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16. Abstract

This report provides preliminary guidelines for determining a) when to operate traffic signal systems in an isolated and in a coordinated mode, and b) when to operate coordinated traffic signals in a traffic responsive and a time-of-day mode. This report recommends that the Interconnection Desirability Index be used to determine when traffic signals should operate in an isolated or coordinated mode. It recommends that traffic responsive mode be used only when traffic conditions are relatively unpredictable, both in the location and time that traffic enters the network. The report also provides a preliminary procedure for setting up a traffic signal system in a traffic responsive mode.

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PRELIMINARY GUIDELINES FOR SELECTING AN APPROPRIATE OPERATING MODE FOR TRAFFIC SIGNAL SYSTEMS

by

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IMPLEMENTATION STATEMENT

This report provides preliminary procedures that can be used to assist Texas Department of Transportation (TxDOT) engineers in determining when to operate signal systems in an isolated versus a coordinated mode. It also contains preliminary procedures for determining when to operate a coordinated signal system in a traffic responsive versus a time-of-day mode. Preliminary guidelines are also provided for determining how to implement a traffic responsive control for a signal system. These procedures should be considered preliminary because they still need to be tested in the field.

DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views of the Texas Department of Transportation or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation, nor is it intended for construction, bidding, or permit purposes. Kevin N. Balke (P.E. 66529) is the Principal Investigator for this project.

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SUMMARY

The purpose of this report is to present preliminary guidelines to help Texas Department of Transportation (TxDOT) personnel in determining 1) when to operate traffic signal systems in an isolated mode versus a coordinated mode, and 2) when to operate closed-loop traffic signal systems in a time-of-day versus a traffic responsive mode. This document contains preliminary guidelines on the types and amounts of data to be collected, procedures to be used for calculating the necessary timing plan selection parameters and thresholds, and recommendations on which detectors to use for selecting appropriate timing plans in a traffic responsive mode.

While there are several methods available for determining when to coordinate traffic signal systems, it is recommended that the interconnection desirability index be used because of its computational simplicity and minimal data requirements. Listed below are the steps required to determine when to operate a traffic signal system in an isolated or coordinated mode:

- Obtain a physical description of the corridor,
- Obtain 15-minute turning movement volumes at each intersection in the corridor,
- Compute the interconnection desirability index for each one-way link in the system,
- Compare the computed index to the threshold selected for the corridor, and
- Establish the times for operating signals in the system in a coordinated and in an isolated mode.

Because frequent timing plan changes can have a deleterious effect on traffic operations in a coordinated system, it is recommended that traffic responsive mode be used at locations where *major shifts* in traffic patterns are likely to occur. Generally, traffic responsive mode should be used where traffic patterns are unpredictable. The following lists situations where traffic responsive mode might be beneficial:

- Locations that are severely impacted by incidents,
- Around major special event centers,
- Locations where unpredictable traffic patterns may require the early exit from a time-of-day plan,
- Locations where adaptive holiday controls might need to be provided, and
- In low volume conditions.

A nine-step process can be used to identify thresholds for operating signal systems in a traffic responsive mode. Although each of the TxDOT approved controller manufacturers uses different parameters and procedures for picking timing plans in a traffic responsive mode, the general procedure for establishing the thresholds needed to pick the timing plans is similar for each controller manufacturer. Generally, the volume and occupancy data from periods where specific timing plans will be implemented are combined using the methodology specific to each controller manufacturer. The volume and occupancy data must be scaled, smoothed, and

weighted again using the procedures and formulas specific for each controller manufacturer. The volume and occupancy data from a specific control condition are then used to compute the timing plan selection parameters for each controller manufacturer. This will allow the engineer to determine the range of the timing plan selection parameters that correspond to a specific control condition. From here, the engineer can set the appropriate thresholds that will implement each specific timing plan for the correct control condition. After the system is implemented in the field, the system should be monitored to determine if the desired timing plans are being implemented in the correct control condition. Fine-tuning of the threshold may be required if this evaluation shows that the correct timing plans are not being implemented by the system.

I. INTRODUCTION

The Texas Department of Transportation (TxDOT) is installing closed-loop traffic signal systems in many locations across the state. These systems can select different timing plans in response to measured traffic conditions. Unfortunately, the traffic responsive capabilities of many of these systems are not being fully used. Most systems operate in a time-of-day mode, where timing plans are implemented based on the time of the day and not measured traffic conditions. One explanation is that most TxDOT personnel have little experience determining when and how to use the traffic responsive features of these systems.

The purpose of this report is to present preliminary guidelines to help TxDOT personnel in determining 1) when to operate traffic signal systems in an isolated mode versus a coordinated mode, and 2) when to operate closed-loop traffic signal systems in a time-of-day versus a traffic responsive mode. This document contains preliminary guidelines on the types and amounts of data to be collected, procedures to be used for calculating the necessary timing plan selection parameters and thresholds, and recommendations on which detectors to use for selecting appropriate timing plans in a traffic responsive mode.

BACKGROUND

Generally, there are three operating modes of closed-loop traffic signal systems: manual mode, time-of-day mode, and traffic responsive mode. In the manual operating mode, decisions as to when to implement a new timing plan are not made automatically by the control system software. Instead, the operator selects a timing plan based on his or her perception of traffic operations in the network. Once implemented, the timing plan remains in effect until the operator implements a new plan.

Under time-of-day mode, the decision to implement a new timing plan is made automatically by the control system software based on the current time of the day. Time-of-day mode assumes that similar traffic demands occur at the same time each day. Using historical data, the traffic engineer identifies the general periods of the day where traffic demands change. Timing plans are developed to accommodate average traffic demands during these periods. The system software then implements the timing plans at the same time each day, regardless of the current traffic conditions. Generally, time-of-day mode works best when traffic demands are relatively predictable, in terms of both when and where they occur in the network (*1-3*). However, in networks where demands are unpredictable, time-of-day mode can cause signal systems to implement timing plans that are not appropriate for the actual conditions that exist in the network.

Traffic responsive mode was developed as a means of ensuring that appropriate timing plans were implemented in response to actual traffic conditions in the network. With traffic

responsive mode, the signal system measures actual traffic demand at strategic locations in the network. The control system software compares the measured traffic demand to established thresholds to determine which timing plan to implement. As a result, the system implements a timing plan that is (theoretically) best suited to accommodate the current traffic demand.

Traffic responsive mode is not the same as full actuated control. With traffic responsive mode, traffic detectors are used to measure large scale changes in traffic demand in the network. Timing plans are selected from a library of established timing plans that have been developed for specific conditions and every signal in the system conforms to the selected timing plan. In most cases, the cycle lengths, phases, and splits at each intersection remain fixed until a new timing plan is implemented. Under full actuated control, however, the signal controller at each intersection responds to local changes in volume by varying the cycle length, phasing, and splits on a cycle-by-cycle basis. Furthermore, under full actuated control, each intersection in the system is not required to operate on the same cycle length.

SELECTION OF OPERATING MODE

The purpose of this report is to provide preliminary guidelines on when to operate signals in an isolated versus a coordinated mode. Once the decision has been made to operate the signals in a coordinated mode, the question then becomes whether to operate the signals in a time-of-day versus a traffic responsive mode. Figure I-1 provides an overview of the process for selecting the appropriate operating mode for a signal system.

Once the need for a signal system has been established, the next step in the process is to determine which intersections need to be operated in an isolated mode and which intersections should be coordinated. A process that can be used to help identify when to operate signals in a isolated or coordinated mode is presented in Chapter 2. If the results of this process indicate that the signals should operate in an isolated mode, then the next step is to develop appropriate timing plans for each of the individual intersections. Standard procedures [such as those specified in the *Highway Capacity Manual (4)* or the *Transportation Engineering Handbook (5)*] can be used to develop the timing plan for operating the signals in an isolated mode.

If the decision is to operate the signals in a coordinated mode, the question then becomes whether to operate the signal system in time-of-day or traffic responsive mode. As mentioned previously, time-of-day mode generally works best when traffic patterns are relatively predictable, whereas traffic responsive mode performs best when traffic patterns are relatively unpredictable (in terms of their time and magnitude). Chapter 3 identifies some of the conditions where traffic responsive mode may be appropriate.

After the decision has been made to operate the system in a traffic responsive mode, the next step in the process is to set up the system to operate in a responsive mode. Generally, the

first step in the process is to determine which system detectors to use to compute the timing plan selection parameters. These detectors can then be used to collect volume and occupancy data that will allow the different control conditions in the corridor to be identified. Standard traffic signal optimization programs, such as PASSER II, PASSERIV and TRANSYT-7F, are then used to develop timing plans for each control condition. After the timing plans have been developed, the engineer needs to set the factors that are used to scale, smooth, and weight the data from the system detectors. These factors can then be used to process the volume and occupancy data from each specific control condition. Using this processed data and the timing plan select parameter specific to the closed-loop system being installed, the engineer can then determine the appropriate thresholds required to call each timing plan for the identified control conditions. Chapter 4 provides guidance into these processes.
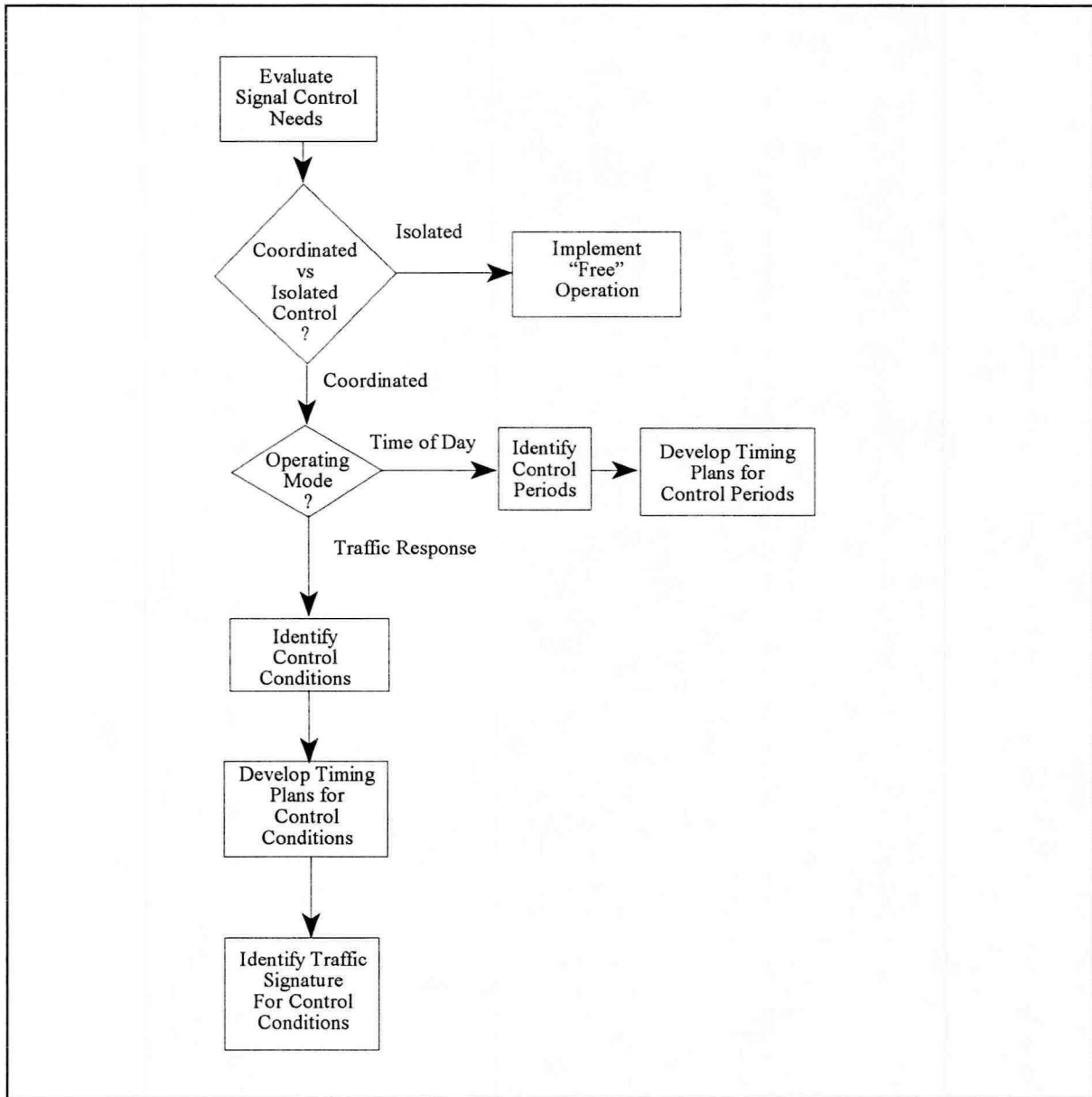
Figure I-1. Overview of Process For Implementing Appropriate Operating Mode For Closed-Loop Traffic Signal Systems

