Integrating LRT into Flexible Traffic Control Systems

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Street medians can be an attractive location for an at-grade light rail transit (LRT) line. Medians offer major advantages such as existing right-of-way and proximity to existing patronage generators located along or adjacent to the street. Medians also at least partially retain lateral separation from street traffic. However, these benefits can be outweighed by delays to either light rail vehicles (LRVs) or street traffic, or both, at intersections that the LRT line crosses at grade. In this paper are describe the planned solutions to this problem for the proposed Woodward Corridor line in and adjacent to Detroit, Michigan, and for the Guadalupe Corridor line presently (1985) under construction in Santa Clara County, California. These two systems demonstrate how a similar approach to the problem can be used in quite different settings.

DESIGN CONSTRAINTS AND OPPORTUNITIES

The designers of an LRT system inevitably have two conflicting demands placed on them when it comes to at-grade operations through street intersections. It is usually expected that LRVs will have priority at intersections in order that total travel time be consistent and kept to a minimum. Yet it is also expected that normal intersection operation will be maintained so that peak-hour traffic delays are not worsened. The extent to which both objectives can be simultaneously met depends on the design constraints and opportunities.

The following items are some of the major constraints and opportunities that face the designer of an at-grade LRT line in a street median:

1. LRV speed,
2. LRT station location,
3. Platform location relative to the intersection,
4. Station dwell time and variability,
5. LRV consists (number of cars trained together),
6. LRV headways,
7. Reverse running policy (emergency two-way operation on one track),
8. LRV acceleration and deceleration performance,
9. Intersection spacing,
10. Street traffic volumes,
11. Street closures,
12. Turning movement restrictions,
13. Traffic signal coordination on this street and crossing streets,
14. Street right-of-way width,
15. Number of traffic lanes,
16. Parking restrictions,
17. Street speed limit and average travel speed,
18. Type of traffic control at intersections, and
19. Traffic and LRT control and operating regulations.

Many of the items in this list are variables, and many are interdependent. The design process ideally involves choosing the optimum combination of all such variables. In practice many of the variables will be predetermined or restricted to small ranges by considerations other than traffic and LRT operational efficiency. For example, the location of stations is usually largely determined by factors such as proximity to major patronage generators.

Not only is it impractical for all of these factors to be optimized for traffic and LRT operations, but some of them are continually changing in a cyclical pattern and may permanently change in unpredictable ways during the life of the LRT system. This is especially true of traffic volumes and LRT headways. What is needed, therefore, is a flexible traffic and LRT control system that can optimize performance for any given set of conditions. Before discussing such control systems designed for use in the Woodward and Guadalupe Corridors, some explanation of the choices available for intersection traffic control devices in the presence of LRT is needed.

INTERSECTION TRAFFIC CONTROL OPTIONS

The safe operation of LRVs through intersections requires that the LRV approach speed be restricted to a level consistent with the type of traffic control provided at the crossing. If the LRT tracks are fully protected by railroad-type gates, then, subject to other safety considerations such as speed differential between automobiles and LRVs and adequate queue clearance, it can be safe to operate LRVs through intersections at speeds as high as 55 mph (88 km/hr). This type of operation requires railroad-type preemption of any traffic signals at the intersection in order to operate the gates in advance of the LRV's arrival. The combination of signal preemption and time lost in operation of the railroad gates can be disruptive to street traffic at the intersection. It is also usually physically impractical to construct an adequately gated crossing in the middle of an intersection because of the physical space requirements of the control hardware.

At signalized intersections LRVs in the median can be provided with a separate traffic signal display and required to stop or proceed in accordance with that signal, in exactly the same way as automobile traffic. All traffic movements that cross the tracks, including left turns, should be protected by a separate traffic signal phase or other means such as illuminated turn restriction signs. Because an LRV may have to stop on short notice when its signal display changes to yellow, the LRV approach speed at signalized intersections must be restricted to a speed from which the vehicle can be stopped in a reasonable time and distance. The deceleration capabilities of LRVs and consideration of the comfort and safety of standing passengers require that LRV speeds be restricted to a maximum of approximately 35 mph (56 km/hr) for this type of control at signalized intersections.

LRVs can also operate safely through intersections that have only stop sign control for opposing traffic. These intersections require careful design to ensure that sight distances are adequate and that points of conflict are clearly defined. This can be an efficient control method where opposing traffic volumes are suitably light. However, it is subject to the capacity limitation of stop sign controlled intersections.

