Methodology for Evaluating Effectiveness of Traffic-Responsive Systems on Intersection Congestion and Traffic Safety

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In 1986, the city of Milwaukee applied for and received approval for a hazard elimination grant to reduce congestion and traffic accidents at the intersection of two major and one minor arterial on the northwest side of the city. The intersection complex had several approaches at or above capacity, associated long queues of traffic, and an annual traffic-accident rate of more than three per 1 million entering vehicles. The hazard elimination grant called for the installation of a closed-loop, traffic-responsive signal system to manage the congestion and to reduce traffic accidents. The intersection complex presented many constraints on traffic-responsive operation, the most critical of which was that the three arterials formed a signal triangle (three separate signalized intersections) with intersection spacing as short as 27.4m (90 ft). FHWA realized the unusual nature of this project and designated it an experimental project in 1987. The development of the traffic-responsive signal system within the many constraints of the location is described. After a lengthy process, the traffic-responsive system became operational in September 1993 and proved to be an operational success by reducing the length of traffic queues. After extensive data collection, an analysis and evaluation confirmed that the traffic-responsive signal system reduced the occupancy levels per vehicle on the system detectors and reduced the incidence of congestion-related traffic accidents.

In 1986, the city of Milwaukee applied for and received approval for a hazard elimination grant to reduce congestion, long queues, and traffic accidents at the intersection complex of West Capitol Drive, West Fond du Lac Avenue, and North 51st Street in the northwest part of the city. The grant called for the installation of a closed-loop, traffic-responsive signal system at this intersection complex. A graphical illustration of the intersection complex is presented in Figure 1. This intersection complex presented many constraints on traffic-responsive operation. West Capitol Drive and West Fond du Lac Avenue are two of the highest-volume principal arterials (34,000 and 34,900 annual average daily traffic, respectively) on the north side of the city of Milwaukee. More important, these two roadways and North 51st Street intersect in a signal triangle (three separate signalized intersections) with intersection spacing as short as 27.4 m (90 ft).

PROJECT DEVELOPMENT

The largest constraint on implementing traffic-responsive operation was the triangle geometry and the unusual signal-timing plan necessary in the triangle. The important part of this timing plan is the relative relationships among the intersections, notjust the phasing at one particular intersection. If these relation-ships were adjusted even slightly, queue spillovers and gridlock could result.

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Requirements for Traffic-Responsive System

To reduce congestion on specific roadways, traffic-responsive operation would have to change the green-to-cycle (g/c) ratio for the congested roadways, but not change the established timing relationships within the triangle described previously. Another requirement of traffic-responsive operation is that the three intersections in the triangle not be allowed to get out of coordination with each other during the changing of coordination plans. If the three intersections lost coordination with each other during plan changes, gridlock would result.

Construction Engineering

The only communication cable installation necessary was from a nearby fire station to the master controller within the intersection triangle and between the master controller and the five local controllers, because cable is available among all municipal buildings. The communication system would allow full system observation; data upload, download, and storage; and controller programming capabilities from a micocomputer in the engineering office or the city's maintenance facility.

System Detector Design

System detector design was an important part of the design process because accurate data from the system detectors are essential to proper closed-loop, traffic-responsive operation. Many of the important concepts used in the design of the system detectors were found in the *Traffic Control Systems Handbook* (*1*). The project engineer observed traffic operation on all critical approaches to the triangular intersection complex during the highest-volume periods, noting queue lengths and so forth. It was critical that congestion conditions be apparent from the system detector data. The detectors had to be far enough from the stop line that normal queues during uncongested conditions could be differentiated from queues caused by congested conditions, but not so far from the stop line that queueing and related speed-reduction zones never occur. The locations of the system detector loops are presented in Figure 1. Detector 2 has data-only function. Detectors 3–6 have plan-selection function.

Master Controller Programming

The existing cycle length for the five intersections was 90 sec. Because of crosswalk lengths and the phasing requirements, it

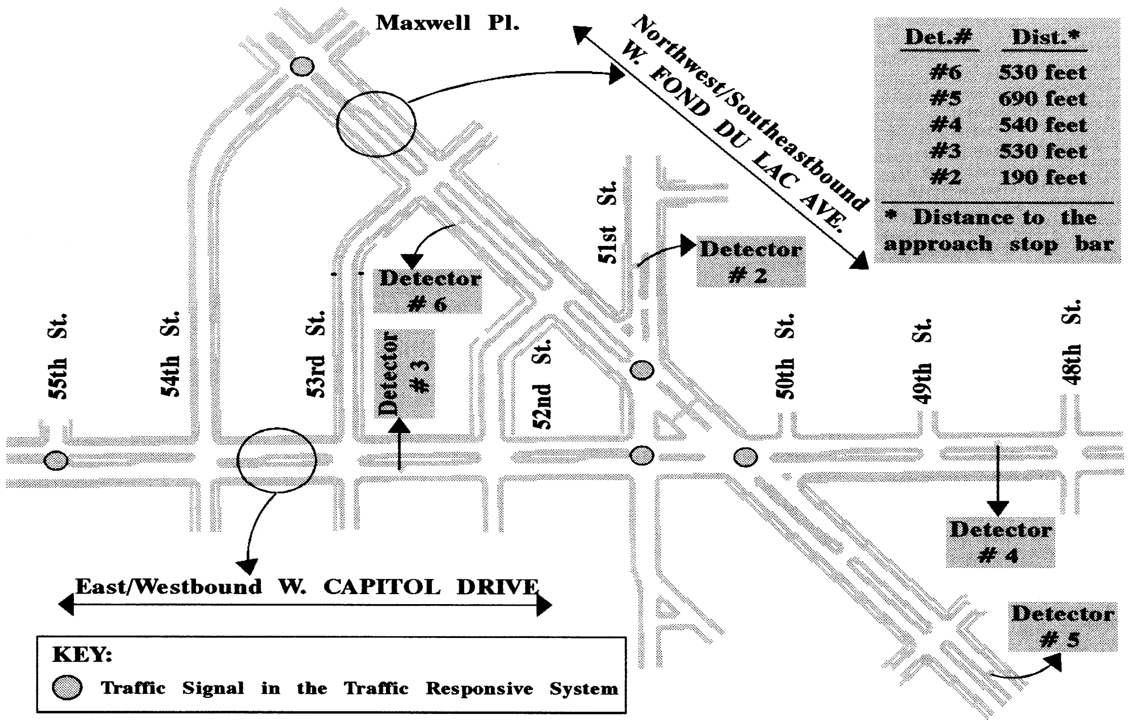


FIGURE 1 Intersection layout with detector locations (1 ft = 0.3 m).

was not feasible to use a shorter signal cycle length. Therefore, the base or uncongested timing plan would be the existing plan. To change splits or *g*/*c* ratios, it was necessary to increase the system cycle length. Following evaluation of progression possibilities and overall delay, it was decided that a 120-sec cycle would be the maximum signal cycle and would be used for any of the congestion-based coordination plans.

Sample Length Selection

The sample length is the period during which data will be gathered from the system detectors and used for plan selection by the master controller. The desired sample length was the lowest common multiple of the base 90-sec cycle and the longer 120-sec cycle chosen to be in effect during congestion. The shorter the sample length, the more rapidly a traffic-responsive system can respond to congestion. The chosen sample length was 6 min.

