An Evaluation of Light Rail Transit Signal Control Options

Thomas Bauer and Patrick Fuller

Abstract. As part of the Central Phoenix/East Valley Light Rail Transit Project, the Cities of Phoenix, Tempe and Mesa, Arizona are proposing a new light rail line, part of which will follow Central Avenue, a major north-south corridor in the City of Phoenix. The service is expected to initially operate with approximately 6-minute headways in both directions. The LRT tracks will be in the center median and will require the incorporation of either train preemption or priority into the signal control system.

This paper reviews the evaluation of three distinct LRT signal control strategies based on a microscopic simulation analysis of future traffic and transit operations through the Central Avenue corridor from Earll Drive to McDowell Road. The individual simulation models include a detailed emulation (in one case an actual interface) of the LRT priority or preemption logic of current off-the-shelf signal control equipment. The three analyzed strategies include:

- NEMA TS/2 with Railroad Preemption[1]
- NEMA TS/2 with Transit Priority (Early Green and Green Extension)
- Type 2070 Predictive Priority[2]

The three LRT signal control strategies are evaluated based on measures of effectiveness such as LRT travel time, general purpose traffic travel time, average intersection delay and queue lengths at critical approaches such as left-turns across the LRT tracks.

This detailed operational comparison using a variety of LRT and general purpose measures of effectiveness provides a good reference for traffic engineers faced with the task of selecting an appropriate LRT signal control strategy.

METHODOLOGY AND APPROACH

OVERALL PROJECT WORK PLAN

This simulation analysis is a task of the overall work plan, which includes the following tasks:

1. Conceptual Engineering Phase
   - SYNCHRO analysis of LRT intersection crossings on alignment, intersections within station areas, and intersections on parallel streets affected by diversion of traffic.
   - Qualitative analysis of impacts.
2. Preliminary Engineering Phase

- SYNCHRO and CORSIM analysis of intersection geometric requirements.
- CORSIM analysis of coordination versus LRT priority control of signals.
- **VISSIM analysis of priority control options for demonstration segment (subject of this paper).**

3. Final Design Phase
    - VISSIM analysis of intersections on alignment and on intersecting and parallel arterials.
    - Signal timings and geometric refinements.

DESCRIPTION OF SIMULATION TOOL – VISSIM

VISSIM is a microscopic simulation model developed to model urban traffic and public transit (including railroad) operations. The program can analyze traffic and transit operations under constraints such as lane configuration, traffic composition, traffic signals, transit stops, etc., thus making it a useful tool for the evaluation of various alternatives based on transportation engineering and planning measures of effectiveness.

VISSIM's traffic flow model is a discrete, stochastic, time step based microscopic model, with driver-vehicle-units (DVU) as single entities. The model contains a psychophysical car following model for longitudinal vehicle movement and a rule-based algorithm for lateral movements (lane changing). The model is based on the continuing work of Wiedemann (1974, 1991, 1999) at the University of Karlsruhe, Germany.

Vehicles follow each other in an oscillating process. A faster vehicle approaching a slower moving vehicle on a single lane has to decelerate. The action point of conscious reaction depends on the speed difference, distance and driver-dependent behavior. On multi-lane links moved-up vehicles check whether they improve their operation by changing lanes. If so, they check the possibility of finding acceptable gaps on neighboring lanes. Car following and lane changing together form the traffic flow model, being the kernel of VISSIM.

The simulation system itself includes first, the traffic flow model and, second, the signal control model (see Figure 1). The traffic flow model is the master program, which sends second-by-second detector values to the signal control program. The signal control uses the detector values to decide on the current signal state. Signal control itself can be performed by the programmable signal control software VAP (Vehicle Actuated Phasing), an external controller (e.g., interface to NEMA TS-2 or Type 170 controller or actual Type 2070 controller software ("virtual controller"). VS-PLUS, actual Type 2070 controller software, was used for this simulation analysis.

