Testing of Light Rail Signal Control Strategies by Combining Transit and Traffic Simulation Models

THOMAS BAUER, MARK P. MEDEMA, AND SUBBARAO V. JAYANTHI

The Chicago Central Area Circulator (CAC) is a light rail transit (LRT) system scheduled to serve downtown Chicago by the year 2000. It will operate in its own travel lane parallel to automobile traffic; however, it will interfere with other surface transportation modes at intersections. The traffic and train signal system controlling the interface will be crucial for the successful performance of all modes. The signal control strategy must balance the needs of LRT, buses, autos, and pedestrians. For this reason, three LRT priority control strategies were developed. The approach used to analyze train and automobile traffic performance for each of these strategies is described. The CAC design team simulated LRT operation, automobile traffic flow, and intersection control units (ISC) as the interface between the two modes for all three control strategies. Two different microscopic modeling tools performed the simulation. TransSim II™ (registered trademark of James R. Hanks dba JRH Transportation Engineering) was selected for the transit and signal controller simulation because it realistically models LRT operation. TransSim II™ can also simulate priority strategies, which include arrival time estimation capability for trains and two-way communication between trains and ISCs. TRAF-NETSIM was selected for the traffic flow simulation because of its ability to reproduce traffic conditions, such as individual vehicles, queuing impacts, and potential spillbacks across adjacent intersections. The interface between the simulation programs is signal phasing and timing. This information calculated by TransSim II™ was read into TRAF-NETSIM. The two simulation processes yielded LRT performance measures of speed, travel time, and delay statistics, and auto performance measures of delay, queue lengths, and spillbacks. This allowed the design team to choose the most appropriate signal control strategy to provide the best overall system performance.

The public transit industry has experienced a resurgence. After the oil embargo in the 1970s and the recession of the early 1980s, interest in transit had declined. With the emphasis now on the economics of traffic congestion, environmental issues and new commuter travel patterns, more cities are looking to transit as a viable solution. New advances in the industry, such as alternative fuel vehicles, light rail transit, and bus signal preemption, are making transit more attractive.

With these new technologies, transportation engineers are looking for ways to make travel more efficient. A new application of microscopic simulation programs in analyzing transit signal control strategies is presented. The setting for this application is the City of Chicago's proposed Central Area Circulator light rail project. The application of Trans Sim II™ (registered trademark of James R. Hank dba JRH Transportation Engineering) and TRAF-NETSIM to simulate transit and traffic operations in downtown Chicago in a transit signal priority environment is described.

T. Bauer, Access Engineering Inc., 1410 Oak Street, Suite 201, Eugene, Ore. 97401. M.P. Medema and S.V. Jayanthi, Barton-Aschman Associates, Inc., 820 Davis Street, Evanston, Ill. 60201.

TransSim II™ as a microscopic transit simulation model was used in conjunction with TRAF-NETSIM, a microscopic traffic simulation tool, to help the designers measure the effects of several different signal control strategies and provide a recommendation based on quantitative analyses. The combination of these two simulation models allows for a detailed evaluation of transit and traffic impacts subject to the signal control strategy in operation.

SETTING

For the light rail project to be successful, light rail transit (LRT) travel speeds should be higher than conventional bus and auto speeds. The City of Chicago realized the importance of transit to the future of the Central Area and recommended that transit modes be given priority in the street system. Giving transit modes priority enables the street system to move the greatest number of people in the shortest period of time, creating a more efficient transportation system. To accomplish this goal, the LRT was given dedicated travel lanes and a priority signal system. The priority signal system will give priority service to the LRT while maintaining reasonable auto traffic performance and a safe pedestrian environment.

Several different signal control strategies were proposed to meet this requirement. The strategies ranged from a simple fixed time signal controller that would provide progression for LRVs to a preemption-type controller that would immediately respond to an LRV-activated call. Each of these signal control strategies had to be evaluated with respect to LRT performance, auto performance, and pedestrian safety.

It is imperative that pedestrian movements in the Central Area be preserved. Pedestrian traffic, particularly high in downtown Chicago, is the predominant mode of transportation. It is also critical that traffic flow in the city be maintained. Property owners and city officials have stressed the importance of unimpeded traffic flow for employee and customer travel in the marketability of commercial developments, and for the operation of businesses receiving deliveries. For this reason, no streets were closed to automobile traffic. The need to maintain reasonable traffic flow required detailed analysis. Other criteria also played a role in a separate set of analyses. Items such as maintenance of the signal system, cost, risk in development, and vendor acceptability were considered separately.