System Detector Data Collection

Data were collected from the system detectors for a few months and analyzed, and an important conclusion was made: Volume data were not a reliable indicator of congestion. In effect, volume and congestion were not a continuous mathematical function. In other words, under heavily congested conditions, the traffic volume passing over a detector can be very low. Plan selection made by volume data would be wrong in this case. There was a continuous relationship between occupancy and congestion levels by which occupancy data could reliably predict or confirm congested conditions. Therefore, only occupancy data would be used for plan selection, not volume data.

Development of Occupancy Thresholds

Extensive logs of data output from the system detectors were made, and these data allowed the calculation of occupancy thresholds that defined congestion on West Capitol Drive and West Fond du Lac Avenue. The detector data verified that Detector 6 (southeastbound Fond du Lac) frequently exceeded thresholds during weekday mornings (7:00 to 9:00, approximately), Saturday afternoons (12:00 to 6:00), and occasionally during the weekday-afternoon peak periods. Detector 5 (northwestbound Fond du Lac) and Detector 4 (westbound Capitol) commonly exceeded thresholds during the weekday-afternoon peak periods (2:00 to 7:00). Overall, it was found that the thresholds for the Fond du Lac Avenue detectors were exceeded more frequently than were the thresholds for the Capitol Drive detectors.

Programming Local Controllers for Traffic-Responsive Operation

Some unusual programming techniques were necessary to allow signal plans (cycle, split) to change without causing the fixed-time controllers to lose coordination with each other. The controllers were programmed with the following coordination plans as defined by the Wapiti W70SM traffic-responsive algorithm for Type 170 controllers:

- Plan 2: uncongested operation,
- Plan 10: Capitol Drive approachs congested,
- Plan 11: Capitol Drive and Fond du Lac Avenue approachs congested, and
- Plan 12: Fond du Lac Avenue approachs congested.

No other plans would be implemented because they were based on volume thresholds. The cycles and splits (coordination plans) were changed by adding time to certain timing intervals. This process had to be done very carefully to avoid changing critical timing relationships within the signal triangle. The green time added per plan and the resulting *g*/*c* ratios for each critical approach are shown in Table 1. The green time added per coordination plan was calculated using the goal of adding as much green as possible to the congested approachs while still providing an adequate *g*/*c* ratio to meet the demand on the uncongested approachs. The resulting *g*/*c* ratios per coordination plan were calculated by summing the Plan 2 green length and the added green (per plan per approach) and dividing by the cycle length for the coordination plan. Several safeguards were added to the intersection signal programming in the unexpected case that the local controllers lost coordination with the master controller.

IMPLEMENTATION AND OPERATION

On September 15, 1993, on-line traffic-responsive signal operation was instituted. Following some minor fine tuning, by October 1, 1993, the traffic-responsive signal control was considered fully operational. This date was the beginning of the period for evaluation of the performance of the new traffic system.

The traffic-responsive control system was very effective in reducing, and in some cases eliminating, queues on southeastbound Fond du Lac Avenue from 51st Street during the morning-weekday peak periods and Saturday-afternoon periods. In addition, the system was able to reduce queues on northwestbound Fond du Lac Avenue from Capitol Drive during the afternoon peak periods, but to a lesser extent. In general, it was noticed that Coordination Plan 12 (favoring Fond du Lac Avenue) was almost exclusively implemented during the weekday-morning peak periods and on Saturday afternoons, and in the weekday-afternoon peak periods Coordination Plan 12 was implemented more frequently than Coordination Plan 10 (favoring Capitol Drive). There was no regular pattern of shifting congestion from one roadway to another as coordination plans changed.

ANALYSIS AND EVALUATION

As demand for limited intersection capacity increases, traffic and transportation agencies also are increasingly involved in implementing systematic procedures to mitigate congestion. The Intermodel Surface Transportation Efficiency Act of 1991 (ISTEA) recognized the importance of this activity by mandating development of six management systems, including a congestion management system (CMS). The regulation governing CMS implementation requires several system components, including methods to measure system performance and procedures to assess alternative congestion-mitigation strategies. Such evaluations require several input variables, two of which are average vehicle occupancy (AVO) and traffic accidents. Although the project involved in this paper was not funded as a part of ISTEA, the system performance analysis should be applicable to projects funded under the act. The basic analysis technique used in the performance evaluation of this project is the simple “before-and-after” method. The before period is September 1, 1991, to August 31, 1993; and the after period is October 1, 1993, to September 30, 1995. The AVO and traffic-accident data used in this study are, in general, used to formulate transportation strategies to analyze the success of different transportation programs.

AVO

The literature shows that vehicle-occupancy data collection methodology has been thoroughly researched for uninterrupted traffic-flow facilities, whereas little was researched for interrupted traffic-flow facilities. A study by Barton Aschman Associates (*2*) reports that trip purpose has the greatest influence on AVO and the trip purpose varies by time of day. The study reports that the lowest AVO rates were associated with home-based work trips and those formulate a large percentage during the morning peak hours and the afternoon peak hours. This may be the case only under uncongested, free traffic flow. Ulberg and McCormack (*3*) examined the accuracy and factors affecting AVO rates. Their study reports human factors, traffic characteristics, and environmental conditions as some of the significant factors affecting AVO estimation. In their research on the accuracy of field-measured AVO data, they identify various sources of error associated with field studies, including weather, time of day, traffic density, vehicle speed, and vehicle weaving and lane changing. These errors must be addressed in the AVO sampling procedures for a statistically valid estimate. The algorithm of the traffic-responsive system implemented at West Capitol Drive, West Fond Du Lac Avenue, and North 51st Street was tailored to provide real-time measurements of total occupancy in seconds per 360-sec sample length and as a function of flow rate at each of the previously discussed detectors.

TABLE 1 Added Green Time per Approach/Coordination Plan (in Seconds)

APPROACH	PLAN 2	PLAN 10	PLAN 11	PLAN 12
CAPITOL DRIVE	0	25	13	5
FOND DU LAC AVENUE	0	5	12	25
51st. STREET	0	0	5	0
RESULTING G/C RATIOS PER CRITICAL APPROACH /COORDINATION PLAN (No pedestrian actuation)				
APPROACH	**PLAN 2**	**PLAN 10**	**PLAN 11**	**PLAN 12**
East/Westbound CAPITOL at FOND DU LAC	0.333	0.458	0.358	0.292
Southeastbound FOND DU LAC at 51st	0.289	0.258	0.317	0.425
Northwestbound FOND DU LAC at CAPITOL	0.267	0.242	0.300	0.408

Analysis Approach

AVO data are valuable input to congestion-management systems. The AVO data collected in this project were based on field real-time measurements at each of the four approaches of the triangle that were used as input to the traffic-responsive algorithm:

- Eastbound approach of West Capitol Drive (west of 51st Street);
- Westbound approach of West Capitol Drive (east of Fond du Lac Avenue);
- Northwestbound approach of West Fond du Lac Avenue (south of Capitol Drive); and
- Southeastbound approach of West Fond du Lac Avenue (north of 51st Street).

