Predictive Priority for Light Rail Transit

University Light Rail Line in Salt Lake County, Utah

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The goal of this paper is to assess the operational implementation of strategies for predictive light rail priority through microsimulation. A 2-mi corridor in Salt Lake County, Utah, where the University Line of light rail line operates, was studied. The study used VISSIM microsimulation models to analyze light rail operations and the effects that light rail priority has on transit and vehicular traffic. Results showed that although the existing priority strategies had no effects on vehicular traffic along the corridor, they reduced train travel times by 20% to 30%. Left turns along the main corridor were slightly affected by the priority. Although the priority strategies could have minor to major effects on vehicular traffic along side streets through increased delays, they reduced train delays by 2.5 min along the corridor. Enabling priority at the 700 E intersection (where the priority was currently not active) would help reduce delays for trains by an additional 10%, with a small increase in vehicle delays. However, the coordinated north–south through movements would experience minimum impacts. Three recommendations emerged from the study: enable priority at 700 E to improve transit without major effects on vehicular traffic; reset priority parameters at intersections adjacent to light rail stations so that the priority call encompasses station dwell times; and consider removing the queue jump strategies, so as to reduce delays for the corridor through movements and help preserve coordination patterns.

Light rail transit (LRT) is the fastest growing rail transit mode in the United States (*1*). LRT has been operating in Salt Lake County, Utah, for more than 10 years, with a great share of transit riders. Utah Transit Authority's (UTA) goals are to maintain LRT operations on a high quality level and make this transit mode more competitive with private cars. UTA's LRT priority control is integrated into the areawide traffic management system, developed separately by the Utah Department of Transportation (DOT) in conjunction with Salt Lake County and Salt Lake City. This system uses tiered progression techniques to provide priority service for LRT vehicles (LRVs) with minimal disruption to traffic signal operation. A combination of techniques are used, such as background timing plans, virtual preemption, and priority control (*2*).

Benefits and effects of the LRT and its priority strategies could not be assessed through field measurements because experimenting with controller settings in the field would bring major traffic disruptions and the results could not be guaranteed. For that reason, a study was begun in which traffic simulation was used to evaluate LRT and traffic operations on a part of the University Line LRT. The main methodology and results are described in this paper.

The research question is whether the LRT priority is justified from transit and general purpose traffic perspectives. The goal of the paper is to assess the operational implementation of the LRT predictive priority strategies. The objective is a trade-off analysis between transit preferences and effects on traffic. The field of study consists of a 2-mi corridor with 12 signalized intersections along the 400 S/500 S corridor, where the University line operates. The study uses VISSIM microsimulation models and Siemens NextPhase Software-in-the-Loop traffic controllers to analyze LRT operations and the effects that LRT priority has on transit and vehicular traffic.

This paper is organized as follows. The next section gives a review of the literature for LRT, transit signal priority (TSP), and use of traffic simulation in these fields. A description of the project and data collection processes follows. The methods of creating, calibrating, and validating simulation models are given in the section on modeling methodology. Results obtained through microsimulation and a discussion of the results are presented next. The major conclusions of the study are discussed in the final section.

LITERATURE REVIEW

LRT was developed from other rail transit modes in the 1950s. It was introduced as a separate rail transit mode in North America in 1972. The TRB Committee on LRT defines LRT as a metropolitan electric railway system that can operate single cars or short trains along exclusive rights-of-way at ground level, on aerial structures, in subways, or in streets and can board and discharge passengers at track or car-floor level (*1*).

To make LRT faster, safer, and more reliable, it is necessary to provide certain priority or preemption to LRVs. Depending on the specific location, traffic operations, and safety requirements, either TSP or preemption for LRT are implemented. TSP is an operational strategy that facilitates the movement of in-service transit vehicles through signalized intersections. It makes transit faster, more reliable, and more cost-effective (*3*). The most important benefits are improved schedule adherence and reliability and reduced travel time for transit. Potential negative effects consist primarily of delays to vehicular traffic, and these delays have proved to be minimal (*3*).

Preemption is conceptually different from TSP. TSP only modifies the normal signal operations to facilitate transit. Preemption interrupts the normal process for special events, such as emergency vehicles or trains, and serves these vehicles without any delay. A study of the downtown Baltimore LRT line showed that preemption is not the best option to provide priority for LRT (*4*). This strategy has large negative effects on vehicular traffic, especially in highly

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congested areas. An upgrade of the system was proposed that would accommodate TSP possibilities enabled in the National Transportation Communications for ITS Protocol (NTCIP) 1211 standard, which allows a number of priority alternatives. The same conclusions were drawn for the Hudson–Bergen LRT line in New Jersey, where it was proposed that preemption be substituted by TSP software on the basis of the NTCIP 1211 standard (*5*).

Priority treatment for LRVs follows detection and subsequent priority request activation. Because of the complexity of the LRT priority treatment, a new approach, called the predictive priority concept, has been developed to provide priority for LRT on a network level (*6*). The predictive priority concept uses TSP strategies and peer-to-peer communications between intersections. It provides requests for priority service in advance and uses detection information to reduce uncertainty. There are three major goals of this concept (*7*). The first is to provide additional LRV service phase opportunities within the existing signal phasing. The second is to provide communication between intersections that sends information about approaching trains. The third goal is to prepare the intersections for the train without causing additional delay to vehicle or pedestrian traffic and to serve the train quickly, maintaining coordinated signal operation.