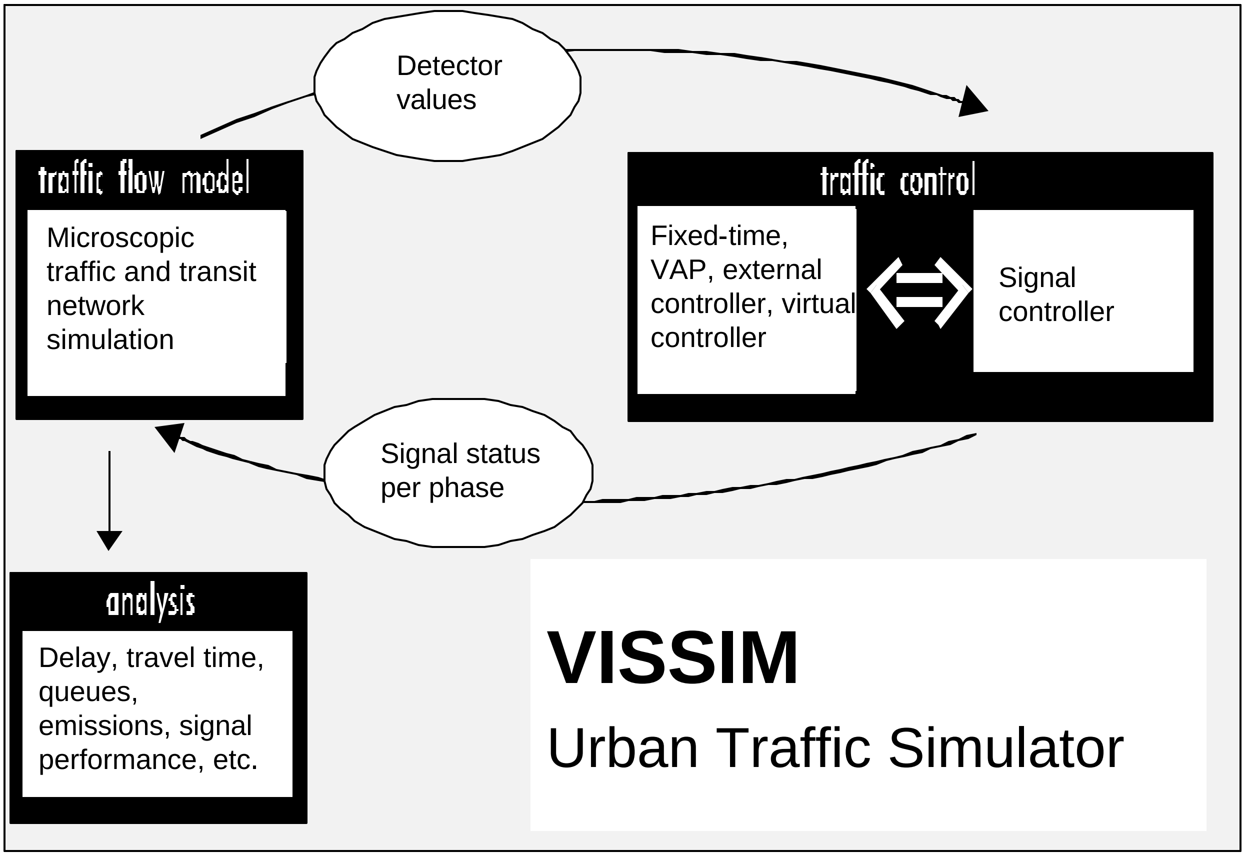

Figure 1. VISSIM Model Architecture

The basic element of the modeled network is a single or multilane link. The network is composed of links and connectors. A connector can be placed at any position on a link. Connectors are valid for all vehicles, certain types (i.e., buses) or a set of vehicles (i.e., only right turning vehicles). Cross section markers are used to model routing decision points for O/D modeling (large network) or turning movement percentage (single intersection).

