Designing At-Grade LRT Progression: Proposed Baltimore Central Light Rail

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Engineers and planners designing at-grade light rail transit (LRT) operations typically are faced with the challenge of balancing two conflicting objectives. On the one hand, the transit authority expects LRT operations to receive full priority at all at-grade crossings in order to achieve minimum travel time. On the other hand, the agency having jurisdiction over the arterial on which the LRT runs expects to maintain normal intersection operations so that peak-hour vehicle traffic delays are not worsened by the implementation of LRT services. The proposed Central Light Rail Line (CLRL) for metropolitan Baltimore was no exception to this situation. The CLRL will ultimately be 27 mi long, with a section of approximately 1.5 mi running along Howard Street through the central business district (CBD) of Baltimore. Howard Street is a two-way, north-south nonprogressive street that intersects with a number of major arterials receiving signal progression during the peak hours. The city is concerned that the proposed LRT will degrade progression on these major arterials and cause unacceptable delays to peak-hour traffic. Using the concept of traffic progression, progressive green bands for the proposed CLRL are developed to enhance its operation and at the same time minimize its effect on cross-street traffic progression. Traffic effects of LRT operations are quantified in terms of disruptions to cross-street progression, intersection level of service, and the performance of a partial CBD street network measured by systemwide criteria. The results reconfirm a previous belief that signal progression for LRT operations is available in the current computerized traffic signal network and that full priority LRT operations along Howard Street could be designed without significantly affecting cross-street progression.

The proposed at-grade light rail transit (LRT) service in central Baltimore between the Camden and North Avenue stations will likely experience substantial delays and schedule variability because of conflicts between LRT and automobile traffic unless traffic operational improvements are implemented. The problem is Howard Street, a two-way street currently receiving low priority in signal progression for automobile traffic. Although certain geometric improvements and traffic route changes are being proposed in conjunction with LRT service on this arterial, no significant signal timing changes on behalf of LRT have been scheduled. Yet the signal timing conflicts potentially cause the greatest disruption to LRT.

A previous study (*1*) of this problem demonstrated the potential for improving LRT travel times along Howard Street by establishing traffic signal progression between Camden Street on the south and Preston/Dolphin Street on the north (see Figure 1). Preliminary estimates are that 3 to 5 min travel time could be saved for LRT operations in each direction with full priority as opposed to partial priority treatment. Schedule variability could also be reduced, making transit service more attractive to users. To develop such a progression along Howard Street requires modifications to green times and signal offsets on many of the side streets currently receiving priority in traffic progression.

The city of Baltimore, however, is reluctant to retime traffic signals along Howard Street because of the perception that retiming will benefit LRT operations at the expense of city traffic. This is a common perception of municipalities involved in the implementation of street-running transit services, according to Fox (*2*). Before any timing changes can be implemented, the city has requested studies to show whether vehicular movements through the larger downtown street grid will suffer.

PROBLEM STATEMENT AND STUDY APPROACH

The computerized signal system for the Baltimore central business district (CBD) was first installed in the early 1970s. The timing plans for the signalized network were based on historic traffic patterns. Over the years, selective local intersection and arterial improvements have been implemented. Signals have not been retimed systematically for the whole downtown since the system was first installed, although patterns of commuting and midday delivery traffic have changed substantially. It is believed that progression could be accommodated on Howard Street for LRT operations and that the cross-street progression could be adjusted so that full-priority LRT treatment would not substantially degrade traffic performance relative to current conditions.

Designing at-grade LRT progression is not new; several previous studies (*2–4*) have discussed problems and operational enhancements related to at-grade LRT operations. Taylor et al. (*3*) discussed the concept of a "coordinated window" (i.e., progression) for at-grade LRT operation through two adjacent intersections at Gage and Florence in Los Angeles. Fox (*4*) used "green phase extension" techniques to provide progression for bidirectional Banfield LRT operations on one-way Holladay Street in Portland, Oregon.

The purpose of this paper is to discuss the development of a full-priority green band that enhances bidirectional LRT operations along Howard Street in Baltimore while minimizing traffic effects on major cross streets. The study approach, consistent with that of other previous studies (*3,4*), was developed after consultation with the staffs of the Mass Transit Administration (MTA) of the Maryland Department of