Traffic signals are perhaps the most practical form of traffic control at most high-volume intersections to be shared with LRT. They allow a reasonable LRV operating speed without the disruptive effects of gated crossings and do not require additional space within the intersection. Signals also offer a degree of flexibility not available with alternatives. Any degree of priority, from none to total preemption, can be given to LRT. Furthermore, the level of priority can be varied during the day or week and can be provided to only selected LRVs such as only those in the peak direction of travel or those that are disadvantaged by the current signal coordination plan. Traffic signal coordination can also be used to provide consistent and predictable LRV travel times without the need for full LRV priority. By providing the same control over LRVs as they do over automobiles, traffic signals allow the total integration of LRT and street traffic operations.

TRAFFIC SIGNAL PHASING AND TIMING

The LRV's unique performance characteristics, size, and location in the street right-of-way require that it be provided with a separate signal phase and special phase timing if it is to operate safely and efficiently through signalized intersections at speeds of up to 35 mph (56 km/hr). The LRV phase can usually operate concurrently with selected automobile phases or phase combinations. However, it must be timed separately in order to efficiently implement the additional clearance times required for LRT.

The service deceleration rate of LRVs is typically restricted to approximately 3 mph/sec (4.4 ft/sec^2 or 1.34 m/sec^2) out of consideration for standing passengers. The rate of jerk at initiation of braking is also normally limited to approximately 3 mph/sec^2 (4.4 ft/sec^3 or 1.34 m/sec^3). It therefore takes approximately 325 ft (93 m) to stop an LRV from 35 mph (56 km/hr) without use of emergency braking provisions. This distance will be referred to as the safe stopping distance. The LRV takes approximately 6 sec to travel this distance at a constant 35 mph (56 km/hr).

The operator of an LRV approaching a red traffic signal, with the expectation that a green signal may be displayed at any moment, can be expected to maintain full speed until shortly before the LRV arrives at the safe stopping distance from the intersection. Assuming that the operator does not begin slowing the vehicle until 2 sec before reaching the safe stopping distance, it follows that the earliest that an LRV traveling at a constant 35 mph (56 km/hr) can arrive at the intersection is 8 sec after the start of the LRV green signal. Another way of explaining the same phenomenon is to say that the green signal must begin at least 8 sec before a full-speed LRV would arrive at the crossing if that vehicle is to continue through the intersection undelayed.

On the other hand, consider an LRV approaching during the LRV green signal display. The LRV green signal can be terminated, and a yellow display begun, while the LRV is still approaching the intersection. In this case the LRV operator will take some time to recognize the change in display from green to yellow, to make a decision whether to stop or continue through the intersection, and to apply the vehicle's brakes if the decision is to stop. There may also be a short delay in the transition from power mode to braking mode after the control lever is placed in the braking position.

Assuming the total operator and vehicle reaction time is 2 sec, a "stop or go decision point" can be located, on the basis of the safe stopping distance plus the distance traveled in 2 sec at the approach speed before the intersection. For a 35 mph (56 km/hr) approach speed and these vehicle performance assumptions, the stop or go decision point is 427 ft (130 m) before the intersection. If the LRV is beyond the stop or go decision point when the signal changes from green to yellow, it will continue into the intersection, and the timing of signal change intervals must take into account the time it takes to reach the intersection from the stop or go decision point.

An LRV traveling at 35 mph (56 km/hr) takes 10 sec to travel from its stop or go decision point to the far side of a 100-ft (30-m) intersection. The total of LRV yellow plus LRV red clearance time therefore needs to also be approximately 10 sec. Then a worst case LRV, one that is traveling at the 35-mph (56-km/hr) maximum speed and has just passed the stop or go decision point when the signal changes from green to yellow, will have the front of the vehicle across the intersection when a conflicting movement first receives a green signal, as shown in Figure 1. Although the rear of the vehicle will not be clear of the intersection until as much as 5 sec later (for a three-car LRV), motorists having just received a green signal will always be able to clearly see the conflicting LRV still across the intersection, even at night.

To avoid delaying the LRV, the LRV phase green time needs to be displayed for approximately 10 sec to ensure LRVs traveling at somewhat less than the maximum speed are beyond the stop or go decision point when the signal changes to yellow. Adding 6 sec of LRV yellow and 4 sec of red clearance gives a total required LRV phase length of as much as 20 sec. Concurrently running automobile phases can be timed independently so that their change intervals always end at the same time as, or later than, the LRV phase change interval. Thus concurrent automobile phases would continue to show green at least throughout most of the LRV yellow interval.