Signal control is modeled by placing the signal heads at the positions of the stop lines. Detectors collect traffic flow data for the signal control (i.e., presence, gap, and occupancy) and for microscopic and macroscopic measurements (i.e., speeds, volumes, and travel times). Semi-compatible movements are modeled with a gap acceptance model.

A transit route is defined in VISSIM as a sequence of stops along routes. Transit routes can operate either on exclusive right-of-way or in mixed-flow lanes. Transit stops are either on the link or adjacent to it in case of a bus pullout. Transit vehicles enter the network according to their scheduled arriving time. Modeling of random "lateness" is accomplished by modeling transit stops (dummy stations) at the entrance to the network.

VISSIM generates arrival time and route (destination) for every vehicle arriving at the entry points of the network. The arrival profile is entered as hourly values for the PM peak period. Within one time interval VISSIM assumes a Poisson arrival distribution.

MODEL ASSUMPTIONS AND CHARACTERISTICS

STUDY AREA

The study area for the roadway network consists of the corridor following Central Avenue from Earll Drive to McDowell Road, including 6 signalized intersections.

TRAIN SCHEDULE

The simulation analysis uses actual proposed train schedules as part of the VISSIM base models. The resulting train headways are 6 minutes in each direction.

SIGNAL PHASING

The simulation analysis assumes signal phase sequences modified for project conditions. In particular, protected left-turns are added for all left-turn movements off Central Avenue to provide safe left-turn movements across the LRT tracks.

SIGNAL OPTIMIZATION

The TEAPAC software suite, including SIGNAL2000 and TRANSYT-7F, was used to optimize the signalized intersections in the model. The signal optimizations used a 100-second cycle length in order to accommodate increased pedestrian clearance times and protected left-turn phases for Central Avenue.

SIGNAL CONTROL

The three analyzed alternatives reflect different traffic and LRT signal control options. Alternative 1 assumes a NEMA TS-2 Type 1 signal controller using its railroad preemption logic for LRT control. Alternative 2 assumes a NEMA TS-2 Type 1 signal controller using its transit priority logic for LRT control. Alternative 3 assumes a Type 2070 signal controller with VS-PLUS 6.1 software using its predictive priority logic for LRT control. Alternatives 1 and 2 are modeled by replicating their respective control logic using VISSIM's VAP macro language. Alternative 3 is modeled by directly interfacing the VS-PLUS controller firmware as a "virtual controller" with VISSIM. Each of the analyzed alternatives is described in further detail below.

Alternative 1 - Railroad Preemption

General Description

Typical railroad preemption interrupts the normal signal operation process in order to provide safe operation during a close-by railroad crossing. The signal detects the approaching train and interrupts the phase that it is currently being served. The signal goes directly to serve the track clearance phase to clear any vehicles that may be stopped on the tracks. During this preemption event, minimum green times and pedestrian clearance intervals may be truncated (although avoided in this project as discussed in the following section). Although necessary from a safety standpoint, this process is very disruptive to normal signal operations.

LRT Priority Treatment

Using the NEMA controller's railroad preemption logic requires special cabinet wiring in order to provide a "GO" signal for the two LRT approaches. It is assumed that this signal would be turned on once both phases #2 and #6 show green and a preemption call is active. However, since the preemption call will stay active until the train has left the intersection, provision of a light rail clearance interval is not required. The specific NEMA controller allows for a two-tiered preemption call. The first call would inhibit further pedestrian calls across the tracks, while the second call would actually trigger the actual preemption event. This feature allows for an advanced pedestrian inhibit call before trains reach nearside stations in order to minimize their waiting time after passenger service is completed. The pedestrian inhibit also avoids truncating pedestrian clearances which leads to a safer operations. Since this alternative uses the railroad preemption logic, there is no explicit protection of vehicular minimum green times. However, this specific NEMA controller provides for a global minimum green time that is observed during a preemption event. This value was set to 7 seconds for this simulation analysis. After the checkout call is received, the controller first checks for the need to serve a special recovery (preemption exit) phase sequence. Spillback detectors are placed on the most critical approaches (typically Central Avenue left-turns) to determine if the actual demand warranted the service of those special recovery phases. However, the resulting phase sequence combined with the frequency of trains strongly suggests the use of lagging left-turns for Central Avenue. Otherwise, the controller would leave the preemption (phases #2 and #6), serve the exit phases (#1 and #5) before going right back to the coordinated phases (#2 and #6), resulting in tremendous impacts on the cross street phases (#4 and #8). After having served the recovery or exit phases, the controller utilizes short-way offset seeking in order to return to signal coordination.