STUDY AREA

The study area network consists of seven north-south streets from Franklin to Wabash, and five east-west streets from Randolph to

Adams in Chicago's downtown Loop area. The network is basically a grid with an average block spacing of 450 ft. All streets in the study network are one-way streets, with the exception of two two-way streets: LaSalle and State.

The proposed light rail system will operate on Madison and State streets in both directions. The eastbound and westbound LRVs will stop on Madison Street at the station west of LaSalle and the station west of Dearborn. On State Street, southbound LRVs will stop at the station between Washington and Madison, and northbound LRVs will stop at the station between Washington and Randolph. The study area includes seven LRT intersections and one LRT junction. Three different routes will operate in the study area. For the purpose of the simulation, the two routes operating on Madison Street and on State Street north of Madison Street are combined into Route No. 1, while Route No. 2 includes the LRT route operating on State Street. The circled portion in Figure 1 shows the study area.

METHODOLOGY

To perform such a complex analysis, several different approaches were analyzed to determine which applies best to this situation. Four approaches were considered for this project.

The first attempt was a macroscopic look at each of the signal control strategies. The traffic performance was measured using the Highway Capacity Manual (HCM). The HCM was used to conduct intersection capacity analyses to determine auto delay. The amount of lost time to the autos due to the LRT phase was coded as an all-red phase. This procedure provided an estimate of the overall intersection performance but failed to consider (*a*) the effects of upstream and downstream intersections, (*b*) the cumulative effects of queuing on downstream street segments as well as at the intersection; and (*c*) the variable phase lengths that could be generated by an LRV-actuated call. This method also could not predict train performance. Pedestrian safety was considered by providing safe pedestrian clearance times during each cycle.

The second attempt was to create a manual approach to show the network-wide effects of the many intersections by developing time-space (T-S) diagrams. The T-S diagrams were able to show the impacts to autos along street segments by showing the progression along street corridors. This provided an indication of the train performance by showing train progression while including station dwell times at each station stop. Combined with the results of the HCM, this method provided a better understanding of the auto and train performance, but still could not predict the effects of the variations in LRT arrivals and the variations in the signal timings.

The third attempt was the application of a microscopic program to show the effects of the variable signal timings. TRAF-NETSIM, a simulation program developed by the FHWA, was used to determine both LRT and auto performance throughout the network. This program allowed the auto lanes and the LRT lanes to be coded as separate links for most of the intersections. Because of a program limit of five approach links to each intersection, occasionally some of the LRT lanes and auto lanes had to be combined. The intersections were coded as actuated signals with detection loops in the transit lanes. This method provided auto performance statistics and LRT performance statistics that incorporated some of the variability of LRT arrival patterns and ability of the signal system to accommodate the transit calls in the signal cycle. This program also allowed the coding of short-term disruptions to the transit lanes. Examples of disruptions include jaywalkers, vehicles turning into alleys, vehicles turning into parking lots, and pedestrians forming queues extending into the street. However, the real signal control strategies that were being developed for this project had some unique capabilities that TRAF-NETSIM was not able to reproduce. The ability to constantly send information from the LRV to multiple controllers to update the LRV arrival time and cancel calls if a delay was experienced could not be analyzed.

Another alternative had to be developed that could improve TRAF-NETSIM's ability to analyze the different types of advanced signal control strategies but still be able to measure auto performance in the way TRAF-NETSIM could. The fourth attempt, therefore, involved TransSim II™, a microscopic simulation tool for transit operations, that became available for the Central Area Circulator (CAC) project. This method employed a two-step process. The first step was to use TransSim II™ to simulate transit operations and signal controllers, and the second step was to simulate traffic operations with TRAF-NETSIM using signal timing and phasing provided by TransSim II™.

SIMULATION MODELS

TransSim II™

TransSim II™ is a simulation program that models light rail transit or bus transit operations. It is a link-node-based model that treats transit operations on a microscopic level and other traffic on a macroscopic level. The utility of the program lies in the abundance of information that is modeled on transit and traffic signal operation.