Data were collected per approach before and after implementation of the traffic-responsive control system. Twenty random samples per each before-and-after period were included in the analysis. Each sample has 240 total traffic-flow occupancy (seconds per 360 sec) measurements. Each total occupancy measurement is a function of traffic flow per lane per 360 sec. All samples included in the analysis occurred under normal weather with dry or wet road surfaces and cover different times of day, lighting levels, traffic density, driver behavior, and vehicle speed. The wide range in traffic volumes encountered during this study over different times of day did produce a sufficient number of occupancy samples at various levels of traffic flow. Occupancy readings were obtained from each detector computer output and for different levels of traffic flow. Before the traffic-responsive system was implemented, more than 2,000 samples (360-sec samples) per detector were compiled and sorted by level of traffic-flow rate and detector. After implementation of the system an equivalent number of samples per detector was compiled and sorted by level of traffic-flow rate and detector.

Evaluation Approach

On the basis of the collected, compiled, and analyzed data, a regression analysis was used to generate a mathematical model to predict total occupancy as a function of traffic-flow rate before and after implementation of the traffic-responsive system. The modeling approach finds a relationship between total occupancy (seconds per 360 sec) and various levels of traffic-flow rate under two conditions:

- Maximum total occupancy condition. This condition presents the worst average vehicle arrival possibility (highest deceleration) per each level of traffic-flow rate.
- Minimum total occupancy condition. This condition presents the best average vehicle arrival possibility (lowest deceleration) per each level of traffic-flow rate.

On the basis of the coefficient of determination (R^2) values, the exponential model fits the data best.

$$\text{total traffic-flow occupancy (seconds per 360 sec)} = e^{[a + b \times \ln(\text{flow rate})]} \tag{1}$$

The parameters (a and b) and R^2 for the relationship between the total traffic-flow occupancy and traffic flow (Equation 1) are presented for each detector in Figure 2.

The incremental change in the total occupancy as a function of the traffic-flow rate was calculated for each approach on the basis of Equation 2 and graphed for both before and after periods in Figure 3(a).

$$\frac{\partial\,(\text{total traffic-flow occupancy, seconds})}{\partial\,(\text{flow rate})} = (b-1) \times e^{a} \times (\text{flow rate})^{b} \tag{2}$$

The AVOs of the 6-ft² loop detector as a function of traffic-flow rate were calculated for each approach on the basis of Equation 3 and graphed for both before and after periods in Figure 3(b).

$$\text{AVO (seconds)} = \frac{\frac{1}{b+1} \times e^{a} \times (\text{flow rate})^{b+1}}{\text{flow rate}} \Bigg|_{\text{flow rate 1}}^{\text{flow rate 2}} \tag{3}$$

Statistical Analysis

A statistical decision process is a procedure for making decisions about a population on the basis of observations or measurements made on a sample. The procedure is set up so that the probability of making an incorrect decision can be made quantifiable. All statistical inferences assume random sampling, that is, that each member of the population has the same chance of being selected in the sample. The test of a statistical hypothesis is about the value of, or relationship between, unknown parameters. A test of a statistical hypothesis is a procedure for deciding, on the basis of a sample, whether to reject the hypothesis. One statistical hypothesis might be that the means of two random variables (AVO before, AVO after) are equal; another, that the mean of one is larger than the mean of the other. One of the statistical hypothesis is chosen to serve as the null hypothesis and usually is denoted by H_o. The test ends by a statement about whether H_o, is rejected. H_o is rejected whenever the outcome is in the rejection region. The probability of an outcome to be in the rejection region when the null hypothesis is true is the probability to reject a correct null hypothesis. This usually is called the level of significance, or the maximum probability of making a Type I error, and is denoted as α. In practice, the analyst doing the hypothesis testing chooses an appropriate value for α.

For each H_o to be tested there is an associated alternative hypothesis, usually denoted by H_1. The alternative hypothesis H_1 reflects the change or difference anticipated. Accordingly, H_1 is the statement that reflects the situation anticipated to be true if H_o is not true (*4*).

In this study of AVO data the paired t-test is used. The paired t-test is used to analyze pairs of observations, AVO before and AVO after, to see if the mean of AVO before (m_{before}) equals the mean of AVO after (m_{after}). The matched pairs of AVO before and after data are reduced to a single sample by subtracting the AVO after implementation of the traffic-responsive system from its respective AVO before for the same traffic-flow rate.

$$\text{Diff}_v = \text{AVO}_{v,\,\text{before}} - \text{AVO}_{v,\,\text{after}} \tag{4}$$

where v is the traffic flow per 360-sec sample. Accordingly, the hypothesis to be tested is H_o: $m_{\text{before}} = m_{\text{after}}$ (no change in the mean AVO), versus H_1: $m_{\text{before}} > m_{\text{after}}$ (the mean AVO is higher before).

For a choice of $\alpha = 0.01$ (99 percent level of confidence), Table 2 summarizes the results of the statistical analysis for the four system detectors.

