Analysis of Flashing Signal Operation

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Flashing traffic signal operation can offer reduced delay over alternative modes of signal operation, such as pretimed and actuated. The research described in this paper was conducted as part of a study on flashing traffic signals. Significant research activities included a review of previous literature, a survey of current practice, an operational analysis of alternative modes of signal operation, and the analysis of traffic volumes during late-night low-volume periods. The literature review found few comprehensive guidelines, although there is evidence that substantial interest exists. The survey of current practice indicated that traffic engineers primarily rely on engineering judgment instead of standards or guidelines. The operational analysis determined that for low volumes, the flashing yellow/red operation will reduce total delay by 50 percent versus pretimed and actuated operation. In general, the red/red flash operation will produce the most amount of delay. Data collection efforts revealed that typically 2.5 percent of the average daily traffic (ADT) occurs during the period between midnight and 6:00 a.m. and that the hourly volume during this period ranges from 0.2 to 0.8 percent of the ADT.

Traffic signals provide a safe and effective means of controlling vehicular and pedestrian traffic at intersections. However, because they assign the right-of-way to the various traffic movements, traffic signals exert a profound influence on traffic flow. *The Manual on Uniform Traffic Control Devices* (MUTCD) (*1*) states that signals should not be installed unless one or more of the signal warrants are met. Two of the warrants are volume based. For an intersection to meet one of these warrants, traffic must be greater than a specified level for at least 8 hr of the day. Even when an intersection meets one of the warrants, there may be periods of time during the day when traffic volumes are below the warrant levels. During these low-volume periods, flashing signal operation is an alternative to normal (green-yellow-red) signal operation. The primary justification for flashing operation is that vehicular delay can be reduced by eliminating or reducing the number of stops.

STUDY ACTIVITIES

The findings presented in this paper were developed from several research activities, which included a review of literature on flashing operation, a survey of traffic engineers on the use of flashing traffic signals, an evaluation of low-volume traffic signal operations, and the analysis of late-night traffic volumes. A significant portion of this paper presents research results based on an operational evaluation. Traffic safety is an important factor to consider before a signal is placed into flashing operation. Because of the amount of accident data and statistical results required to adequately cover the safety issues, they cannot be presented here with the operational analysis. However, the literature review in this paper does address past research efforts in identifying the safety aspects of flashing operation.

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Literature Review

Probably the most important source of guidelines or standards on any traffic control device is *The Manual on Uniform Traffic Control Devices* (MUTCD). In the 1988 edition (*1*), the use of flashing signals is mentioned, but few guidelines are provided for implementing flashing operation. It is noted that earlier editions of the MUTCD provided more guidelines than does the 1988 edition. For example, in the 1935 edition (*2*) it is stated that "when the total vehicular volume entering an intersection having fixed-time signals falls below 500 vph for a period of two or more consecutive hours, the fixed-time signal shall be operated as flashing." With regard to actuated signal operation, the 1935 MUTCD states that "because actuated control adjusts itself to varying traffic volume and involves relatively little vehicular delay during light traffic, it is not necessary to change to flashing operation at any time."

Texas is one of the states that publishes its own edition of the MUTCD. The 1980 edition of the Texas MUTCD (*3*) contains the following guideline for implementing flashing operation:

> When for a period of four or more consecutive hours of the late evening and/or early morning periods, any traffic volume drops to 50 percent or less of the stated volume warrants, pretimed traffic control signals should be placed on flashing operation rather than continue normal operation.

Guidelines Based on Traffic Volume

The most significant research study of flashing traffic signals was conducted as part of an FHWA study of traffic signal operation (*4*). The FHWA study recommended using flashing yellow/red operation when the two-way traffic volumes on the major street are below 200 vph. Flashing yellow/red operation may also be used when the two-way major street volume is greater than 200 vph provided the ratio of major-street volume to minor-street volume is greater than 3.

Guidelines Based on Accidents

The safety aspect of flashing operation has been addressed in several different studies (*4–6*). The FHWA report (*4*) found that, in general, flashing yellow/red operation increased the accident rate. The exception was at intersections with a high ratio of major-street to minor-street volume. Accident rates at these intersections were lower with flashing operation than with normal operation. Accidents, particularly right-angle accidents, were higher with flashing yellow/red than with normal operation.

The FHWA study (*4*) analyzed accident files from around the nation and found that flashing yellow/red operation, in general, significantly increased the hazard of driving at night. The major exceptions were intersections at which the volume ratio is equal to or greater than 3 or at which the major-street two-way volume is less than 200 vph during flashing operation. In addition, the study found that the most hazardous driving time was the first hour after drinking establishments closed.

