Signal Timing Optimization Methodologies and Challenges for the City of Baltimore, MD, USA, Central Business District and Gateways

THIS FEATURE DISCUSSES CHALLENGES AND METHODOLOGIES FOR A 425-SIGNAL OPTIMIZATION PROJECT IN THE CITY OF BALTIMORE, MD, USA. THIS PROJECT INCLUDED 250 SIGNALS IN A GRID CENTRAL BUSINESS DISTRICT (CBD) AND 175 SIGNALS ON GATEWAYS LEADING TO AND FROM THE CBD. THE BENEFITS IN REDUCED DELAYS, STOPS AND EMISSIONS PAID FOR THE PROJECT IN LESS THAN 3 MONTHS.

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THE BALTIMORE CITY, MD, USA, signal optimization project followed on the heels of the city-wide signal controller replacement and system upgrade project that replaced 1,300 signal controllers and upgraded the central signal system. The system upgrade project continued concurrently with the signal optimization project. The last system-wide signal optimization project was performed in the 1970s.

Since that time, the city has performed routine maintenance retiming, such as responding to citizen complaints, but has not modified the original cycle lengths. Expectations for benefits were high due to the approximately 30-year period between signal optimization projects. The overall goal was to reduce stops and delays by 15 percent.

STUDY BOUNDARIES AND SIGNAL TIMING PATTERNS

The major arterials and/or freeway terminal locations within the central business district (CBD) define the boundaries of the CBD study area. The grid street network contains 250 traffic signals with an average signal spacing of approximately 400 feet. Across these boundary roadways, traffic volumes change significantly, either allowing for a natural break in the coordinated signal system or transitioning from a signalized roadway to urban expressway. The boundary streets are:

- southern boundary: Conway Street and Hamburg Street
- western boundary: Martin Luther King Jr. Boulevard (MLK)/Howard Street
- eastern boundary: President Street and Fallsway
- northern boundary: North Avenue

The CBD traffic signals are operating under a pre-timed mode under central signal system control. Several intersections, such as at parking garages, have vehicle detectors, and some isolated intersections have pedestrian pushbuttons. Under the “before” condition, the CBD signals generally operated on a 110-second cycle length in peak periods and a 90-second cycle length during the off-peak period. The special-event cycle length is 140 seconds and is programmed to begin 1 to 3 hours prior to the start of the event.

The study included nine gateway corridors radiating from the CBD to the eastern, northern and western suburbs of the city. These operate in a semi-actuated or pre-timed mode under time-based coordination. The signals generally operate at cycle lengths of 110 to 130 seconds during peak periods and at cycle lengths of 80 to 90 seconds during the off peak. Table 1 summarizes the specific characteristics of each gateway corridor. Figure 1 shows the study area.

DATA COLLECTION AND BASELINE DOCUMENTATION

Turning Movement Counts

Vehicular and pedestrian turning movement counts were collected at all 425 signalized intersections during the morning (7:00 a.m. to 9:00 a.m.), midday (11:30 a.m. to 1:30 p.m.) and afternoon (4:00 p.m. to 6:00 p.m.) peak periods. Due to the large amount of data collected, turning movement counts within the same area often were collected days or even weeks apart.

Prior to inserting the data into the traffic signal timing model, the raw counts

Table 1. Summary of gateway corridors.