Traffic simulation is a powerful tool to analyze different aspects of traffic and transit operations. A Central Phoenix–East Valley LRT Project study used VISSIM microsimulation to evaluate three different alternatives for providing priority for LRT: NEMA TS 2 Railroad Preemption, NEMA TS 2 Transit Priority (green extension/early green), and Type 2070/VS-PLUS predictive priority (*8*). The study results showed the advantages of the predictive priority concept, which gave the best balance between LRT benefits and effects on vehicular traffic. A follow-up study of the same LRT line used VISSIM simulation coupled with Siemens NextPhase virtual traffic controllers to estimate the predictive priority abilities of the software that would be implemented in the field (*9*). Another integration of VISSIM simulation software and the Siemens NextPhase virtual traffic controller was used to simulate predictive priority for an LRT line in Houston, Texas (*7*). This study showed the benefits of this concept and justified its implementation in the field. A study of the 3rd Street LRT in San Francisco, California, compared four options of providing priority for LRVs (*10*). The first two options were with fixed time conditions (optimized for LRVs and vehicular traffic), the third was NextPhase software, and the last was VS-PLUS software. The study showed the numerous advantages of NextPhase and VS-PLUS over fixed signal timings. Predictive priority was also tested on the Huntington Avenue LRT corridor in Boston, Massachusetts, by using VISSIM and vehicle actuated programming (*11*). The advance detection and subsequent cycle adaptation were proved to provide improvements to light rail travel time and regularity with negligible effects on other traffic. They were also found to be more effective than simple preemption.

This paper explains how predictive priority works and how different TSP strategies can be combined in this concept. Microsimulation and NextPhase Software-in-the-Loop traffic controllers are used to analyze benefits and the effects of LRT operations and predictive priority strategies.

PROJECT DESCRIPTION

The University Line LRT [part of UTA's LRT system, Transit Express (TRAX)] connects the University of Utah campus and downtown Salt Lake City, providing further transit connections. The line is 5.7 mi long with 14 stations. The terminals of the line are the Medical Center Station and Salt Lake Central Station. The TRAX line is shown in Figure 1.

This project addresses a University line corridor along the 400 S/500 S Streets, from Main Street to 1300 East (Stadium station). This corridor is 2 mi long with 12 signalized intersections.

During peak hours the intersections operate in a coordinated pattern. Along the studied corridor, the eastbound and westbound through movements are coordinated (except at 700 E). During the studied p.m. peak period, intersections operate on a 120-s cycle. On weekdays, LRT trains operate 18 h a day on 15-min headways.

Unconditional predictive train priority is enabled at all intersections, except at 700 E. This is a major north–south arterial in this part of the county, and it is estimated that train priority at this

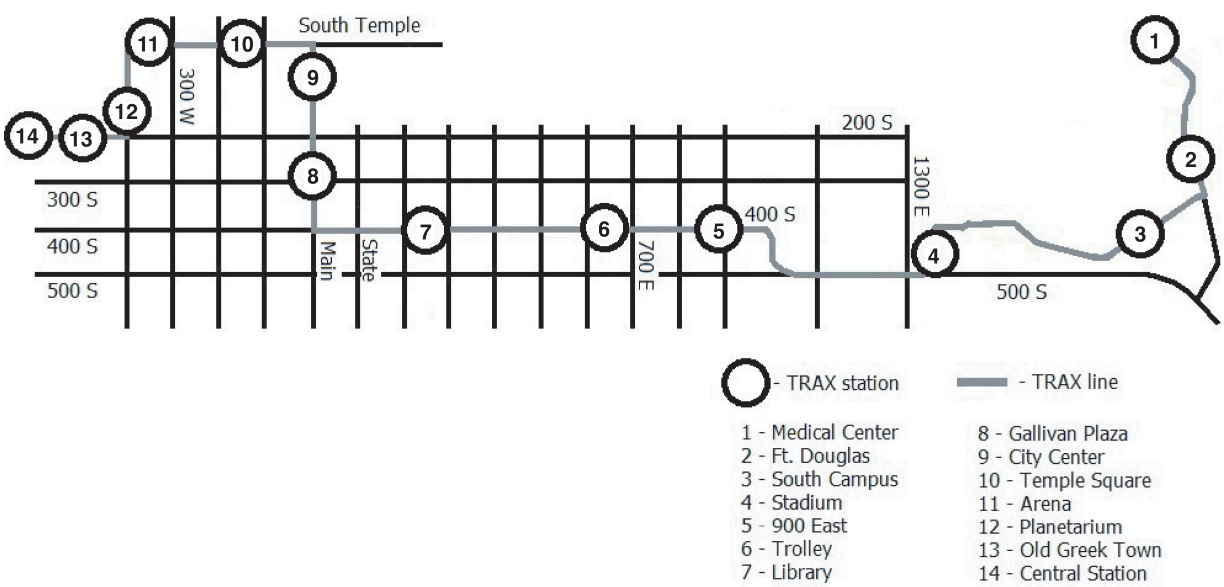

FIGURE 1 University TRAX line.

intersection would disturb main street coordination. The LRT priority is achieved by using overlap intersection phasing and a series of logical commands defined in the controllers. For every intersection controller, the signal settings have nine major parts:

1. General intersection setup,
2. LRT priority setup,
3. Green extend or insertion phases or both,
4. Early phase termination,
5. Phase rotation strategy,
6. Queue jumping,
7. Peer-to-peer calls,
8. LRT signage, and
9. Shared lane logic.

The general intersection setup defines general inputs (detector actuations), outputs (phases and overlaps), and NEMA TS 2 cabinet functions. The LRT priority setup defines basic LRT inputs, such as eastbound and westbound LRT check-in and checkout actuations and LRT advance and midblock calls. The outputs in this case are so-called state phases (generally, they turn on the "Train Approaching" or "Stay off Track" signs or both), and they serve as inputs for priority logic activation.