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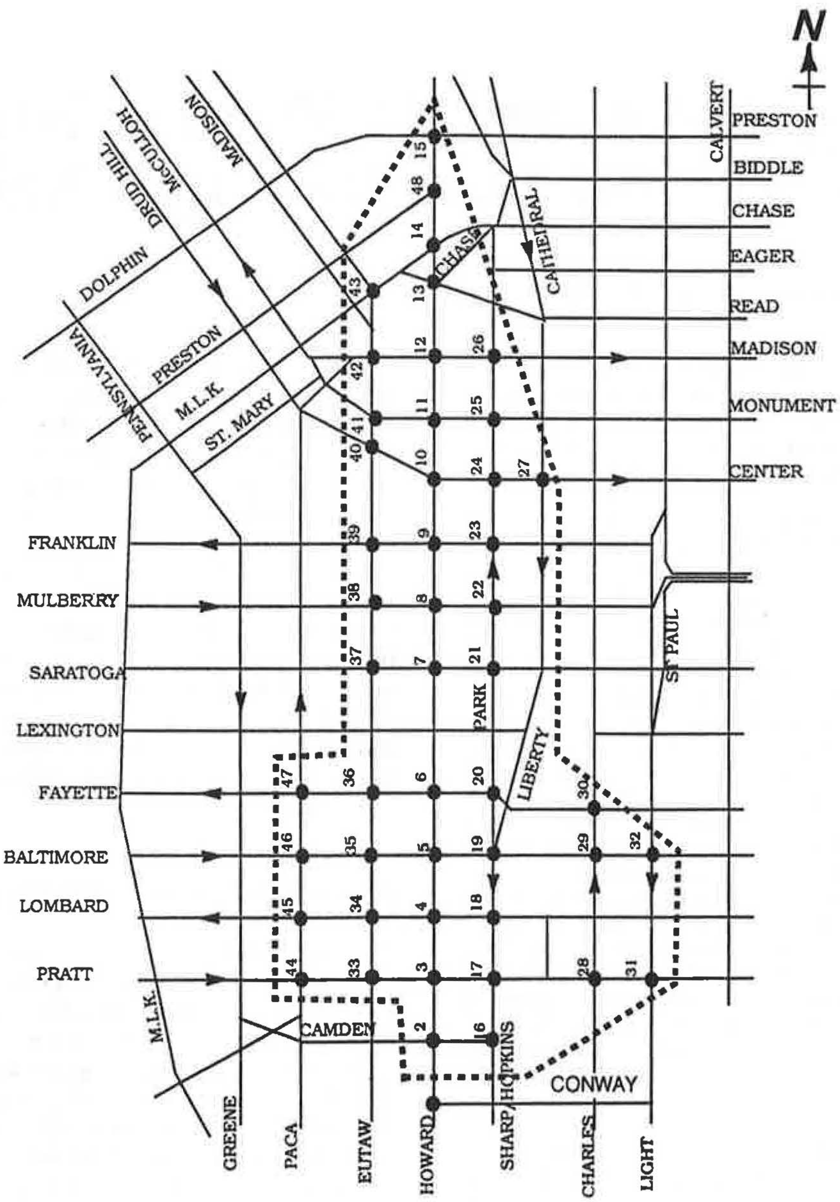

FIGURE 1 Study area.

Transportation and the City of Baltimore. The study involved the optimization of a large signalized network with about 200 nodes subject to the constraint that Howard Street signal progression be maintained to facilitate the LRT operation. Commercially available traffic network optimization programs, such as Passer II-87 and Maxband that deal with arterial progression and the microcomputer version of TRANSYT-7F that was developed originally for signalized networks, were evaluated for adaptation to the study but found to produce nontransparent results. A manual method was preferred over the "black box" computerized approach (*5*) for producing signal offsets and splits for LRT progression. TRANSYT-7F, however, was used to evaluate traffic impacts at the network level once basic signal timing plans for LRT had been developed. The program's simulation capabilities were used to compare two scenarios, one with and one without LRT.

In the remainder of this paper, the study area and the data requirements are described, existing conditions on arterial progression are evaluated, the progression for Howard Street LRT operation is developed, and the impact of signal timing improvements for LRT on Howard Street and on the larger signalized network are assessed. The results presented are for a.m. peak-hour conditions. The analysis could be expanded to other time periods using the same study approach, although this was not part of the original project.

STUDY AREA AND DATA REQUIREMENTS

The project study area, shown in Figure 1, includes all of the major downtown arterial streets timed to receive progression as well as other downtown arteries with significant traffic volumes but no progression. The progressive arterials, mainly one-way streets, are critical in the operation of the city's downtown grid. Study area arterials are given in Table 1, which also indicates their primary or secondary status as progressive streets.

Four types of data were required for all intersections within the study area: signal data, turning movement counts, intersection geometrics, and type of traffic control. In addition, block distances between intersections, average arterial operating speeds, bus routes and service frequency, and vehicle classification data were obtained.

To obtain existing vehicle operating speeds, studies on travel time and delay were conducted during the peak period for 19 major arterials during September and October 1989. Procedures documented in the *Highway Capacity Manual* (*6*) were followed. The existing average operating speeds were used in developing potential green bandwidth for LRT and in calibrating existing traffic conditions for the TRANSYT-7F evaluation of network effects from LRT operations.

EXISTING CONDITIONS ON ARTERIAL PROGRESSION

Most CBD signals are two-phase, pretimed signals. Several are three-phase, pretimed or semiactuated signals. For all pretimed signals, the peak-hour cycle length is 110 sec. The computer program TS/PP DRAFT was used to generate time-space diagrams and determine the green bands of the progressive streets from the signal timing data. By adjusting travel speeds within reasonable limits that ranged from 20 to 35 mph, maximum achievable arterial bandwidths were determined.