II. COORDINATED VERSUS ISOLATED MODE

Some of the greatest benefits to be achieved in traffic signal control come from coordinating the operations of two or more traffic signals. The objective of providing coordination between traffic signals is to minimize the number of stops and delays experienced by traffic traveling in a particular direction on an arterial. However, there is a trade-off associated with providing coordination. Even with the best coordinated traffic signal systems, some vehicles (particularly those on the cross-streets) may experience slightly longer delays under coordinated mode than under isolated (or local) mode. Because of this, coordinated mode should be used only when there are system-wide benefits to be achieved. Therefore, it is critical to evaluate these potential benefits when considering whether or not to include an approach or intersection in a coordinated system.

It should be noted that the need to provide coordination could vary by time of day. There may be periods during the day where traffic performance may be enhanced by dropping or including different traffic signals from a coordinated system. An approach needs to be developed that would identify not only which intersections should be included in a coordinated system, but also when those intersections should be operated in a coordinated versus an isolated mode.

BENEFITS OF PROVIDING COORDINATION

The purpose of providing coordination between two traffic signals is to facilitate the progressive flow of traffic. This is done by ensuring that a green indication at the downstream approach is provided in sufficient time to permit vehicles to travel through the intersection without stopping. Coordination can be either one-way (where traffic flow in one direction is favored over all other directions) or two-way (where traffic flow in two opposite directions is favored). While the primary benefits of providing progression are to minimize the number of stops and delays in a particular direction of travel in the corridor, there are other benefits associated with providing coordination between traffic signals including the following:

- the conservation of energy by minimizing fuel consumption,
- the preservation of the environment by reducing air pollution,
- the maintenance of a preferred travel speed in a direction of flow,
- the promotion of smooth flow by a platoon of vehicles, and
- the prevention of queues from exceeding available storage capacity at specific turn bays and approaches.

FACTORS AFFECTING PROGRESSION

In order to achieve the full benefits of coordination, three conditions must be present on a roadway. First, a predominant movement must exist between two or more intersections. In other words, one movement at an upstream intersection (either the through, left turn, or right turn movement) must have significantly more traffic than the other movements. This promotes the formation of a natural platoon at a downstream intersection. When there is not a predominant movement at the upstream intersection, arrival patterns at the downstream intersection tend to be uniform.

In addition to one movement being predominant at the upstream intersection, traffic patterns have to repeat every cycle. Because phase sequence and offsets usually remain constant from one cycle to the next, it is difficult to provide good coordination if the predominant movement varies from cycle to cycle.

Finally, the physical conditions of the roadway and the traffic demands at the intersection must support progression on the roadway. For example, traffic patterns at multiple intersections must be similar enough so that the intersections can operate with the same cycle length. Furthermore, the intersections must be located so that effects of progression in one direction do not negate the effects of progression in the other direction. Other factors that affect the ability to provide good coordination between intersections include the following (6):

- inadequate roadway capacity,
- substantial side friction (such as parking and multiple driveways),
- complicated intersections which require multi-phase control,
- wide variability in traffic speeds (like those caused by heavy truck traffic),
- very short spacings between signalized intersections, and
- heavy turning volumes either into or out of the street.

All of these factors can cause platoons to disperse more rapidly than in situations where these factors are not present, and can reduce any incentives to establish coordinated signal control.

EXISTING EVALUATION TOOLS

A review of the literature revealed that three different evaluation tools have been developed for determining when to provide coordination between two intersections. Each of these methods is discussed below.

Cost Function

A "cost" or "penalty" function has been proposed by McShane and Roess (*6*) for evaluating when to provide coordination between two signals. As shown in the equation below, this cost function is a weighted combination of stops and delays.

$$Cost = A \times (total\ stops) + B \times (total\ delay)$$

A and B are weighting factors that are set by the engineer to reflect the estimated economic cost of each stop and delay. The amount that each timing plan reduces the cost of control in a corridor is used in a cost-benefit analysis to evaluate whether coordinated mode should be provided. Additional terms can be added to the equation to account for other factors that may affect the decision of whether or not to provide coordination (such as fuel consumption, vehicle emissions, etc.).

Coupling Index

Yagoda, et al. (*7*) developed a coupling index to determine which links in a network should be grouped together in a coordinated system. The index is the ratio of the volume of traffic on a link to the distance between two intersections:

$$I = \frac{V}{L}$$

where,

$I =$ coupling index,
$V =$ hourly approach link volume (vph),
$L =$ link length to next signal (feet).

To determine which links should be coordinated in a system, the coupling index is computed for each link in the system. As shown in Figure II-1, links with low index values are selectively removed from the potential control area until the network degenerates into smaller, more manageable subareas.

The threshold for retaining links using the coupling index is set to meet local conditions and requirements. For example, the City of Arlington, TX uses two different thresholds: a coupling index of 0.3 or more during any hour is used for planning purposes while an index value of 0.5 or more is used in operational analyses (*8*).

Interconnection Desirability Index

The interconnection desirability index is another approach that has been proposed for determining when to provide coordination between two signals (9). One-way link volumes are used to assess the need for progression in each direction on an arterial. The index also contains a factor to account for the effects of platoon dispersion. The formulation of the index is provided in the equation below:

$$I = \frac{0.5}{1 + t} \times [\frac{x \times q_{max}}{q_1 + q_2 + \ldots + q_x} - 1]$$

where,

t = Link travel time (link length divided by the desired progression speed), expressed in minutes,

x = Number of departure lanes from upstream intersection,

q_{max} = The flow rate of the highest movement from the upstream intersection (usually the through movement), expressed in vehicles per hour, and

$q_1 + q_2 + \ldots + q_x$ = The sum of all the flow rates of the movements comprising the total flow arriving at the downstream approach, expressed in vehicles per hour.

The value of the index ranges from zero to one. A value of one indicates a highly desirable condition for providing coordination. At the other end of the scale, an index value of zero represents a condition where coordination is least desirable. As shown in Figure II-2, if the index is below 0.25, isolated operation is recommended. When the index is 0.5 or more, coordinated operation is recommended. When the index falls between these thresholds, other factors should also be considered in assessing the need for interconnection (9). One study recommends that coordination should be provided when the index equals or exceeds 0.35 (10). An example of how the interconnection desirability index can be applied to determine the need for coordination is shown in Figure II-3.

It should be noted that q_{max} represents the movement to be progressed from the upstream intersection through the downstream intersection. While this is usually the through movement, a heavy turning movement may also represent the majority of through traffic at the downstream intersection. The interconnection desirability index could also be used to identify those situations where it may be desirable to provide progression to a heavy turning movement.
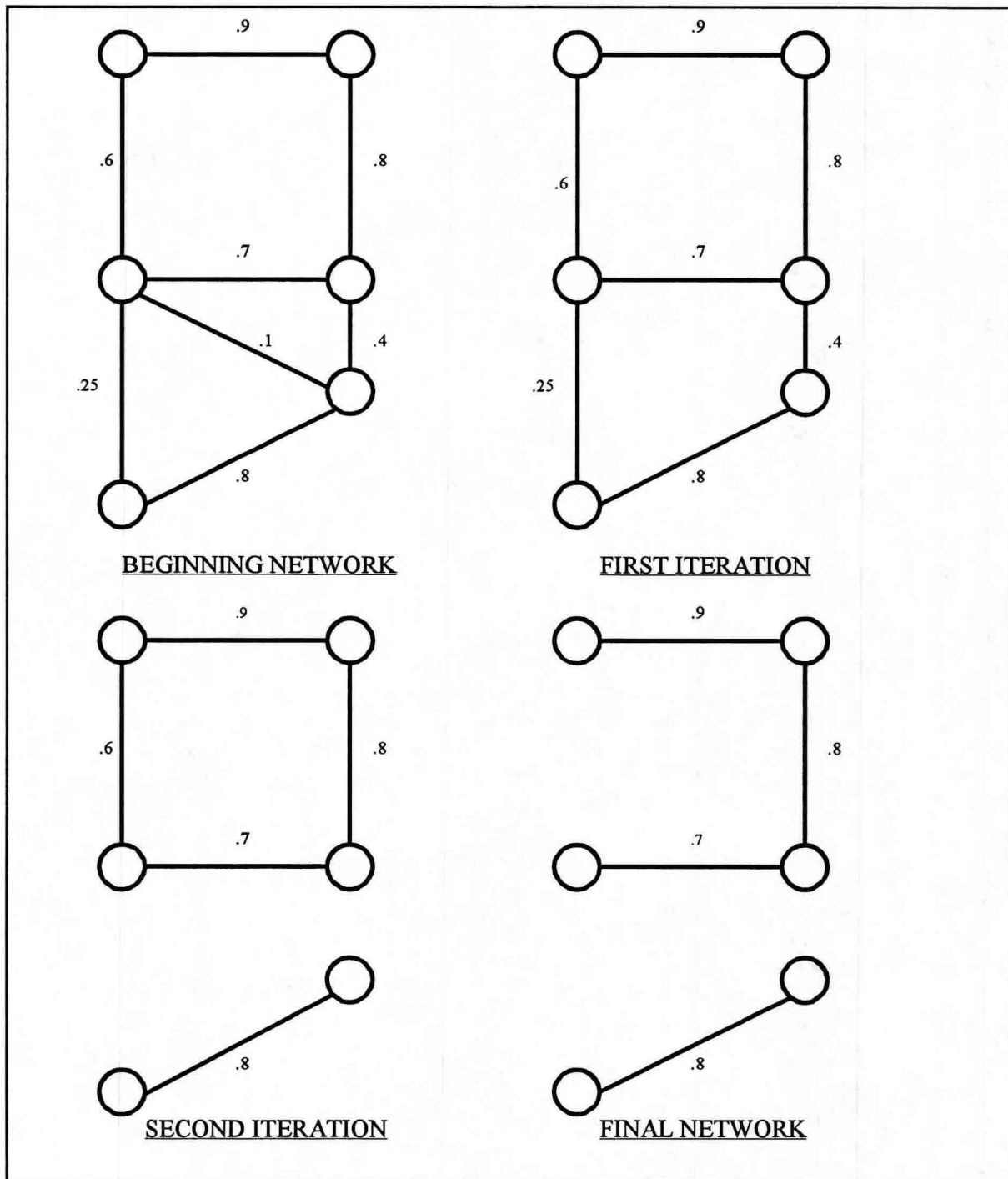
Figure II-1. Example of Subdivision Process Using Coupling Index (7)
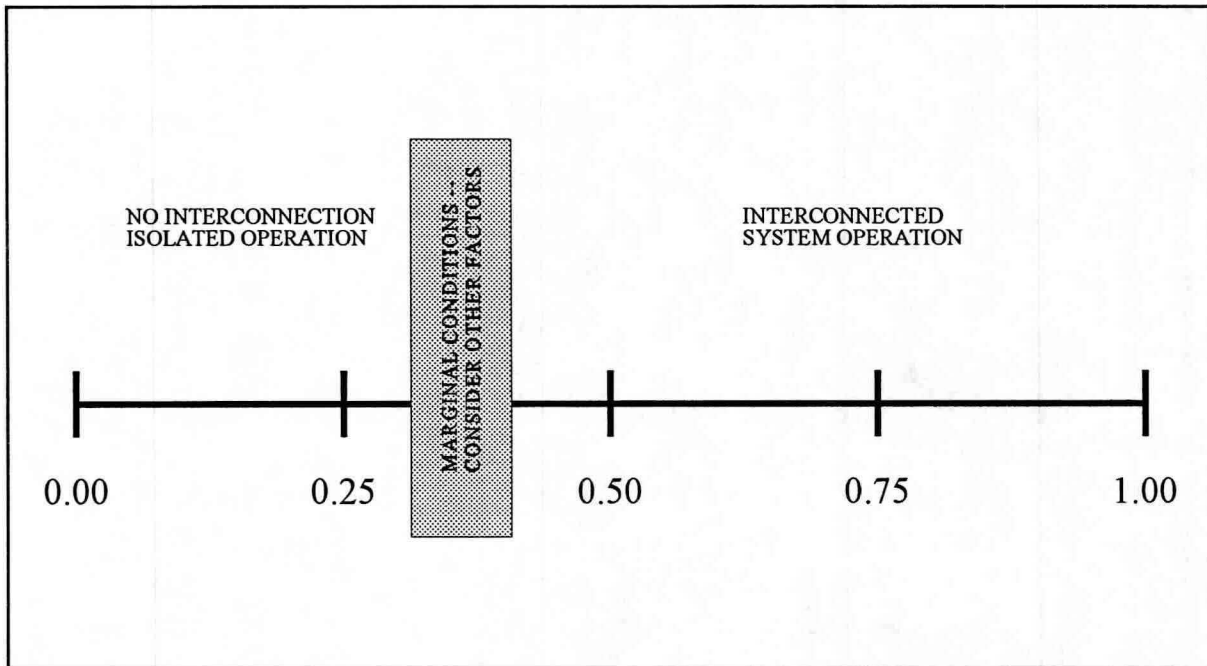
Figure II-2. Scale of Interconnection Desirability Index (9)