Green extend–insertion phases logic allows extra green time for LRVs once they have been detected approaching an intersection. There are several phases in phase rings used by the LRT overlap phases, depending on the moment in a cycle when an LRV has been detected. General logic for an intersection in this case is to extend the LRT phase overlaps until the train has cleared the intersection (reached the checkout point). However, this maximum time allowed for the LRVs is limited by the maximum phase time for the inserted phases, or until the LRT detectors have timed out. Usually, if the LRT detector is activated more than 90 s, it will be turned off automatically, which prevents LRT calls in the case of a detector failure (such as checkout failure).

If the LRT overlap is timing red when a train is approaching, the early phase termination logic will terminate all conflicting phases that are timing green at that moment to allow the LRT overlap to be served with priority. This logic turns the conflicting phases' detectors off, allowing these phases to be terminated once they have reached the minimum green time.

The intersections along this corridor, from State Street to 1300 E, operate with leading left turns and lagging through movements. If the LRT overlap is timing red when a train is approaching an intersection, the phase rotation strategy will rotate phases for through movements and left turns, allowing the through movements with concurrent LRT overlaps to be served first and the left turns after that. This phase rotation is achieved by using additional left-turn phases in the ring, which are activated through the phase rotation strategy.

The LRT overlaps are timing concurrently with the vehicular through movements along the main corridor. However, if a train and through vehicles are waiting at the red light at an intersection, the queue jumping logic allows an earlier start for the train. The start of the through movements will be delayed for 5 s, allowing the train to clear the intersection before the vehicles. The intention of this strategy is to improve safety, so that there would be no confused drivers who would attempt a left turn once the through movements get green and directly conflict the train.

A peer-to-peer call is information about the presence of trains that is being sent between intersections. In that way an intersection can start preparing for the approaching trains, turning on the "Train Approaching" sign or "Stay off Track" sign or both and going into the transition to allow train priority.

Special outputs from the controller logic settings are dedicated to the LRT signage. They turn on the "Train Approaching" sign or "Stay off Track" sign or both when a train is approaching an intersection and turn them off once the train has cleared it.

The shared lane logic is a special type of function active at the shared lane sites. Those are the sites where the left turns and trains share the same lane in the right-of-way. The sites along this corridor are 1300 E, 1100 E (westbound), 700 E (where the priority is not active), and State Street. The logic activates track clearance by allowing left turns before the train if there are left-turning vehicles in the shared lane. The "Stay off Track" signs are aimed to inform drivers not to enter the sharing left-turn lane if a train is approaching. However, it often happens that there are some vehicles in the lane in front of the train. The logic allows discharging of the left-turning vehicles and then allows the train to clear the intersection.

All of these strategies are aimed to facilitate LRT along the corridor with minimum effects on vehicular traffic. The true benefits and effects cannot be measured in the field, so they are addressed in this paper through microsimulation.

DATA COLLECTION

A series of data collections was performed along the corridor. These measurements were used to analyze current traffic and transit operations and to develop microsimulation models. The data collected in the field were intersection movement counts for three major intersections (1300 E, 700 E, and State Street), vehicular travel times, and LRT travel times. Intersection movements for other intersections were obtained from VISSIM models of this area that Fehr & Peers created in 2002. These flows were balanced to match the flows collected at the three intersections.

Travel time was measured for TRAX and vehicular traffic. The measurement was used to determine the level of service (LOS) for the vehicular traffic along the corridor. The *Highway Capacity Manual* defines LOS on urban streets according to the urban street class and the average travel speed along segments and corridors (*12*). The studied corridor belongs to the third urban street class with a typical free-flow speed of 35 mph (speed limit). Table 1 shows average travel speeds and travel times for vehicular traffic and TRAX along the corridor and its segments. LOS is calculated for vehicular traffic and given in the table. The data collected in the field were used to create microsimulation models and to calibrate and validate model parameters.

Modeling Methodology

LRT operations and the benefits and effects of the train priority were evaluated through VISSIM microsimulation models. Modeling and evaluations were performed for the p.m. peak period, from 4:00 to 6:00 p.m. Three model scenarios were used in the process: Base Case model, No Priority model, and 700 E Priority model. The simulation network consists of the corridor along 400 S/500 S from 1300 E to Main Street. This corridor is 2 mi long with 12 signalized intersections.

Base Case Model

The existing network was modeled, calibrated, and validated for field data (network geometry, traffic, and transit operations). The

TABLE 1 Arterial Travel Speed, Travel Time, and LOS

Segment	Vehicular Traffic			TRAX Average Travel Time (s)
	Average Speed (mph)	Average Travel Time (s)	LOS	
Eastbound				
Main St.–State St.	14.36	57	D	59
State St.–200 E	28.37	20	B	26
200 E–00 E	19.86	49	C	93
300 E–400 E	27.90	22	B	21
400 E–500 E	17.61	34	D	25
500 E–600 E	20.99	30	C	26
600 E–700 E	17.15	61	D	99
700 E–800 E	29.32	18	B	22
800 E–900 E	20.37	39	C	79
900 E–1,100 E	23.72	66	C	56
1,100 E–1,300 E	17.92	78	D	114
Total	16.17	474	D	620
Westbound				
1,300 E–1,100 E	29.68	40	B	48
1,100 E–900 E	24.34	63	B	66
900 E–800 E	16.28	46	D	64
800 E–700 E	15.62	45	D	91
700 E–600 E	28.67	21	B	63
600 E–500 E	17.16	50	D	26
500 E–400 E	18.70	39	C	18
400 E–300 E	15.03	51	D	27
300 E–200 E	18.64	37	C	81
200 E–State St.	12.12	63	E	47
State St.–Main St.	12.93	64	E	62
Total	14.50	519	D	593

final output from this process was a calibrated and validated simulation model of the existing conditions for the 2-h p.m. peak period, with 15-min buildup time. The same network model was later used in hypothetical scenarios. All VISSIM simulations were run for five random seeds, and all results represent averaged values from five measurements.