The FHWA study recommended against using flashing yellow/red operation if the following conditions are met or exceeded at an intersection:

- Three right-angle accidents in one year during flashing operation (short-term rate).
- Two right-angle accidents per million vehicles during flashing operation if the rate is based on an average of three to six observed right-angle accidents per year (long-term rate), or
- 1.6 right-angle accidents per million vehicles during flashing operation if the rate is based on an average of six or more right-angle accidents per year (long-term rate).

Studies performed by local agencies in Portland, Oregon (*5*), and Oakland County, Michigan (*6*), agreed with the FHWA study finding indicating that right-angle accidents occur at significantly higher rates when flashing yellow/red signal operation is used. The Portland study recommended the use of flashing operation for low-volume conditions when the volume ratio is less than or equal to 2. The Michigan study recommended removing flashing operation if the volume ratio is 4 or less.

A follow-up to the Michigan study (*7*) analyzed traffic accident data at 59 intersections that were changed from flashing signal operation to 24-hr normal operation. The results of this study indicated that changing signal operation from flashing to normal operation was effective in reducing the frequency of total right-angle and personal injury right-angle accidents during nighttime hours. However, there was no noticeable change in the frequency of total rear-end or personal injury rear-end collisions. The follow-up study reconfirmed the findings of the original study and no new recommendations or findings were added.

Survey of Flashing Practice

Because of the limited amount of previous research on flashing operation, most traffic engineers make decisions related to flashing operation on the basis of engineering judgment or field experience. Therefore, a survey was developed to identify flashing signal practice in Texas. The survey provided the opportunities to gather information about many different aspects of flashing operation and also to assist the research team in their data collection efforts. Recognizing these opportunities, the research team established two objectives for the survey of flashing signal operation: (*a*) to identify where and how flashing operation is currently utilized on a regular basis in Texas and (*b*) to determine the guidelines or warrants that agencies use to implement flashing signal operation.

Survey Methodology

The survey was developed so that it could be sent to many agencies and quickly answered by the traffic engineering personnel at the various agencies. Some of the more significant questions and their responses are shown in Table 1. Surveys

TABLE 1 Survey Questions and Responses

Question	Responses
Use flashing operation on a regular basis.	70%-Yes 30%-No
Conditions when flashing operation is used.	96%-Emergency (due to signal failure) 68%-Signal installation and/or removal 66%-Early morning hours 55%-Railroad preemption 21%-Low-volume periods other than early morning 17%-School areas
Factors addressed in flashing guidelines.	49%-Traffic volume 47%-No guidelines 40%-Time of day 23%-Accidents 19%-Other
Usefulness of guidelines for flashing operation.	59%-Useful 32%-Might be useful 9%-Not useful
Use flashing operation with actuated controllers.	47%-Use 11%-Sometimes use 38%-Do not use
Analysis of flashing operation.	8%-Have performed an analysis 92%-Have not performed an analysis
Basis for selecting flashing indications.	Volume ratio Consistency

were received from 24 Texas Department of Transportation (TxDOT) districts and 23 city transportation departments in Texas.

Survey Results

The survey results indicated that 70 percent of the respondents use flashing operation on a regular (or normal) basis. Normal operation includes all types of flashing other than emergency or railroad preemption flashing. Among the choices (multiple-choice format) for regular flashing operation, early morning flashing and signal installation and removal flashing were the two most common uses; both were used by approximately two-thirds of the respondents. Flashing during early morning hours was more common among the local agencies (74 percent) than the TxDOT districts (58 percent), and flashing for signal installation and removal was more common with the districts (75 percent) than with the local agencies (61 percent).

Flashing in an emergency situation related to signal failure is used by virtually all the respondents (96 percent). Railroad preemption flashing is also commonly used (55 percent). There was a fairly significant difference between the districts and the local agencies in the use of flashing with railroad preemption (71 versus 39 percent). This difference seems logical when one considers that railroad preemption as used by the local agencies probably displays a green indication to the nonconflicting movement.

Almost half (47 percent) of all the respondents indicated that they have no formal guidelines for implementing flashing operation. Among those agencies that do have guidelines, the specific factors that are considered in a decision to implement flashing operation are traffic volume (49 percent), time of day (40 percent), and accidents (23 percent). Other factors were also identified but are used to a lesser extent: day of the week, relationship to other intersections, geometrics, posted speeds, weather effects, and type of signal operation.