The use of a 10-sec change interval for LRV phases is conservative compared to the operation of other vehicles at traffic signals, especially buses. Buses also have standing passengers and therefore cannot

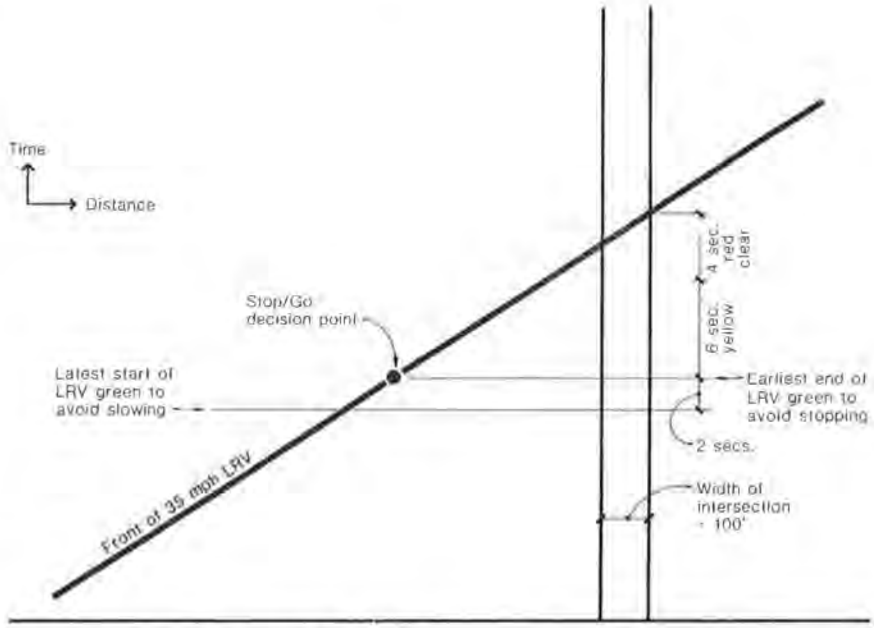

FIGURE 1 Derivation of LRV signal timing.

be stopped as rapidly as can other road vehicles, yet they operate at 35 mph (56 km/hr) or more through signalized intersections with change intervals typically between 4 and 5 sec. These vehicles occasionally enter intersections during the red signal display, but accidents are avoided because they are conspicuous and because opposing traffic takes some time to start up. However, LRVs are longer and less maneuverable than a bus, and more conservative signal timing is therefore appropriate.

A separate LRV phase is also required to avoid conflicts with parallel traffic turning left across the LRV tracks during a left-turn phase. Figure 2 shows three typical phase sequences for a multiphase vehicle-actuated signal. In each case the LRV phase cannot be tied to any one automobile phase because there is no assurance that that phase will not run concurrently with a left-turn phase that conflicts with the LRV phase. Instead it is necessary to treat the LRV phase as entirely separate from any single automobile phase and to allow the LRV phase to operate only while both parallel automobile through phases are simultaneously active.

The LRV phase can be actuated by detection of an approaching LRV so that the phase appears only when needed and only for as long as needed. Advance detection of LRVs also permits a variety of active LRV priority measures to be implemented. In this way full flexibility in normal traffic signal control is retained, and provision is made for the safe and efficient passage of LRVs when they arrive at the intersection.

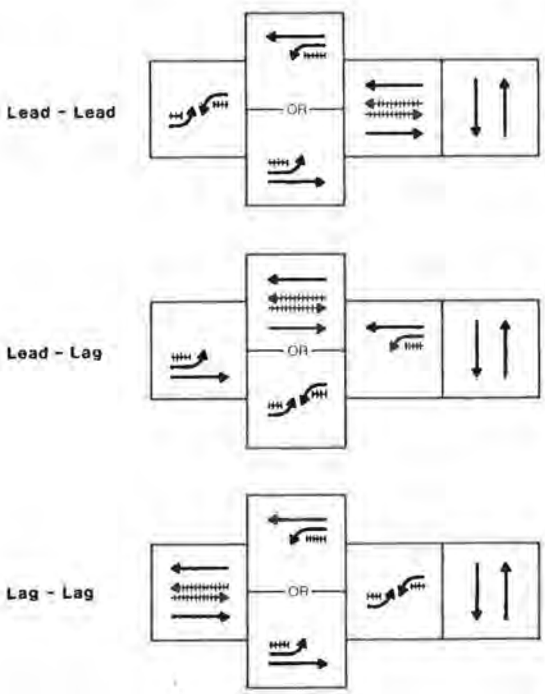

FIGURE 2 Typical actuated phase sequences.