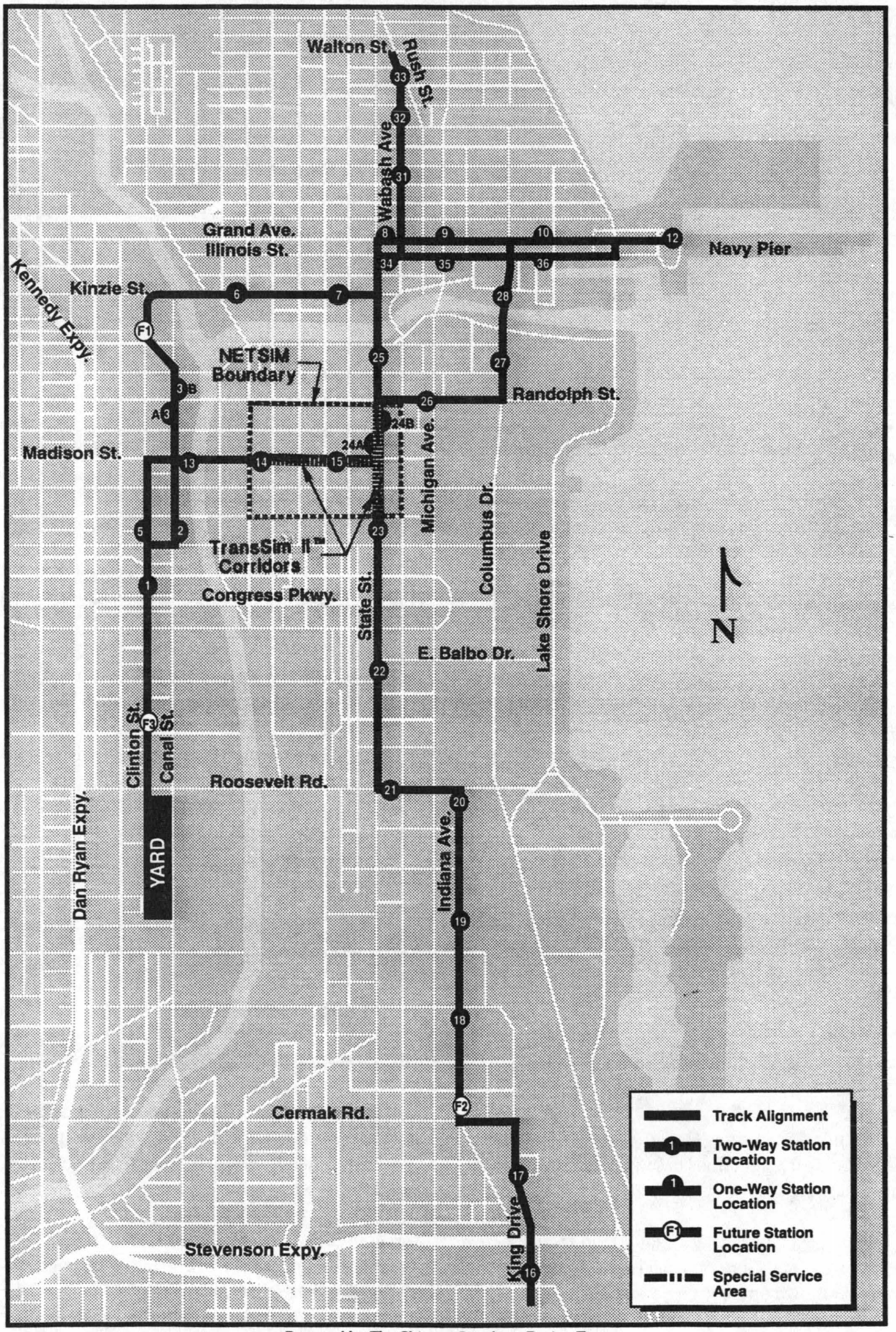
Transit operations are modeled on a real-time basis through a traffic-signal, controlled-street network. The transit operations output shows (*a*) the overall travel time for each transit vehicle and all vehicles, cumulative and averaged; (*b*) detailed point-to-point travel times; (*c*) the time and duration of delays at traffic signals and stations; and (*d*) the time and duration of traffic signal preemption at each intersection. This is accomplished by input data that describe the exact transit route (including the location of stations and intersections) and operating parameters, such as acceleration, deceleration, speed zones, and station dwell times.