Alternative 2 – NEMA TS-2 Transit Priority

General Description

Typical transit signal priority (TSP) is designed to modify the normal signal operation process to better accommodate transit vehicles. This specific NEMA controller provides two TSP strategies, early green and green extension. In the case of early green, the signal detects the transit vehicle (typically a bus) during a conflicting phase and begins to shorten the green time for phases preceding the phase(s) that serves the bus. This approach expedites turning the signal green for the bus without much disruption (and likely unnoticeable to motorists) of the other movements. In the case of green extension, the signal detects the approaching transit vehicle while its phase is served. It then holds this phase(s) in order to allow the bus to continue through the signal without stopping. Both strategies are designed to improve the service to the transit vehicle, while not interrupting coordinated signal operation. However, minor movement phases are not compensated for green time lost due to TSP. Therefore, in order to control the impact on those minor movements, the controller firmware features a fixed, non-user-definable "Re-arm" timer that prevents TSP calls during consecutive cycles.

LRT Priority Treatment

As with railroad preemption, the NEMA controller's transit priority logic also requires special cabinet wiring in order to provide a "GO" signal for the two LRT approaches. However, a special LRT clearance interval is required since the LRT "GO" signal can actually time out before the train has reached the intersection. LRT clearance times for two-car trains running at about 35 mph are typically in the range of 15 seconds, about 10 seconds longer than standard traffic clearance intervals. This clearance interval is created by using phases #2 and #6 for LRT "GO", phases #9 and #10 for LRT Clearance ("Flashing Stop") and overlaps between phases #2 and #9 and #6 and #10 for the automobile traffic parallel to the LRT tracks. This solution allows for safe LRT operation with the necessary clearance interval, but it also requires that phases #2 and #6 terminate together, which in turn requires leading left-turn operation along the LRT corridor.

As mentioned above, the objective of the controller's transit priority logic is to maintain coordinated signal operation at all times, while providing additional green time for the transit vehicle. While this objective completely protects the coordinated movements parallel to the tracks, it also prevents any green time compensation for minor movements such as the left-turn phases across the tracks. Furthermore, any additional green time given to the LRT phases has to come from the cross street phases out of a single cycle. This requirement and the fact that cross street through phases have extremely long associated pedestrian phases results in only minor early green or green extension time availability. In addition, the fixed "Re-arm" timer interval of one cycle causes rather random delay to light rail trains resulting in a negative impact on schedule reliability and thus on LRT operation.

Alternative 3 - VS-PLUS Predictive Priority

General Description

VS-PLUS is a phase-based controller software with 64 signal phases and operates without rings or barriers, instead using a matrix for phase conflict designation. Starting with its original development, VS-PLUS was designed for multi-modal urban signal control. Dynamically upgradeable priority levels that are assigned to the individual signal phases according to their level of importance allows for various levels of priority treatment for bus transit, light rail, railroad, and emergency vehicles.

A family of support tools accompanies VS-PLUS for timing plan generation, field controller support and maintenance, and signal timing quality control. The first installation was in 1983 in Switzerland and there are more than 1,600 installations of VS-PLUS in Europe today. In the United States, the first field installation on a Type

2070 controller was completed in Vancouver, Washington in 2001 with other implementations in Fort Collins, Colorado and Newark, New Jersey.