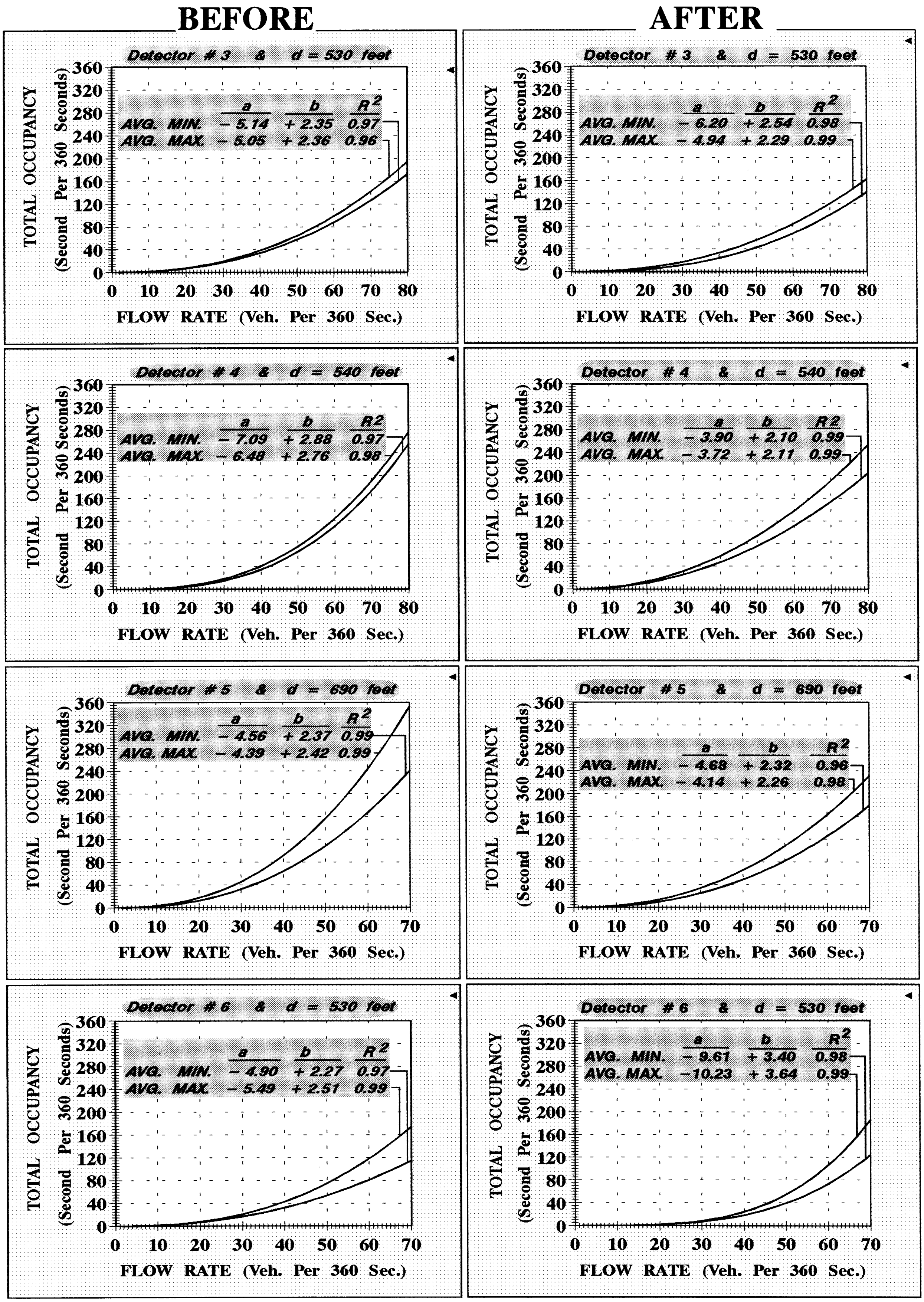


FIGURE 2 Parameters for relationship between total traffic-flow occupancy and traffic flow (1 ft = 0.3 m).

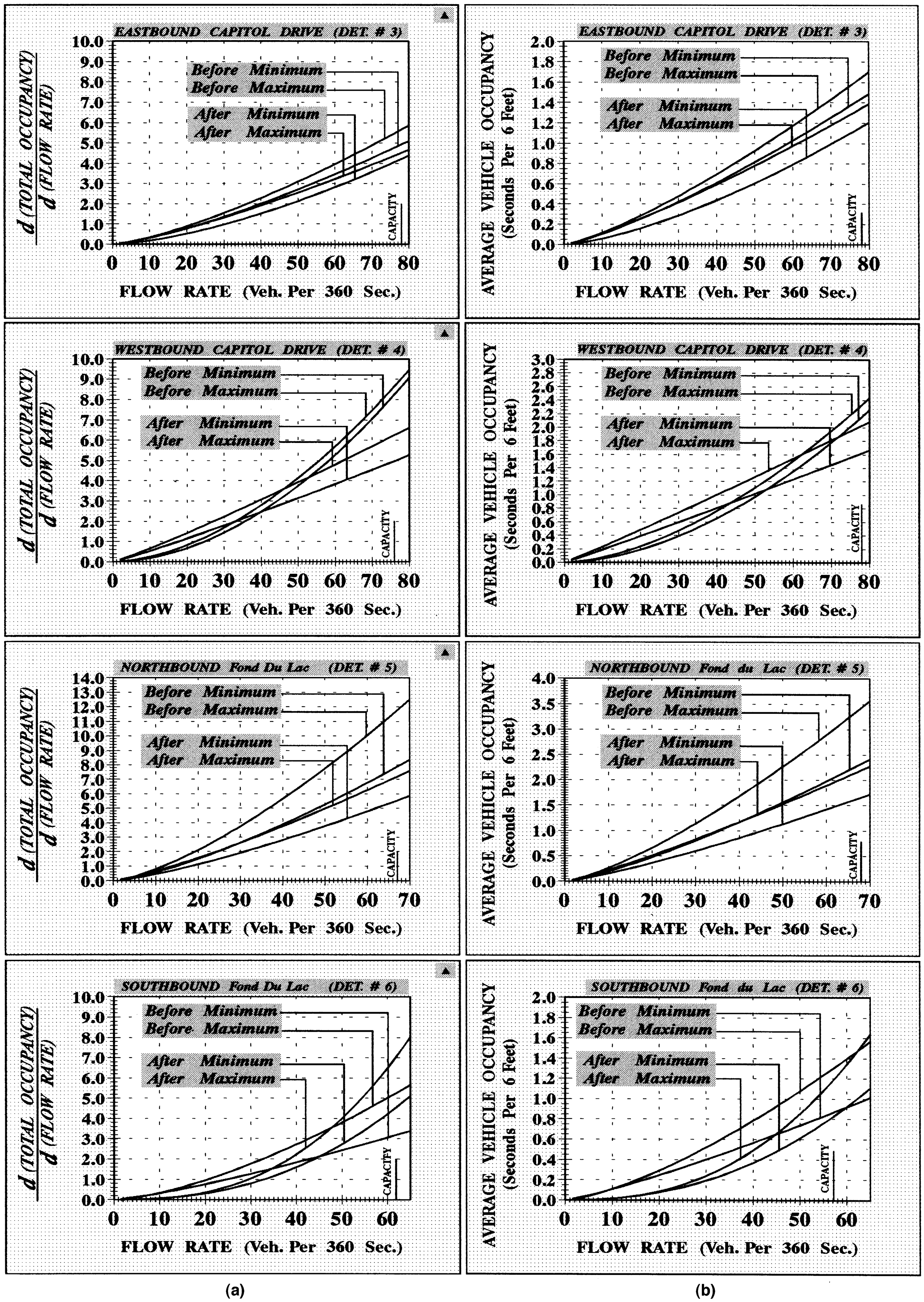


FIGURE 3 Incremental change in total traffic-flow occupancy (*a*), and average vehicle occupancy as function of traffic flow rate (*b*), (1 ft = 0.3 m).

TABLE 2 AVO Paired *t*-test ($\alpha = 0.01$)

DETECTOR	AVO	MEAN	Standard Deviation	SE MEAN	T	P	Result* Yes or No
NO. 3	MIN.	+0.176	0.089	0.010	124.60	0.000	Yes
	MAX.	+0.148	0.121	0.013	89.90	0.000	Yes
NO. 4	MIN.	+0.094	0.341	0.036	30.30	0.000	Yes
	MAX.	−0.029	0.260	0.028	35.28	0.000	Yes
NO. 5	MIN.	+0.420	0.312	0.033	42.90	0.000	Yes
	MAX.	+0.752	0.618	0.066	26.74	0.000	Yes
NO. 6	MIN.	−0.057	0.316	0.034	28.14	0.000	Yes
	MAX.	−0.072	0.450	0.048	19.45	0.000	Yes

* If $P < \alpha$ Reject H_0 and accept H_1 = Yes Otherwise No

On the basis of the results of the statistical analyses presented in Table 2, H_o is rejected for all detectors, and it is concluded that the mean AVO has decreased from before to after implementation of the traffic-responsive system. The *P*-value is too small for all detectors, so there is very little chance of making a Type I error.

Roadway Safety and Congestion

Balancing the competing demands for roadway improvements is a difficult task. As peak-period traffic flows continue to increase, engineers endeavor to improve roadway operation by reducing the extent and duration of congestion while trying to increase safety for all road users. Certain traffic-flow improvements may enhance safety, but little is known about the interaction between safety and traffic-flow treatments for roadway sections or spots. The purpose of this project was to enhance roadway safety by reducing congestion. This analysis was undertaken to determine the relationship of the interaction between congestion and safety at urban signalized intersections and adjacent roadway segments.