The maximum bandwidth attained through this process was designated the "potential green bandwidth," because it is based on adjusted speeds and not necessarily on the actual observed speeds. Using the potential green bandwidth ensured a more conservative assessment of LRT effects, since the potential green bandwidth for an arterial is typically wider and more apparent than any bandwidth determined from highly variable field conditions. In almost all cases, however, actual

TABLE 1 Potential Existing Green Bandwidth for Major Progressive Streets

Arterial		Cross Street From	Cross Street Through	Potential Bandwidth (Seconds)	Speed (mph)	Efficiency (Percent)	Degree of Progression
East-West Arterial							
1. Pratt Street		Greene	Gay	30	30	27%	Good
2. Lombard Street		Gay	Charles	42	30	38%	V.Good
		Hopkins	Greene	24	30	22%	Fair
3. Baltimore Street		Greene	Charles	12	35	11%	Poor
4. Fayette Street		(No Progression)		0	NA	0%	None
5. Saratoga Street (SB)		Paca	Park	20	25	18%	Fair
6. Mulberry Street		Greene	Liberty	47	30	43%	V.Good
7. Franklin Street		St.Paul	Paca	35	38	32%	Good
8. Centre Street		(No Progression)					
9. Monument Street		Paca	Park	34	30	31%	Good
10.Madison Street		Calvert	Charles	36	30	33%	Good
		Cathedral	Howard	28	30	25%	Good
11.Preston Street		Fallsway	St.Paul	27	25	25%	Good
		Charles	Cathedral	30	25	27%	Good
North-South Arterials							
1. MLK	NB	Washington	Mulberry	30	35	27%	Good
	NB	Pennsylvania	Eutaw	45	35	41%	V.Good
	SB	Madison	Franklin	20	35	18%	Fair
2. Greene Street		Saratoga	Pratt	32	25	29%	Good
3. Paca Street		Pratt	Redwood	25	30	23%	Fair
		Redwood	Mulberry	32	30	29%	Good
		Franklin	McCulloh	40	30	36%	Good
4. Howard Street		(No Progression)		0	NA	0%	None
5. Hopkins/Liberty/Cathedral		North	Preston	46	25	42%	V.Good
		Biddle	Saratoga	42	25	38%	V.Good
6. Charles Street		Mt. Vernon	North	30	25	27%	Good
7. Light/St.Paul Street		North	Centre	47	30	43%	V.Good
		Pleasant	Pratt	40	30	36%	Good
8. Calvert Street		Pratt	Lexington	25	30	23%	Fair
		Saratoga	Monument	50	30	45%	V.Good
		Madison	North	35	30	32%	Good
9. Guilford/South/Light		Madison	Baltimore	23	30	21%	Fair

Legends: Efficiency
0% - 12% = Poor Progression
13% - 24% = Fair Progression
25% - 36% = Good Progression
37% - 100% = Very Good Progression

operating speeds along CBD arterials were found to be close to the adjusted speeds. The analysis, summarized in Table 1, found that piecewise progression exists for many arterials and that several east-west arterials exhibit continuous progression over most of their length.

East-west arterials receiving good to excellent progression (i.e., green bands amounting to more than 25 percent of cycle length) include Pratt, Lombard, Mulberry, Franklin, Monument, Madison, and Preston streets. North-south streets receiving good to excellent progression include Martin Luther King Boulevard, Greene, Paca, Hopkins, Charles, Saint Paul, and Calvert streets. Baltimore and Guilford/South/Light streets exhibit only poor to fair potential progression over certain roadway segments. Howard, Centre, and Fayette streets exhibit no progression within the study area.

HOWARD STREET PROGRESSION FOR LRT OPERATION

As noted, traffic signal progression does not exist on Howard Street. The first step in developing a full-priority progression for the LRT operations was to develop a profile for typical LRT travel times between intersections. As with automobile traffic on an arterial subjected to progression, it is the expected travel time between intersections that is used to modify the signal offsets necessary for progression. For LRT, however, the situation is complicated by unique characteristics of train acceleration and deceleration, station dwells, track geometry that restricts cruise speeds, and two-way operations.

LRT Operating Characteristics and Profile

The proposed CLRL will have two lines, the North and South lines, as shown in Figure 2. The North Line will start from the north terminal at Hunt Valley, with Camden Station as its last station. The South Line will start from the south terminal at Dorsey Road, with North Avenue Station as its last station. Along Howard Street itself, the Cultural District Station is the northernmost station and Camden Station is the southernmost station. There are four other intermediate stations on Howard Street.