LRT Priority Treatment

As a signal control software designed for LRT control, VS-PLUS provides a whole array of tools for LRT signal control. Most importantly, VS-PLUS allows for specific LRT phases with their own timing parameters including dual clearance intervals. This specific LRT feature allows the controller to use a short clearance interval if a train checkout call was received (i.e., train has already reached the intersection, clearance interval only required for actual train length to clear intersection). A longer, more conservative clearance interval is used if a checkout call was not received (i.e., train has not reached the intersection, clearance interval equal to travel time from stop/go decision point and train length to clear intersection). This dual clearance interval feature typically results in a 6-second clearance time savings and thus a reduction in the duration a LRT priority event.

The most powerful LRT control feature of VS-PLUS is its train arrival prediction capability. Using multiple advanced detection points, the software constantly maintains an estimated time of arrival (ETA) window, even in situations where stations are located between the advanced detection point and the actual intersection. The ETA window marks the earliest (normal conditions) as well as the latest arrival (delayed condition) and is used to continuously evaluate priority options such as early green, green extension, phase insertion, phase rotation, etc. Of course, only priority options that are permitted by the user are actually implemented. Other LRT priority features include a phase change matrix which allows the user to specify phase change parameters between individual phases; a feature especially useful and efficient for intersections where light rail trains actually turn. The software also allows for dynamic selection of the level of priority granted to the light rail trains. For example, it can be set only to permit full LRT priority in cases where the train is actually behind schedule or has more than 100 passengers on board, etc.

Recovery from a LRT priority event is typically accomplished by jumping back to the background cycle, thus avoiding any impacts on coordination. However, since this could result in dramatic impacts on minor movements, especially on the track-crossing left-turns, VS-PLUS provides various parameters (e.g., maximum waiting time, queue spillback detectors, etc.) that allow it to override the standard recovery mode. In the case of queue spillback detectors, VS-PLUS constantly monitors queuing on the specified approaches and if a spillback is detected, the software moves that approach into a higher priority class, thus allowing it to be served outside its normal permissive period.

VS-PLUS signal control for this simulation analysis was set up to allow full LRT priority at all signalized intersections.

EVALUATION RESULTS

CORRIDOR TRAVEL TIMES

Corridor travel times for light rail and automobile traffic were evaluated for the three signal control scenarios. Four travel time segments were built into the model to monitor changes in travel time along the major corridor. LRT travel time segments begin and end approximately 300 feet north of Earll Drive and approximately 600 feet south of McDowell Road. The southbound traffic travel time segment begins approximately 850 feet north of Earll Drive and ends approximately 600 feet south of McDowell Road. The northbound traffic travel time segment begins approximately 2,000 feet south of McDowell Road and ends just north of Earll Drive. Travel times averaged over 10 runs are shown below in Table 1. The VS-Plus alternative has the shortest LRT travel times, the Transit Priority alternative has the shortest traffic travel times, while the Preemption alternative shows travel time results between Predictive Priority and the Transit Priority alternative. This reflects the strategies employed by each of the analyzed control strategies. The Transit Priority logic protects coordinated operation, while the employed VS-PLUS logic provides full LRT priority and compensates minor movements for their lost green time to the detriment of Central Avenue coordination. However, it should be noted that the maximum difference in LRT travel time between VS-PLUS and the Transit Priority Alternative is 87 seconds (12.4 second savings per signal), while the maximum difference in automobile travel time is only 16 seconds.