The relationship between traffic flow and accident experience is poorly understood, especially under conditions in which traffic flow approaches capacity (congestion or near-congestion). There is convincing evidence (*5*) that traffic-accident rates are highest at night, when traffic flows are relatively low. This may be due to tired or impaired drivers, the difficulties of driving in the dark, or the small denominator in the traffic-accident rate equation. It is clear, however, that most congestion-related improvements will not be of significant benefit during low-volume night conditions. The technical literature provides little guidance on what to expect at or near congestion. Higher traffic volumes and the larger denominator in the traffic-accident rate equation would tend to decrease the traffic-accident rate. However, the stop-and-go traffic conditions that prevail as facilities become congested provide many opportunities for collisions. In these situations, improvements to facility capacity would decrease the incidence of stop-and-go driving, but their effect on traffic-accident experience is less obvious. One might conclude that a facility with better traffic flow must inherently provide safer operation. Realistically, there may be tradeoffs between factors that improve traffic flow and those that improve traffic safety.

Analysis Approach

Traffic accidents are indicative of failures in the travel interactions of driver, vehicle, roadway, traffic, and environmental conditions. A traffic accident is a discrete variable, measured by a numerical scale with a zero point, and assumes only integer values. A traffic-accident frequency is the number of occurrences of a traffic accident during a period. Exposures in roadway safety studies are used as a measure of opportunities for traffic accidents to occur. A traffic accident is the product of an unstable condition of one or more exposures or an unbalanced interaction between two or more exposures, or both. Typical exposure measures for traffic accidents include the number of sites considered, the length of the period for which traffic-accident data are available, the total length of the sites, environmental condition, and the total vehicle-kilometers of travel on those sites. The greater the exposure, the greater the number of traffic accidents that would be expected to occur (*6*).

To determine whether there are more or fewer traffic accidents than expected at a site (or group of sites), both an accident frequency and an exposure measure are needed. Thus safety measures used in traffic-accident surveillance often combine both traffic-accident and exposure measures for a given time.

$$\text{traffic-accident rate} = \frac{\text{measured traffic-accident frequency}}{\text{exposure under prevailing condition}} = \frac{A}{E} \qquad (5)$$

Thus the traffic accidents form the numerator and the exposure forms the denominator of the traffic-accident rate expression. During periods of traffic congestion, complicated interactions take place between exposure data and traffic-accident potential (*6*):

$$\text{traffic-accident rate}_{\Delta t} = \frac{\sum_{t=t_1}^{t=t_2} (A_1 + A_2 + A_3 + \ldots + A_n)_t}{\sum_{t=t_1}^{t=t_2} (E_1 \times E_2 \times E_3 \times \ldots \times E_n)_t} \qquad (6)$$

where

$A_{i,t}$ = total categorized traffic accidents per exposure i and per unit time t;
$E_{i,t}$ = exposure i (where $i = 1, 2, \ldots, n$) per unit time t; and
n = maximum number of exposures at any time.

In many safety projects it is desirable to collect data under only certain conditions of traffic volume, weather, lighting, and so forth. Although it generally is advisable to collect data under a representative range of conditions, it is usually neither possible nor desirable to gather data for every condition. This is not as critical for problem diagnosis, but it can be critical for evaluation. Because of the problems associated with the complexity of exposure data, a criterion was developed in another study (*6*) to evaluate roadway safety by comparing various conditions with their respective accident rates under normal conditions. The developed criterion is based on generating a reference scale to measure the inflation in hazardous conditions from the condition that has the lowest traffic-accident rate (normal ideal condition) to each prevailing condition.

Exposure Data The exposures that were considered to have a variable effect on the probability of traffic-accident occurrence were traffic flow (for both intersections and roadway sections between intersections) and distance between intersections (for only roadway sections between intersections). On the other hand, all other exposures that have a possible effect on the probability of traffic-accident occurrence or these variable exposures were considered constant and around their averages for the before and after conditions.

- Traffic flow. Because traffic volume variation is a function of time or location or both, traffic flows were considered a variable exposure affecting the probability of traffic-accident occurrence on the roadway. Data on hourly traffic volume were collected for each approach of the triangle before and after implementation of the traffic-responsive system. Hourly traffic volumes also were retreived for the entire project period (September 1991 through September 1995) from the automated traffic recorder located at the center of the triangle. These data reflect the traffic volume variation between the before and after periods. A summary of the traffic volume variation is illustrated in Figure 4. A formula was derived to estimate hourly traffic volumes before and after implementation of the traffic-responsive system for each approach.

$$\begin{aligned}\text{estimated hourly traffic volume} &= \text{base volume} \times \mu \times \beta \times i \\ &= \text{base volume} \times f \qquad (7)\end{aligned}$$

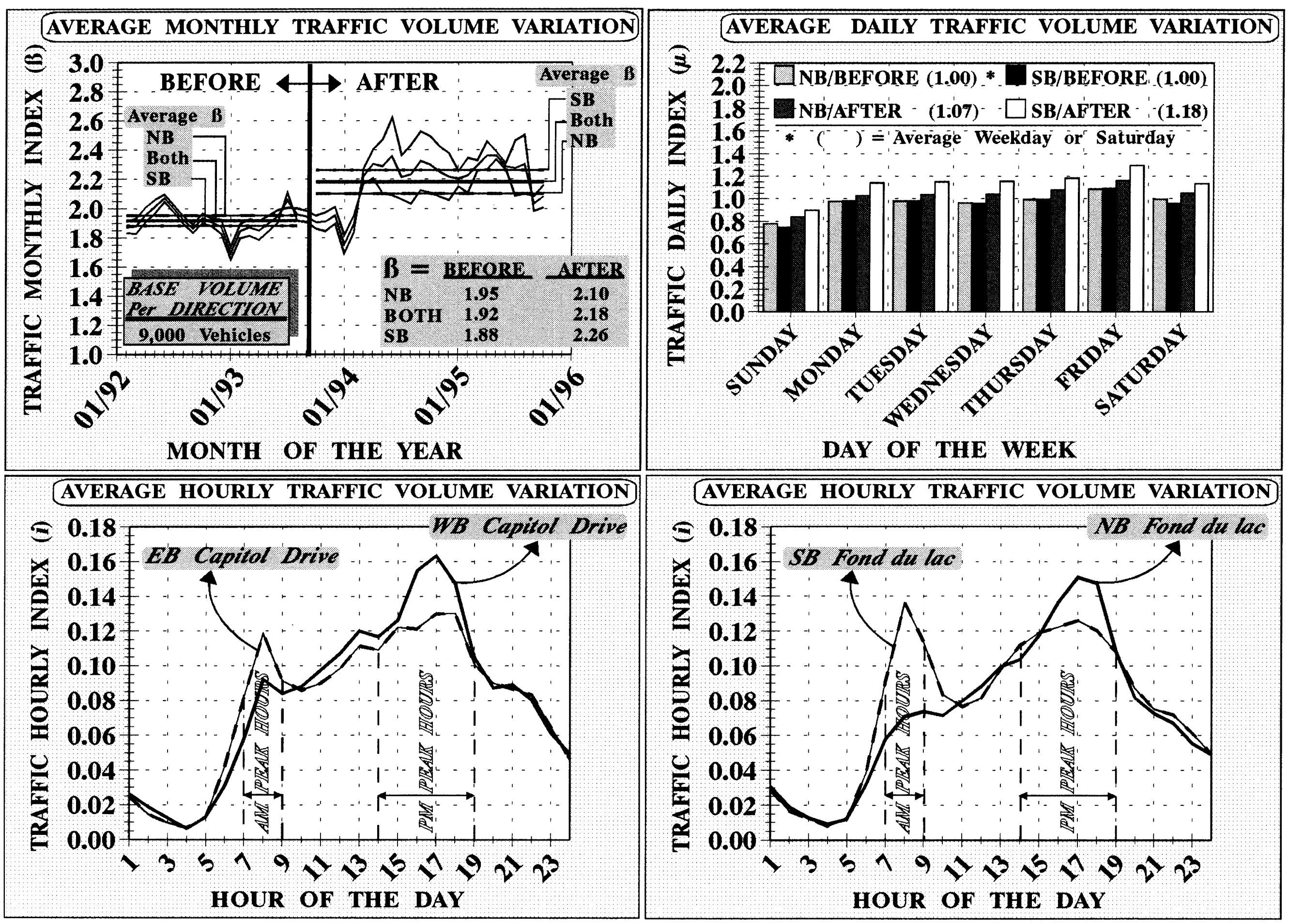


FIGURE 4 Estimated traffic volume per hour per direction.

where

μ = traffic daily index;
β = traffic monthly index;
i = traffic hourly index; and
f = traffic inflation or deflation factor from the base volume.