The network was created and loaded with traffic according to the data collected in the field in 2008 and 2009. The traffic was generated and distributed on the network by using static assignment. The traffic composition was defined as 98% passenger cars and 2% heavy vehicles. The speed distribution for vehicles along the corridor was defined according to the posted speed limits (35 mph along the main corridor) and field observations and measurements.

The field traffic controllers at intersections are Siemens NextPhase 1.7.4 controllers, which determined the choice of the signal control emulator in the VISSIM model. In this research, Siemens NextPhase 1.4.4 Software-in-the-Loop Virtual NextPhase (VNP) was used to model the actual traffic control because it uses the same traffic control algorithm as NextPhase 1.7.4. However, there were some limitations with the VNP controllers; some resulted from the different NextPhase versions, and some were the limitations in the VNP itself. The solution for some of the problems was suggested by the Utah DOT engineers. For example, the peer-to-peer calls could not be modeled as they are in the field, so for this purpose the advance and midblock train detectors were used.

The biggest limitations were at the intersections where left turns and LRT share the same right-of-way. VNP allows a maximum of 14 detectors per controller, whereas at these sites more detectors are needed. In the field some of these detectors are not physical detectors, but they are mapped through the controller logic. VNP demands that all VISSIM detectors be physical detectors that exist in the modeled network. In the model, this problem was overcome by defining maximum recall for the main coordinated phases, thus eliminating the need for detection for these phases. Also, the advance and midblock train detectors (which should be two different calls at these sites) were set to be the same. These actions solved problems for the shared lane sites.

Controller's operations and structure at the Main Street intersection are very complex, mostly because this controller handles eight phases for vehicular traffic, three conflicting LRT movements, and pedestrian operations in the downtown area. VNP was not equipped with all facilities of such complex controllers, so operations of this controller could not be modeled in VNP in the same way as executed in the field. For that reason the traffic controller for Main Street in the VISSIM model operated slightly differently from the field controller. However, considering that this intersection represents a bordering intersection of the model and that its controller operates in free mode, the operations of the Main Street traffic controller did not affect other intersections in the model.

The signal timing settings for the intersections were downloaded by using Utah DOT's i2 software, which enables a direct communication link to the field controllers. The controller logic settings were obtained from Utah DOT. LRT operations were also modeled by using field data. Arrivals and departures of the trains were modeled according to the real UTA train schedules for the University line. Also, the boarding and alighting of passengers at each LRT station were modeled on the basis of field data obtained from UTA.

Calibration and Validation of Base Case Model

Calibration and validation of the simulation model were based on the field traffic data. The model was calibrated for recorded traffic movements at the three major signalized intersections in the network: 1300 E, 700 E, and State Street. Travel times between each pair of signalized intersections were used to validate the model.

Intersection movements were compared for eight 15-min intervals. The comparison gave a high R^2 value of .99, showing a good correlation between the two data sets. The results were checked with a two-tailed *t*-test for paired samples, with a 5% level of confidence ($\alpha = 0.05$). The traffic movements from the field and the simulation were tested, resulting in a *t*-test value of 0.87, which proves good calibration efforts.

The 400 S/500 S corridor was divided into 11 eastbound and 10 westbound segments between each pair of signalized intersections. The field travel times were averaged from 14 eastbound and 15 westbound car runs and compared with the simulation travel times. For both directions, the R^2 value between the two sets was .91. The *t*-test values of 0.86 in the westbound and 0.09 in the eastbound direction shows that there was no statistically significant difference between the field and simulation travel times. Figure 2 shows calibration and validation results.

To validate TRAX travel times from the simulation, modeled travel times were compared with those from the field for each segment. The