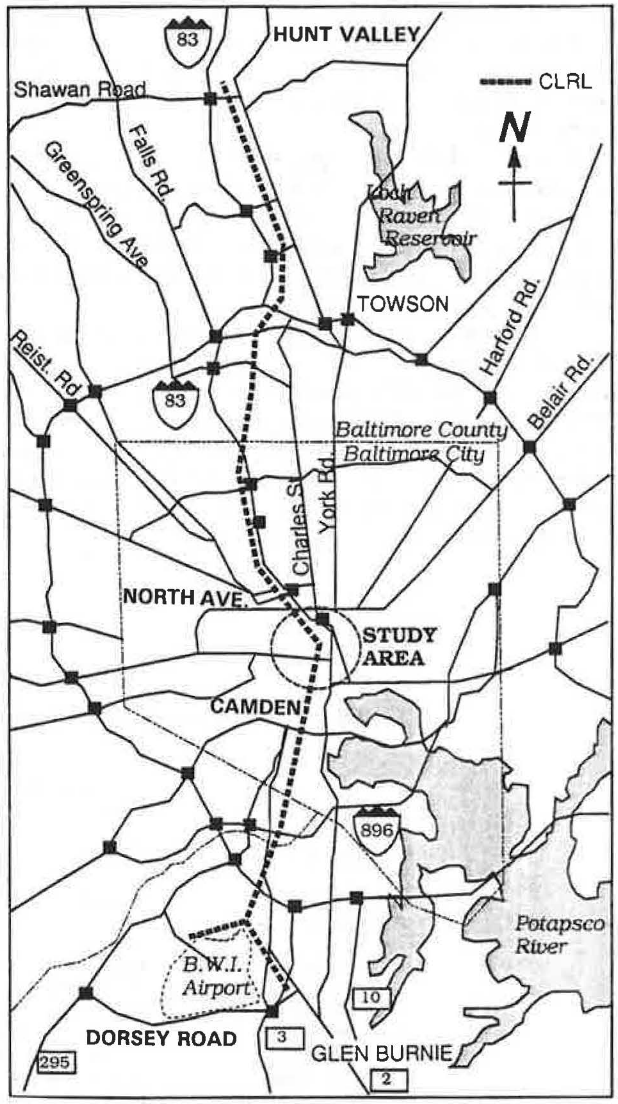

FIGURE 2 Baltimore Central Light Rail Line.

The average peak-hour headway for both lines will be 15 min. Since the two lines overlap on the section along Howard Street between the Camden and Cultural District stations, there will be a train passing through the study area every 7.5 min in each direction, on average. A combination of three-car and two-car trains, with a maximum of five train trips, will be operated during peak hours on each line. Two-car or one-car trains will be used during off-peak hours. The length of an LRT car will be 95 ft, a total of 285 ft for a three-car train.

The LRT maximum cruise speeds between intersections were obtained from the LRT track charts. Higher cruise speeds of 25 to 30 mph are possible on tangent track in the north sections of Howard Street. Lower operating cruise speeds of 15 to 20 mph elsewhere are necessary, primarily because of sharper track curvature.

The acceleration and deceleration rates assumed for the LRT were constant rates of 2.75 and 2.5 ft/sec^2, respectively. Although LRT typically has nonconstant (nonlinear) rates of acceleration or deceleration, the assumption of linear rates is reasonable for low cruise speeds. A constant station dwell time of 30 sec was also assumed. A typical LRT operating profile based on the above assumptions is presented in Figure 3. The solid line represents the front of the train, and the shaded area represents the tail of the train.

Howard Street Progression for LRT

To create a progression for LRT, the LRT operating profile needs to be "circumscribed" by a progressive green band for Howard Street. This was done by overlaying the LRT operating profile on a second time-space diagram reflecting existing signal timing for Howard Street intersections (i.e., "without LRT") between the Camden and Cultural District stations.

Figure 4 shows the existing time-space diagram on Howard Street without LRT, in which cross-street signal timing data

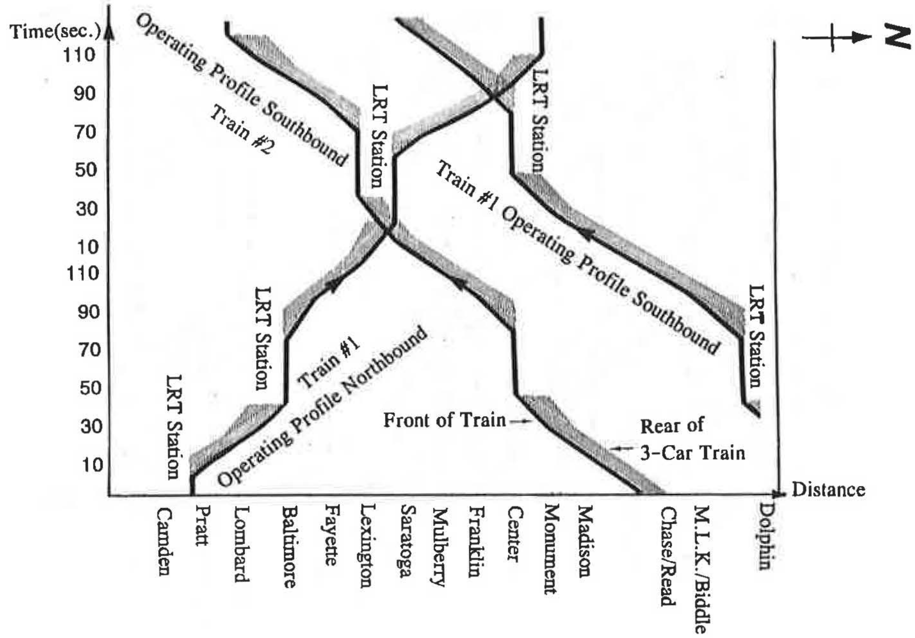

FIGURE 3 Train operation profile.

are plotted on a vertical time scale and the cross-street locations are plotted on a horizontal distance scale. The superimposed LRT operating profile was manually adjusted to achieve minimum impacts on existing cross-street progression. Cross streets given the highest priority for retaining maximum green time and progression included Pratt, Lombard, Mulberry and Franklin.

Selection of Green Band for LRT

After identification of the best location of the LRT operating profile that minimized disruption to cross-street timing while retaining LRT progression along Howard Street, a band providing adequate green time for the LRT to cross each intersection was drawn on the time-space diagram. Figure 5 shows only the southbound band, but a similar band exists for northbound trains. The resulting changes in cross-street signal offsets and green time were documented.

