Figure 4. The system will use advanced computing technology and a communication network. Although the use of complex hardware is required, the system still relies heavily on human involvement.

Implementation of the system will occur in two phases, the basic and the advanced. In principle, both phases use identical measures, but they differ in the extent of

Figure 3. Typical layout of an outlying LRT station.



their features in terms of complexity and geographic application. Major elements of the system are shown in Figure 5.

LRT AND TRANSPORTATION MANAGEMENT

The operation of the LRT system will resemble in part a subway operation and in part a modernized streetcar system; it will have both grade-separated and surface sections. The trains (up to four cars) will be operated by one motorman who will maintain the schedule by consulting an instruction board similar to that used by the bus fleet. The vehicle chosen is a six-axle, two-section articulated double-ended light-rail vehicle (LRV) manufactured by Duwag. It is 24.3 m long, 2.7 m wide, and 3.3 m high. It weighs 31 Mg and has adhesion of 23 Mg. Its capacity is 64 seated and 97 standing (4 passengers/m^2). It has an electronically controlled motor-driven camshaft controller. The system will operate on 1.435-m (standard gauge) track at a maximum speed of 80 km/h and an average speed of 20 km/h; the rate of acceleration is 1 m/s^2 and that of deceleration, using dynamic braking, is 1.3 m/s^2. The minimum turning radius is 35 m for loaded cars and 25 m for empty cars.

The performance of the system depends greatly on the optimum use of the tunnel portion, which in turn depends on the regularity of headways on surface portions.

Figure 4. Concept of Edmonton's transportation management system.

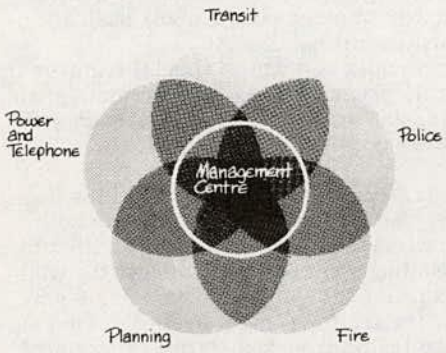
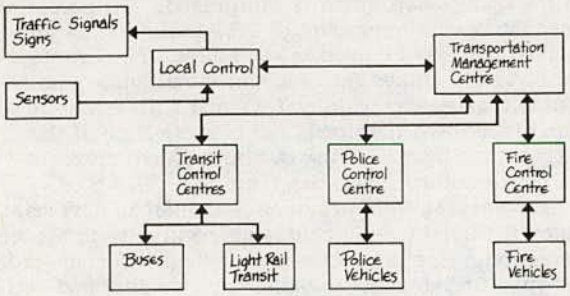


Figure 5. Elements of the transportation management system.



Since in the future the tunnel portion will become a trunk line for more surface lines, any disturbance of service on the surface may result in a complete disruption of the system. For that reason, great emphasis was placed on system controls. The control functions will be centralized; computing facilities and personnel will be located in the city's Transit Control Center, which will be an integral part of the TMS.

For control purposes the LRT line is divided into six blocks whose average length is 1 km. Each block includes one station. A red or green wayside signal advises the motorman of the occupancy of the block ahead. At the beginning of each block there is an overlay circuit approximately 230 m long, a distance sufficient for safe train stopping. The operation of the block system is illustrated in Figure 6. For a train at station C, signal C remains red until the train ahead clears the overlay circuit of block B. At this point, signal C turns green, permitting the train to proceed to station B. As this train enters block C, signal C returns to its red aspect. In this way, the minimum possible separation between successive trains is the length of the overlay circuit. Normally, however, since a train would not stop just beyond the overlay circuit, the separation of trains would be much longer. Any violation of a red signal will trigger automatic braking of the train to a complete stop. This is an additional safety feature that ensures a stop in the event that a motorman ignores a signal.

At the downtown end of the line, single-track operation for reversing the trains has been temporarily adopted. A train is permitted to enter only if this track portion is clear. Initially, only one direction of travel is automated. When the system is expanded, crossover maneuvers in both directions will be under computer control. The outlying end of the line will maintain a single-crossover movement from northbound to southbound track only.

A special problem was encountered near the middle of the line, where LRT trains entering the line from the maintenance yard or heading into the yard have to cross the parallel CNR line. This maneuver is facilitated by a diamond crossover that will have fully interlocked switches on the LRT tracks. Crossing maneuvers will require detection of an LRV entering or leaving the depot by means of a catenary sensor. If the railway tracks are clear, CNR signals will display red, switches will be set and locked, and LRT signals will turn to green. After the LRT train has left the conflict area, all signals and switches will be automatically reset to allow normal railway operation again.

LRT red and green signals will also be used in front of the nine at-grade crossings of roadways (3). These signals will ordinarily display red and will change to green only after an LRT train activates a demand for road closure and the gates have started their closing action. The gates will lift immediately after the train leaves the conflict area. If the gates fail to operate, the signal will remain red. Should the motorman fail to obey the red signal, automatic braking will be initiated so that the train will be stopped in front of the grade crossing.

The instruction board, supplemented by wayside signals, would not suffice under unusual circumstances.

Figure 6. Operation of the LRT block system.

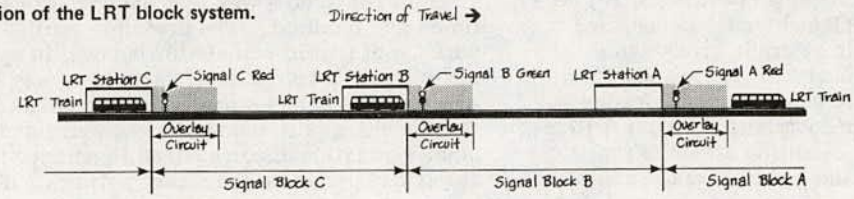


Figure 7. Typical peak-hour conditions at one of the at-grade crossings.