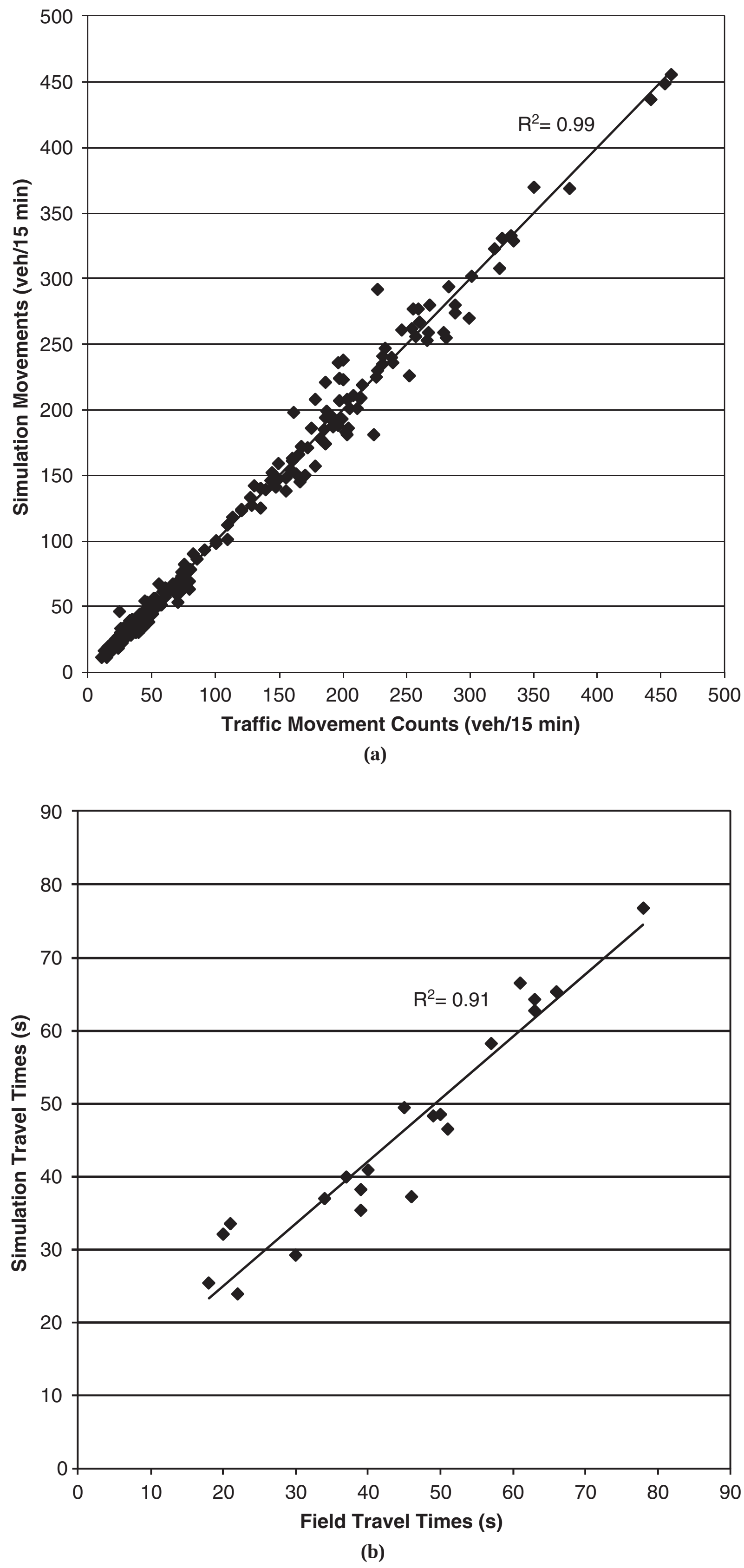

FIGURE 2 Model results: (*a*) calibration and (*b*) validation.

R^2 value between the two data sets was .93. The t-test values of 0.48 in the westbound and 0.85 in the eastbound direction show no statistically significant difference between the data sets.

No Priority Model

The No Priority model was developed to assess the effects of the LRT priority on transit and vehicular traffic. Results from the No Priority model were compared with the Base Case model to justify the use of LRT priority and show that the LRT priority does not have significant negative effects on vehicular traffic, while bringing significant benefits to LRT operations. The No Priority model represents a copy of the Base Case model, with the only difference being that the train priority is turned off. In the VISSIM model, no priority was accomplished by removing train detection at the intersections.

700 E Priority Model

In the existing conditions train priority exists at all intersections along the studied corridor, except at the 700 E intersection. 700 E is a major north–south arterial in this part of the county, and it carries more traffic than 400 S. For that reason the intersection of 400 S and 700 E facilitates coordinated traffic progression in the north–south direction. To prevent major coordination disruptions and increase in delays for the major traffic flows, the LRT priority originally designed for this intersection is not active. Train priority strategies for this intersection have been defined by Utah DOT; the phase splits for the LRT phases were defined as part of the present research effort. For the purpose of evaluating priority strategies at 400 S and 700 E, a VISSIM model with enabled train priority strategies at this intersection was developed. The results from the simulation were compared with the existing conditions to assess all benefits and effects that such an LRT priority would have.

RESULTS

Vehicular Travel Times

Usually a change in intersection signal timings or the provision of priority for transit vehicles can have some effects on vehicular travel times along a corridor. A comparison of travel times for the three described model scenarios is given in Figure 3.

Transit Travel Times

Transit travel time can be considered the attribute of a transit system that LRT riders care the most about. It is also important to transit agencies as an indication of the LOS offered to LRT riders. The TRAX travel times along the corridor were modeled in the three scenarios, and their comparison is shown in Figure 4.

Intersection Delays and Level of Service

The best way to assess performance of a signalized intersection is by investigating control delays at the intersection. Table 2 shows intersection delays per vehicle and the changes in delays for the two hypothetical scenarios compared with the Base Case.

To further investigate specific effects of the LRT priority at the 700 E intersection, simulation results for each intersection movement were analyzed individually. This type of analysis can help to identify how the LRT priority affects individual intersection movements and decide whether it should be enabled at this intersection. Table 3 shows movement delays per vehicle and the corresponding LOS for current conditions, the priority scenario, and the change in delays.

DISCUSSION OF RESULTS

This section provides major findings based on the results presented in the previous section. The results are discussed in the same order as they are presented.

Vehicular Travel Times

A comparison of vehicular travel times along the corridor given in Figure 3 shows that the general purpose traffic is not affected by the existing LRT priority strategies. Furthermore, it would not be affected if the train priority was given at the 700 E intersection. Some smaller changes in travel times along certain segments are caused by the changes in coordination patterns, resulting from the presence or absence of train priority. A two-tailed t-test for paired samples with a 5% level of confidence ($\alpha = 0.05$) was used to compare vehicular travel times between the three scenarios for both directions. Test results vary between 0.44 and 0.98, and they show that there is no statistically significant difference between the vehicular travel times.

Transit Travel Times

Opposite from the vehicular travel times, the LRT travel times would experience major effects if no priority is given. Without the existing priority, LRT travel times would increase approximately 30% in the eastbound and 20% in the westbound direction. The 700 E scenario results show that the eastbound LRT travel times would not be affected, whereas in the westbound direction the travel times would decrease approximately 3%. Overall, from the aspect of LRT travel times, providing LRT priority is justified.