Since it is essential for the rear of the LRT train to pass through an intersection before the cross street receives a green phase, LRT clearance times and green intervals had to be established. LRT clearance time is the time it takes for the train to travel through an intersection and is a function of crossing speed, train length, and travel distance. The green

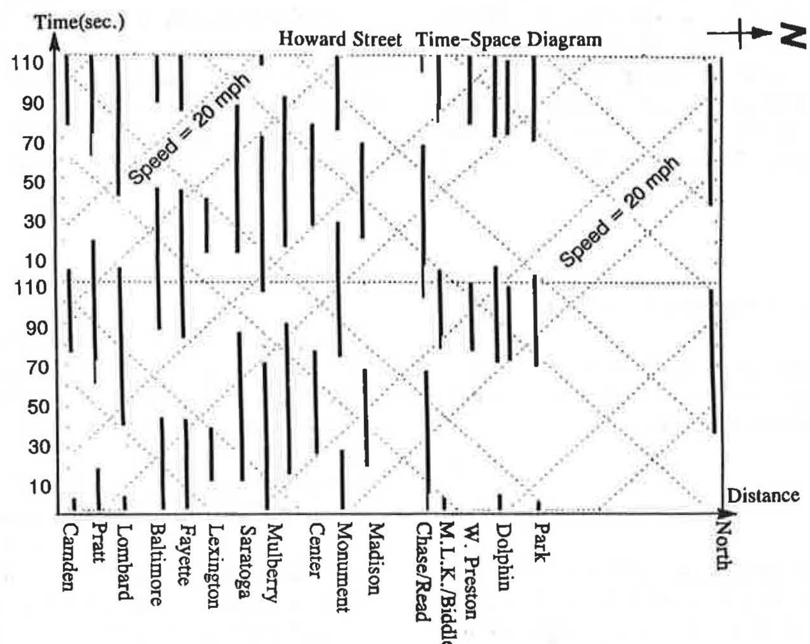

FIGURE 4 Existing signal timing on Howard Street.

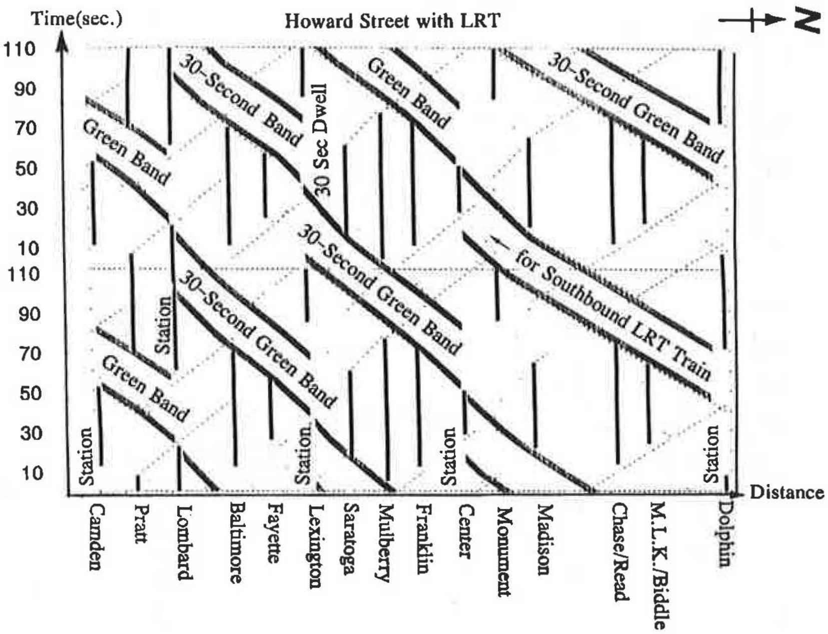

FIGURE 5 Adjusted signal timing (with LRT).

interval is defined as the time period during which the front of the LRT train can safely enter an intersection given the required clearance time (i.e., the green interval equals the green band less the clearance time).

For the best case, as defined by a 30-sec green bandwidth and a one-car train, the LRT green interval was calculated to be 19 sec for signals next to LRT stations and 24 sec for signals between stations. For the worst case, as defined by a 25-sec green bandwidth and a three-car train, the maximum LRT green interval was 9 sec for signals adjacent to stations and 10 sec for signals between stations. On the basis of these results and following discussions with LRT operations analysts, 30 sec was selected as the preferred green bandwidth for LRT. This interval accommodates the proposed longer train length and likely run time variability of the manually operated LRT system. It also allows some flexibility in protecting left turns from Howard Street onto certain side streets, turns that can only be made safely when LRT movements are restricted.

EFFECTS OF LRT ON CROSS-STREET TRAFFIC

The effects of LRT operations on cross-street traffic on Howard Street were analyzed in terms of changes in cross-street progression and intersection level of service.

Cross-Street Progression

Impacts were assessed by comparing two scenarios, with LRT and without LRT, in terms of green bandwidth. Table 2 summarizes the direct effects on cross-street green intervals and green bands as a consequence of proposed LRT operations.

The moderate to large changes in green intervals or green bandwidth or both occur on Pratt, Baltimore, Fayette, Saratoga, Franklin, Centre, Monument, and Dolphin/Preston streets. Since there is no progression on Fayette, Saratoga, Centre, and Dolphin/Preston streets, the changes in green intervals at their intersections with Howard Street will affect only the intersection level of service. For Pratt, Baltimore, Franklin, and Monument streets, a close examination of the time-space diagrams indicated that the changes in cross-street green bandwidth at Howard Street can be minimized or restored by adjusting signal offsets at the downstream or upstream intersections, or both, along each cross street.