The survey also addressed operating an actuated signal in the flashing mode. This question was added to the survey because of conflicting opinions about whether flashing operation is appropriate at intersections with actuated signals. Intuitively, it would seem that flashing operation would not be needed at such an intersection because of the ability of an actuated signal to respond to traffic demand. However, the responses to this question indicate that there is greater use of flashing with actuated controllers than originally thought. One possible explanation for the large number of responses for use of flashing with actuated control is that the flashing might be limited to certain applications resulting from emergencies, conflicts, maintenance, preemption, and installation and repair. However, conversations with some of the survey respondents indicated that flashing an actuated signal during low-volume periods is not unusual.

The basis on which traffic engineers select the mode of flashing operation (yellow/red or red/red) varied among respondents. This can be attributed largely to the lack of any formal guidelines. One of the biggest concerns of the survey participants was the potential for confusing drivers by displaying two different modes of flashing operation at a single intersection during different times of the day. Typically this would involve using a yellow/red flash for normal operation and a red/red flash for conflict operation. Some of the common responses to the question on selecting the mode of flashing were as follows:

- If the intersection traffic volume is close to being equal on all approaches, flash red to all approaches. If the intersection traffic volume is not equal but generally greater than 2:1, flash yellow on the major street and red on the minor street.
- The normal flash is yellow/red, and the conflict or emergency flash is red/red.
- The red/red flash is used for all occasions (normal and emergency).
- Flashing operation is not used at all, to avoid driver confusion. High accident rates have been linked with motorist confusion associated with the yellow/red flash.
- The red/red flash is used for all diamond interchanges.
- The red/red flash is used at intersections with sight distance restrictions or accident history.
- Other responses to the question of guidelines for use of flashing signals included consistency with other signals, speed, geometrics, accident history, arrangement of STOP signs before signal installation, and police input.

Operational Analysis

Traffic simulation models were used to compare flashing operation with normal operation. The total intersection delay for yellow/red flash, red/red flash, pretimed, and actuated signal operation were compared for isolated intersections and three-intersection signal systems.

Signal operation at isolated intersections was simulated using the TEXAS and TRAF-NETSIM models. Although the TEXAS model can simulate all four types of signal operation, NETSIM does not have the capability to model a four-way stop-controlled intersection because it cannot model red/red flashing operation. The latest version of the TEXAS model, which has been improved to provide more accurate representation of delay at four-way stop intersections, was used in the simulation (*8*). Earlier versions overestimated delay at four-way stop-controlled intersections (*9*). Operation of a signal system was simulated using NETSIM, because the TEXAS model cannot simulate more than one intersection.

Because both models are stochastic, replicate runs using different random number seeds were made. As a minimum, five runs were made for each scenario used in the analysis. Afterwards, the average total delay per vehicle was computed and used in the analysis.

Simulation Assumptions

In order to simplify the analysis, the study team identified a basic intersection geometric configuration associated with common or fundamental signal operation, or both. In most cases, assumptions were established that would simplify the operation and thus provide a clear understanding of the fundamental relationship between the alternative modes of signal operation. For the selected traffic volumes modeled, an optimal signal timing was developed. Therefore, the delay data are reflective of the signal operation (i.e., normal versus flashing operation) and not a misallocation of effective green time. The general assumptions are given in Table 2.

Results of Operational Analysis

The various types of signal operation at an isolated intersection were analyzed using both the TEXAS and NETSIM models, and the analysis of a signal system was performed with the NETSIM model. Total intersection delay was used as the basis of comparison and the impact of volume was normalized by using the ratio of major- to minor-street approach volume. The presentation of the results was simplified by dividing the analysis into three groups of major-street approach volumes: less than 125 vph, 250 to 500 vph, and 750 to 900 vph.

Isolated Intersection Analysis The analysis results from the two models were basically similar. However, because NETSIM cannot analyze red/red flashing operation, only the results of the TEXAS model are presented here.

The results show a clear relationship between the volume ratio and total delay. Typically, as the traffic volume on the major arterial increases, the total delay increases. This trend is consistent with fundamental practice and understanding of traffic signal operation. The minor-street volume does not influence the total delay if the volume ratio is greater than 3.

Figures 1 through 3 show the results from the TEXAS model for major-street volumes of less than 125 vph, 250 to 500 vph, and 750 to 900 vph, respectively. It can be seen that, in general, flashing yellow/red signal operation produces the lowest amount of delay, followed by actuated, pretimed, and then flashing red/red signal operation. The only exception to this trend is found in Figure 3 for equal traffic volumes on the major and minor streets. At this point, the delay for flashing yellow/red increases asymptotically and parallel to the 1.0 volume ratio. At this volume ratio, normal signal operation produces the least total delay.