Gateway	Number of lanes/ speed	Mileage	Number of signals	Signal spacing	Distribution a.m. (inbound), directional p.m. (outbound)	Before signal timing cycle lengths and patterns
Belair Road	4 lanes, 30 mph	4.3	19	400 feet to one-quarter mile	60 percent a.m., 75 percent p.m.	80 seconds – off peak, 110 seconds – a.m., p.m.
Eastern Avenue	4 to 6 lanes, 30 mph	3.8	35	400 feet to one-quarter mile	60 percent a.m., 80 percent p.m.	West 80 seconds – off peak, 110 seconds – a.m., p.m. East 130 seconds, all patterns
Edmondson Avenue	6 lanes, 35 mph	2.9	18	1,000 feet	70 percent a.m., 60 percent p.m.	90 seconds – off peak, 110 seconds – a.m., p.m.
Falls Road	4 lanes, 30 mph	2.7	10	400 feet to one-half mile	60 percent a.m., 55 percent p.m.	Uncoordinated. Cycles range from 70 to 150 seconds.
Harford Road	4 lanes, 30 mph	5.0	26	400 feet to one-half mile	60 percent a.m., 75 percent p.m.	80 seconds – off peak, 110 seconds – a.m., p.m.
Pulaski Highway	6 lanes, 40 mph	2.4	13	500 feet	70 percent a.m., 70 percent p.m.	Some isolated uncoordinated. West 80 seconds – off peak, 110 seconds – a.m., p.m. East 100 seconds – a.m., off peak 150 seconds – p.m.
York Road	4 lanes, 25 mph	4.2	23	400 feet to one-half mile	75 percent a.m., 55 percent p.m.	80 to 110 seconds – off peak, 110 seconds – a.m., p.m.
North Avenue	6 lanes, 30 mph	3.2	22	400 to 1,000 feet	50 percent a.m., 50 percent p.m.	90 seconds – off peak, 110 seconds – a.m., p.m.
Boston Street	4 lanes, 25 mph	2.0	9	400 feet to three-quarters mile	50 percent a.m., 50 percent p.m.	90 seconds – off peak, 110 seconds – a.m., p.m.
TOTAL		**30.5 miles**	**175 signals**			

were smoothed using volume balancing techniques. As in any large data collection effort, recounts were performed at the discretion of the engineer at locations where the data seemed inconsistent with historical data or with data collected at upstream/downstream locations.

Travel Time and Delay

The travel time runs were performed along 25 roadways: nine runs on gateway streets and 16 runs in the CBD. In total, travel time studies were performed on approximately 20 miles of roadways in the CBD and the entire 31 miles of the studied gateway streets. The purpose of the travel time runs was twofold: to serve as a baseline for the "before" signal timings for future comparison with "after" signal timing travel time runs and for model calibration.

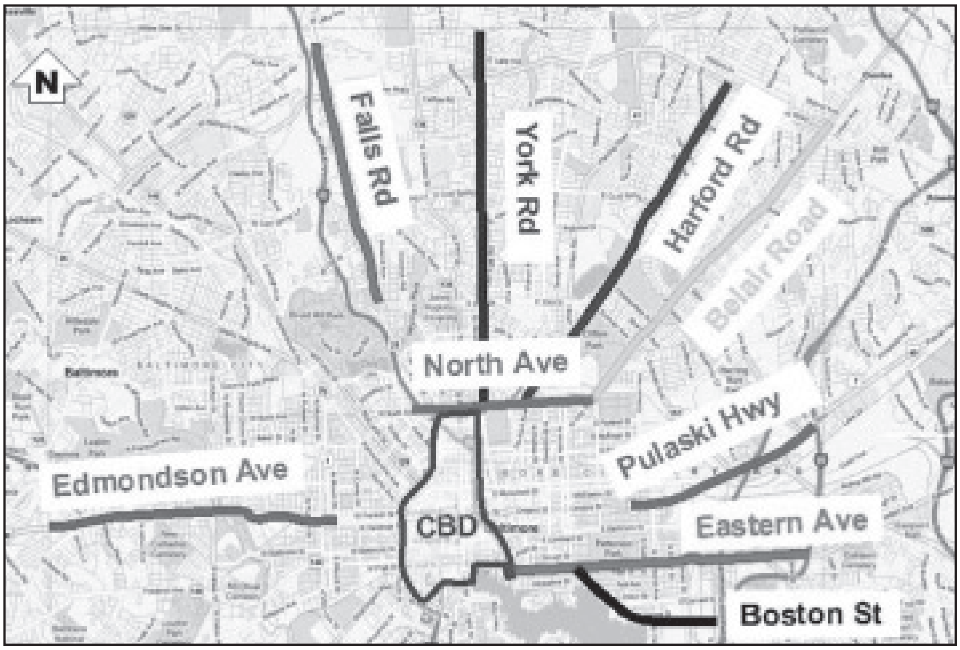

Figure 1. CBD and gateway corridors study boundaries.