Intersection Delays and Level of Service

Results on the average intersection delay and changes, given in Table 2, can provide an overall assessment of the intersection delays along the corridor. The existing train priority increases delays for vehicles at intersections by approximately 18 s (5%) along the entire corridor. The majority of the delay increase is experienced by vehicles on side streets, but some delay is also experienced by vehicles on through and left movements along the main corridor. The increase in delays on side streets is caused by earlier phase terminations or later phase starts or both when the LRT priority is active. Left turns along the main corridor are affected by the phase rotation strategy, which delays the start of left turns. The through movements along the main corridor are affected by the queue jump strategy, which delays the phase starts when this strategy is active, but also by the effects on coordination. When the LRT priority is active, signal controllers are forced to go through the transition process, which can affect the coordination along the corridor.

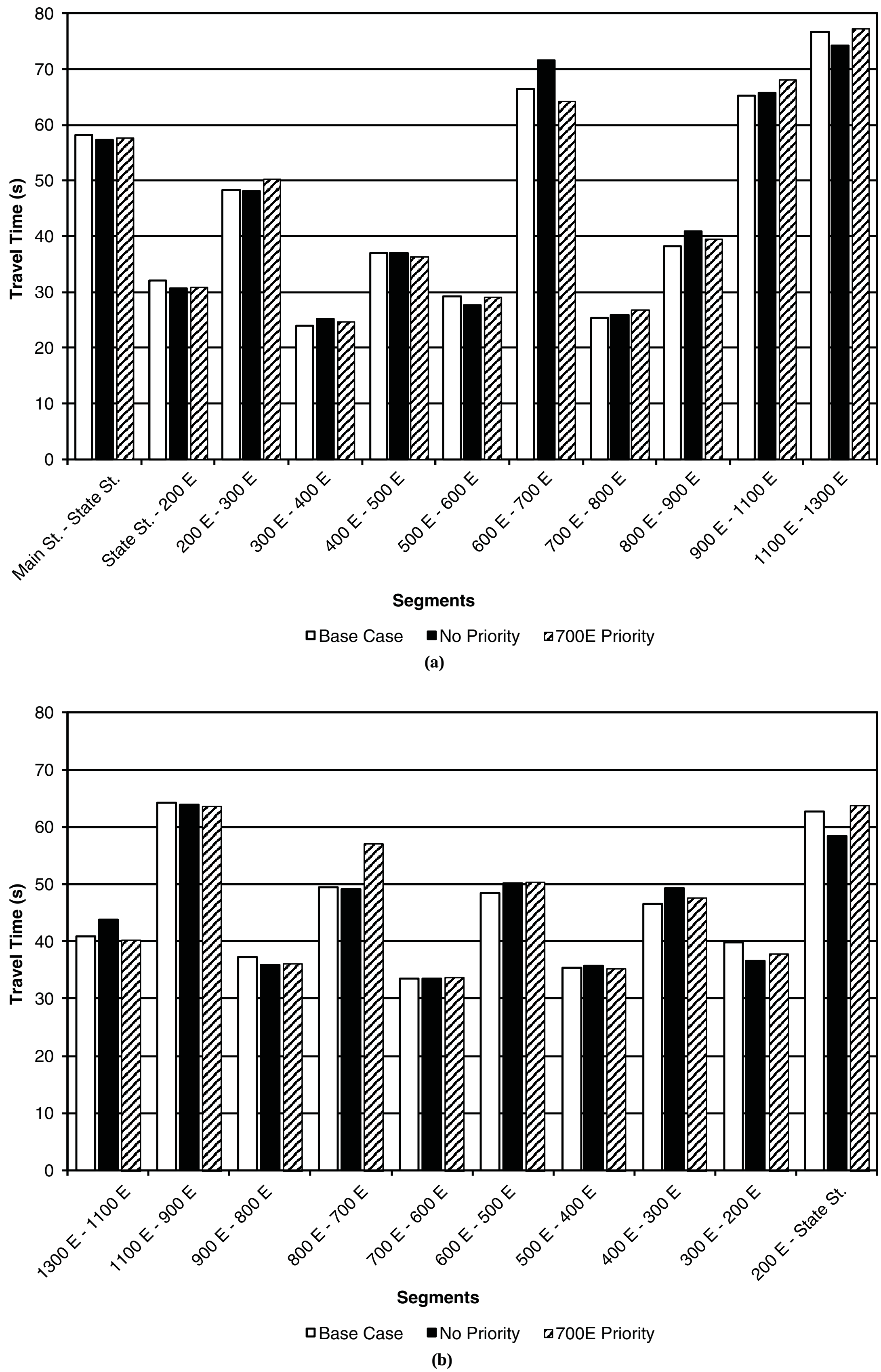

FIGURE 3 Vehicular travel times comparison: (*a*) eastbound and (*b*) westbound.