Red/Red Flashing Operation Red/red flashing produces the highest total intersection delay for all volume ratios greater than 3. For volume ratios less than 3, pretimed operation generally produces the highest total delay. For major arterial volumes less than 500 vph, the red/red flash curve is relatively flat. In other words, very little change in total delay results from a decrease in minor-street volume. For major-street volumes greater than 500 vph, the volume ratio must be less than 4 for the minor street to have an effect on the total intersection delay.

Yellow/Red Flashing Operation As stated previously, yellow/red flashing operation generally involves the least amount of total delay, producing less than 5 sec of delay per vehicle if the major-street volumes are less than 125 vph (Figure 1). When the major-street volumes are greater than 125 vph but less than 750 vph, the intersection delay is less than 6 sec (Figure 2). If the major-street volume is greater than 750 vph, total intersection delay is more than under pretimed or actuated operation and red/red flashing operation with balanced flow (Figure 3). Beyond a volume ratio of 3, the total delay drops below 5 sec per vehicle.

Pretimed and Actuated Operation For lower traffic volumes on the major arterial, actuated signal control produced approximately one-half the delay produced by pretimed signal operation. For higher traffic volume on the major arterial, actuated operation reduces delay by 3 or more seconds over pretimed operation.

TABLE 2 Assumptions for Operational Analysis

Geometric Assumptions
• 4-legged intersection with 5 lanes on major arterial and 4 lanes on minor street.
• Lane width of 3.66 meters.
• System of 3 intersections separated by 305 meters.
Operational Assumptions
• Turning movements: 10% left, 10% right, and 80% through vehicles.
• Traffic volume ranged from 25 to 900 vehicles per approach on both major and minor street.
• Travel speed of 48 kilometers per hour on both major and minor streets.
• Pretimed operation used a 3-phase leading-left phasing arrangement.
• The minimum cycle length was 40 seconds.
• Yellow clearance of 3 seconds and an all-red clearance of 1 second.
• The Cycle Capacity Probability Design Curve (10) used to determine phase clearance values.
• Offset values for the signal system determined by PASSER II-90 traffic operations optimization program.
• Actuated operation used the 3-phase operation developed for pretimed operation.

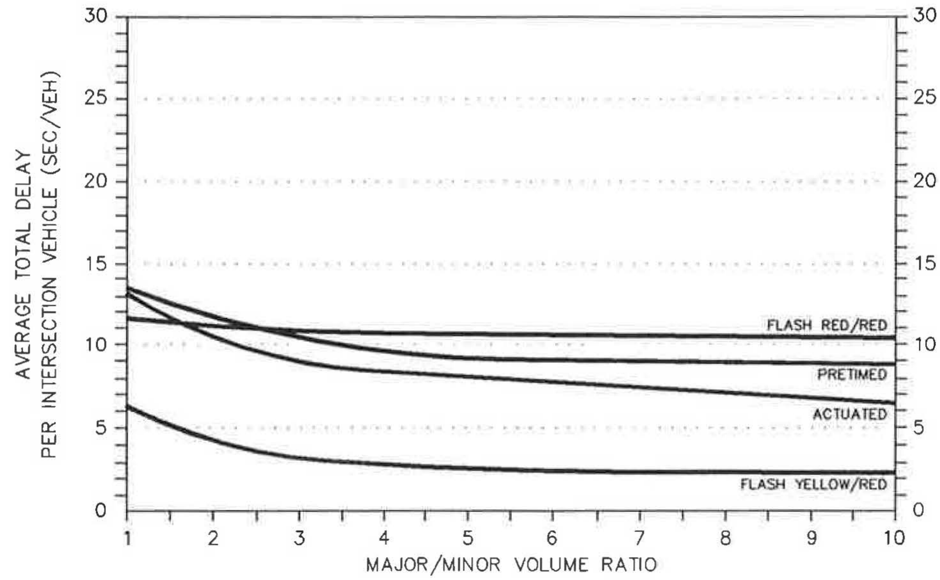

FIGURE 1 Isolated intersection operation with major-street volume less than 125 vph.