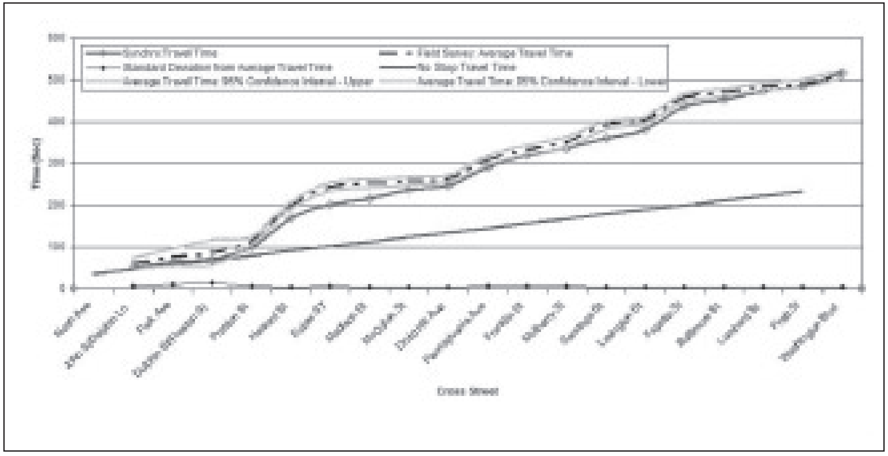

Figure 2. Calibration diagram.

Travel time runs were conducted using the floating car methodology. Travel time data were collected using state-of-the-art global positioning system (GPS) equipment and analyzed using the PC-Travel software program. GPS equipment records the position of the vehicle (using latitude and longitude) every second and calculates the speed and position of the vehicle within the network. The software program uses the second-by-second position information to calculate signal delays (based on the user defined inputs as to the location of traffic signals), number of stops and travel time.

Signal Timing, Phasing and Roadway Geometry

Signal timing was available for all intersections in the CBD. The signal timings for the gateway signals were collected from the controllers. Signal phasing was field-collected. Roadway geometry was collected using the city's geographic information system (GIS) and field inventory. Intersection spacing, number of lanes and turning bay lengths were measured using GIS. Speed limits, bus stops, parking restrictions and turn restrictions were collected in the field.

Saturation Flow Rates

Saturation flow rates were measured in the CBD area at approximately 50 intersections. The study was performed in accordance with the methodology outlined in Chapter 16 of the *Highway Capacity Manual* (HCM). Saturation flow rate data were collected to validate and adjust the default values in the traffic model used for signal optimization. Representative intersections were selected to obtain a sample of the study area. In this way, the saturation flow rates were applied to intersections that had similar characteristics to those where the studies were performed.

The study intersections were classified in groups according to factors such as the number of lanes, pedestrian activity, travel speeds, presence of exclusive turn bays and one-way versus two-way operations. Saturation flow rates were measured for a variety of lane groups (i.e. right-turn-lane only, shared through/left lane, etc.) through the CBD study area. The results were aggregated based on the classification.

The average saturation flow rate, measured in vehicles per hour per lane, was 1,570, with the measurements ranging from a low of 1,300 to a high of 1,750. For comparison purposes, the ideal saturation flow rate in Baltimore City would range from 2,000 to 2,300 vehicles per hour per lane, which is higher than the default ideal saturation flow rate value in HCM of 1,900.

The study showed that motorists in Baltimore City are driving more aggressively than the default values assumed in HCM and therefore need less green time to process the same amount of traffic than other areas with ideal saturation flow rates in the 1,900 range. Without this exercise, the optimized signal timing values would have required a substantial effort of fine-tuning in the field.