Table 1. Segment Travel Time Results (sec)

SCENARIO	LRT		TRAFFIC	
	NB	SB	NB	SB
NEMA PREEMPTION	288.5	296.5	280.8	254.4
NEMA TRANSIT PRIORITY	362.1	317.4	266.0	253.6
PREDICTIVE PRIORITY	275.2	273.5	276.8	257.0

TRAFFIC DELAY

One of the most critical measures of effectiveness from a traffic point of view is the average intersection delay, which in turn relates to the Highway Capacity Manual level of service concept. Generally speaking, all three analysis scenarios result in the same intersection levels of service. Differences between scenarios at individual intersections typically average around 5 seconds/vehicle. McDowell, however, exhibits the largest difference of around 8 seconds/vehicle between Transit Priority and Preemption. Total system delay ranges between 22.9 seconds/vehicle for Transit Priority and 27.8 seconds/vehicle for the Preemption scenario.

Table 2 below summarizes the individual intersection delay and LOS results.

Table 2. Intersection General Purpose Traffic Delay (sec)[3]

INTERSECTION	PREEMPTION		TRANSIT PRIORITY		PREDICTIVE PRIORITY	
	DELAY	LOS	DELAY	LOS	DELAY	LOS
EARLL	27.3	C	21.7	C	22.9	C
CATALINA	5.4	A	3.6	A	4.9	A
THOMAS	33.2	C	28.5	C	28.0	C
VIRGINIA	20.0	C	15.6	B	16.3	B
ENCANTO	10.1	B	10.1	B	10.2	B
PALM LANE	25.3	C	20.5	C	22.2	C
MCDOWELL	41.1	D	32.8	C	34.6	D
TOTAL SYSTEM	27.8	C	22.9	C	23.6	C

Individual movement delay was also reported for the two critical intersections, Thomas and McDowell. The results clearly show the differences between the individual control strategies. Specifically, the Transit Priority scenario shows the best results for the heavy EB and WB through movements since this strategy maintains coordination at all times and their green time is protected by associated pedestrian phases. The Predictive Priority scenario exhibits the most balanced results, not favoring any particular approach, but also maintaining service levels for the critical east/west through movements. Table 5 and Table 4 below show the individual movement delays for Thomas and McDowell.

Table 3. Intersection Delay by Movement (sec)[3] – Thomas Rd.

	NB			SB			EB		WB	
	LT& U	T	R	LT& U	T	R	T	R	T	R
PREEMPTION	47.9 (D)	25.4 (C)	22.9 (C)	65.8 (E)	22.2 (C)	21.0 (C)	33.4 (C)	12.4 (B)	40.0 (D)	17.1 (B)
TRANSIT PRIORITY	52.7 (D)	23.7 (C)	21.1 (C)	59.2 (E)	23.0 (C)	22.8 (C)	27.9 (C)	9.7 (A)	28.8 (C)	11.4 (B)
PREDICTIVE PRIORITY	49.1 (D)	21.0 (C)	19.5 (B)	64.4 (E)	17.8 (B)	18.0 (B)	29.4 (C)	10.1 (B)	30.1 (C)	12.2 (B)

Table 4. Intersection Delay (sec) by Movement[3] – McDowell Rd.

	NB			SB			EB		WB	
	LT& U	T	R	LT& U	T	R	T	R	T	R
PREEMPTION	109.5 (F)	33.7 (C)	32.5 (C)	53.8 (D)	12.6 (B)	11.1 (B)	31.0 (C)	7.8 (A)	54.7 (D)	54.4 (D)
TRANSIT PRIORITY	79.4 (E)	34.8 (C)	34.1 (C)	63.3 (E)	10.1 (B)	8.5 (A)	27.4 (C)	6.5 (A)	31.0 (C)	28.8 (C)
PREDICTIVE PRIORITY	52.3 (E)	43.5 (D)	44.5 (D)	55.4 (D)	12.6 (B)	10.9 (B)	28.1 (C)	7.0 (A)	34.7 (C)	32.7 (C)

QUEUE LENGTH AND AVERAGE VEHICULAR STOPS

Approach queue lengths (90 percentile) are reported for both critical intersections, Thomas and McDowell, in Tables 7 and 8, respectively. As expected, the queue length comparison between the analysis scenarios matches the individual movement delay comparison. As mentioned above, the Transit Priority scenario shows the best queuing results for WB and EB through movements, while the Predictive Priority scenario results in the best queuing results for the critical (i.e., over-spilling) NB/SB left-turns.