Little or no change in green intervals or green bands occurs at other cross streets. One case receiving special study is the interconnected Chase/Read and MLK intersections. Because of the unique LRT alignment, intersection redesign involving a shift from the center of Howard Street to the east side right-of-way is under study in the area for both LRT and traffic to operate properly.

Detailed Analysis of Impacts

As an example of how cross-street progression can be maintained despite potential LRT signal timing conflicts, time-space diagrams for existing with LRT and revised with LRT conditions along Franklin Street have been included as Figures 6 and 7.

Franklin Street is a westbound-only arterial with a wide potential green band for traffic (35 sec). With improved signal timing at the Howard Street intersection to accommodate LRT, the offset shifts and narrows the green band to less than 30 sec, as shown in Figure 6. The signal timing at the Upper St. Paul and Charles Street intersections constrains the potential bandwidth.

TABLE 2 Effects on Cross-Street Green Resulting from Howard Street LRT Operation

	W/O LRT			W/ LRT						
Intersection	Offset	Howard Street Green	Side Street Split	Offset	Howard Street Green	Side Street Split	Changes In Side Street Green	Level of Change	Changes In Side Street Band	Level of Change [1]
Howard &										
Camden	6	70	40	59	70	40	0	None	0	None
Pratt	20	52	58	8	62	48	-10	Moderate	-15	Large
Lombard	7	34	76	22	38	72	-4	Little	0	None
Baltimore	45	42	68	69	53	57	-11	Moderate	-12	Large
Fayette	44	39	71	56	79	31	-40	Large	0	No Band
Lexington	40	84	26	0	84	26	0	None	0	None
Saratoga (SB)	86	38	72	60	68	42	-30	Large	0	None
Mulberry	71	34	76	76	39	71	-5	Little	0	None
Franklin	90	37	73	71	51	59	-14	Moderate	-11	Moderate
Centre	77	60	50	50	88	22	-28	Large	0	No Band
Monument	29	45	65	0	83	27	-38	Large	-29	Large
Madison	68	63	47	64	67	43	-4	Little	0	None
Chase/Read [2]	67	51	59	73	50	60	1	Little	0	No Band
MLK/Biddle [2]	6	78	32	63	70	40	8	Little	0	No Band
Preston (Closed)	0	77	33	0	110	0	NA	Closed	NA	Street Closed
Dolphin/Preston	8	63	47	53	83	27	-20	Large	0	No Band

[1] Level of change relative to existing band
[2] Future lane configuration still undetermined, therefore timing and phasing subject to change

The offsets on both Upper St. Paul and Charles streets can be adjusted, however, to cause their green intervals to occur sooner and consequently shift the green band and restore its original width (see Figure 7). Although the offset changes will have some effect on any progression along either Upper St. Paul or Charles Street, analysis of existing signal timing for these streets indicated that the proposed Franklin Street offset adjustments would not have significant traffic effects. Neither street has evident progression. A timing adjustment should have no effect as long as total green time is unchanged.

The other progressive streets were similarly analyzed for timing adjustments that would restore potential green bands. Except for Baltimore Street, it was possible in all cases to adjust downstream or upstream signal offsets, or both; restore the existing bandwidth; and not significantly affect other cross-street traffic. In the case of Baltimore Street, the offset change at Howard Street divided the existing progression into two pieces but did not reduce the existing bandwidth. Since existing progression along Baltimore is considered poor, the substitution of piecewise progression is not expected to have a significant effect on intersection operation. Nonetheless, monitoring of conditions would be recommended should LRT timing plans be implemented as proposed.

Intersection Performance

The effects of LRT on intersections along Howard Street were determined by performing capacity analysis for two scenarios: with LRT and without LRT. Steps required to establish future traffic conditions on Howard Street were as follows: (a) identify future lane configurations and turning movements, (b) estimate

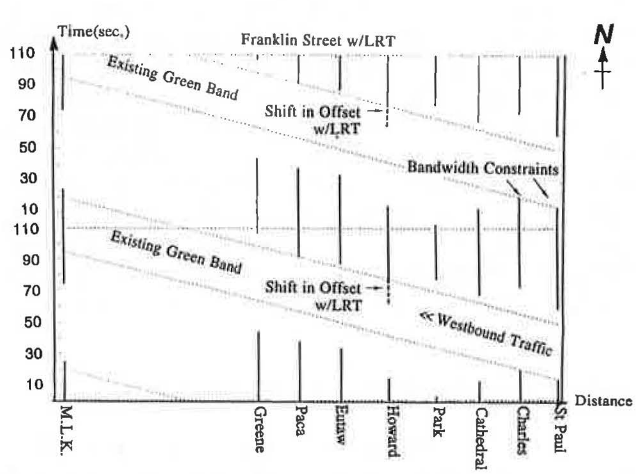

FIGURE 6 Effects of LRT signal timing, Franklin Street.