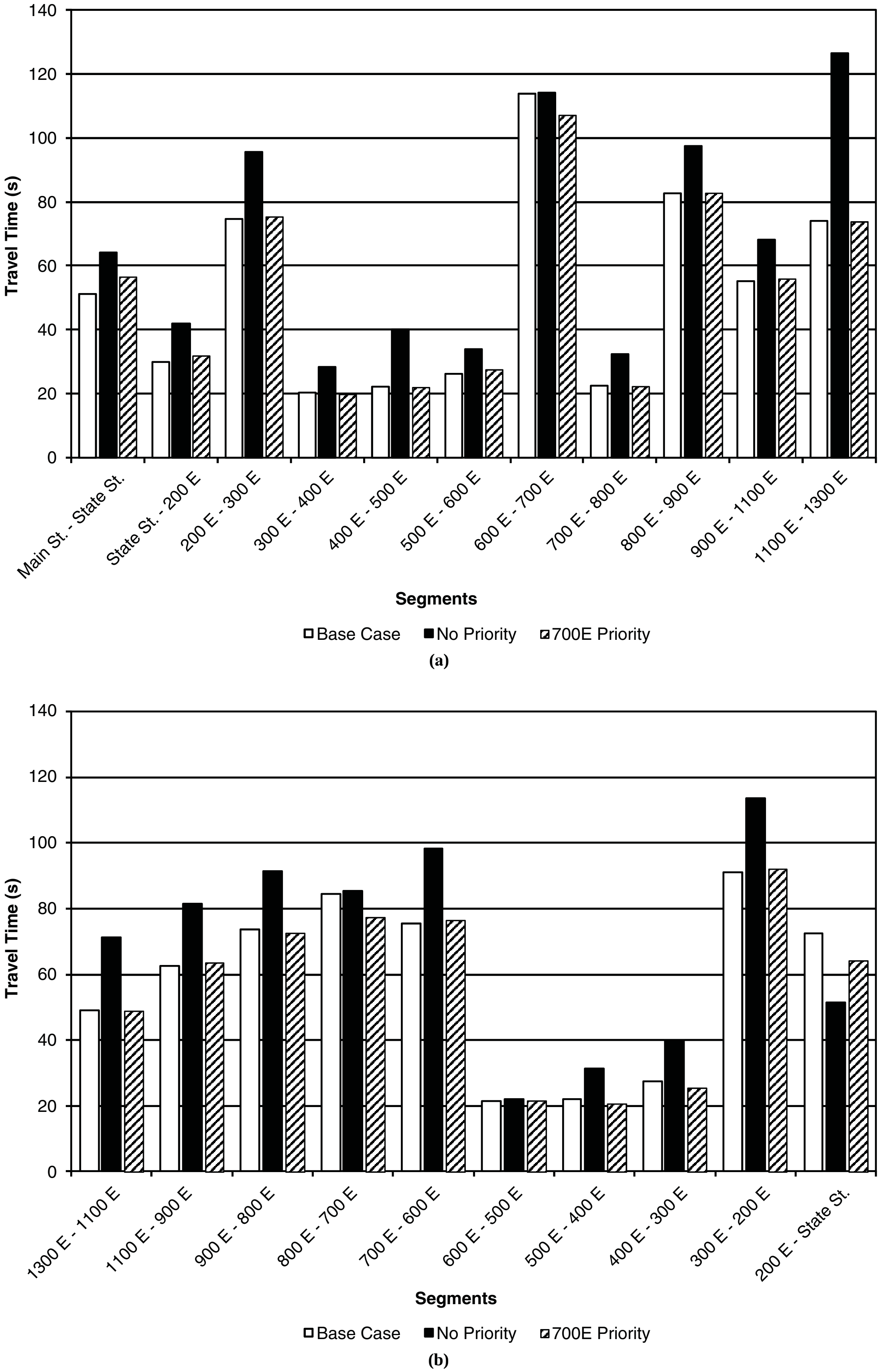

FIGURE 4 Transit travel times comparison: (*a*) eastbound and (*b*) westbound.

TABLE 2 Average Intersection Delays

		Base Case		No Priority			700 E Priority		
Intersection	Mode	Delay (s)	LOS	Delay (s)	Change (s)	Change (%)	Delay (s)	Change (s)	Change (%)
State St.	Car	39.1	D	34.6	–4.5	–11.5	38.0	–1.1	–2.8
	LRT	37.0	D	36.1	–0.9	–2.4	35.3	–1.7	–4.6
	All	38.8	D	34.8	–4.0	–10.3	37.6	–1.2	–3.1
200 E	Car	30.8	C	27.4	–3.4	–11.0	31.3	0.5	1.6
	LRT	16.5	B	36.9	20.4	123.6	17.3	0.8	4.8
	All	28.6	C	28.8	0.2	0.7	29.2	0.6	2.1
300 E	Car	39.0	D	36.8	–2.2	–5.6	38.7	–0.3	–0.8
	LRT	14.5	B	31.8	17.3	119.3	14.3	–0.2	–1.4
	All	35.5	D	36.1	0.6	1.7	35.2	–0.3	–0.8
400 E	Car	14.1	B	13.7	–0.4	–2.8	14.1	0.0	0.0
	LRT	4.2	A	11.3	7.1	169.0	3.1	–1.1	–26.2
	All	12.7	B	13.3	0.6	4.7	12.5	–0.2	–1.6
500 E	Car	39.4	D	38.6	–0.8	–2.0	41.3	1.9	4.8
	LRT	2.2	A	11.3	9.1	413.6	2.0	–0.2	–9.1
	All	34.1	C	34.7	0.6	1.8	35.7	1.6	4.7
600 E	Car	22.6	C	20.4	–2.2	–9.7	22.0	–0.6	–2.7
	LRT	12.2	B	22.8	10.6	86.9	13.2	1.0	8.2
	All	21.0	C	20.8	–0.2	–1.0	20.7	–0.3	–1.4
700 E	Car	35.1	D	36.9	1.8	5.1	37.7	2.6	7.4
	LRT	63.1	E	56.6	–6.5	–10.3	56.7	–6.4	–10.1
	All	39.1	D	39.7	0.6	1.5	40.4	1.3	3.3
800 E	Car	25.1	C	21.9	–3.2	–12.7	25.2	0.1	0.4
	LRT	11.8	B	25.1	13.3	112.7	11.2	–0.6	–5.1
	All	23.2	C	22.4	–0.8	–3.4	23.2	0.0	0.0
900 E	Car	28.3	C	26.5	–1.8	–6.4	28.2	–0.1	–0.4
	LRT	12.1	B	25.6	13.5	111.6	12.4	0.3	2.5
	All	25.8	C	26.4	0.6	2.3	25.8	0.0	0.0
1,100 E	Car	26.1	C	24.8	–1.3	–5.0	26.0	–0.1	–0.4
	LRT	5.8	A	23.0	17.2	296.6	6.2	0.4	6.9
	All	23.0	C	24.5	1.5	6.5	22.9	–0.1	–0.4
1,300 E	Car	41.3	D	41.6	0.3	0.7	41.3	0.0	0.0
	LRT	36.3	D	88.5	52.2	143.8	31.5	–4.8	–13.2
	All	40.6	D	48.3	7.7	19.0	39.9	–0.7	–1.7
Total	Car	340.9	N/A	323.2	–17.7	–5.2	343.8	2.9	0.9
	LRT	215.7	N/A	369.0	153.3	71.1	203.2	–12.5	–5.8
	All	322.4	N/A	329.8	7.4	2.3	323.1	0.7	0.2

NOTE: N/A = not applicable.