WOODWARD CORRIDOR CASE STUDY

The Woodward and Guadalupe Corridors are good examples of how this integrated and flexible approach to LRV and traffic control will be applied in quite different settings. Figure 3 shows the location of the proposed Woodward Corridor LRT line in Detroit and that segment of the line planned to operate in the Woodward Avenue median. It is 4 mi long and includes three stations spaced approximately 1 mi apart. This section of Woodward Avenue is intersected at grade by only two major cross streets. Of the numerous minor side streets, only four cross Woodward at normal intersections. The remainder form unsignalized T junctions or have partial median closures that permit only right turns from the side street. The total street right-of-way width between property lines is approximately 204 ft (62 m). this includes 8 to 10 through traffic lanes, on-street parking, and a median that is typically 50 to 70 ft (15 to 21 m) wide. All left turns are banned at all cross streets except one. Existing traffic signals are coordinated in two subsystems at cycle lengths ranging from 50 to 80 sec. Woodward Avenue carries up to 3,000 vehicles per hour in the peak direction. Maximum three-car LRV consists are projected to operate at minimum headways as short as 4 min.

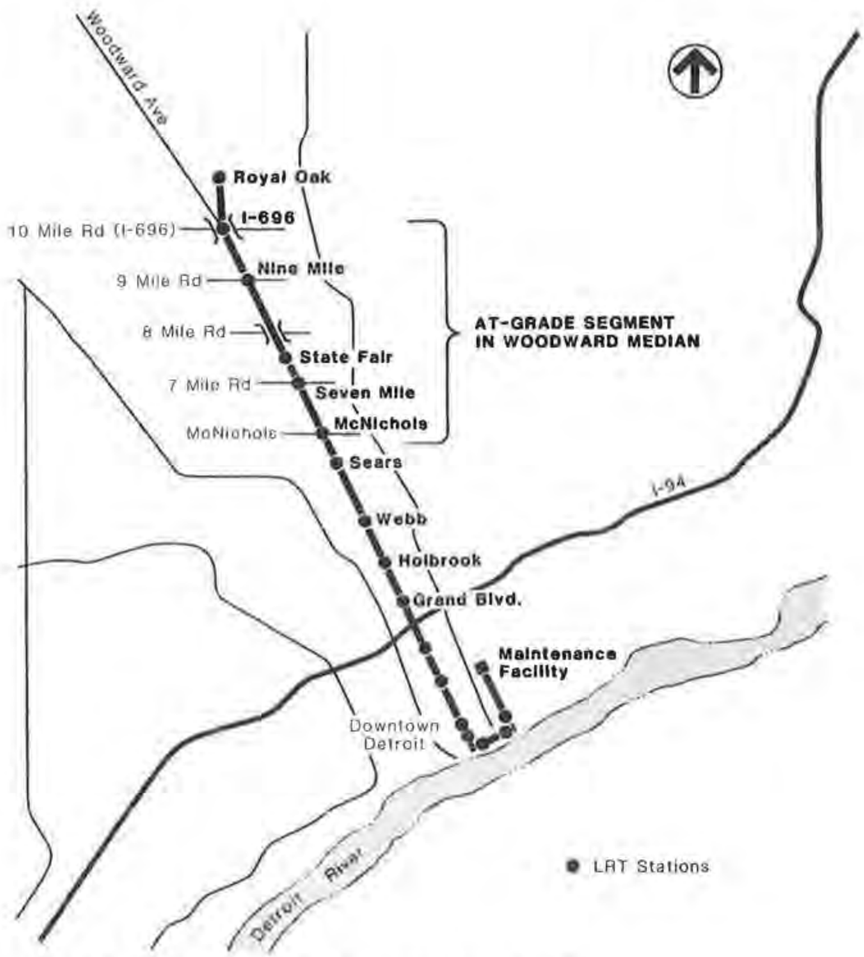

FIGURE 3 Location of proposed Woodward Corridor LRT.

The first task undertaken in the traffic operations design of this segment of the LRT line was to consolidate the numerous median openings into a few strategically located openings that allowed U-turns and some left turns from the main street, but no direct left turns from side streets. These median cross-overs or "U turn slots" will be located back to back with an island separating them so that when signalized they could also provide signalized two-stage pedestrian crossings. A typical arrangement is shown in Figure 4. If a separate signal controller is provided for each U-turn slot, they can have independent offsets in a coordinated signal system and therefore can be set for perfect green wave progression in the same way as signals on one-way streets. This is important on Woodward Avenue where good two-way signal progression has existed for many years and is required to be maintained despite the proposed increase in the number of traffic signals from the current 12 to 31.