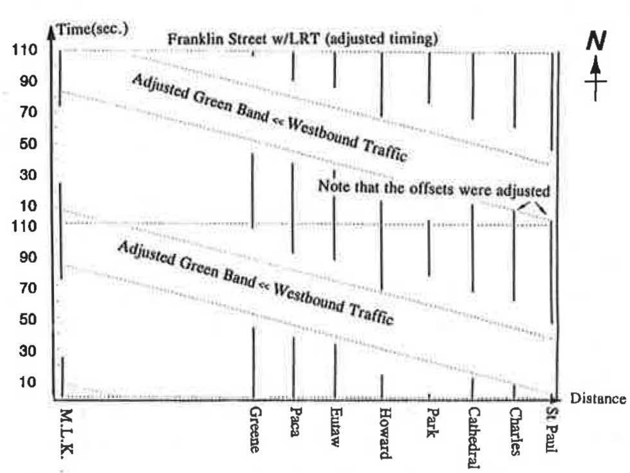

FIGURE 7 Adjusted signal timing (with LRT), Franklin Street.

future traffic volumes, and (c) establish future traffic signal timing and turning phases for Howard Street intersections.

The changes in traffic flow due to LRT implementation included converting the segments of Howard Street between Fayette and Madison to a one-way northbound street for transit buses only. Only LRT will operate freely southbound in this area.

Assumptions used to develop future traffic volumes included inflating 1988 count volumes by an annual rate of 0.5 percent; diverting southbound traffic on Howard Street to parallel north-south arterials on the basis of evaluations of existing turning movements and intersection capacity; and rerouting cross-street traffic currently turning onto Howard Street along the closest parallel north-south arterials that permit similar turning movements. Future bus traffic, modified to reflect route changes to be implemented with LRT service, was added to the automobile traffic. Using 2 sec average car headway, 16 sec maximum intersection clearance time for LRT, 2.5 passenger car equivalents for a typical bus, and an average LRT headway of 7.5 min per direction, the hourly LRT volume was converted to 26 bus equivalents per hour per direction.

Future signal timing data were obtained from the time-space diagram for Howard Street with LRT on the basis of the 30-sec (bidirectional) green bandwidth (Table 2). At five locations a third phase for protected left-turn movements required for traffic leaving Howard Street was added.

Level-of-Service Results

Table 3 shows the results of the capacity analysis for intersections on Howard Street. Level of service (LOS) is indicated for a base year (1988) and the target opening year (1991) for LRT. Cross-street LOS is calculated, in addition to intersection LOS, in order to isolate the operational impacts on the downtown east-west arterials carrying major automobile traffic volumes.

Only one intersection was found to suffer a major degradation in service as a result of signal timing changes for LRT. Centre Street at Howard Street will fail (LOS F) with significant reduction in cross-street green time. An additional 15 sec in green time for Centre will bring the LOS up to an acceptable level (LOS D). The eastbound approach for Pratt Street at its intersection with Howard Street was found to degrade to LOS D in 1991 from an existing LOS B. A few additional seconds in green time for eastbound traffic will improve the LOS to C.

The performance of the Dolphin-Preston/Howard Street intersection was found to fail under both existing and future conditions. The westbound and eastbound approaches tend to worsen in the future with LRT signal timings. It is clear that intersection performance cannot be improved without modifying intersection geometry.

Three other intersections, at Fayette, Saratoga, and Monument, were found to experience modest deterioration in LOS, all going from an LOS B to C. For the remaining Howard Street intersections (Lombard, Baltimore, Mulberry, Franklin, and Madison), effects of LRT timing changes were found to be insignificant.

TABLE 3 Level of Service for a.m. Peak Hour

Intersection		1988 Base Year	1991 Opening Year
Camden	Whole Intersection	C	B (1)
	Side Street (WB&EB)	C	C
Pratt	Whole Intersection	C	C
	Side Street (EB)	B	D (2)
Lombard	Whole Intersection	B	B
	Side Street (WB)	B	B
Baltimore	Whole Intersection	C	B
	Side Street (EB)	B	B
Fayette	Whole Intersection	B	C
	Side Street (WB)	B	C
Saratoga	Whole Intersection	B	C
	Side Street (WB)	B	C
	Side Street (EB)	B	C
Mulberry	Whole Intersection	B	B
	Side Street (EB)	B	B
Franklin	Whole Intersection	B	B
	Side Street (WB)	B	B
Centre	Whole Intersection	B	FAIL (3)
	Side Street (EB)	B	FAIL (3)
Monument	Whole Intersection	C	B
	Side Street (WB)	B	C
	Side Street (EB)	B	C
Madison	Whole Intersection	B	B
	Side Street (WB)	B	B
Chase/Read	Whole Intersection	C	(4)
	Side Street (EB)	C	(4)
MLK	Whole Intersection	Fail	(4)
	Side Street (WB)	E	(4)
Dolphin/Preston	Whole Intersection	Fail	Fail
	Side Street (WB)	E	Fail
	Side Street (EB)	C	D

(1) Assumes no RT from SB Howard Street in opening year
(2) By adding 3 seconds to Pratt Street the LOS will be "C"
(3) By allocating an additional 15 seconds to Centre Street the LOS will be "D"
(4) Intersection improvements still uncertain; addition of separate LRT or combined LRT/SB Howard phase to existing geometry will likely result in intersection failure at both MLK and Chase/Read

EFFECTS OF LRT ON STREET NETWORK AS A WHOLE

To evaluate the effects of LRT operation on the street network and on Howard Street as a whole, the simulation capability of TRANSYT-7F was used. Three simulation runs were performed: existing conditions, target year without LRT, and target year with LRT.