Selection of Evaluation Approach

In selecting an evaluation methodology, a number of factors need to be considered. The first consideration is that the evaluation methodology must be easy to use. To be useful to practicing engineers, the evaluation approach cannot require anything more complicated than a spreadsheet to perform the calculations. The second consideration was that the data requirements of the evaluation methodology cannot be extensive. The data needed to perform the calculations must be relatively easy to collect and typical of the type of data normally needed to operate traffic signals. A final consideration was that the evaluation methodology has to be adaptable to real-time operation. In the future, it may be desirable to decide in real-time whether or not to operate an intersection in a coordinated versus an isolated mode.

At first glance, the cost approach appears to be simple; however, in reality, it is quite complex. The approach requires that estimates of stops and delays be developed. This is typically done with a traffic signal optimization program. In order to use this approach to identify when traffic signals should be operated in an isolated versus a coordinated mode, at least two runs of a traffic signal optimization program (one with the intersections operating in a coordinated mode and one with the signals operating as isolated intersections) would have to be performed for each evaluation period. This could be a time-consuming process for large signal systems.

Furthermore, the data required to code and calibrate many traffic signal optimization programs can be extensive.

The coupling index, on the other hand, is computationally simple and requires very little data. The problem with the coupling index is that it does not adequately address all the factors that potentially affect progression on an arterial street. Recall that coordination works best where there is a predominant movement to be progressed. Since the coupling index uses only link total volume, it is not possible to determine whether or not the predominant movement exists on a link. Another problem with the coupling index is that it does not allow each direction of flow to be analyzed separately. Therefore, additional analyses would be required to determine if progression should be provided in only one or both directions on an arterial.

In contrast, the interconnection desirability index satisfies all of the selection criteria. The interconnection desirability index is computationally simple. Although it does require a more detailed data collection effort than the coupling index, the type of data needed to compute the index is often required to develop traffic signal timing plans for the intersections anyway. Furthermore, the type of data that is needed to compute the index (e.g., 15-minute turning movement counts) can often be automatically collected by many closed-loop traffic signal systems. In addition, the index can also be adapted relatively easily to operate in real-time if this feature is deemed to be important for future operations of signal systems.

PROPOSED PROCEDURE

One objective of this research project is to develop guidelines and procedures to assist TxDOT engineers in determining when the signals in a closed-loop system should be operated in a coordinated or an isolated mode. The following contains the proposed procedures for determining when to operate signals in an isolated or coordinated mode. A flow chart summarizing the proposed procedure is included in Figure II-4, and is based on the Interconnection Desirability Index.

Step 1. Obtain Physical Description of Corridor

The first step in the procedure is to obtain a physical description of the corridor to be studied. This includes performing a complete inventory (including the number of lanes on each approach) of each intersection being considered in the system. Other important information that should be included in the physical description is the distance between signalized intersections and the desirable travel speed on each link. In most cases, the desired travel speed will be the posted speed limit.

900 m

200 vph

$Vs = 56$ kmph

1000 vph — 3 LANES

300 vph

(i-1)   (i)
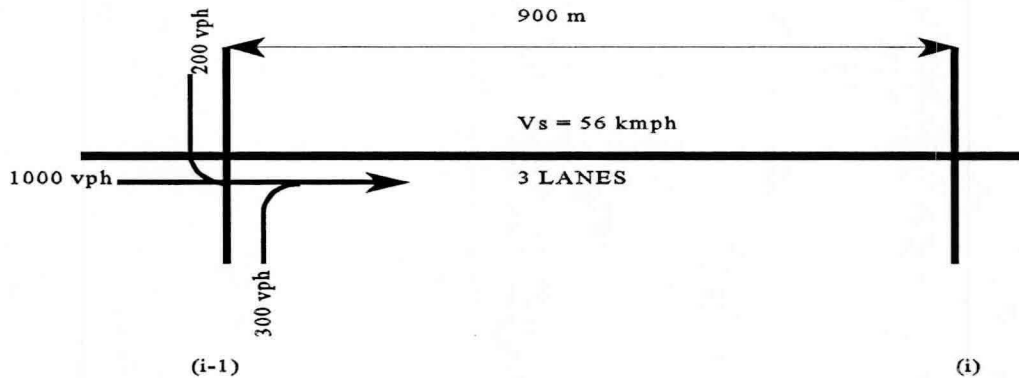
$$t = \frac{(900 \text{ m}) (60 \text{ min/hr})}{(56 \text{ kmph}) (1000 \text{ m/km})} = 0.96 \text{ min.}$$

$$I = \frac{0.5}{1 + 0.96} \left[\frac{(3) (1000)}{1000 + 300 + 200} - 1 \right]$$

$$= \frac{0.5}{1.96} \left[\frac{3000}{1500} - 1 \right]$$

$$= 0.25, \text{ WHICH INDICATES ISOLATED OPERATION ACCEPTABLE}$$

230m

75 vph

$Vs = 48$ kmph

800 vph — 3 LANES

200 vph

(i-1)   (i)
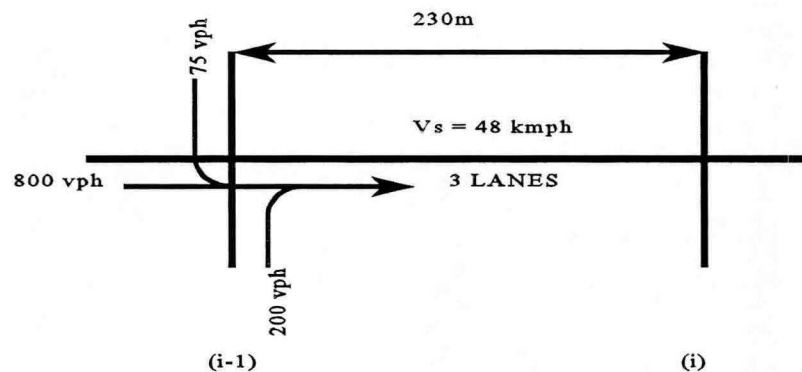
$$t = \frac{(230 \text{ m}) (60 \text{ min/hr})}{(48 \text{ kmph}) (1000 \text{ m/km})} = 0.28 \text{min.}$$

$$I = \frac{0.5}{1 + 0.28} \left[\frac{(3) (800)}{800 + 200 + 75} - 1 \right]$$

$$= \frac{0.5}{1.28} \left[\frac{2400}{1075} - 1 \right]$$

$$= 0.48, \text{ WHICH INDICATES INTERCONNECTED}$$
$$\text{OPERATION DESIRABLE}$$

Figure II-3. Examples Illustrating the Application of the Interconnection Desirability Index (*11*)

```
┌─────────────────────────────┐
│      OBTAIN PHYSICAL        │
│  DESCRIPTION OF CORRIDOR    │
│   -  Intersection geometry  │
│   -  Distance between intersections │
│   -  Desirable link travel speed │
└─────────────────────────────┘
              │
┌─────────────────────────────┐
│     OBTAIN 15-MINUTE        │
│    TURNING MOVEMENT         │
│    VOLUMES FOR EACH         │
│      INTERSECTION           │
└─────────────────────────────┘
              │
┌─────────────────────────────┐
│ COMPUTE INTERCONNECTION     │
│   DESIRABILIY INDEX FOR     │
│    EACH ONE-WAY LINK        │
└─────────────────────────────┘
              │
           ◇ DOES
           COMPUTED
           INDEX EXCEED    ──YES──►  ┌─────────────────────┐
           THRESHOLD                  │ OPERATE SIGNALS IN  │
           ?                          │ COORDINATED MODE    │
              │                       └─────────────────────┘
             NO                                │
              │                                │
┌─────────────────────────────┐               │
│     OPERATE SIGNALS IN       │              │
│      ISOLATED MODE           │              │
└─────────────────────────────┘               │
              │────────────────────────────────┘
              │
┌─────────────────────────────┐
│   ESTABLISH TIMES FOR       │
│    COORDINATED AND          │
│   ISOLATED OPERATIONS       │
└─────────────────────────────┘
```