The wide street right-of-way on Woodward Avenue makes it feasible to ban left turns at all intersections except U-turn slots purposely located opposite side streets. This will force traffic turning left from Woodward to go beyond the intersection and make a U-turn followed by a right turn. Side street traffic wishing to turn left onto Woodward must first turn right and then make a U-turn. This arrangement is already used on several of the broad urban arteries around Detroit. It will thus be possible to operate just two phases at all traffic signals. The distances between the cross intersections are all close to multiples of 2,950 ft (899 m). Good two-way progression through the entire 4-mi segment could therefore be achieved at a 60-sec cycle length and a 34-mph progression speed. An 80-sec cycle length is needed to accommodate peak-period traffic, which involves some sacrifice in progression for traffic traveling in the counter-peak direction.

At all traffic signals LRVs will have two separate signal phases, one for each direction of travel. These LRV phases will have yellow and red clearance intervals of approximately 6 sec and 4 sec, respectively, and will operate as separate phases called only when an LRV is approaching. At the normal cross intersections, the LRV phase, when called, will run concurrently with the parallel through-traffic signal phase. At U-turn pairs, there is no guarantee that the through phases in both directions will be active at the same time. It is therefore necessary to provide for preemption of at least one of the two adjacent slots because there is no space between the slots in which an LRV can stop and wait for a green signal at the second slot.

By allowing LRVs to travel only within a signal progression band, signal preemption, and its associated traffic disruption, can be limited to one of the two signals at U-turn slot pairs. Because the LRV will be traveling in the signal progression band for parallel traffic in the same direction, the near-side slot is the one requiring preemption because its offset is determined by traffic in the opposing direction. Preemption will be allowed only during that part of the signal cycle when the far-side slot is able to simultaneously display a green signal to the LRV. In this way an LRV is assured

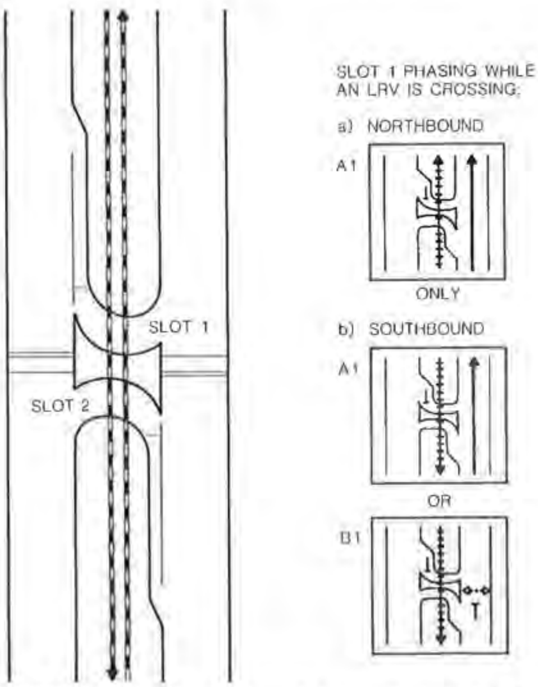

FIGURE 4 Signalized U-turn slot operation with LRT.

passage through both signals when the near-side signal has been preempted, and LRVs will be forced to travel in a signal progression band.

To prevent disruption of automobile progression in subsequent signal cycles, the main street phase offset at U-turn slots will not be altered following a preemption. Instead, the time needed for the LRV phase will be taken entirely from the U-turn-left-turn phase. Signal preemption can cause the preempted U-turn-left-turn phase to be totally skipped in some cycles. However, the controllers will be programmed to not permit phases to be skipped in consecutive cycles. At a few of the U-turn slots that serve heavy volumes, the phase will be prevented entirely from being skipped. In this case, the LRV will be denied passage if its phase cannot be accommodated together with the minimum automobile phase time.

All side street phases, including U-turn-left-turn phases at U-turn slots, will be subject to "green shortening" to widen or "stretch" the progression window for LRVs in either direction. However, the maximum amount of window stretching will be set independently for each intersection, for each direction of LRV travel, and for each coordination plan. Therefore a phase will be skipped only if the maximum amount of window stretching requires it, only if the LRV is traveling in the nonprogression direction for that phase if it is a U-turn-left-turn phase, and only if phase skipping is permitted at that intersection.

Projected LRV headways as short as 4 min on part of the segment may result in a phase being skipped in every third 80-sec cycle during the peak period because a phase can be preempted only by LRVs traveling in one direction. Phase splits will allow for clearance of traffic from two cycles where this is likely to occur. Even though a vehicle phase green may be shortened or skipped entirely, the associated pedestrian phases and background cycle will continue uninterrupted. Pedestrians will cross each roadway separately and will be able to cross to or from the wide median while an LRV is passing.