Summary of Isolated Intersection Analysis Results The following conclusions can be drawn from Figures 1 through 3:

- Yellow/red flashing operation produces the least amount of total intersection delay, followed by actuated, pretimed, and red/red flashing operation.
- Red/red flashing produces approximately 7 sec more than yellow/red flashing when the major-street volume is less than 125 vph and approximately 8 and 13 sec for major-street volume with less than 500 and 900 vph, respectively.
- Red/red flashing produces a relatively constant delay when the major-street volume is less than 750 vph. When the major-street volume is greater than 750 vph, the delay becomes constant at volume ratios greater than 4.
- If the major-street volume is less than 250 vph, total intersection delay can be reduced by one-half if pretimed operation is changed to actuated operation and reduced by approximately one-third if changed to yellow/red flashing.
- If the major-street volume is less than 750 vph, total intersection delay can be reduced by one-half if red/red flashing is changed to actuated signal operation and reduced again by one-half if actuated operation is changed to yellow/red flashing.
- If the major-street volume is greater than 750 vph, the same general trend is present as previously described, but only for volume ratios greater than 3.

Results of Signal System Analysis The signal system was analyzed using the NETSIM model. A clear relationship was shown between the volume ratio and total delay. Typically, pretimed, actuated, and yellow/red flashing operation pro-

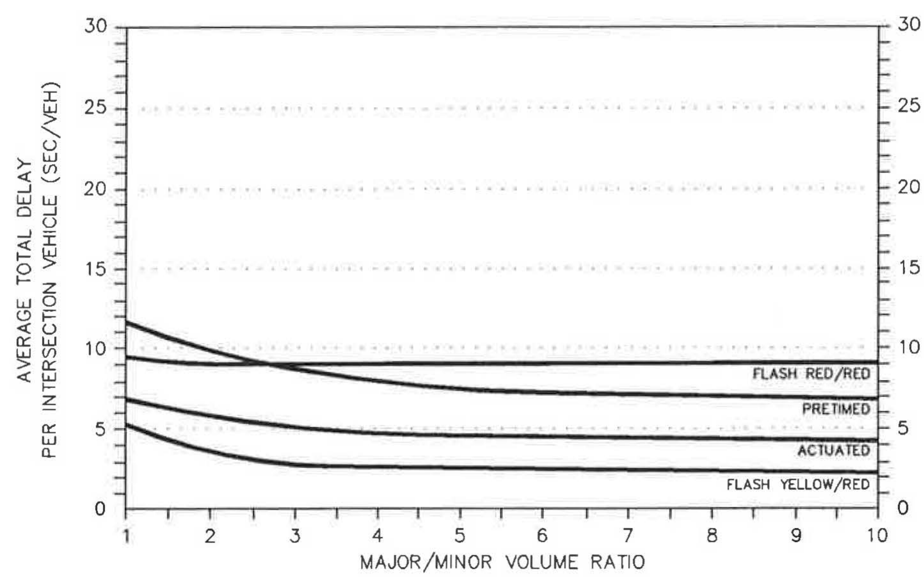

FIGURE 2 Isolated intersection operation with major-street volume between 250 and 500 vph.

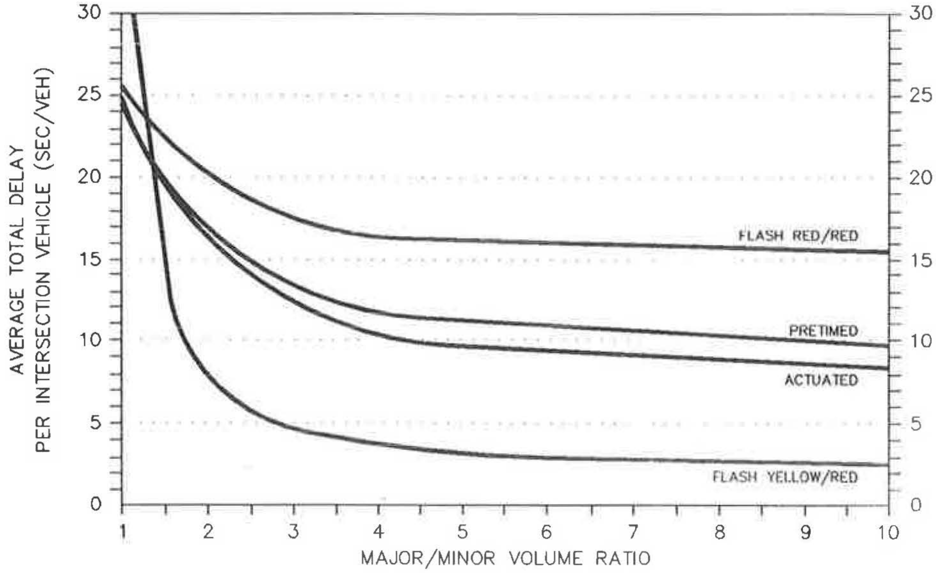

FIGURE 3 Isolated intersection operation with major-street volume between 750 and 900 vph.

duced 2 to 3 sec more delay than that produced in the isolated intersection simulation. Figures 4 through 6 show the results for major-street volumes of less than 125 vph, 250 to 500 vph, and 750 to 900 vph, respectively.