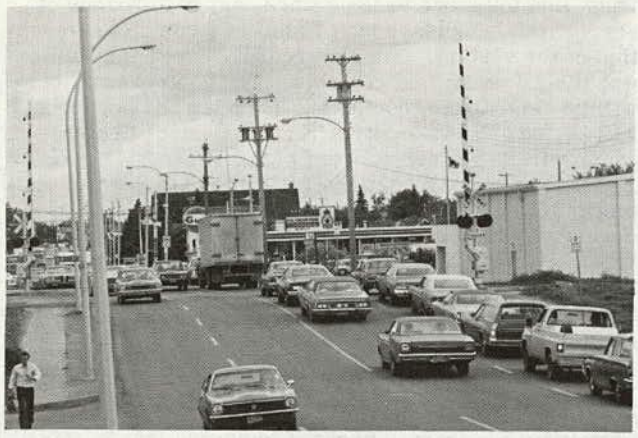
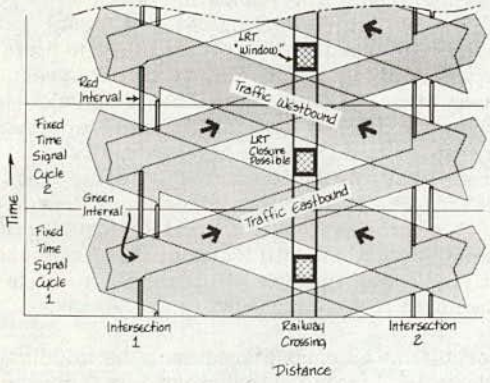


Figure 8. Time-space diagram of the LRT window principle of traffic signal coordination.



For special conditions, such as difficulties in maintaining schedules, breakdowns, or crossing of the railway main line, two-way radio communication between the motorman and the central control will be used. For track maintenance or train emergencies, a system of wayside telephones can also be used if these measures prove to be insufficient. A digital data communication system can easily be incorporated as an integral part of the system if it is required in the future. All stations will be equipped with closed-circuit television cameras, both for communication and for security purposes; the transmissions will go to the Transit Control Center.

Another option that will be evaluated after some experience with the system is the application of either wayside or in-cab speed signals. They may be especially useful in the control of train arrivals at grade crossings.

INTEGRATION WITH OTHER MODES

Three major concerns were identified with respect to interaction between LRT and other modes of transportation: (a) safety of grade-crossing operations, (b) regularity of service of both LRT and feeder buses, and (c) minimum disruption to traffic at grade crossings.

In addition to LRT trains and CNR trains, the grade crossings are used by private vehicles, LRT feeder buses, express buses, and pedestrians. Figure 7 illustrates the typical peak-hour condition at one of the crossings. Concerns about the safety of operation of grade crossings that carry 15 000 to 30 000 vehicles/d were determining factors in the selection of protection devices and their timing (to allow one LRT train to pass, the gates have to be closed for about 40 s). One solution to all of these problems would have been the construction of structural grade separations; these would have cost $3 million to $4 million each and required 2 years of construction time. A more cost-effective solution, in the short term at least, has been found in the development of integrated controls for LRT and other modes of transportation (3). In order to implement such a scheme, three major principles for the design of grade-crossing controls were adopted.

1. The first principle was coordination of traffic signals so that extensive queuing of vehicles across the railway crossing would be eliminated. This is achieved by controlling the capacity of upstream road signals that feed this link and reducing the queuing in front of the downstream intersections to an acceptable length. Subsequently arriving vehicles can then move through the downstream intersection without stops. This measure reduces the number of stops and delays in the system. In most cases, vehicles will be stopped only on the approaches to the upstream intersection and will move through the system in a green wave.
2. The second principle was integration of the operation of traffic signals with LRT controls. The objective was to use the periods of time provided by the shadow of the red signals at adjacent intersections for LRT crossings of the road link (Figure 8). Ideally, the time provided by this window should exceed the closure timing required for the crossing. This is difficult to achieve because of the number of other constraints, such as LRT scheduling and operation.
3. The third principle was use of special features in intersection control, preemption of downstream signals, warning of drivers, and changing of signal sequence in the case of excessive queuing.

These principles, which satisfy all three of the concerns noted above, require some adjustments to both LRT and traffic controls. For example, in addition to a set of LRT scheduling requirements to meet the window principle, a special LRT signal at the middle station will be tied to the traffic-control system. This signal will release the trains from the station at the most suitable period of time. On the other hand, traffic signals in the adjacent network possess enough flexibility so that the period during which the LRT station signal blocks the train's departure is minimized. The potential to adjust the operating speeds of LRT trains is not currently used but may be used in the future. The crossing-control logic also takes into account simultaneous or almost simultaneous arrivals of LRT and CNR trains in opposite directions; it extends the closure time of the crossing rather than allowing two successive closures without a safe interval between them.

Another service TMS provides to transit in northeast Edmonton is assistance in achieving regularity in feeder-bus operation. Bus schedules are designed to connect to LRT at specific intervals to achieve convenient and reliable transfers between routes.

Traffic signals along the route are therefore programmed in such a way that the variations in bus running times are minimal. The principle applied here is coordination of traffic signals for buses. In special cases, other types of bus priority measures may be applied. Adjustments in bus stop locations and bus schedules, as well as changes in the street geometry and parking and other regulations are required to achieve this principle at various points on the street network. The assistance

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

Edward A. Burgin, Louis T. Klauder and Associates, Philadelphia

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.