Traffic signals will continue to be synchronized from an existing regional master controller. All the special control features will be embodied in the individual controllers. Three separate signal coordination plans for use at different times of the day will incorporate all the planned signals in the segment in a single coordination system. Cycle lengths will be 80 sec in the morning and evening peak periods and 60 sec at other times. These plans will optimize automobile progression through the 31 traffic signals at the respective times of the day and still cause total delay to the "typical" LRV of less than 86 sec, or approximately 12 percent of the segment run time, in both directions in all three plans.

GUADALUPE CORRIDOR CASE STUDY

The Guadalupe Corridor LRT line will include an 8-mi (12.9-km) segment in the medians of North First Street and Tasman Drive, north of downtown San Jose, as shown in Figure 5. North First Street is a four- to six-lane radial artery with right-of-way width varying between approximately 80 and 130 ft (24 and 40 m). Tasman Drive is a four- to six-lane crosstown artery that also provides access to industrial parks in the north of San Jose and in the city of Santa Clara. Tasman Drive has a 48-ft (14.6-m) median for most of its length. All left turns from both streets are made from separate turn lanes in the median.

Some minor median openings will be closed, but neither street is wide enough for U-turns by full-size trucks, and adjacent street networks are such that it is not feasible to prohibit left-turn movements on any significant scale. Only a few intersections adjacent to the downtown transit mall will remain unsignalized; the remaining 34 intersections will be signalized with separate phases for all left turns from the main street. Intersection spacing is irregular, and there are no natural cycle length and speed combinations that allow good two-way progression. A further obstacle to signal coordination for LRVs is the 13 LRT stations being built in this segment.

LRT headways will be as short as 6 min in each direction during the peak periods. Many of the intersections are, or will be, operating at capacity. It is therefore not feasible to avoid LRV delay by preempting all signals, at least not during peak traffic periods. On the other hand, if LRVs are not given some priority, their travel times will be unacceptably long because good two-way progression via signal coordination is not possible.

The northern segment also includes traffic signals controlled by three separate agencies, and each has different objectives and signal operation practices. Also, although in most cases the LRT line is paralleling the heavy traffic volumes on North First Street, there is at least one intersection of a major artery with North First Street where both the through traffic on the artery and the turning volumes are extremely high, and the intersection is currently operating at a low level of service. The signal operation strategy required at this intersection will, of necessity, differ somewhat from that employed at the other North First Street intersections. To further complicate the situation, part of the segment passes through presently undeveloped land that will be developed within the next 10 years. At least in these areas, the peak-period traffic volumes and LRT frequencies are likely to vary considerably over the design life of the system.

To provide the flexibility of operations required to meet these varying demands, a modified National Electrical Manufacturers Association traffic signal controller will be installed at all intersections. The controller will use standard hardware but will

FIGURE 5 Location of northern segment of Guadalupe Corridor LRT.

incorporate special software. In this way manufacturing costs will be virtually the same as for a standard controller. Initial software development cost will be spread over all signal installations. The operation and software maintenance of the controllers will be made more complex by the addition of LRT phases and associated parameters, but controller hardware maintenance costs will not increase because all standard components are used.

Two inductive quadrapole loop detectors will be provided to detect LRVs on each approach to a traffic signal. These will use standard traffic detector components. One detector will be placed immediately downstream of the adjacent upstream intersection, to provide as much advance warning of the approach of an LRV as possible. The other will be placed approximately 70 ft (21 m) before the intersection and will serve as both a release detector to terminate the LRT phase green and a call detector if the LRV signal is showing red. This detector arrangement will be modified in blocks containing an LRT station. A typical LRV detector arrangement is shown in Figure 6.

The controller will accommodate eight normal vehicle phases, four normal pedestrian phases, two normal phase overlaps, four special LRT phases, and a time-based coordinator. Although the LRT phases will operate concurrently with nonconflicting automobile and pedestrian phases, it cannot be simply associated or overlapped with the other phases. As shown in Figure 2, the LRT phases in most situations can run only while two parallel automobile phases are simultaneously active. The controller will initiate an LRV phase only if it is demanded and only if both of its associated automobile phases are currently active. Furthermore, the LRT phase will be timed independently of the associated automobile phases and can terminate before the associated phases.

Time-based coordination was chosen primarily for the flexibility it offers in subsystem arrangement and its ability to fit in with other coordination systems along the corridor. Several major cross streets will also have arterial coordination. Time-based coordination is a relatively inexpensive means of allowing traffic signals on the LRT corridor to be synchronized with either adjacent signals on the corridor or signals on the cross street, or both, depending on the cycle length requirements at different times of the day and days of the week.