SIGNAL TIMING OPTIMIZATION

Coding and Validation

Synchro™ software is the City of Baltimore's prescribed tool for signal timing analysis and optimization. The signal timing optimization process began with coding a model of the "before" conditions of the morning, mid-day and afternoon peak hours. The model coding consisted of entering the field-collected data (link lengths, lane configurations, balanced traffic volumes, etc) into the model. The quality assurance/quality control plan was integral to the validation of the model and was a significant portion of the work in this phase of the project. This included independent field checks of the lane configurations, link lengths and signal timing and phasing coding. In addition, field reviews of each corridor used time-space diagrams (TSD) to ensure that the model replicated the actual field conditions. The TSD check proved useful in identifying coding errors with offsets and offset references (i.e. start of yellow versus start of green).

Calibration

The traffic signal timing model was calibrated before using it to perform optimization. The goal was to ensure that the model was accurate enough to replicate actual field conditions before using it to predict future results of signal timing changes. The primary calibration measures were the field-collected travel times and field observations. The calibration process modified default input parameters until the model's predicted travel times matched the field-collected travel times within a reasonable margin of error (10 to 20 percent) and the simulations using the SimTraffic function of the software suite represented reasonable observed field conditions to the engineer's satisfaction.

In general, the model calibrated well and very few modifications to the default parameters were necessary. The utilization of measured saturation flow rates, rather than relying entirely on the default rates, improved the calibration work. Often, only the link speeds were changed in order for the model to calibrate. The spreadsheet tool standardized the process by plotting the model's arterial travel time versus the field-collected travel times with the upper and lower limits of the 95th-percentile confidence interval to identify how well the model represented actual travel times (see Figure 2).

Table 2. Comparison of before and after CBD cycle lengths.

Zone	a.m pattern		p.m. pattern		Off-peak pattern	
	Before	After	Before	After	Before	After
MLK/Howard Street	110	110	110	110	90	90
President Street	165	**110**	165	**110**		90
CBD north	110	**80**	110	**80**		**60**
CBD west		**80**		**100**		90
CBD south		110				90

Network Partitioning

The network partitioning was performed using a combination of engineering judgment based on knowledge of the city's traffic patterns and the software's recommendations on how the zones should be divided and coordinated with consideration to factors such as traffic volumes; distance between signalized intersections; queue storage and travel patterns; and the software's "Optimize Network Cycle Length" tool. Each zone or partition would be a group of coordinated signals with harmonic cycle lengths.

The benefits of partitioning the study area into multiple zones were to be able to reduce cycle lengths; ease signal timing maintenance; ease updates of signal timings; reduce stops and delays; and improve overall signal coordination.

The CBD was partitioned into five zones:

- MLK/Howard Street corridor;
- President Street corridor;
- CBD north;
- CBD south; and
- CBD west.

The partitioning of the MLK/Howard Street corridor was logical because they function as arterials and are at the limits of the CBD boundary. The CBD south/CBD west zones are divided by Howard Street.

Howard Street is a one-way, single-lane, northbound, shared vehicle and light-rail transit (LRT) corridor. The City of Baltimore provides transit signal priority along Howard Street to improve travel time and reduce delays for LRT vehicles. The Howard Street signals were included with the CBD south area. Due to potential operational problems at the Howard Street boundary, only the morning peak period pattern utilized this zone. The mid-day and afternoon patterns combined the CBD south and CBD west zones to minimize queue problems associated with non-harmonic cycle length across Howard Street.

WALK and DON'T WALK Evaluation

The calibrated traffic model could be used for evaluation of signal timing optimization strategies. However, prior to developing optimization alternatives, the pedestrian clearance intervals were updated based on the 2003 *Manual on Uniform Traffic Control Devices* (MUTCD) criteria (4- to 7-second WALK and DON'T WALK of sufficient time to cross the entire street). A walking speed of 3.5 feet per second was used to calculate the DON'T WALK intervals. Because of the reduction in walking speed from 4.0 to 3.5 feet per second and other considerations, the pedestrian clearance intervals were increased. In areas of high pedestrian activity, such as the Inner Harbor areas of Baltimore, the WALK time was set to 10 seconds; otherwise, 4 to 7 seconds was used based on the amount of pedestrian activity.