- Distance between intersections. Because of the variation in distance between intersections, distance was considered a variable exposure affecting the probability of traffic-accident occurrence on the roadway section between intersections. Figure 5 shows all distances between intersections (midblocks) in feet. These data were used to account for distance exposure to adjust for traffic accidents occurring between intersections.
- Weather data. Weather data were obtained from the National Climatic Data Center in Ashville, North Carolina, through its climatological data monthly report for the city of Milwaukee. In this study, all periods that had adverse weather conditions were excluded from the analysis and these were limited to conditions of snow or ice on the roadway pavement.

Traffic-Accident Frequency In this study and to make this analysis complete, traffic-accident data were included for both intersection and nonintersection (midblock) locations. Midblock traffic accidents are critical in this study because multiple-block queues were observed frequently on certain approaches to the traffic signal triangle during congestion periods. These queues created conditions conducive to congestion-related midblock traffic accidents, particularly rear-end accidents. On the other hand, one of the stated purposes of implementing the traffic-responsive system in this project was to reduce congestion and delay by reducing or eliminating queues, and this in turn should improve safety.

Hardcopy reports for all the traffic accidents included in this study were obtained from the city's computerized accident data base. A total of 1,513 traffic accidents occurred on the locations covered during the analyzed period (2 years before and 2 years after implementing the traffic-responsive system). The number and location of each traffic accident occurring on any location within the analyzed areas along West Capitol Drive and along West Fond du Lac Avenue (Figure 5) during the researched period were identified by category (fatal, injury, or property damage only), by type (rear end, angle, left-turn, and same-direction sideswipe), and by occurrence time (date and hour). The traffic-accident data reported for North 51st Street were insufficient for further analysis.

Traffic-Accident Rates A number of relationships between traffic-accident frequencies and traffic volumes have been suggested over the years. A comprehensive survey of these relationships has been discussed by Chapman (*7*) and Satterthwaite (*8*). Others (*9–11*) suggest that traffic-accident frequency is directly proportional to the sum of traffic volumes that enter the intersection. This approach is simple, but its shortcoming is that it is logically unsatisfactory and not a suitable basis for the engineering analysis, which attempts to link cause and effect. Hauer (*12*) presents an example on the weaknesses of this approach. One expects that the number of rear-end traffic accidents at an intersection approach will depend strongly on the traffic volume of Approach A, and will depend less on the traffic volume of Approaches B, C, and D. Similarly, one should expect that collisions between vehicles from Streams A and B lead to the logical difficulty that one will predict

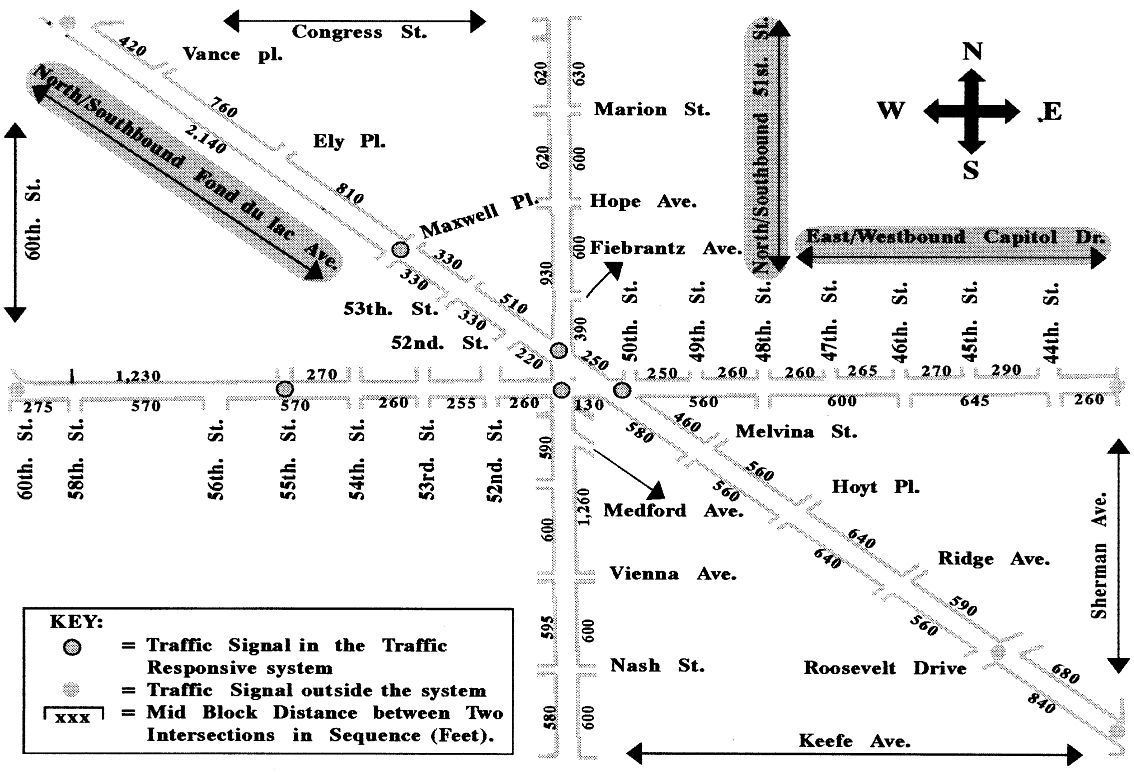


FIGURE 5 Distances between intersections, in feet (1 ft = 0.3 m).

accident occurrence even when one of the traffic volumes is zero, and to use A + B + C + D produces a poor prediction. Some research (*13–15*) relates traffic accidents to the products of the conflicting flows. In other empirical research (*16,17*) it has been found that the number of traffic accidents is not proportional to the product of the flows but rather is related to the product of traffic flows with each flow raised to a power of less than 1.

In this study, an attempt is made to relate traffic accidents to traffic congestion. It was observed that recurring congestion occurs only during the following peak traffic periods:

- Weekdays, 6:00 a.m. to 9:00 a.m.;
- Weekdays 2:00 p.m. to 7:00 p.m.; and
- Saturdays, 12:00 p.m. to 6:00 p.m.

Accordingly, the analysis in this study was limited to those periods. The rationale for this approach is that the traffic-responsive algorithm would implement only congestion-related coordination plans during periods of congestion. During periods without congestion it is expected that the traffic-responsive algorithm would implement the base coordination Plan 2, which is identical to the timing plan implemented in the before period.