The controller has been designed to permit any degree of LRV priority, from none to full, to be implemented at any intersection, for any period of the day or the week, and separately for each direc-

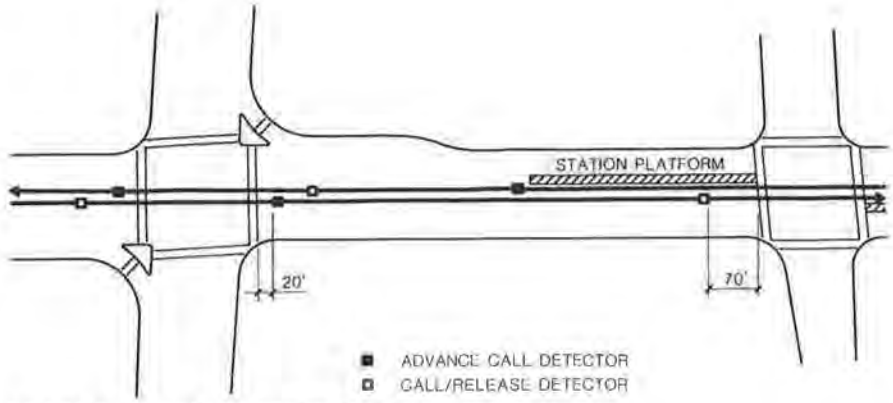

FIGURE 6 Typical LRT detector loop location.

tion of LRV travel. The controller will allow window stretching, or partial priority, for LRVs during coordinated operation, and LRV phase insertion at any point in the signal cycle, or full priority, during free (uncoordinated) operation. Figure 7 shows the logic involved in implementing LRV priority.

Partial priority is a method of widening the green window for LRVs at a coordinated traffic signal. The green window is the amount of time in the signal cycle during which an LRV can pass through the intersection. This window is widened beyond the normal LRV phase green time by allowing the LRV phase to start earlier than normal (early green) or by allowing the LRV phase to finish later than normal (extended green). In each case, the extra time given to the LRV phase must be taken from other phases within the fixed-length cycle. A wider window reduces the probability that an LRV will have to stop at the signal. The controller will allow the signal operator to set limits on the amount of early or extended LRV green in accordance with conditions at each individual signal in each coordination plan.

Full priority is a means of inserting an LRV phase in a signal cycle operating in the free or uncoordinated mode. The controller terminates the current phase or phases after pedestrian and minimum times have been satisfied and implements the LRV phase, together with its associated automobile phases. In this way the LRV is able to pass through the intersection with little or no delay, regardless of which signal phase is active when it arrives. Because the signal is vehicle actuated and not coordinated when full priority is in operation, it will automatically adjust subsequent phase splits to accommodate any unusual queues resulting from the preemption. Such preemptions will not be permitted in consecutive signal cycles.

To accommodate the different signal operating philosophies of the different agencies, the controller will enable any one of three alternative recovery