**Figure II-4. Proposed Procedure for Evaluating When to Operate Signals in a
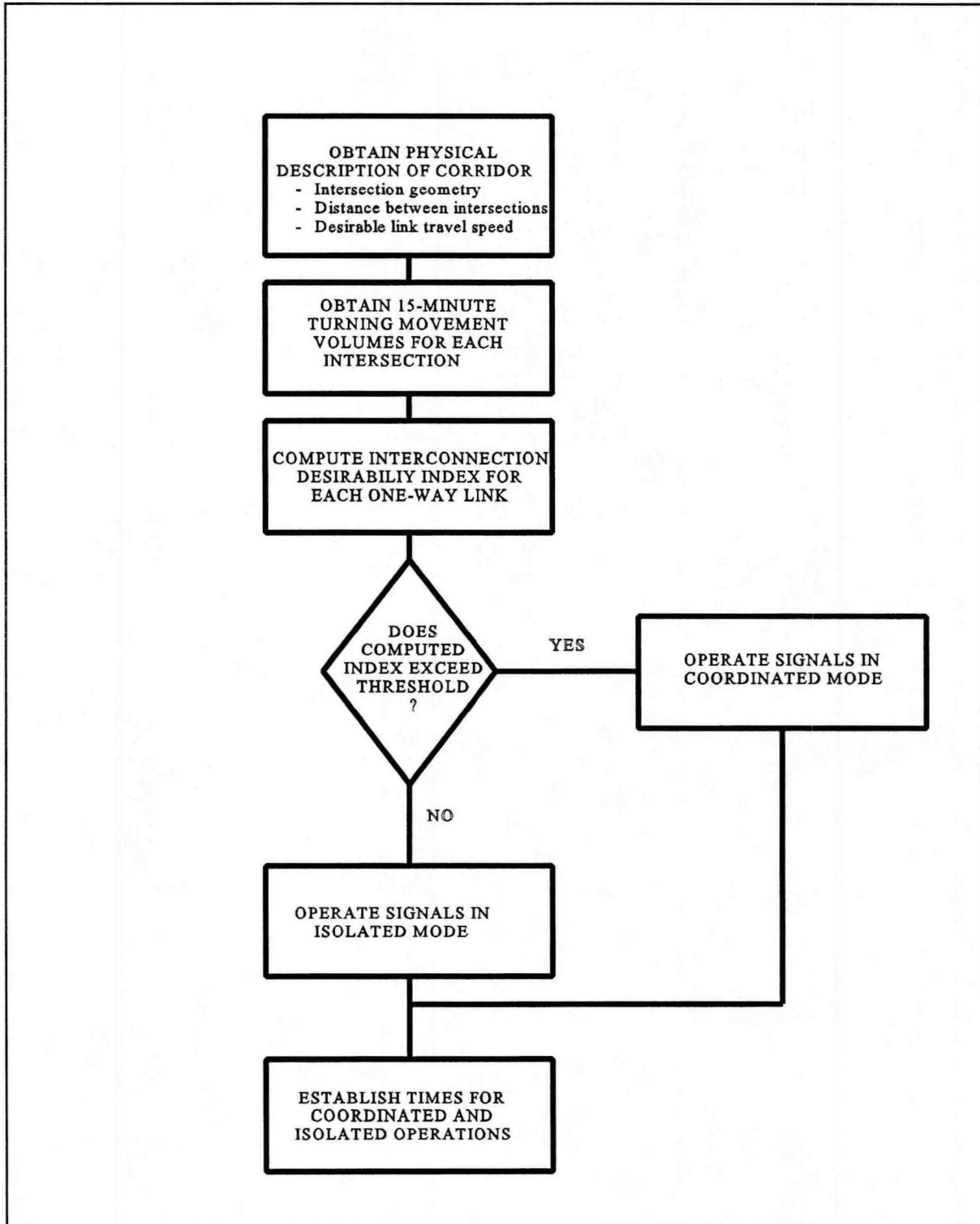Coordinated Versus an Isolated Mode**

Step 2. Obtain 15-Minute Turning Movement Volumes

The next step in the procedure is to obtain the 15-minute volumes for all movements (including the left turns and right turns, and the through movements) at each intersection. The turning movement volumes should cover the periods in which the signals will be potentially operating in a coordinated mode. For example, if the policy of the district is to operate the signals in a normal operating mode between 6:00 a.m. and midnight (and flashing the signals during the early morning hours), then it is desirable to have 15-minute turning movement counts that cover this entire time.

Step 3. Compute Interconnection Desirability Index

Using the data collected in Steps 1 and 2, the interconnection desirability index for each link in the corridor should be computed for each 15-minute interval. The intersection desirability index is calculated using the following equation:

$$I = \frac{0.5}{1 + t} \times [\frac{x \times q_{max}}{q_1 + q_2 + \ldots + q_x} - 1]$$

where,

$t =$ Link travel time (link length divided by the average speed), expressed in minutes,

$x =$ Number of departure lanes from upstream intersection,

$q_{max} =$ The flow rate of the highest movement from the upstream intersection (usually the through movement), expressed in vehicles per hour, and

$q_1 + q_2 + \ldots + q_x =$ The sum of all the flow rate of the movements comprising the total flow arriving at the downstream approach, expressed in vehicles per hour.

Step 4. Compare Computed Index to Threshold

Once the desirability index has been computed for each 15-minute period, the index is then compared to the established threshold to determine whether to operate the signal in a coordinated versus an isolated mode. Research suggests that a threshold value of 0.35 be used to determine whether or not to provide coordination between two intersections (*10*). If the computed index exceeds the established threshold, then traffic operations between the two intersections should be coordinated. On the other hand, if the computed index does not exceed the desired threshold,

then traffic operations are not likely to benefit from coordinated operations and the signals should be operated in an isolated mode.

Step 5. Establish Times for Coordinated and Isolated Modes

Once the interconnection desirability index has been computed for each 15-minute interval on every link in the corridor, the results of the comparisons can be combined to establish the operating modes of the signals in the system on a time-of-day basis. As shown in Table II-1, establishing the appropriate operating mode (isolated versus coordinated) can be accomplished by grouping those periods where the index indicates a similar operating mode. As shown in this hypothetical situation, the index indicates that coordination should be provided between 6:30 and 8:45 in the "A" to "B" direction, and that coordination should be provided between 7:30 and 9:45 and between 10:00 to 10:45 in the "B" to "A" direction.

Recall that the index serves only as a guideline for determining periods when coordination should be provided. The index is not intended to replace sound engineering judgement. There may be instances (such as those shown at 9:30 in the A→ B direction and at 9:45 in the B→ A direction in Table II-1) where the index indicates that either a) the signals should be coordinated when in the surrounding periods isolated mode is recommended or b) the signals should operate in an isolated mode when coordinated mode is recommended in the surrounding periods. In these situations, engineering judgement should be used to determine whether isolated or coordinated mode is warranted. For the example in Table II-1, the traffic engineer may choose not to interconnect the signals in the "A" to "B" direction at 9:30, but maintain coordination in the "B" to "A" direction at 9:45.

It should also be noted that because the analyses uses directional traffic volumes, it is possible that different limits of coordination will be identified in each direction. An example of this situation is shown in Figure II-5. In this example, the interconnection desirability index was used to determine that coordination should be provided on all of the approaches from "D" to "A" in one direction ; however, the interconnection desirability index showed that coordination should be provided only starting at intersection "B" in the opposite direction of travel.

Table II-1. Example of Interconnection Desirability Index to Determine Need for Coordination

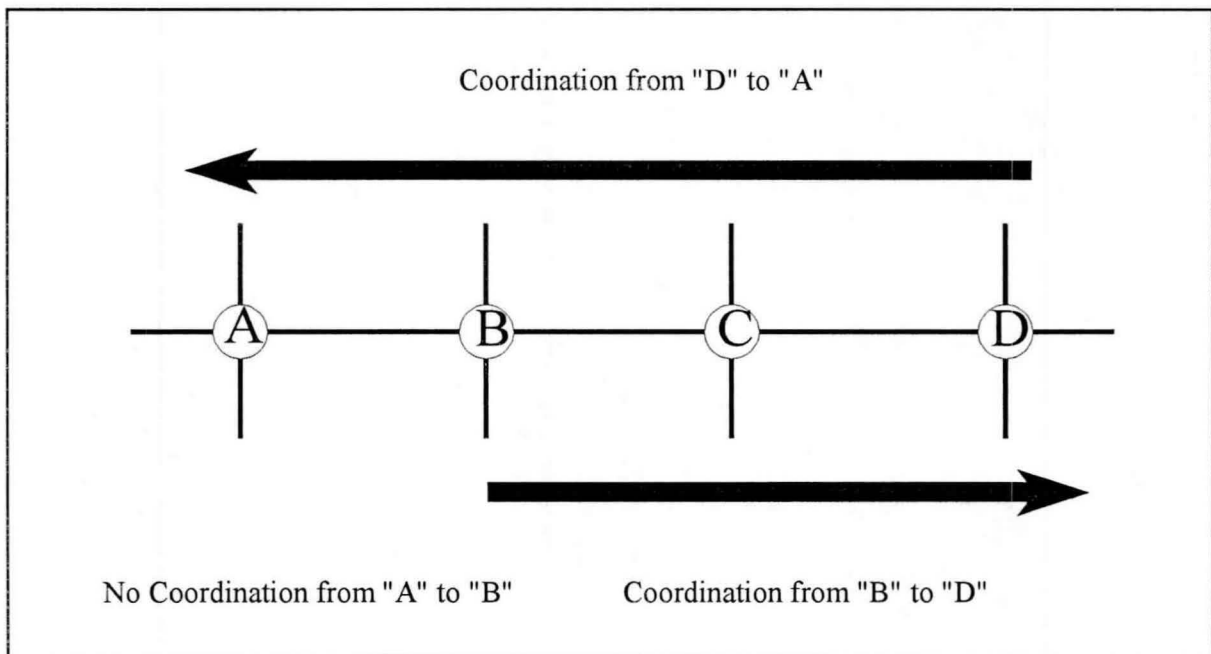| Time-of-Day	A → B		B → A	
	Index Value	Interconnect ?	Interconnect ?	Index Value
6:00	0.20	No	No	0.15
6:15	0.26	No	No	0.20
6:30	0.35	Yes	No	0.19
6:45	0.36	Yes	No	0.22
7:00	0.40	Yes	No	0.28
7:15	0.45	Yes	No	0.34
7:30	0.46	Yes	Yes	0.39
7:45	0.41	Yes	Yes	0.37
8:00	0.50	Yes	Yes	0.45
8:15	0.52	Yes	Yes	0.43
8:30	0.47	Yes	Yes	0.48
8:45	0.34	No	Yes	0.53
9:00	0.21	No	Yes	0.44
9:15	0.19	No	Yes	0.42
9:30	0.35	Yes	Yes	0.38
9:45	0.15	No	No	0.34
10:00	0.23	No	Yes	0.39
10:15	0.26	No	Yes	0.37
10:30	0.30	No	Yes	0.35
10:45	0.33	No	No	0.30
11:00	0.36	Yes	No	0.27

Figure II-5. Example of Different Progression Requirements in Each Direction

III. TIME-OF-DAY VERSUS TRAFFIC RESPONSIVE MODE

Most closed-loop signal systems today are capable of being operated in either a time-of-day or traffic responsive mode. With time-of-day mode, traffic signal timing plans are automatically selected from a library of timing plans on a time-of-day and day-of-week basis. In a time-of-day mode, the timing plans are selected without regards to the current traffic conditions that exist in the network. Under traffic responsive mode, however, the signal system automatically selects a timing plan from a stored library of timing plans that provides the best control for the measured traffic conditions. Each timing plan in the library has a unique volume and occupancy signature. Recent volume and occupancy measurements from the system detectors are compared to the signatures of the stored timing plans. The timing plan that best matches the measured traffic conditions is then automatically implemented by the signal system.