Cycle Length Evaluation

One of the city's goals was to reduce cycle lengths in the CBD area. Reduction in queuing problems associated with the 400-foot spacing of signals on the grid network and reduction in pedestrian delays waiting to cross the streets drove this goal. As discussed, the software's "Optimize Network Cycle Length" tool was used to compare queues, delays and stops under several different cycle length scenarios. In addition, simulation analyses and intersection levels of service were compared under various options.

The pedestrian timing requirements often required a side-street split higher than necessary to accommodate pedestrians crossing the mainline roadway. A competing requirement was to provide adequate green intervals to process traffic on the mainline approaches while also reducing the cycle length. Due to the competing nature of these requirements, the minimum practical cycle length in the CBD during the peak periods was 80 seconds. Table 2 summarizes the before and after signal timing optimization cycle lengths. As shown, the existing cycle lengths were reduced in most zones during the a.m. and p.m. peak patterns.

In a similar manner to the CBD study area, cycle length evaluation was performed on each of the gateway corridors. Of the gateway streets that have been re-timed, all of the existing cycle lengths were retained.

Offset Seeking Transition Logic

When changing between signal timing patterns with different cycles and/or offsets, there are several different methods of transitioning with the city's Naztec™ controllers. The city uses the "short/long" transition method and excludes the coordinated phase from transitioning. This is an internal logic to these controllers that calculates the shortest time-path between signal timing patterns. "Short" refers to the logic where the offsets are reduced between patterns; "long" refers to the logic where the offsets are extended between patterns. While the controllers are in transition, coordination may not be guaranteed. With the short/long transition method, there are user-defined inputs for how much the offset can vary from cycle to cycle.

The offset seeking transition logic affected the split and cycle length calculations. Each split needed to be 2 to 3 seconds greater than the minimum split to provide for transitioning between signal patterns. The split had to be higher in cases where the controller selected the "short" method and the split was reduced. Because the minimum cycle length is a function of the minimum splits on each phase, this setting affected the minimum cycle length that could be implemented in the city.

Split and Offset Evaluation

In the CBD grid network, the offsets were developed using a priority structure in order to meet the competing demands of east-west versus north-south traffic flows. The split and offset optimized in the grid network were performed in eight steps, as follows:

- Initial software-based split and offset optimization;
- Manual adjustment of splits;
- Assign priority number to high-volume roadways;
- Software-based offset optimization for priority 1 roadway;
- Manual adjustment of offsets for priority 1 roadway;
- Lock offsets for priority 1 roadway;
- Repeat steps 5, 6 and 7 for all high-volume roadways; and
- Software-based offset optimization of remaining grid network.

In some cases, the software recommended a split greater than the engineering team thought necessary. This was in part because the 95th-percentile conditions do not occur because traffic demands are constrained and demand is equal to capacity. In these cases, splits were manually adjusted based on hand calculations:

Split = Volume per Lane / Number of Cycles per Hour x Surge Factor of 1.5

Upon completion of the split times, the offsets were re-optimized holding the splits constant. The final step was manually adjusting the software-derived offsets using the time-space diagram, to account for mid-block friction and other unique driver behaviors.

Subsequently, each roadway was assigned a priority number based on its importance in the network. In some cases, roadways that did not cross each other were assigned the same priority number. Only high-volume roadways were assigned priority numbers. The roadway with the highest priority was optimized first, and its offsets were "locked" so they could not be changed by subsequent offset optimizations of lower-priority roadways.

This process continued until the roadways with priority numbers were optimized. The remaining roadways (those that were not assigned priority numbers) then were optimized. The split and offset evaluation was performed in four steps without the iterative prioritization on the gateways and in the MLK/Howard Street and President Street CBD zones. A final test was made comparing the offset evaluation of the entire zone versus the method described above. Network measures of effectiveness were compared between the two options to ensure that the manual method provided logical results.