The program contains logic that allows the modeling of real-world situations affecting transit operations:

- Maximum operating speeds may vary along the route to account for operating in separate rights-of-way, mixing with automobile traffic, negotiating curves, or other conditions;
- Station dwell times are calculated, taking into account a randomly generated variable, the mean dwell time, and the time gap to the proceeding train; and
- User-defined random delays may be input at any location for any duration.

All common types of controllers can be modeled, from fixed-time to fully actuated control, at isolated intersections or in coordinated systems. Traffic signal controllers are simulated on a second-by-second basis and may be set to provide full preemption and most common types of transit priority treatment.

TransSim II™ can simulate traffic operations on a macroscopic second-by-second basis. However, this traffic model cannot show the effects of queue spillbacks or heavy pedestrian flows. For these



Prepared by The Chicago Circulator Design Team

FIGURE 1 Boundaries of study area (*1*).

reasons, TRAF-NETSIM was used for traffic simulation instead of TransSim II™'s in-built traffic model.

TRAF-NETSIM

TRAF-NETSIM, a microscopic traffic computer simulation model developed by the FHWA, is used to simulate urban surface-street networks. This model tracks individual vehicles as they traverse the study network. After entering the network, vehicles move according to the vehicle-following logic by responding to traffic control devices and other factors, such as pedestrians, buses, etc. Individual driver behavior characteristics also are represented through random sampling from probability distribution to reflect real-world processes.

The physical structure of the roadway is represented as a network consisting of nodes and unidirectional links. The links represent the streets, and the nodes represent the intersections or the points at which a geometric property changes (e.g., a lane drop, a change in grade, or a major mid-block traffic generator). Because of its detailed view of traffic operations, TRAF-NETSIM is a valuable tool for understanding the performance of different transportation system strategies.

The input parameters for the model include: traffic volumes, lane geometrics, lane usage, grades, pedestrian intensity, start-up lost times, mean headways, average free-flow travel speeds, signal phase splits, signal phase movements, bus routes, dwell times, etc. TRAF-NETSIM produces vehicle statistics by individual links. The operational performance of the transportation system can be evaluated by using one or more of the following measures of effectiveness produced by TRAF-NETSIM. They are: average stopped delays, total delays, percentage of stops, average travel speeds, average and maximum length of queues, total travel time, vehicle emissions, and derivatives of these. Individual turn-movement-specific statistics also can be obtained. The output results can be viewed graphically or numerically. The graphical capabilities of TRAF-NETSIM provide easy explanations of traffic performance for laypeople and easy verification of operations.

APPLICATION

Tested Priority Strategies

Three signal control strategies for the LRT operations were proposed and evaluated. The logic behind the three strategies is as follows:

Strategy 1: Operates under fixed-time signal controller logic at intersections and semiactuated at junctions based on a signal timing plan balancing progression for LRT and autos.

Strategy 2: Same as Strategy 1, but LRVs can extend their green window by early termination of the previous phases ("early green") or later termination of their own phase ("green extension").

Strategy 3: LRVs can predict their arrival time at the intersections. Two-way communication between LRVs and signal controllers then allows the signal controllers to optimize signal timing to minimize delay for light rail. Controllers also have the capability to return to coordination in the absence of LRV calls.

TransSim II™

Input Data

In addition to geometric information, several basic assumptions were made for the simulation of the CAC network:

- In the year 2010 all trains will be 55 m (180 ft) long (two-car trains), resulting in LRV clearance times of 9 sec for through movements and 21 sec for turning movements.
- Operating rule requires a minimum spacing of one 128-m (420-ft) long block between two consecutive trains.
- Acceleration and deceleration rates are set to 1.1 m/sec^2 (3.5 ft/sec^2) and 1.4 m/sec^2 (4.5 ft/sec^2), respectively, according to design specifications.
- Entrance times for trains to the simulation network are defined for each train individually based on earlier simulation efforts.
- User-defined random delays are defined by coding delay locations and durations for each train specifically based on the assumption of an exponentially distributed average delay of 7.5 sec per train-kilometer (12 sec/mil) traveled (D. Allen, unpublished data).
- Signal control-related input data includes the base timing plan (phase lengths and offsets). This information was prepared by adjusting an automobile traffic-oriented timing plan to better accommodate LRVs with their exceptional travel characteristics.