Despite the added flexibility offered by operating signal systems in a traffic responsive mode, most closed-loop signal systems today operate in a time-of-day mode. In part, this is because comprehensive guidelines do not exist for determining when to operate signal systems in a time-of-day or a traffic responsive mode. An objective of this research project is to develop and test guidelines for identifying when to operate a signal system in time-of-day or traffic responsive mode.

APPLICATION OF TRAFFIC RESPONSIVE MODE

Historically, traffic engineers use the traffic responsive mode in two different ways: 1) to pinpoint when time-of-day timing plan changes need to be made, and 2) to provide better control during atypical events (such as a sporting event, concert, or incident) that cause *major shifts* in traffic patterns in a control area. With the first application, the traffic responsive mode is used to monitor changing traffic patterns throughout the day and implement new timing plans as conditions warrant. As a result, the time that a specific timing plan is implemented can vary as traffic demands vary on the network, instead of being implemented at a specified time.

Research has shown that using traffic responsive mode to pinpoint when to implement time-of-day plans results in only marginal benefits over properly designed time-of-day mode (*1-3*). This is because minor fluctuations in traffic demand can cause frequent timing plan changes. Other research has shown that frequent timing plan changes over a short period can have a deleterious effect on the performance of a signal system (*12*). Frequent timing plan changes can actually impede traffic operations because of the transition that is required between timing plans. Therefore, the benefits achieved by implementing a new timing plan to pinpoint when time-of-day changes occur may often be offset by the delays associated with transitioning between timing plans.

Another way that engineers have used the traffic responsive mode is to provide control when unexpected major shifts in traffic patterns occur in the network. Unexpected major shifts are usually caused by atypical events (such as sporting events, concerts, incident conditions, and holidays) occurring in or near the control network. Usually, the size of the change in traffic patterns associated with these events is known (e.g., the amount of traffic at a sporting event is dictated by the size of the sporting arena). What is often not known in many situations, however, is the exact time the traffic demand on the network will change. For example, although an engineer may know the exact time that a special event (like a football game or concert) begins, the exact time that the event ends varies. Because the exact ending time is not known, it is difficult to implement a time-of-day plan that can accommodate the demand from these events. Furthermore, the amount of traffic (and thus the duration of the increased demand) may vary from event to event. With a signal system in a traffic responsive mode, conditions in the control area can be monitored to detect when significant changes in traffic occur in the control area.

GUIDELINES FOR USING TRAFFIC RESPONSIVE MODE

Unfortunately, a single set of guidelines for when to implement traffic responsive mode cannot be applied uniformly to all situations and signal systems. Each situation and system must be examined separately to determine whether or not it is beneficial to operate the signal system in a traffic responsive mode. Listed below are several situations where it is believed traffic responsive mode might prove to be beneficial. It should be noted that not all of these conditions must exist in order to operate a signal system in a traffic responsive mode. Engineers must examine local conditions to determine which of the below conditions may apply in their specific locale.

Incidents

Incidents, by their nature, are unpredictable events and can have a dramatic impact on traffic patterns in a control area; therefore, areas that are subject to changes in traffic patterns due to incidents are likely locations for implementing traffic responsive mode. The impacts of an incident on the traffic conditions varies depending on whether the incident occurs inside or outside the control area. When an incident occurs on an arterial within the control area, traffic flow upstream of the incident generally becomes more congested, while traffic flow downstream of the incident becomes less congested. Engineers may find it desirable to use traffic responsive mode to detect when these situations occur in the network and implement a timing plan that is specifically designed to accommodate traffic demands and manage queues that are associated with incidents.

Incidents that occur outside of the actual control area can also impact traffic operations within the control area. Traffic diverting from another arterial street or from a freeway can

dramatically alter traffic patterns in a control area. Diverting traffic may result in a general increase in traffic demand throughout the entire network. If the signal systems are operating in a traffic responsive mode, these changes in traffic patterns can be detected and a new timing plan can be implemented that could mitigate the impacts of the incident on traffic flow in the control area.

Special Events

One situation where traffic responsive mode may be particularly beneficial is in providing control after a special event (such as a football game, concert, etc.). The problem with providing time-of-day mode for special events is that, although the starting time of the event is known, the precise ending time is often unpredictable. Therefore, it is difficult to develop a time-of-day plan that can be implemented for special events. In a traffic responsive mode, the system detectors can be used to monitor traffic conditions to determine when the event ends. As traffic builds in the network, the signal system could then implement a plan specifically designed to accommodate traffic from the special event.

Early Exit of Time-of-Day Plan

Another situation where traffic responsive mode may be beneficial is in identifying when it may be appropriate to leave a particular time-of-day plan early. The need to exit a specific time-of-day plan early can arise when an expected traffic demand does not materialize on the network. For example, fluctuations in peak period demand may make it necessary to leave a peak period plan early. By operating the signal system in a traffic responsive mode, the signal system can implement appropriate timing plans when demands do not materialize as expected. In the case where the ending point of the period remains relatively constant from day to day, a time-of-day operating mode would be more appropriate. Figure III-1 illustrates how the signal system is envisioned to operate in this situation. First, the signal system would begin operating at a particular time (e.g., peak period) in time-of-day mode (e.g., with the peak period plan). After a certain period (e.g., 15 to 30 minutes), the signal system would then enter a traffic responsive mode of operation. If traffic demand in the system decreased unexpectedly after this time, the signal system would then automatically implement a timing plan appropriate for the measured traffic conditions.

Adaptive Holiday Control

Another potential application for operating traffic signal systems in a traffic responsive mode is to provide for adaptive control during holiday periods. With some holidays (e.g., near Christmas), traffic patterns can be heavier than normal. With other holidays, traffic patterns can

be lighter than normal. If traffic patterns are known, then the traffic responsive mode can be used to adapt timing plans to meet holiday conditions. This may include extending the peak plan past its normal time-of-day ending point, implementing a weekday peak timing plan during a weekend period, or exiting a time-of-day plan early because the normal traffic demands did not materialize due to the holiday period.
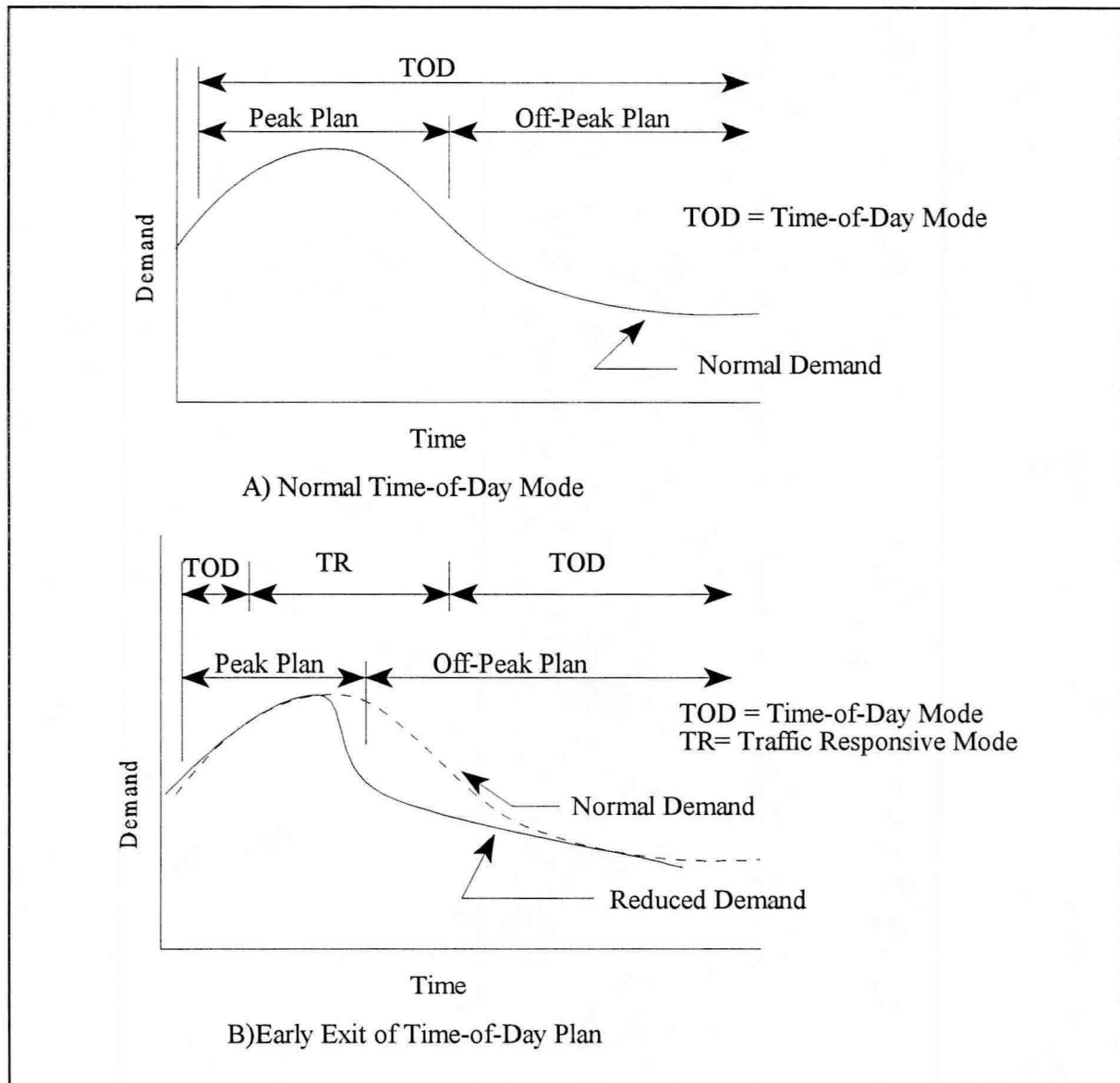

Figure III-1. Example of Using Traffic Responsive to Exit a Time-of-Day Plan Early

Low Volume

A final situation where traffic responsive mode might prove to be beneficial is during low volume conditions (e.g., like those occurring at night). Under these conditions, traffic volumes are generally unpredictable and can vary from cycle to cycle. As a result, it is difficult to provide good coordination during low volume conditions. The traffic responsive mode can be used to bring the signals into and out of coordination, as necessary.

FREQUENCY OF TIMING PLAN CHANGES

How frequently timing plans are changed is a major issue when a closed-loop signal system is operating in a traffic responsive mode. With most systems, the user defines how much time must elapse after a timing plan has been changed before a new timing plan can be implemented in a traffic responsive mode. If the time is too long, the system is not responsive to changing traffic conditions. If this time is too short, the system operates inefficiently, constantly in a state of transition between timing plans.

Few research studies have been performed on the amount of time that must pass before a new timing plan should be implemented. Early research with the Urban Traffic Control System (UTCS) recommends that the minimum time between timing plan changes should be 15 minutes (*1*); however, one study suggests that because of the delays associated with transitions, thirty-minutes between timing plan changes is too short for the benefits of the new timing plan to offset the transition effects (*12*). In the absence of clear research findings, it is recommended that at least 15 minutes be provided between timing plan changes when a system operates in a traffic responsive mode.

IV. PROCEDURES FOR IMPLEMENTING TRAFFIC RESPONSIVE MODE

The literature has shown that traffic responsive operation works best when the control condition is known, but the time when the plan should be implemented is not known. Therefore, in order to achieve the maximum benefit from operating a signal system in a traffic responsive mode, the engineer must know the following:

- the type of situation that is to be controlled (e.g., football game, incident, etc.), and
- the traffic patterns associated with the control condition.