Accordingly, traffic accidents were analyzed carefully. Traffic accidents categorized as rear-ends, angle, left-turn, and same-direction sideswipe were considered to be related to congestion. Thus, only traffic accidents of those types were included in the analysis.

To account for exposures at the intersections, a traffic-volume adjustment factor (f) was applied to the traffic-accident frequencies (A) before and after implementation of the traffic-responsive system as follows:

$$\text{adjusted } A_{\text{before, category}} = \frac{A_{\text{before, category}}}{f_{\text{before}}} \qquad \text{adjusted } A_{\text{after, category}} = \frac{A_{\text{after, category}}}{f_{\text{after}}} \tag{8}$$

All traffic-accident frequencies were adjusted on the basis of Equation 8 and are graphed in Figure 6. A similar procedure was followed for roadway segments at midblock. To account for exposures at blocks, a traffic-volume adjustment factor (f) and a distance-adjustment factor (d) were applied to the traffic-accident frequencies before and after implementation of the traffic-responsive system as follows:

$$\text{adjusted } A_{\text{before, category}} = \frac{A_{\text{before, category}}}{f_{\text{before}} \times d} \qquad \text{adjusted } A_{\text{after, category}} = \frac{A_{\text{after, category}}}{f_{\text{after}} \times d} \tag{9}$$

where d is the distance between two consecutive intersections in hundreds of fret.

Figure 5 presents all midblock distances. All traffic-accident frequencies were adjusted on the basis of Equation 9 and are graphed in Figure 6.

Evaluation Approach

On the basis of the collected, compiled, and analyzed data, a comparison was made between categorized traffic-accident frequencies before implementation of the traffic-responsive system and its respective after-implementation values for both intersections and midblocks. The changes in traffic-accident frequencies from before to after implementation of the traffic-responsive system were calculated for intersections and midblocks. The comparison results are presented in Table 3.

Statistical Analysis

The statistical analysis procedure used to analyze categorized traffic-accident frequencies before and after implementation of the traffic-responsive system resembles the procedure discussed and presented earlier for AVO. Accordingly, the hypothesis to be tested is H_o: $m_{\text{before}} = m_{\text{after}}$ (no change in the mean of traffic accidents), versus H_1: $m_{\text{before}} > m_{\text{after}}$ (the mean of traffic accidents is higher before).

For a choice of $\alpha = 0.01$ (99 percent level of confidence), Table 3 summarizes the results of the statistical analysis for both intersections and midblocks.

On the basis of the results of the statistical analyses presented in Table 3, H_o is rejected for all intersections and all but three midblock approaches. It is concluded that the mean congestion-related traffic-accident frequency has decreased from before to after implementation of the traffic-responsive system for all locations except where H_o is not rejected.

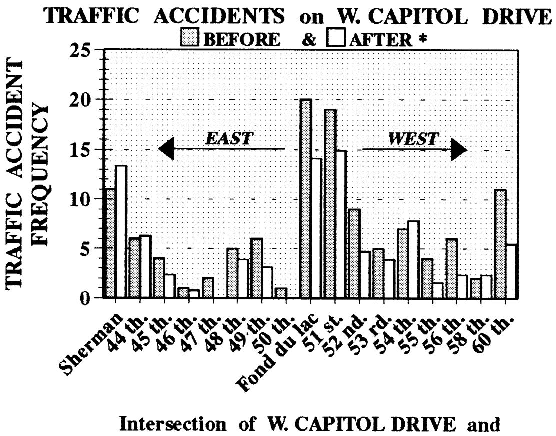
CONCLUSIONS

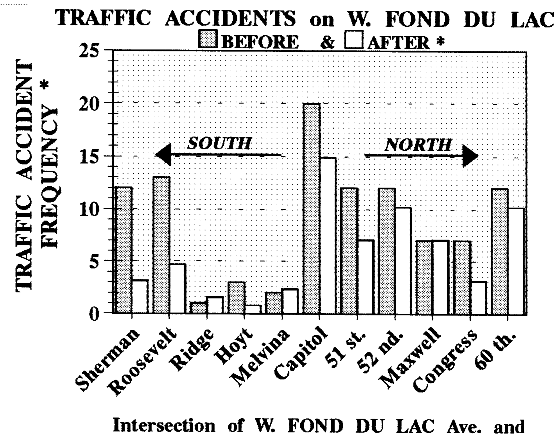
Completing this experimental project (*18*) represented a considerable investment of effort, time, and resources. The amount of time required to complete the project was far greater than originally anticipated. However, the project goal of reducing traffic accidents by managing and reducing congestion at signalized intersections appears to have been realized. The use of traffic-responsive, closed-loop signal control to manage traffic congestion at a geometrically constrained intersection complex was appropriate and successful.

The overall results of this project are summarized according to vehicular delay and safety as shown below:

- Delay
  - Significant reduction in AVO,
  - Increase in effective approach capacity, and
  - Increase in average vehicle speed over system detectors.
- Safety
  - Significant reduction in adjusted frequency of congestion-related intersection accidents,
  - No increase in accidents at adjacent signalized intersections outside of the traffic-responsive system,
  - Overall reduction in congestion-related midblock accidents, and
  - Increased in adjusted frequency of congestion-related midblock accidents on a few blocks.

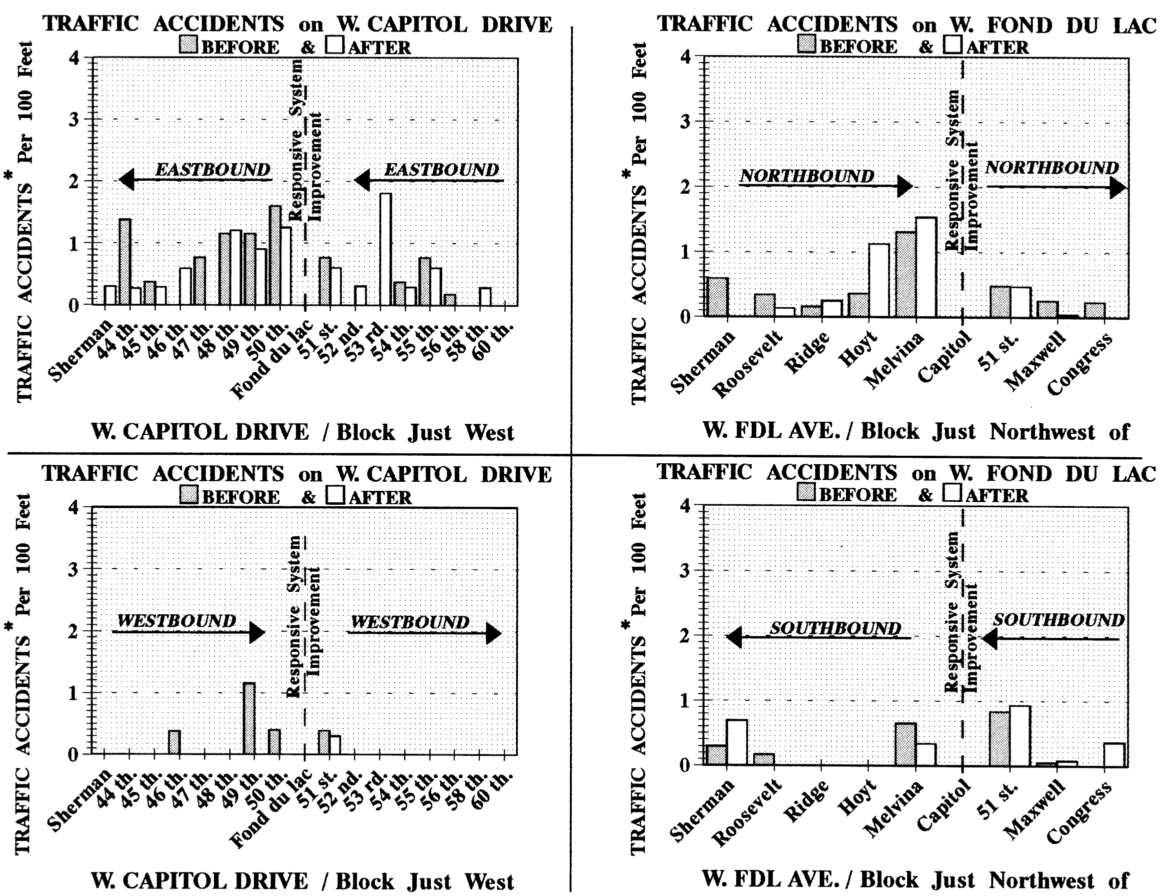
Considerable effort was made to analyze the congestion-related midblock accidents along Capitol Drive and Fond du Lac Avenue. As was stated earlier, it was felt that including these accidents was critical because of the long vehicle queues that develop on certain approaches to this intersection complex. Separating the midblock accidents by direction and block was a further attempt to isolate