Output Data

Output data from TransSim II™ contained a variety of information and included (*a*) measures of effectiveness (MOEs) for the light rail system and (*b*) the lengths of all signal phases for each cycle during the simulated period of time.

The MOEs presented for each light rail vehicle are:

- total travel time in seconds,
- station dwell time in seconds,
- average speed (route length divided by total travel time) in km/h (mph),
- variation from an ideal run (without any delay caused by longer-than-expected dwell times, traffic signals, interference with other LRVs, or user-defined delay) in seconds,
- stop line delay (the accumulated time the LRV was waiting at traffic signal stop lines) in seconds,
- time-to-green delay (the accumulated time from when the LRV passes a decision point, breaking distance to stop line, to the start of LRV GO) in seconds,
- non-station delay (the total delay the LRV receives neglecting any variation of station dwell time) in seconds, and
- user-defined delay (the sum of all random delays defined for the LRV) in seconds.

For all LRVs of each route and direction, TransSim II™ then presents minimum, maximum, mean, and standard deviation for the MOEs. For better interpretation of the results, the ideal travel time and corresponding ideal speed also are presented.

The last part of the comprehensive transit results shows the accumulated time-to-green and stop line delays, and the fraction of vehicles that actually come to a stop for each traffic signal. The mean stop line and time-to-green delay per intersection and train is then displayed as a general MOE for each route and direction.

Signal timing data to be input into TRAF-NETSIM was stored in one data file for each traffic signal of the simulated network. These files included the phase number and its duration of green time and clearance time in the sequence they appeared during the simulation.

TRAF-NETSIM

Input Data

TRAF-NETSIM requires extensive input data, and a description of the important variables is as follows:

- The future lane geometrics, balanced auto volumes, and bus volumes were coded in the network.
- The pedestrian traffic factor that takes a high pedestrian volume of 250 to 500 pedestrians per hour is used.
- The start-up lost time, which is the delay experienced by all lead vehicles in a queue when responding to a phase change from red to green, is set at 2 sec.
- The mean time gap and the free-flow speeds used in the network are 2 sec and 48 km/h (30 mph), respectively.
- Right-turns-on-red are permitted for auto traffic at all intersections.
- Average dwell times for buses are specified as 10 sec.

The signal control strategies were tested with TRAF-NETSIM using the signal timings generated by TransSim II™. Because the format of signal timings generated by TransSim II ™ output is not compatible with that of TRAF-NETSIM, adjustments were made. TransSim II™ generates a series of signal phase sequences and corresponding splits at each intersection for a fixed duration. To use exactly the same signal timings, the time period capability of TRAF-NETSIM had to be used.

Changing conditions with varying signal timings can be simulated using time periods. Each time period should be an integer multiple of a time interval. The time interval is the most commonly used cycle length (in this case 75 sec). The maximum number of phases allowed in each time period is 12. At some intersections, the cycle uses up to 6 phases. These limitations restrict the user to only two time intervals in each time period. This means that it is feasible to input an equivalent of 150 sec of phase splits in each time period under the existing circumstances. TransSim II™'s signal timing output at each intersection is broken down into 150-sec intervals and re-formatted to match TRAF-NETSIM's format. Since TRAF-NETSIM allows the use of a maximum of 19 time periods, it is possible to simulate up to a maximum of 2,850 sec.

The model was thoroughly calibrated to replicate real-world conditions before the testing of the strategies began. This was accomplished by comparing the average stopped delays, queues, and the traffic volumes obtained from the field with TRAF-NETSIM's results.

Output Data

TRAF-NETSIM produces an abundance of MOEs in which the maximum queue lengths and the stopped delays were selected to evaluate the non-LRV traffic operational performance. Stopped delay is the amount of time an average vehicle is forced to stop at the intersection due to traffic conditions. The maximum queue length is the longest queue that has occurred during the simulation. The systemwide MOEs were calculated from the individual link-by-link statistics.

Results

The results of the analyses include average train speeds, delays experienced by auto vehicles, and the maximum queue lengths that develop on each leg of an intersection. Table 1 shows the average train speeds, and Table 2 shows the total systemwide auto delay and the relative differences (in percent) for the three strategies.