A nine-step process has been developed for setting up a closed-loop to operate in a traffic responsive mode. This process is shown in general in Figure IV-1 and discussed in detail below. Within each step of the process, specific guidelines are provided for implementing traffic responsive mode for each of the three closed-loop signal system manufacturers approved by TxDOT.

STEP 1. IDENTIFY SYSTEM DETECTORS

The first step in setting up a closed-loop traffic signal system to operate in a traffic responsive mode is to identify which detectors should function as system detectors. System detectors are used to gauge the prevailing traffic patterns that exist throughout the entire system. The proper placement of system detectors is critical to the successful operation of traffic responsive signal systems. System detectors should be located at strategic locations in the corridor where true traffic demands can be measured quickly and accurately.

During the mid-1970's, research was conducted on determining the most appropriate location for system detectors (*13*). The authors of this research recommend that a single detector located in the critical lane of the main arterial be used as a system detector. In this research, the critical lane is defined as the lane carrying the greatest volume, which is usually evident by observing the length of queues at each of the intersections in the system. The authors recommend that the detector be located downstream of the zone of acceleration for vehicles entering the link. This distance is approximately 70 meters from the stop line of the upstream intersection. The authors also recommend that the detector be located upstream of the point beyond which standing queues of vehicles do not typically extend. Although this is a function of numerous factors (including signal timing, traffic demands, and intersection geometry), the authors recommend that system detectors be placed 60 to 76 meters upstream of the intersections in an urban grid and 90 to 106 meters upstream of intersections on a suburban arterial. When both of the above criteria

cannot be met, however, the authors recommend that locating the detector upstream of the queue is more critical.

Step 1

| Identify System Detectors |

Step 2

| Collect Volume and Occupancy Data |

Step 3

| Identify Control Conditions |

Step 4

| Develop Timing Plans |

Step 5

| Set Scaling Factors |

Step 6

| Establish Smoothing Factors |

Step 7

| Set Weighting Factors |

Step 8

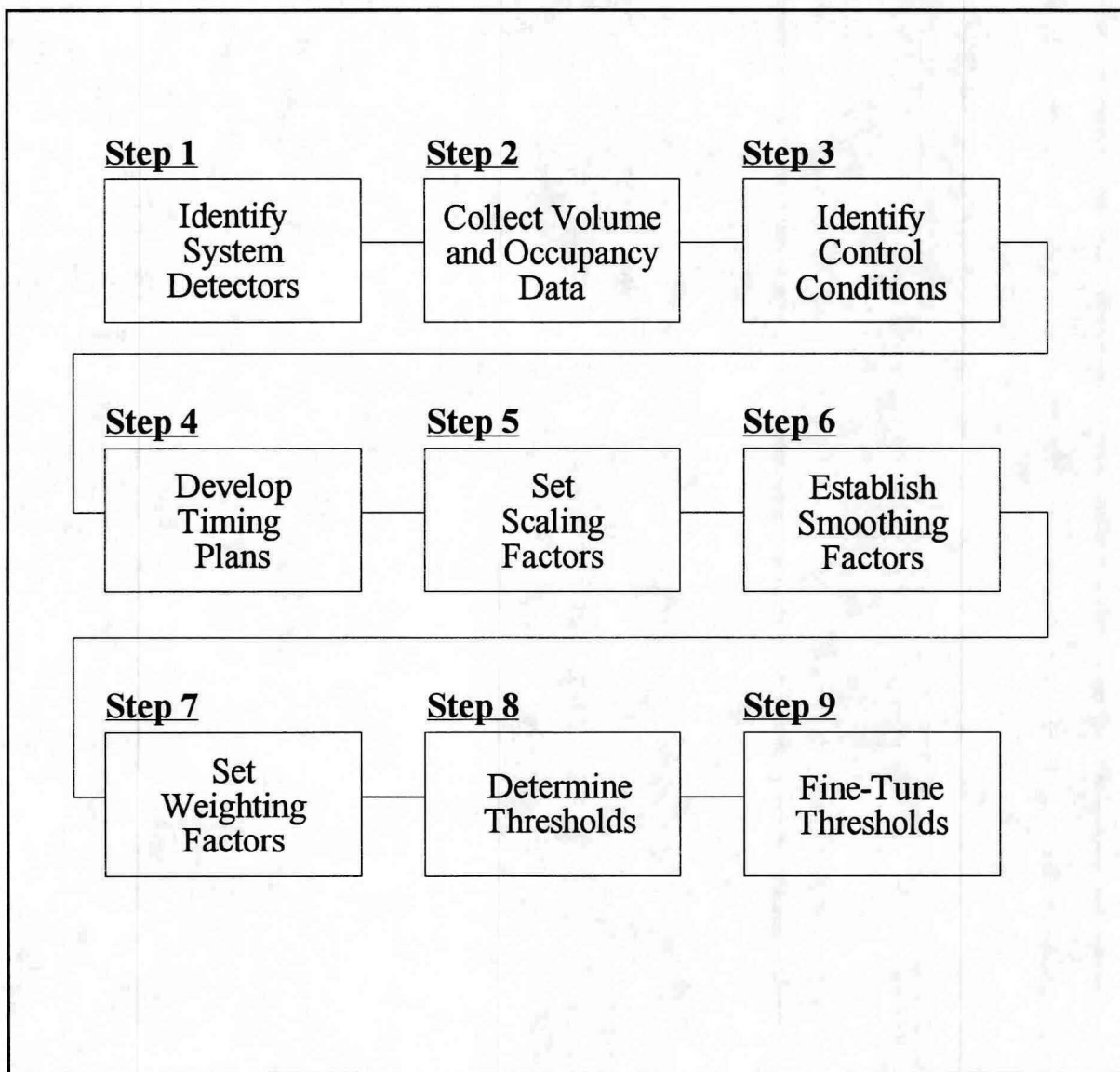| Determine Thresholds |

Step 9

| Fine-Tune Thresholds |

Figure IV-1. General Process for Implementing Traffic Responsive Mode for Closed-Loop Traffic Signal Systems

A recent TTI study provided the following criteria for locating system detectors for arterial street signal systems (*14*):

- The detector system should measure the demand at points where the change in demand has been demonstrated to be a forerunner of a change downstream or locations which have the potential for doing so,
- The location should be away from the path of turning vehicles and outside the queue space of an intersection,
- There should be as few detectors as practical to reduce the computations, but sufficient to measure the major demand changes on the system, and
- Generally, a sampling detector should be placed at an average of about every 800 meters along the coordinated arterial street.

With most closed-loop signal systems, the user is required to assign the system detectors to each of the timing plan selection parameters. Often, there is a limit to the number of system detectors that can be assigned to each selection parameter. For example, the Naztec Closed-loop system allows up to 10 system detectors to be assigned to each flow parameter while the Econolite system allows only 4 detectors to be assigned to each of the selection parameters. Because of these restrictions, the engineer needs to be careful about placing the system detectors where they can measure the prevailing traffic conditions in the system. As a general guideline, the system detectors need to be located throughout the system where they can best detect the following changes in traffic conditions:

- Increases or decreases in overall demand levels that might require modifying the cycle length for the system,
- Shifts in directional demand that might require different offset plans, and
- Changes in cross-street directional demand that might require different split plans.

Because all signals in a coordinated system are required to operate on the same cycle length, there is one intersection in any system that dictates the cycle length for the remaining intersections in the system. This intersection is typically called the critical intersection. It generally experiences the greatest demands and is most likely to become congested first in the system. Because different intersections can become critical (i.e., control the timings of the other intersections) at different times during the day, it is recommended that system detectors be placed on all approaches to the critical intersections in the system. These detectors need to be assigned to those traffic parameters that are responsible for determining the cycle length in a traffic responsive mode.

System detectors are also needed to measure changes in the directional distribution of traffic in the system. These system detectors need to be assigned to the traffic parameters that are responsible for selecting the offset in a traffic responsive mode. As a general guideline, these system detectors need to be located as closely to the source of the directional change as possible. For example, if the source of a change in the directional distribution occurs outside the limits of the system (i.e., from traffic entering at the ends of the system), then the system detectors should be placed at the ends of the system. However, if the source of change in directional distribution

occurs at an location within the system boundaries (i.e., from turning traffic entering the system from an internal signalized intersection or driveway), a system detectors needs to be located near this location to measure this change in demand. Where this occurs, the system detectors should be located on the main-street downstream of where the traffic is entering the system.

Some closed-loop systems permit different split plans to be implemented based on a comparison of cross-street traffic to main-street demand. Therefore, system detectors need to be assigned that measure the cross-street demands in the system. As in the cycle length, there is generally one intersection that is critical in terms of the amount of time that must be provided to the cross-street. Generally, this is the same intersection that dictates the cycle length for the system. Therefore, the same system detectors that are used to measure changes in cycle length can also be used to measure changes in split requirements, except that the detectors on the side-street need to be assigned to the cross-street selection parameter while the detectors on the primary street need to be assigned to the main-street selection parameter.

STEP 2. COLLECT VOLUME AND OCCUPANCY DATA

Once it has been determined which detectors can be used as system detectors, the next step is to collect volume and occupancy data from these system detectors. These data are needed to establish the thresholds for selecting the timing plan. Care should be taken to ensure that the data represent the actual conditions in the field, and are free from errors caused by malfunctioning detectors or other special operating conditions (such as when the system is operating in a preempt mode). Volume and occupancy data should be collected during the entire time different timing plans are needed. It is recommended that, at a minimum, two weeks of volume and occupancy data should be collected from the system detectors. This should allow the engineer to identify any daily and weekly trends that normally occur in the system.

STEP 3. IDENTIFY CONTROL CONDITIONS

After collecting the volume and occupancy data from the system detectors, the next step in the process is to identify the conditions that will be controlled by the signal system. In identifying the control conditions for a system, the engineer should examine the data from the system detectors for the following operational conditions:

- Changes in overall traffic volume levels that might require different cycle lengths,
- Changes in directional distributions that might require different offset conditions, and
- Changes in the cross directional demand that might require different split plans

A relatively simple technique that may be used to identify the need for individual timing plans is based on the fluctuations of directional traffic demand during an average day (*3*). Using data from the system detectors, three indices can be computed for the critical intersection(s) in the system: the Total Demand (TD), Main-Street Directional Demand (MD), and Cross Directional Demand (CD). The formulas for computing these indices are as follows:

Total Demand

$$TD = (N,S)_{max} + (E,W)_{max}$$

where,

$$TD =\text{Total Demand index,}$$
$$(N,S)_{max} =\text{Maximum of either northbound } \underline{or} \text{ southbound demand, and}$$
$$(E,W)_{max} =\text{Maximum of either eastbound } \underline{or} \text{ westbound demand.}$$

Main Street Index

$$MD = \frac{N}{N+S} \quad or \quad \frac{E}{E+S}$$

where,

$$MD =\text{Main-Street Directional Demand index,}$$
$$N =\text{Demand in the northbound direction,}$$
$$S =\text{Demand in the southbound direction,}$$
$$E =\text{Demand in the eastbound direction, and}$$
$$W =\text{Demand in the westbound direction.}$$

Note that the Main-Street Directional Demand Index depends on the direction of flow of the main street.