THE BENEFITS DERIVED FROM THIS PROJECT PROVED THAT SIGNAL TIMING SHOULD NOT BE COMPROMISED IN THE FIELD, AND AN EFFORT LIKE THIS TO PERFORM CITY-WIDE SIGNAL TIMING OPTIMIZATION IS WELL WORTH THE MONEY.

Signal Timing Implementation and Fine-Tuning

The CBD signals operate under a central computer system with monitoring and upload/download capabilities. As mentioned previously, the initial system upgrade project was completed prior to the start of the signal optimization project. The new signal grouping scheme needed to be created because the existing condition in the CBD was one group. New pattern numbers also were developed so as not to overwrite the "before" timing patterns. This was done so that in case the "after" timings were disappointing, the "before" timing patterns could be quickly be returned.

Typically, the optimized timing plans were entered into the central computer a few days before the nighttime test. The tests were performed at night, under low traffic volumes so as not to disrupt critical peak period traffic operations, in case there were problems with erroneous data entry. On the day of the nighttime test, the "after" timings were downloaded to the field controllers at 7 p.m.

Typical problems encountered were with the old communication system and user errors due to the large number of staff working with the new central computer software. Often data were not downloaded to controllers or only part of the data were downloaded due to communication issues with the city's twisted-pair copper cables. The nighttime tests consisted of troubleshooting communication problems and field-testing the new timing patterns.

The central computer system and closed-circuit TV surveillance enabled some of the fine-tuning to be performed in the traffic management center office. The field fine-tuning was performed during the peak periods and consisted of driving through the network and identifying congestion-related problems. In most cases, these problems were addressed through offset changes.

In one case, a signal was moved between groups to provide for more queue storage on the link between differing cycle lengths. In several instances, splits were adjusted to reduce queuing. At some intersections, splits were increased to hold a platoon from releasing toward a downstream intersection that was in red to minimize the number of stops.

BENEFITS

Measure of Effectiveness

To determine whether the signal timing optimization was successful from an economic standpoint, a benefit-cost analysis was performed. Benefits were measured in terms of travel time savings, reduction in vehicle operating costs (measured in stops per vehicle), fuel consumption savings and emissions reductions. Costs included traffic data collection, consulting fees for developing new timing plans and labor costs associated with city review of timing plans, uploading the new timing plans into the signal controllers and fine-tuning. Benefits in this study are estimated for a period of one year.

Table 3. Benefits of CBD-optimized timing plans.

Measure of effectiveness	Delay (hours)	Stops	Fuel consumption (gallons)	Emissions of carbon monoxide (kilograms)	Emissions of nitrogen oxide (kilograms)
Before	11,351	699,260	17,359	1,208	236
After	7,972	605,960	14,155	990	193
Improvement	3,379	93,300	3,204	219	43
Percent improvement	30	13	18	18	18
Annual benefit	$26,132,499	$653,100	$4,806,000	$765,706	$308,818
Total benefit	$32,666,123				
Cost	$762,500				
Benefit-cost ratio	43 : 1				

Quantification Methods

The benefits are calculated by assigning monetary values to each measure of effectiveness comparing the condition before and after the signal timing improvements. Total delay (hours), stops, fuel consumed (gallons), carbon monoxide emissions (kilograms) and nitrogen oxide emissions (kilograms) were calculated using Synchro.[1–5] Benefits were estimated for the morning, mid-day and afternoon peak hours and multiplied by the number of hours in the peak period (2 hours) to estimate the benefits per peak period.

The sum of the morning, mid-day and afternoon peak periods represented the weekday daily operating cost. The annual operating cost is based on 250 weekdays per year. It should be noted that benefits derived from reductions in travel time, stops and fuel consumption were not estimated for non-peak periods.