Figure 2 shows the relationship between train performance and auto performance for each of the different signal control strategies and their alternatives. A linear relationship is shown illustrating how train performance and auto performance are related. As train performance increases, auto performance decreases. This is intuitive as autos and trains must share a fixed amount of space and time.

Compared with Strategies 1 and 2, the average LRT operating speeds are significantly higher in Strategy 3. The auto performance is better in Strategy 1 and is identical for Strategies 2 and 3.

CONCLUSION

The use of TransSim II™ and TRAF-NETSIM allowed the Chicago Circulator Design Team (CCDT) to identify the most suitable transit priority strategy for the proposed light rail system in downtown Chicago. The detailed analysis that TransSim II™ provided for transit operations and TRAF-NETSIM for automobile traffic enabled the CCDT to predict impacts on light rail and traffic operations from various signal control strategies.

The detailed quantification of the light rail and non-light rail operational performances helped the CCDT select an appropriate

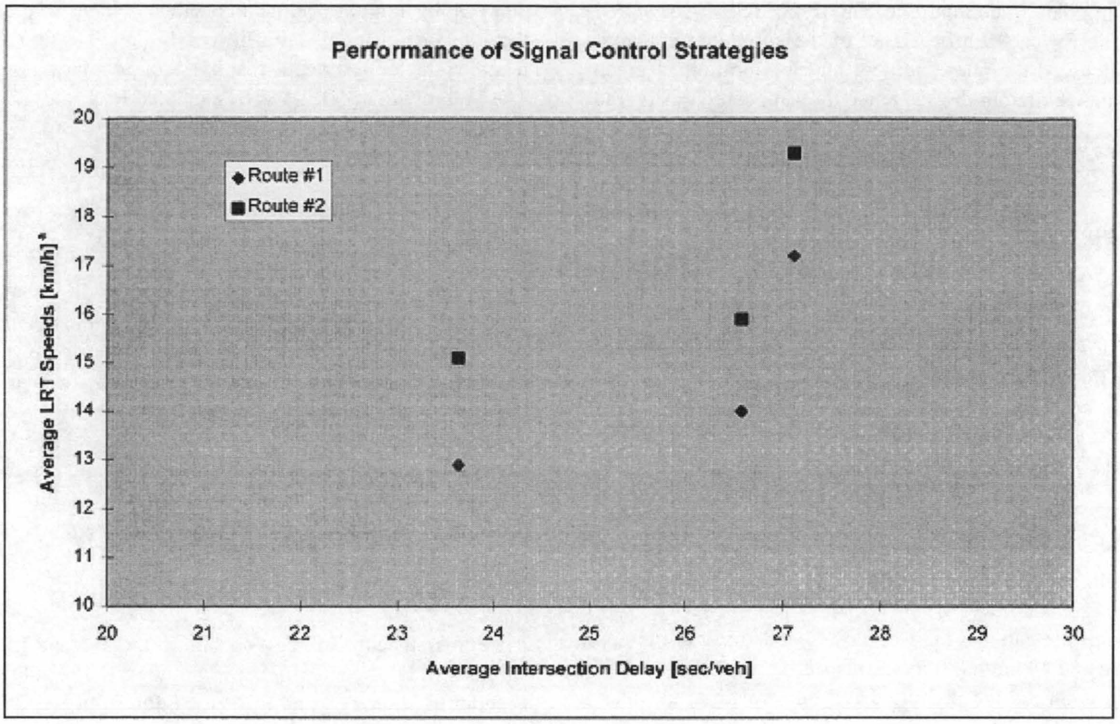
TABLE 1 Average Train Speeds in km/h for pm Peak Period

Route	Strategy 1	Strategy 2	Strategy 3
#1	12.9	14.0	17.2
#2	15.1	15.9	19.3

1 km/h = 0.6 mph

TABLE 2 Summary of Traffic Performance for pm Peak Period

Criteria	Strategy 1	Strategy 2	Strategy
Systemwide Delay [sec]	827	930	950
Change from Alternative 1 [%]	n/a	12.5	14.9



* 1 km/h = 0.6 mph

FIGURE 2 Interdependence between transit and traffic performance.

signal control strategy for the proposed light rail system in downtown Chicago.

The simulation models also helped quickly evaluate several additional variations to the input to understand the effects on train and traffic operational performances given different constraints to the signal control strategies.

REFERENCES

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