Network Definition

The network for TRANSYT-7F simulation, as shown in Figure 1, included Howard Street and the portion of the street network that will be affected directly by LRT operations. North-south intersections along Eutaw Street and Park Avenue, and selected east-west intersections along Pratt, Lombard, Baltimore, and Fayette streets, were included because signal timing at these intersections will need to be modified to produce the desired green band for the LRT. The resulting network, consisting of 47 total intersections with LRT passing through 15 intersections, represents a manageable network size that can reasonably be used to assess LRT effects.

Model Calibration and Development of Scenarios

The base year was simulated by using intersection signal timing, lane configurations, and observed arterial operating speeds for existing traffic conditions. Individual link performance, as measured by the degree of saturation flow and the length of maximum queue, was examined. The maximum calculated queue length for a selected number of links was compared with field conditions.

The scenario of 1991 without LRT differed from the base-year scenario only in the traffic volumes. The without-LRT scenario, required to isolate the effects of LRT, was created by increasing the base-year traffic volumes by 0.5 percent for 2 years. For the with-LRT scenario, the new signal timing data proposed for LRT progression were used. LRT movements were modeled as bus traffic by inserting additional transit links into the network and assigning 26 bus equivalents per hour per direction. A dwell time of 30 sec at the predetermined LRT stations was also used. To further account for the increased friction between LRT and vehicle traffic, the platoon dispersion factor of the model was changed from the default value of 0.35 to 0.45. Modifications to the traffic volumes were also included to reflect changes in traffic rerouting resulting from the LRT operations.

Effects on the Network

Nine measures of effectiveness (MOEs) for system performance were used to evaluate the effects of LRT on the street network. The MOEs were (a) total distance traveled by all vehicles per hour, (b) total travel time by all vehicles per hour, (c) total vehicle delays per hour, (d) average vehicle delay, (e) total number of vehicle stops per hour, (f) total fuel consumption in gallons per hour, (g) total estimated operating costs in dollars per hour, (h) average system speed, and (i) performance index.

The results, as shown in Table 4, quantify the effects of LRT operations relative to the scenario of 1991 without LRT. LRT was found to increase the total distance traveled, travel time, delay, number of stops, and operating costs. On average, individual vehicle delay will increase by 2.3 sec (or 14 percent), and average operating speed will decrease by 0.8 mph (or 7 percent). However, the magnitudes of change in the systemwide MOEs indicate only moderate traffic effects from LRT.

SUMMARY, CONCLUSIONS, AND FUTURE ACTIVITIES

The feasibility of enhancing bidirectional movements of LRT trains along Howard Street while keeping the traffic effects to a minimum has been examined. The focus was on identifying a potential green band for LRT operations and quantifying potential changes in cross-street traffic progression, intersection LOS, and network performance.

The existing cross-street progression was analyzed using existing signal timing data by graphically showing the potential green band along each major east-west arterial intersecting Howard Street from Camden Street (south) to Preston/Dolphin Street (north). Future with-LRT cross-street progression was similarly analyzed using the revised offsets and green times that resulted after imposing a 30-sec LRT green band along Howard Street.

Four cross streets—Pratt, Baltimore, Franklin, and Monument streets—were found to experience significant changes in progression following the introduction of LRT along Howard Street. It was shown, however, that satisfactory progression could be restored to Pratt and Franklin streets by making moderate adjustments to the signal timing at selected intersections, either east or west of Howard Street. The loss of progression along Monument Street was found not to be significant for traffic operations. The proposed with-LRT signal timing at the Baltimore and Howard intersection blocks the progression, dividing it into piecewise progression.

Intersection operations for Howard Street and major cross-street intersections were determined by comparing levels of service for existing without-LRT and future with-LRT (1991) conditions. The analysis found that the proposed with LRT signal timing changes did not significantly reduce intersection performance, with one exception: Centre Street at Howard Street. The poor performance of the Dolphin/Preston Street intersection, both for existing and future conditions, appeared to require improvements to intersection geometry or a redesign of traffic operations before changes in LRT signal timing plans would be warranted.

Certain traffic treatments along Howard Street are still under review. The LRT station between Lexington and Saratoga

TABLE 4 Changes in Systemwide Measures of Effectiveness Resulting from the LRT Operation

Scenario	Measure of Effectiveness								
	Total Distance Traveled (veh-mi/h)	Total Travel Time (veh-h/h)	Total Delay (veh-h/h)	Average Delay (sec/veh)	Total Uniform Stops (veh/h)	Total Fuel Consumption (gal/h)	Operating Cost ($/h)	Average Operating Speed (mi/h)	Perfor-mance Index
Base Year Condition	7,940	758	406	16	46,722	850	2,550	11	419
1991 without LRT	8,017	767	412	16	47,314	860	2,580	11	425
1991 with LRT	8,139	840	477	19	52,983	933	2,767	10	492
% Change from 1991 w/o LRT	2%	10%	16%	14%	12%	8%	7%	-7%	16%
% Change from Base Year	3%	11%	17%	14%	13%	10%	9%	-7%	17%

streets has been split, with the southbound platform moved one block south between Lexington and Fayette, in order to better serve commercial uses along Howard Street. Further changes in turning movements and station locations will likely require reconstruction of the LRT green band and revisions to signal offsets and green time.

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