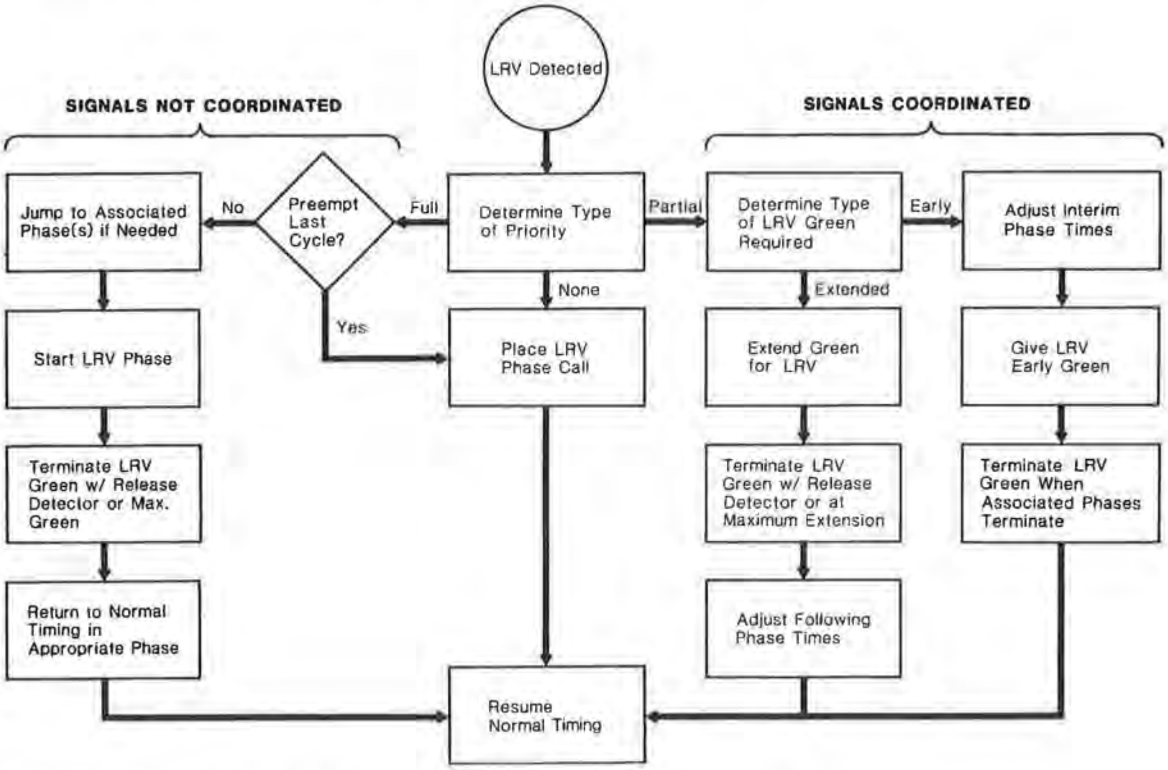

FIGURE 7 Overview of LRV priority.

algorithms to be used following a full priority LRV phase insertion. One method is to continue normal operation from the associated automobile phases. Another is to return operation to the phase that would normally have followed the phase or phases that were being served when the preemption occurred. The third algorithm simply returns operation to the phase or phases that were being served when the preemption occurred. Recovery from window stretching during coordinated operation will be achieved in the same cycle so that the progression band for automobile traffic is never interrupted.

LRT priority reduces the capacity of the intersection; partial priority takes green time from the minor phases; and full priority increases lost time. The capacity needed to accommodate traffic varies as traffic volumes vary during the day. There are also different amounts of spare capacity available at different intersections at any given time. The signal controllers specified for use on the Guadalupe Corridor will allow the amount of LRT priority to be varied to take advantage of the spare capacity available at each intersection at each time of day. It will also allow different amounts of priority to be allocated to LRVs in each direction of travel. Thus the capacity available for priority can be given to the direction that has the greater need. The signal system operation can also be varied and fine tuned as conditions change in the long term or as objectives or priorities change.

It is also intended that quite different control strategies be implemented during different times of the day and days of the week. When traffic volumes are light and LRT headways are large, such as at night, it may be best to operate signals in the free mode (uncoordinated) and provide full priority for LRVs. During peak periods, signal coordination and window stretching at selected intersections would be more appropriate. By allowing the amount of LRV priority to be varied, interruptions to automobile traffic can be limited to the extent tolerable or necessary for the current conditions at each intersection.

CONCLUSION

The microprocessor traffic signal controller provides the opportunity to implement a flexible and relatively low-cost system of controlling light rail vehicles at signalized intersections. The signal controller can accommodate special LRT phases that are timed independently of concurrent automobile phases. Each direction of LRV travel can have its own phase, and these can be called and terminated by ordinary inductance loop detectors. Different levels of LRV priority, combined with different controller timings and parameter settings at different times of the day, can provide the flexibility needed to accommodate a wide variety of operating conditions and philosophies.

The traffic signal systems proposed for the Woodward Corridor LRT line in Detroit and the Guadalupe Corridor line in Santa Clara County demonstrate how this approach is intended to be used in quite different operational settings. In Detroit, all the traffic signals will have only two phases, and many will be controlling U-turn slots in a wide median. The signals will be coordinated at all times. Partial priority for LRVs will allow selective widening of the LRV green windows where two-way progression for LRVs cannot be provided.

The Guadalupe Corridor system will involve multiphase vehicle-actuated traffic signals. These signals will be coordinated at some times of the day and will run free, or uncoordinated, at other times. Partial priority for LRVs will allow window stretching during coordinated operation, and during free operation full priority will allow an LRV phase to be inserted at any point in the variable length signal cycle.

The proposed signal systems involve the total integration of LRV control into the traffic signal controller logic. This permits the signal controller to serve LRVs without any priority treatment when appropriate, and also allows variable degrees of LRV priority to be implemented selectively when needed. In this way it is hoped the disruption and capacity reduction often associated with in-the-median LRT operation can be minimized while a reasonable level of service for LRT is provided. It will also permit operational strategies to be fine tuned in the field and altered over time as conditions or priorities change.

ACKNOWLEDGMENT

The authors wish to thank the Southeastern Michigan Transportation Authority and the Santa Clara County Transportation Agency for their permission to publish information pertaining to their respective LRT system designs. Any views expressed are those of the authors and not necessarily those of the transportation agencies.