Yellow/Red Flashing Operation As found in the isolated intersection analysis, yellow/red flashing produced the least amount of total delay, less than 7 sec if the major-street volume is less than 125 vph. This is compared with 5 sec of delay produced for the isolated intersection for the same traffic volume. The added delay results from minor-street vehicles, which are required to stop for the flashing red signal. The major arterial continues progressive movement without any additional delay. As the major-street volume increases, there is added friction among the vehicles. Total delay increases with increasing major-street volume and increasing minor-street volumes for volume ratios less than 4 (Figures 4–6).

Red/Red Flashing Operation It was stated previously that the NETSIM model cannot simulate red/red flashing operation; therefore, no systemwide results are available for this type of operation. However, it seems unlikely that red/red flashing would be used in a signal system, so the lack of results for this case is not significant.

Pretimed and Actuated Operation Pretimed signal operation produced no more than 3 times the delay produced by

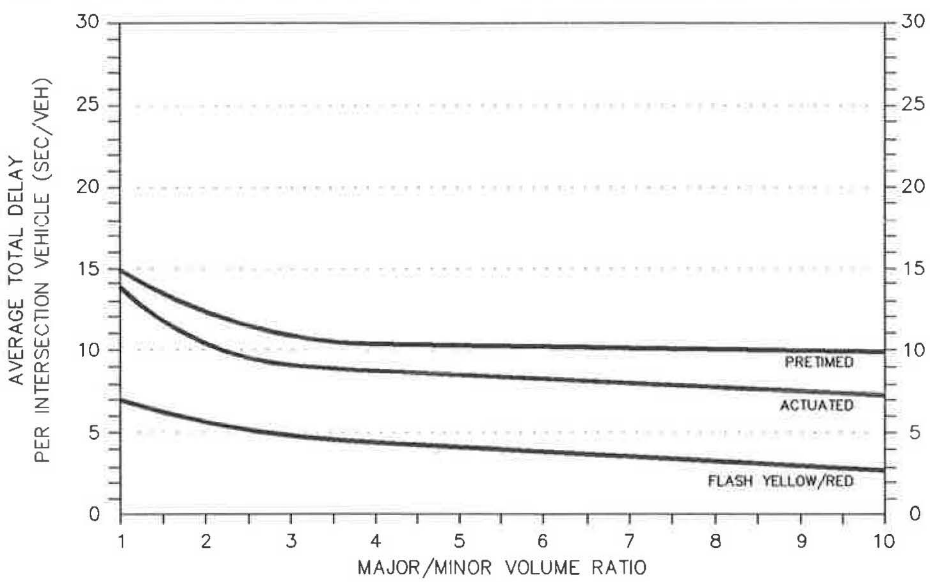

FIGURE 4 Signal system operation with the major-street volume less than 125 vph.

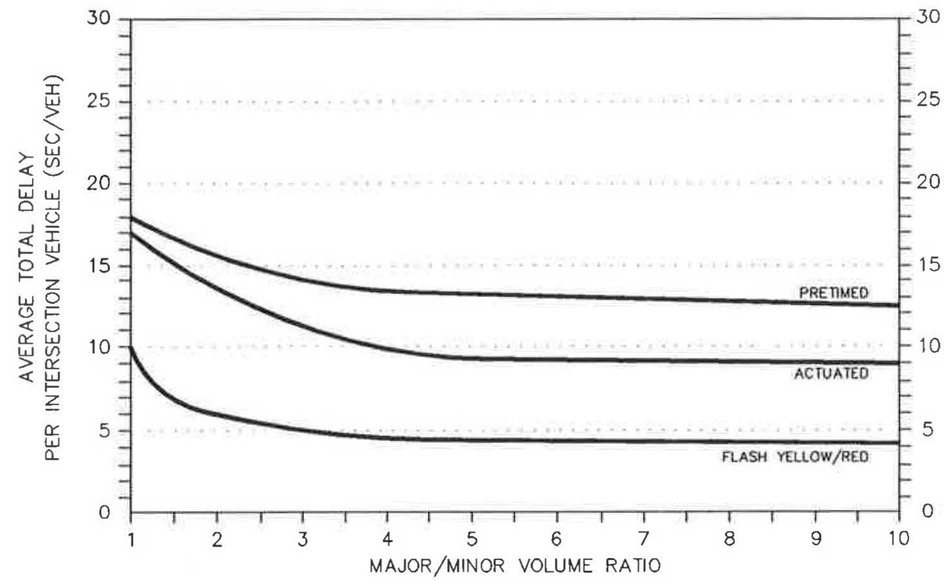

FIGURE 5 Signal system operation with the major-street volume between 250 and 500 vph.