The real extent of the priority strategies can be seen when train delays at intersections are analyzed. The existing priority reduces LRV intersection delays by approximately 2.5 min (71%) along this corridor. If the train priority was introduced at 700 E, delays for vehicular traffic at this intersection would increase slightly. The main corridor would be affected by the phase rotation strategy (left turns) and the queue jump strategy (through movements). Along the entire studied corridor, priority at 700 E has almost no effects on vehicular traffic (0.9% increase in delays), and it slightly decreases intersection delay for trains (approximately 6%).

Detailed delay analysis for 700 E, presented in Table 3, can give a clearer picture of priority effects on each intersection movement individually. The results show that the southbound and westbound movements would experience a certain increase in delays (from 8% to 24%). The LOS would remain unchanged for the majority of movements. The westbound through movement, would drop from C to D. The southbound right turn would drop from A to B. Another movement with a slight increase in delays would be the northbound through movement; changes in delays for all other movements would be unnoticeable. Both light rail movements would experience a decrease in delays from 9% to 11%. Overall, priority at 700 E would increase delays for vehicular traffic approximately 7%, while decreasing delays for trains approximately 10% at this intersection.

CONCLUSIONS

The main conclusion of the study is that the existing priority brings major improvements to LRT, reducing travel times and delays. Because the University light rail line is the major transit line in this part of the county and carries many passengers throughout the day, its fast and reliable functioning is essential. The importance of the line justifies the implemented priority strategies, and the effects they have on the vehicular traffic are minimal when compared with the benefits they bring to transit.

A big concern of traffic and transit officials is the effects of train priority at the 700 E intersection. The analysis shows that certain effects could be expected, but they are minor for the coordinated

TABLE 3 Intersection Delay and LOS: Base Case Versus 700 E

Movement	Base Case Delay (s)	Base Case LOS	700 E Delay (s)	700 E LOS	Change in Seconds	Percentage Change
EBR	22.0	C	21.2	C	–0.8	–3.6
EBT	48.4	D	46.5	D	–1.9	–3.9
EBL	67.0	E	66.2	E	–0.8	–1.2
WBR	5.9	A	6.4	A	0.5	8.0
WBT	34.4	C	42.6	D	8.2	23.9
WBL	60.9	E	67.9	E	7.0	11.5
NBR	5.2	A	5.4	A	0.2	2.9
NBT	25.9	C	27.8	C	1.9	7.4
NBL	55.2	E	57.9	E	2.7	4.8
SBR	9.9	A	11.9	B	2.0	19.2
SBT	30.3	C	34.4	C	4.1	13.7
SBL	56.4	E	63.8	E	7.4	13.2
EBT LRT	61.1	E	55.6	E	–5.5	–9.1
WBT LRT	65.2	E	57.7	E	–7.5	–11.4
Car	35.1	D	37.7	D	2.6	7.2
LRT	63.1	E	56.7	E	–6.4	–10.3

NOTE: EB = eastbound; WB = westbound; NB = northbound; SB = southbound; R = right turn; T = through traffic; L = left turn.

north–south through movements, so effects on coordination along 700 E should be minimal. However, the priority would bring certain benefits for LRT, so the recommendation is that enabling priority at this intersection should be considered. Two more recommendations have emerged from the study. One is related to the priority calls at the intersections adjacent to train stations. The priority call for a certain intersection is placed when the train is at the previous one. However, the train dwells at the station for a certain amount of time (30 to 50 s, depending on the station and direction), so the priority call comes too early, causing the intersection to prepare for the train priority. The priority is active even if the train is stopped at the station, minimizing benefits that trains have from the priority, while having an effect on all conflicting traffic flows. Sometimes the priority call can even cause the priority to be active during two consecutive cycles, further increasing the effects on vehicular traffic. That is why it is recommended that the priority call be delayed for those intersections for at least 30 s, allowing more time to serve conflicting traffic. Effects on vehicles would be minimized, and the trains would get priority once they clear the station and approach the intersection.

The last recommendation concerns the queue jump priority strategy. When trains and vehicles are waiting at the red light, this strategy gives an earlier start to trains through delaying the through movements for 5 s. The intention of this strategy is to improve safety, so that there would be no confused drivers who would attempt a left turn once the through movements get green and directly conflict the train. However, all the left turns along the main corridor are protected, with an improved signage in the case of an approaching train. Also, this line has been in service for a long time, and most of the regular drivers along the corridor are familiar with the traffic patterns. These reasons can justify the idea of removing the queue jump strategy. It would decrease delays for the through movements and improve coordination along the corridor that is disrupted by the priority. These recommendations should be considered by traffic and transit officials. It is believed that an agreement to apply these recommendations in the field would be beneficial for vehicular traffic and LRT.

Future work should follow any changes in traffic and transit patterns, such as changes in traffic volumes, signal retiming, transit ridership, and train schedules. The microsimulation models developed for the study can be used to test any priority strategy as well as changes in signal timings or even to design changes before their implementation in the field. It can help to decide whether or not the proposed changes are justified.

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