To calculate the benefit-cost ratio, project costs were also calculated. Costs include traffic data collection, consulting fees and city labor costs. The total estimated cost is $3,050 per intersection, based on the following:

- $1,000 per intersection to perform a turning movement count.
- $2,000 per intersection for consulting fees for signal timing optimization.[6]
- $50 per intersection for city labor costs.[7]

Table 3 summarizes the benefits and costs for the CBD study area, which shows a net benefit of $32.7 million. In order for a project to be considered worthwhile, the benefit-cost ratio should exceed 1.0. The overall benefit-cost ratio was 43:1, meaning that the project was highly valuable.

Benefits are not calculated for the gateways because the project is not fully completed. For the seven gateways that are completed, the annual benefit is $7 million, with a benefit-to-cost ratio of 17:1.

Before and After Results

"After" travel time and delays studies are being performed as of the publication of this feature. Preliminary data are available for several corridors. The field-collected data are consistent with the data reported in Table 3. The following are generalized results based on data collected on approximately one-half of the corridors in the project (gateways and CBD study areas):

- Average travel times are reduced by 30 percent.
- Stops are reduced by 15 percent.

CONCLUSION

At the conclusion of this project, it was clear to all involved parties that this effort could not have been possible to accomplish in a 12-month period without using a computerized tool for signal timing evaluation and optimization. The use of the traffic signal timing model to code this large network by multiple users, perform independent signal timing evaluation and subsequently merge the files to a single working file was invaluable.

The associated microsimulation software also demonstrated its strength and effectiveness when developing and visualizing alternative offset and split solutions and corresponding progressions plans. The model calibration process was educational and enforced the fundamental concepts and principles of traffic flow theories. This project proved that with good understanding of signal timing concepts, the user could leverage the strength of signal timing models and engineering judgment.

Finally, the benefits derived from this project proved that signal timing should not be compromised in the field, and an effort like this to perform city-wide signal timing optimization is well worth the money. The benefits outweighed the costs of the entire project in less than 3 months and exceeded the expectations of city and public officials. ■

References

1. $15.86 per hour of delay: The average wage rate in Baltimore City of $21.73, multiplied by a 50-percent reduction factor (recommended by the Federal Highway Administration when converting wage rates into values of time to account for non-work trips) and a 1.46 occupancy rate were applied to determine the cost of time per person in a passenger car of $15.86. To determine the cost of time for each truck, a 1.1 occupancy rate was applied to the average truck rate of $21.69; assuming a 2-percent truck percentage, an average cost of time per truck of $15.37 was calculated. The average hourly wage rates were determined from the Department of Labor, Licensing and Regulation's weekly wage rates at www.dllr.state.md.us/lmi/emppay/tab1md.htm.

2. 0.014 per stop: Texas Transportation Institute Study.

3. $3.00 per gallon of gasoline: Reasonable assumption based on the current price of gasoline.

4. $7.011 per kilogram of carbon monoxide:

"Evaluation of the Benefits of a Real-Time Incident Response System," presented at the 9th World Congress Conference on ITS, Chicago, IL, USA, October 14–17, 2002.

5. $14.192 per kilogram of nitrogen oxide: "Evaluation of the Benefits of a Real-Time Incident Response System," presented at the 9th World Congress Conference on ITS, Chicago, October 14–17, 2002.

6. This cost is based on fees under this contract, which is similar to recent fees for signal optimization projects within other jurisdictions within Maryland. This cost includes before and after travel time and delay studies; coding the traffic model with geometry, signal timings, traffic data and signal phasing; field studies; model validation and calibration; and fine-tuning of signal timings in the field. This is based on 20 hours of labor per intersection and an average loaded (including profit and overhead) rate of $50 per hour.

7. This cost includes time to upload new timing plans from the traffic management center (approximately one-half hour per intersection) and fine tuning of the after signal timings in the field (approximately one-half hour per intersection). The city labor cost is based on 1 hour of labor per intersection and an average loaded (including profit and overhead) cost of $50 per hour.

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