yellow/red flashing (Figures 4–6). Less than 15 sec of total intersection delay was produced by pretimed operation with major arterial street volume less than 125 vph. As the volume ratio approached 10, total delay was reduced to 10 sec. For this same traffic volume (125 vph and less), actuated operation produced approximately 3 sec less delay than pretimed operation. As the major-street volume increased, actuated operation produced approximately two-thirds the total delay found with pretimed operation.

Summary of Signal System Analysis Results The following conclusions can be drawn from Figures 4 through 6:

- Yellow/red flashing operation produces the least amount of total intersection delay, followed by actuated and pretimed signal operation.
- Total intersection delay can be reduced by as much as one-third if pretimed operation is changed to actuated (coordinated) operation and reduced by approximately two-thirds if changed to yellow/red flashing operation.

Analysis of Late-Night, Low-Volume Periods

Flashing signal operation is normally implemented during low-volume periods. During the day, there are periods that are commonly referred to as "off-peak" times. However, the traffic volumes during which flashing operation should be considered are substantially lower than the daytime off-peak volumes. For Figures 1 through 6 to be useful to the practicing traffic engineer, the nighttime hourly volumes must be known.

Late-night traffic volumes were obtained as part of this study. The objective was to identify relationships between

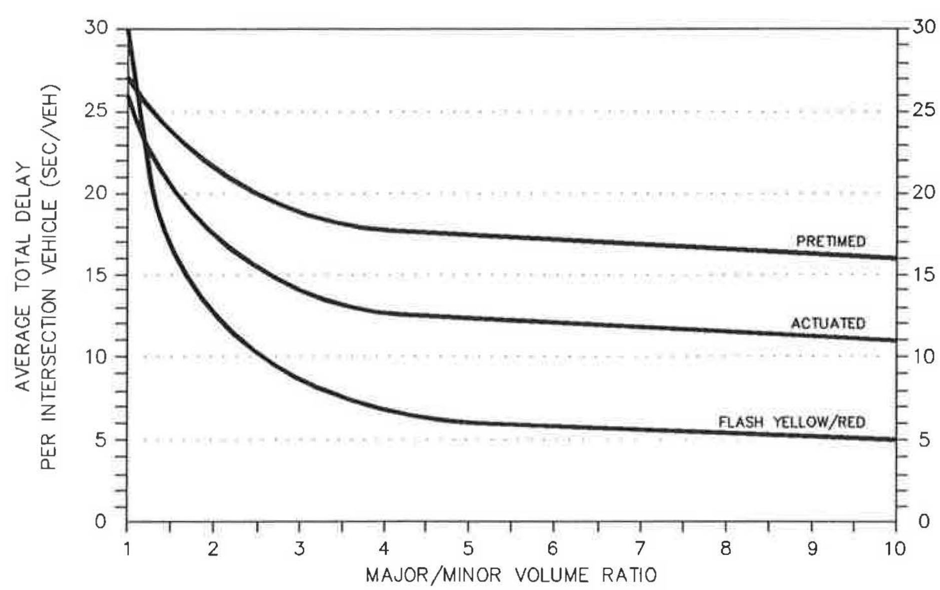

FIGURE 6 Signal system operation with the major-street volume between 750 and 900 vph.

these volumes and ADT. The study team analyzed 24-hr traffic volumes from 12 study sites in Austin, Bryan, and College Station, Texas. The ADTs for these sites varied from 6,000 to 30,000. An attempt to establish a relationship by ADT was made using the following six classes: less than 10,000; 10,001 to 15,000; 15,001 to 20,000; 20,001 to 25,000; 25,001 to 30,000; and more than 30,000.

The results identified the relationship between total ADT and late-night traffic volumes. It was found that a typical hour between midnight and 6:00 a.m. averaged 0.4 percent of the ADT, with a range of 0.1 to 1.7 percent. Total average values for the period between midnight and 6:00 a.m. ranged between 1.6 and 4.4 percent of the ADT. The overall average of traffic volumes was 2.6 percent of the ADT for the total volume between midnight and 6:00 a.m. Table 3 shows the average volume for each of the hours from midnight to 6:00 a.m. No relationship was found among the different ADT classifications.