Table 5. Queue Length (ft) – Thomas Rd.

	NB		SB		EB		WB	
	LT & U	**T & R**	**LT & U**	**T & R**	**T**	**R**	**T**	**R**
PREEMPTION	262	318	423	272	344	43	466	92
TRANSIT PRIORITY	239	298	807	279	279	39	298	69
PREDICTIVE PRIORITY	233	276	358	256	292	43	308	89

Table 6. Queue Length (ft) – McDowell Rd.

	NB		SB		EB		WB
	LT & U	**T & R**	**LT & U**	**T & R**	**T**	**R**	**T**
PREEMPTION	469	584	233	194	253	49	741
TRANSIT PRIORITY	338	558	210	148	207	52	344
PREDICTIVE PRIORITY	259	748	200	190	213	52	387

SUMMARY AND CONCLUSIONS

This paper based on the Phoenix LRT At-Grade Signal Control Strategy Analysis showcases a simulation analysis of traffic and transit operations in an urban arterial street corridor controlled by three different LRT signal control systems: NEMA Railroad Preemption, NEMA Transit Priority and 2070/VS-PLUS Predictive Priority. Measures of effectiveness used for comparing the three signal control systems include light rail corridor travel time and intersection delay as well as general purpose traffic corridor travel times, intersection delay, critical approach queue lengths and number of stops (i.e., quality of signal progression).

The results of this simulation study lead to the conclusion that the NEMA Transit Priority scenario results in slightly lower general purpose traffic corridor travel times, average intersection delay and cross street queue lengths than any of the other alternatives. However, LRT travel times by far exceed any of the other alternatives. The NEMA Railroad Preemption scenario results in the highest traffic impacts in comparison to all other scenarios, while significantly reducing LRT travel times compared to the Transit Priority scenario. The 2070/VS-PLUS Predictive Priority scenario results in the shortest LRT travel times combined with the traffic impacts comparable to the Transit Priority scenario (NB and SB left turn queue lengths are even shorter than for the Transit Priority scenario and thus result in shorter left-turn storage requirements). In contrast to the Preemption scenario, the 2070/VS-PLUS Predictive Priority scenario also maintained the service levels for the critical east/west through movements at the Mile Street intersections of Thomas and McDowell. In short, the 2070/VS-PLUS Predictive Priority minimizes LRT travel times while not significantly impacting general traffic operations and thus combines the LRT benefits of preemption with the traffic benefits of transit priority.

In summary, this paper clearly shows how advanced traffic signal control can maximize the efficiency and service levels for all roadway users. It also illustrates the importance of clearly specifying the exact signal control operation early on in a light rail project. Although all three analyzed LRT control systems satisfied the requirement of light rail signal priority, only one of them performed to the satisfaction of traffic agency and LRT operator.

REFERENCES

PTV AG, "VISSIM 3.60 User Manual", Karlsruhe, Germany, January 2002

Valley Connections, "VISSIM Analysis of Traffic Signal Operating Strategies", Presentation to Cities of Phoenix, Tempe, and Mesa, Phoenix, AZ, April 2001

AUTHORS' INFORMATION

Thomas Bauer, Member
President
Innovative Transportation Concepts, Inc.
1128 NW 2nd Street, Suite 204
Corvallis, OR 97330
tbauer@itc-world.com

Patrick Fuller
Area Manager
PB Farradyne, Inc.
411 N. Central Avenue, Suite 211
Phoenix, AZ85004
pfuller@valleyconnections.com

---

[1] The controller used for this evaluation was an ECONOLITE ASC/2S.

[2] The firmware used for this evaluation was VS-PLUS.

[3] LOS criteria based on 2000 HCM, Exhibit 16-2 control delay.