	EAST		WEST	
	INJ.	PDO	INJ.	PDO
Before	1.63	2.88	3.00	3.29
After	1.27	2.45	1.79	2.24

	SOUTH		NORTH	
	INJ.	PDO	INJ.	PDO
Before	1.80	4.40	4.75	4.75
After	1.10	1.41	3.91	3.72



*** A Traffic Volume and/or Distance Factors are included to adjust for EXPOSUREs.**

FIGURE 6 Average traffic accidents per intersection (*top*) and per 100 ft (*bottom*) (1 ft = 0.3 m).

TABLE 3 Midblock and Intersection Traffic Accidents Described

MIDBLOCK TRAFFIC ACCIDENTS (accidents per 100 feet)							MIDBLOCK TRAFFIC ACCIDENTS Paired−t Test (α = 0.01)					
DIRECTION	INJURY			PROPERTY DAMAGE ONLY			MEAN	Standard Deviation	SE MEAN	T	P	Result
LOCATION	Before	After	Change	Before	After	Change						Yes/No
EB CAPITOL												
West of 51 st.	0.39	0.09	−0.30	0.19	0.47	+0.28	−0.259	0.715	0.270	2.74	0.0340	NO
East of Fond Du Lac	0.19	0.23	+0.04	0.61	0.38	−0.23	+0.202	0.552	0.195	6.16	0.0005	YES
WB CAPITOL												
West of 51 st.	0.00	0.00	0.00	0.06	0.04	−0.02	+0.012	0.032	0.012	84.91	0.0000	YES
East of Fond Du Lac	0.05	0.00	−0.05	0.19	0.00	−0.19	+0.241	0.408	0.144	8.60	0.0000	YES
NW FOND DU LAC												
Southeast of Capitol	0.15	0.12	−0.03	0.40	0.49	+0.09	−0.057	0.503	0.225	4.19	0.0140	NO
Northwest of 51 st.	0.11	0.02	−0.09	0.21	0.16	−0.05	+0.152	0.123	0.071	16.22	0.0040	YES
SE FOND DU LAC												
Southeast of Capitol	0.08	0.08	0.00	0.15	0.13	−0.02	+0.017	0.265	0.119	8.56	0.0010	YES
Northwest of 51 st.	0.14	0.15	+0.01	0.16	0.31	+0.15	−0.164	0.177	0.102	8.18	0.0150	NO

INTERSECTION TRAFFIC ACCIDENTS (accidents per intersection)							INTERSECTION TRAFFIC ACCIDENTS Paired−t Test (α = 0.01)					
ROADWAY	INJURY			PROPERTY DAMAGE ONLY			MEAN	Standard Deviation	SE MEAN	T	P	Result
LOCATION	Before	After	Change	Before	After	Change						Yes/No
W. CAPITOL							+1.888	2.293	0.556	5.19	0.0001	YES
at Fond du lac	7.00	4.00	−3.00	13.00	14.00	+1.00						
at 51st.	7.00	6.00	−1.00	12.00	13.00	+1.00						
East of Fond du lac	1.63	1.27	−0.36	2.88	2.45	−0.43						
West of 51st.	3.00	1.79	−1.21	3.29	2.24	−1.05						
W. FOND DU LAC							+3.275	3.277	0.988	4.33	0.0015	YES
at Capitol	7.00	4.00	−3.00	13.00	15.00	+2.00						
at 51st.	3.00	4.00	+1.00	9.00	5.00	−4.00						
Southeast of Capitol	1.80	1.10	−0.70	4.40	1.41	−2.99						
Northwest of 51st.	4.75	3.91	−0.84	4.75	3.72	−1.03						

the effect of congestion on accidents as vehicles approached the intersection complex.

Although there was an overall reduction in congestion-related midblock accidents within the entire analysis area, the before-after adjusted accident frequencies on certain blocks approaching the intersection complex were somewhat disappointing. Both approaches to the intersection complex along Fond du Lac Avenue showed relatively small increases in adjusted accident frequencies in the after period despite observed and recorded reductions in vehicle queues on these approaches. There is no definitive reason for this slight increase, although it may be related to increased average speeds during congested time periods.

Although the nonintersection congestion-related accidents along Capitol Drive generally showed a favorable trend in the after period, one approach block (5300–5399) showed a large increase in adjusted traffic-accident frequency in the after period for eastbound traffic. It appears that this block was negatively affected by traffic-responsive signal operation. This approach to the intersection complex generally did not exhibit congestion or long queues in the before period. Because Coordination Plan 12 (favoring Fond du Lac Avenue) was implemented much more frequently than Plan 10 (favoring Capitol Drive) in the after period, the eastbound approach on Capitol Drive experienced an overall reduction in average g/c ratio during congestion periods. This change would have resulted in somewhat longer queues and increased overall congestion on this approach to the intersection complex and may have contributed to the increase in traffic accidents.

DISCUSSION OF RESULTS

A few recommendations can be made regarding closed-loop, traffic-responsive signal operation as a result of this project. First, a good communication system is absolutely essential for this type of signal operation. If communication cable is used, it is recommended that the cable system be checked for proper connections and good integrity before the traffic-responsive operation is implemented. In addition, thorough observation of critical approaches in a signal system is recommended to ensure that system detector loops are properly placed and will provide reliable data.

Although the overall results of this project were positive, it would be desirable for the traffic-responsive control system to respond more quickly to the onset of congestion. The traffic-responsive system used in this project is able to change coordination plans only as frequently as once each sample length. Although it would have been desirable to shorten the sample length in an effort to increase the response rate of the system, this was not possible because of the reasons described earlier in this paper. The sample-length restriction is common to all closed-loop traffic-responsive systems.

With the development and deployment of adaptive signal systems, the possibility of more rapid system response should be realized. It is reasonable to assume that the level of benefits derived from this traffic-responsive system may have been even greater had adaptive signal control been implemented. Unfortunately, when this project was developed there were no planned or operational adaptive traffic signal systems in the United States. This technology was being developed and implemented in other areas of the world, however.

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