CONCLUSIONS

The research described in this paper led to a number of conclusions related to flashing signal operation and how flashing operation compares with normal signal operation. These findings should provide some assistance to traffic engineers faced with deciding whether to implement or remove flashing signal operation.

The literature review found that many guidelines have been suggested for implementation, removal, or both of flashing operation of traffic signals. The majority of these guidelines are based on traffic volumes and accidents. The traffic volume guidelines are typically based on (*a*) the traffic entering an intersection, (*b*) the ratio of major-street to minor-street volume, and/or (*c*) a percentage of the existing traffic signal warrant volumes. Accident guidelines are usually stated as a condition to remove flashing signals. In some cases, the guidelines from different studies disagreed or conflicted with one another. For example, the Portland study (*5*) recommended placing signals into flashing operation if the volume ratio was equal to or less than 2, whereas the Michigan study (*6*) recommended removal of flashing operation when the volume ratio is equal to or less than 4.

The traffic engineer survey indicated that there is widespread use of flashing operation. The majority of traffic engineers make decisions on flashing operation without guidelines, depending on field experience and engineering judgment. It is recognized that these two qualities are valuable, but comprehensive guidelines based on relevant research should be available to assist the engineer in making the decision. The survey found that many traffic engineers do not feel comfortable with selecting flashing signal operation because of concerns about motorist behavior at such signals.

TABLE 3 Typical Relationship Between 24-Hr Volume and Late-Night Traffic Volume

Hour of the Day	Percent of 24-Hour Traffic Volume
12:00 to 1:00 a.m.	0.8 %
1:00 to 2:00 a.m.	0.5 %
2:00 to 3:00 a.m.	0.4 %
3:00 to 4:00 a.m.	0.2 %
4:00 to 5:00 a.m.	0.2 %
5:00 to 6:00 a.m.	0.5 %
Total 12:00 to 6:00 a.m.	2.6 %

An evaluation of various types of traffic signal operation was made using the TEXAS and NETSIM models for isolated intersections and for signal systems. The following conclusions can be drawn:

- For isolated intersections, the volume ratio must less than 3 before the minor street affects total intersection delay. For signal systems, the volume ratio must be less than 4 before the minor street affects total intersection delay.
- For major-street approach volume less than 750 vph, yellow/red flashing produces approximately one-third the delay produced by pretimed operation for volume ratios greater than 3. For volume ratios less than 3, yellow/red flashing produces approximately one-half the delay produced by pretimed operation.
- For major-street volume over 750 vph, yellow/red flashing produces approximately one-third the delay produced by pretimed operation for volume ratios greater than 4. For volume ratios less than 4, yellow/red flashing approaches the same delay as pretimed operation.
- Red/red flashing operation produces a relatively constant amount of delay when the major-street volume is less than 750 vph, and becomes constant after reaching a volume ratio of 4 for major-street volumes greater than 750 vph.

The conclusions reached from the operational analysis considered only the traffic volume relationship of flashing operation and not its safety impacts. Consideration should be given to the potential increase in accidents that the literature review found may accompany flashing operation. In addition, the operational results reflect the conditions and assumptions in Table 2 (i.e., 5 × 4 intersection geometrics and three-phase leading-left phasing arrangement).

An analysis of late-night, low-volume periods indicated that, as a general rule of thumb, the total volume between midnight and 6:00 a.m. is 2.6 percent of the ADT. For a typical hour during this time period, the volume is 0.4 percent of the ADT. Traffic volumes drop off after 2:00 a.m. Roadways with higher ADTs do not experience higher late-night traffic as compared with roadways with lower ADTs.

On the basis of the operational analysis of flashing signal operation only, the following observations are presented. These findings accounted for the number of lanes used in the geometric analysis, and therefore delay per vehicle is expressed in per-lane terms.

- Yellow/red flashing operation can significantly reduce overall delay at intersections with pretimed or actuated signal controllers when all of the following conditions are met: volume ratio greater than 3, major-street approach volumes less than 250 vph per lane, and higher approach minor-street traffic volume less than 85 vph per lane.

• Red/red flashing operation produces less delay at intersections with pretimed signal controllers when the following conditions are met: volume ratio is less than 3 and major-street volume is less than 250 vph per lane.

ACKNOWLEDGMENT

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