Cross Directional Demand

$$CD = \frac{(N,S)_{max}}{TD} \quad or \quad \frac{(E,W)_{max}}{TD}$$

where,

$$CD =\text{Cross Directional Demand index}$$
$$TD =\text{Total Demand index}$$

$(N,S)_{max}$ = Maximum of either northbound <u>or</u> southbound demand, and

$(E,W)_{max}$ = Maximum of either eastbound <u>or</u> westbound demand.

The Total Demand index provides an indication of the loading that occurs at the critical intersection(s). It can be used to provide an indication of the control periods that might require different cycle lengths. In general, periods that exhibit a lower index value require a shorter cycle length. Conversely, a high index value would imply that a higher cycle length is required to accommodate demand.

The Main-Street Directional Demand (MD) index indicates the need to provide a timing plan favoring a particular direction of flow. A high MD ratio is indicative of a need for a timing plan favoring one direction of flow on the main street. Conversely, a low MD value of the index indicates that a timing plan favoring the other direction traffic is needed. An value near 0.5 is indicative of a balanced (equal flow in each direction) condition. These indices can be used to determine the need for different offset patterns to accommodate directional flows on the main street.

The Cross Direction Demand (CD) index provides an indication of the need for different split patterns. A high index value implies that traffic on the main street is heavier than traffic on the cross street, while a low index value is indicative of a need to favor cross-street traffic.

The volume data collected in Step 2 can be entered into the equations above to identify likely periods when different timing plans might be required. It is recommended that these indices be plotted as a function of time so that periods when different control conditions exist can be readily identified. An example of how these parameters can be used to determine different control conditions is provided in Figure IV-2.

STEP 4. DEVELOP TIMING PLANS

After identifying when different control conditions exist, the next step in setting up a closed-loop system to operate in a traffic responsive mode is to develop timing plans for each of the identified control conditions. Timing plans can be developed using turning movement counts collected at each intersection in the system during each identified control period and standard traffic signal optimization programs (such as PASSER II, PASSER IV, or TRANSYT 7-F). The turning movement data should reflect the average or typical conditions that exist during the control period.
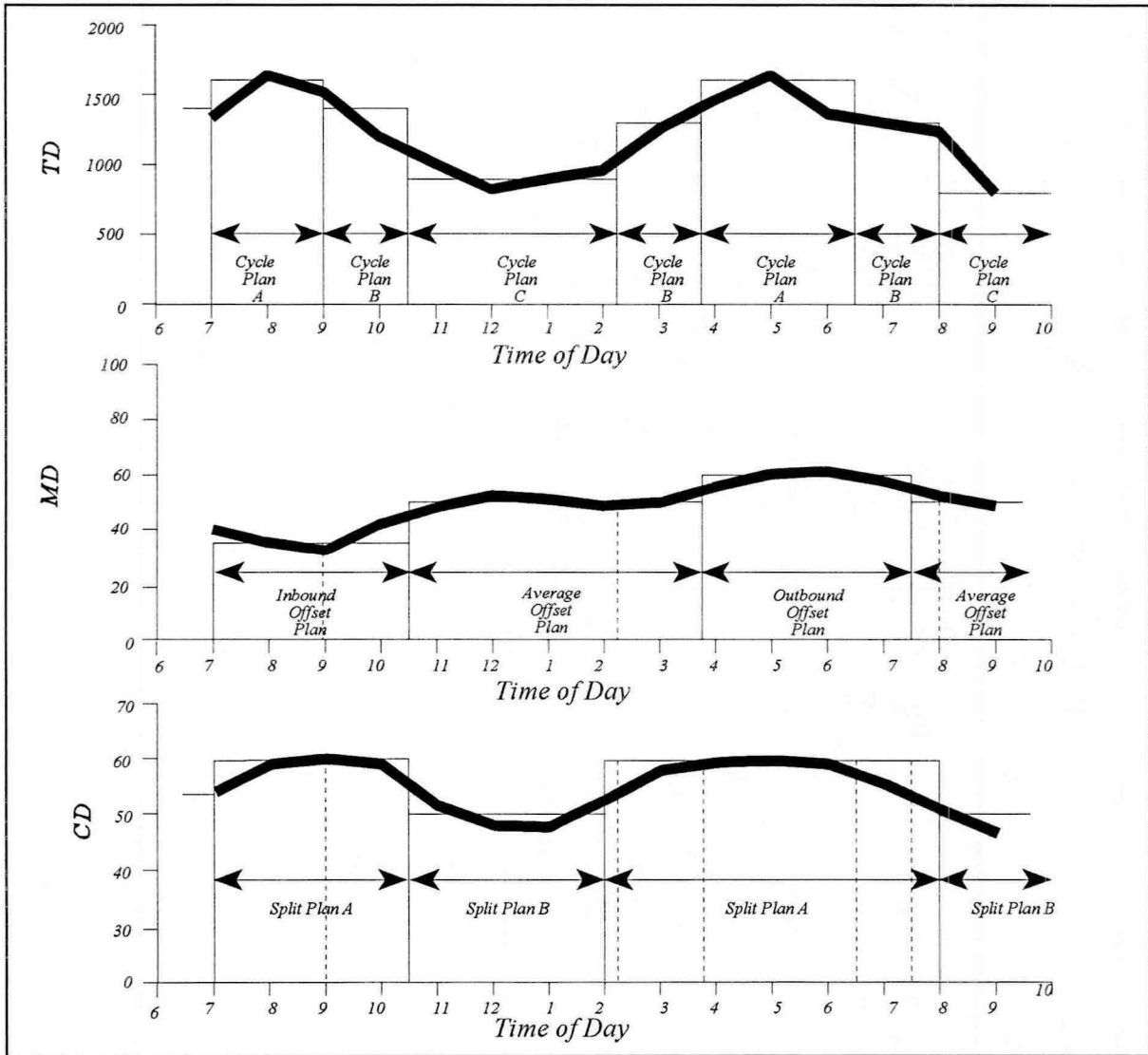
Figure IV-2. Example of Using Demand Indices to Identify Control Conditions

The maximum number of timing plans that can be developed for a system depends on which of the TxDOT approved closed-loop manufacturers is used. Table IV-1 shows the maximum number of cycle lengths, offsets, split plans, and special timing plans available for use under each of the TxDOT approved vendors.

Table IV-1. Maximum Number of Timing Plans Available for Use by the TxDOT Approved Closed-Loop Signal System Venders

System Vendor	Cycle Length	Offsets	Split Plans	Special Timing Plans	Total Number of Plan Combinations
Naztec	6	4	6	-	144
Econolite	5	3	4*	5	65
Eagle	4	3	4	4	52

* Up to four split plans can be developed for each cycle / offset combination.

STEP 5. DETERMINE SCALING FACTORS

After developing the timing plans for each expected control condition, the next step in the process of setting up a closed-loop system to operate in a traffic responsive mode is to enter the appropriate volume and occupancy scaling factors for each system detector. Since raw volumes and occupancies are a function of the capacity of the approach where the system detector is located, scaling factors are used to convert the raw volume and occupancy measurements into consistent values, independent of the available capacity on an approach. By using scaling factors, the volumes and occupancies for every system detector can be normalized to range between 0 and 100%. The scaled values provide an indication of how close traffic is on an approach to reaching capacity.

Generally, each signal manufacturer requires two different scaling factors: one for volume and another for occupancy. As a general guideline, the volume scaling factor should be set to the saturation flow rate of the approach where the system detector is located. The saturation flow rate represents the maximum rate of flow that can be achieved on an approach irrespective of the traffic signal. It is a function of the number and width of the lanes, the grade, the number of heavy vehicles and buses, and the amount of parking that occurs on an approach. The procedures discussed in the 1995 *Highway Capacity Manual* (4) can be used to compute the saturation flow rate at each system detector. Generally, the saturation flow rate on an approach varies between 1600 and 1900 vehicles per hour per lane, with a typical value of 1750 vehicles per hour per lane.

For occupancy, the appropriate scaling factors depends upon whether or not queues build over the system detectors. In the case where queues do not block flow over the system detectors, the scaling factor should be set so that an occupancy of 25% or 30% would produce a scaled occupancy of 100%. This is because research has shown that an approach begins to become congested when the occupancy level reaches 25% or 30% (*17*). On those approaches where congestion is known to impede flow over the system detectors, the scaling factor should be set to equal the highest occupancy level likely to occur over the system detector. This can be determined by looking at historical occupancy levels for each system detector.

STEP 6. ESTABLISH SMOOTHING FACTORS

As shown in Figure IV-3, detector data generally has many short-term fluctuations (or noise). These fluctuations are generally caused by the random arrival of vehicles over the system detector. Smoothing is a mathematical technique for producing a weighted average of a traffic variable. The idea behind smoothing is to eliminate these short-term fluctuations so that true trends in the data can be determined. Figure IV-3 illustrates detector data that has been smoothed.

Generally, there are two types of approaches used in closed-loop signal systems for smoothing data. The first approach is called "filtering." With the filtering approach, the difference between an old smoothed value of a variable (such as volume or occupancy) and the latest unsmoothed valued of the same variable are multiplied by a smoothing factor and added to the last smoothed value of the variable. The equation representing this process is as follows:

$$\bar{\bar{x}}_{new} = \bar{x}_{old} + k(x_{new} - \bar{x}_{old})$$

The smaller the value of the filter (represented by k in the above equation) causes the new data to have less of an influenced on the smoothed data. As a result, smaller values of k lessen the impacts of random fluctuations in the detector data; however, they also cause a time delay before true changes in traffic conditions can be detected. Therefore, when filtering is used to smooth detector data, it is recommended that the smoothing factor (k) be set to 0.5.

Averaging is another approach that is commonly used in closed-loop systems to smooth data. With this approach, new volume or occupancy data are averaged with a user-defined number of past volume or occupancy measurements. The equation generally used to smooth volume and occupancy measurements using the averaging approach is as follows:

$$y_t = \sum_{k=0}^{M} \frac{1}{M+1} x_{t-k}$$
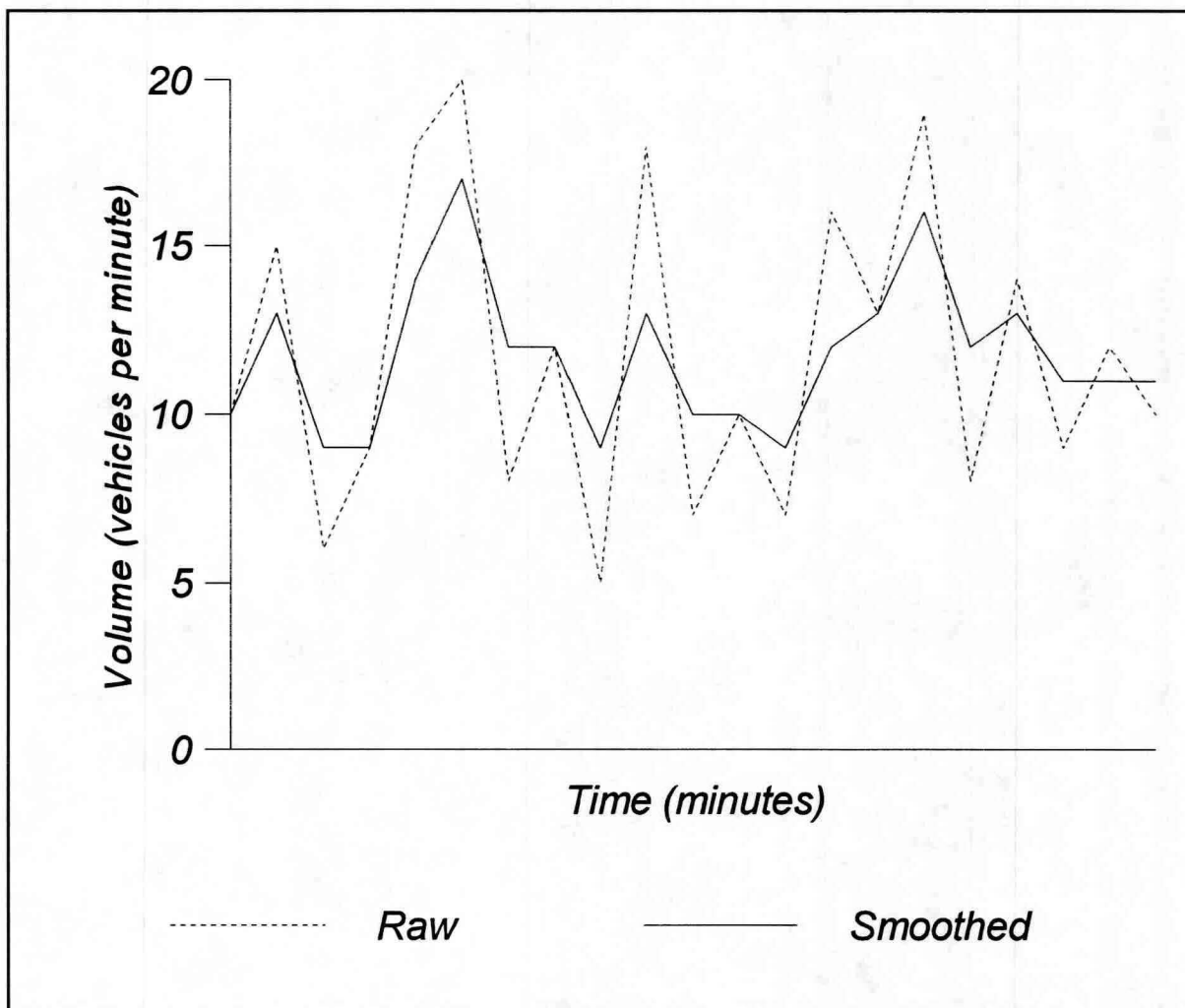
Figure IV-3. Effects of Smoothing Raw Volume Data

where,

y_t = New smoothed volume or occupancy value

M = Number of past time intervals averaged with the current data value, and

x_{t-k} = Past volume and occupancy measurements (Note: $k = 0$ represents the current data).

With the averaging technique, the response of the system to new changes in data is controlled by the number of past data points averaged with the current value. The greater the number of past value, the less sensitive the system is to change.

All three of the TxDOT approved close-loop venders permit the system detector data to be smoothed before it is used to determine the timing plan selection parameters. Unfortunately,

each manufacturer uses a slightly different approach for smoothing the data. The techniques used by each of the TxDOT approved venders are discussed in the attached appendices.

STEP 7. DETERMINE WEIGHTING FACTORS

Some of the TxDOT approved closed-loop manufacturers permit the volume and occupancy measurements to be weighted. The purpose of the weighting is to allow the user to change the relative "importance" of the volume and occupancy parameters from specific system detectors. For example, if the user wanted to make the volume and occupancy parameters from the critical intersection have greater "weight" in the timing plan selection process, he or she could assign these detector groups a higher weighting factor. Unless special circumstance are already know to the engineer at the time the system is implemented, it is recommended that each of the detector parameters be weighted equally at the initial implementation of the system. The weighting factors can be fine-tuned later if the performance of the system dictates.

STEP 8. DETERMINE THRESHOLDS

After deciding how to smooth and weight the data from the system detectors, the next step in the process is to establish the thresholds that determine the conditions under which each specific timing plan is to be implemented by the system. The threshold values should represent the traffic conditions for which the timing plan is valid. Both minimum and maximum thresholds should be developed, with the minimum threshold defining the lowest level of traffic that can be accommodated efficiently by the traffic signal timing plan and the maximum threshold defining the upper level of traffic that can be effectively accommodated by the traffic signal timing plan.

Using a spreadsheet and the volume and occupancy data collected at each of the system detectors, the selection parameters (usually one parameter each for determining each cycle length, offset, and split) should be computed using the volume and occupancy data from system detectors for each interval during the control period. Each closed-loop vendor has a slightly different way of determining when to select new timing plans; therefore, it is important that the engineer use the method for the particular closed-loop vendor being installed at a location. The appendices attached to this report provide specific guidelines on how to use the timing plan selection procedures for each of the three TxDOT-approved closed-loop vendors in establishing thresholds.

Once the timing plan selection parameters have been computed for each of the control periods, they can be plotted as a function of time. Since the timing plan is developed for a specific time period for which the traffic conditions are known, the timing plan selection parameters have a direct correlation to the traffic conditions that would typically be experienced during the control situation. By plotting timing plan selection parameters as a function of time, the engineer can quickly see the range of each parameter likely to occur during the control period.

Using this graph, the engineer can extract the appropriate thresholds for entering and exiting a given timing plan. An example of how this graphical approach can be used to select cycle length thresholds for a given control condition is shown in Figure IV-4.
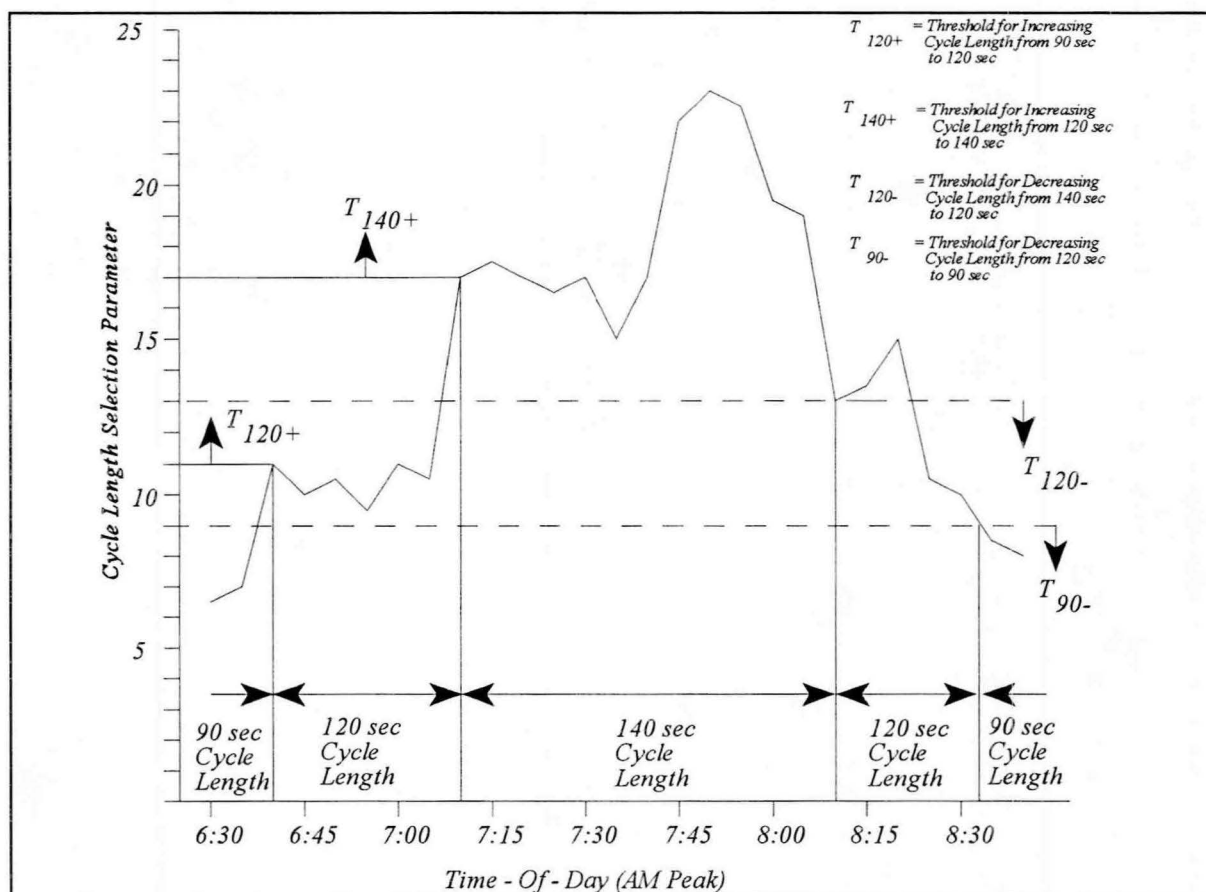
Figure IV-4. Timing Plan Selection Parameter for A.M. Peak Plan

STEP 9. FINE-TUNING THRESHOLDS

After the thresholds have been estimated and implemented in the field, some fine-tuning of the thresholds may be required to ensure that the proper timing plans are selected during the desired conditions. It is recommended that the operation of the system be monitored for approximately two weeks after the initial implementation of the system. The engineer is strongly encouraged to make periodic field visits to the system to ensure that it is functioning as designed.

V. SUMMARY OF RECOMMENDATIONS

Listed below is a summary of the major recommendations of this report.

• While there are several methods available for determining when to coordinate traffic signals, it is recommended that the interconnection desirability index be used because of its computational simplicity and minimal data requirements. Listed below are the steps required to determine when to operate a traffic signal system in an isolated or coordinated mode:

- Obtain a physical description of the corridor,
- Obtain 15-minute turning movement volumes at each intersection in the corridor,
- Compute the interconnection desirability index for each one-way link in the system,
- Compare the computed index to the threshold selected for the corridor, and
- Establish the times for operating signals in the system in a coordinated and in an isolated mode.

• Because frequent timing plan changes can have a deleterious effect on traffic operations in a coordinated system, it is recommended that traffic responsive mode be used at locations where *major shifts* in traffic patterns are likely to occur. Generally, traffic responsive mode should be used where traffic patterns are unpredictable. Situations where traffic responsive mode might be beneficial include the following:

- Locations that are severely impacted by incidents,
- Around major special event centers,
- Locations where unpredictable traffic patterns may require the early exit from a time-of-day plan,
- Locations where adaptive control during holiday is needed, and
- In low volume conditions.

• A nine-step process can be used to identify thresholds for operating signal systems in a traffic responsive mode. Although each of the TxDOT approved controller manufacturer uses different parameters and procedures for picking timing plans in a traffic responsive mode, the general procedure for establishing the thresholds needed to pick the timing plans is similar for each controller manufacturer. Generally, the volume and occupancy data from periods where specific timing plans will be implemented are combined using the methodology specific to each controller manufacturer. The volume and occupancy data must be scaled, smoothed and weighted again using the procedures and formulas specific for each controller manufacturer. The volume and occupancy data from a specific control condition are then used to compute the timing plan selection parameters for each controller manufacturer. This will allow the engineer to determine the range of the timing plan selection parameters that correspond to a specific control

condition. From here, the engineer can set the appropriate thresholds that will implement each specific timing plan for the correct control condition. After the system is implemented in the field, the system should be monitored to determine if the desired timing plans are being implemented in the correct control condition. Fine-tuning of the threshold may be required if this evaluation shows that the correct timing plans are not being implemented by the system.

VI. REFERENCES

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APPENDIX A:

GUIDELINES FOR IMPLEMENTING TRAFFIC RESPONSIVE MODE WITH A NAZTEC CLOSED-LOOP SIGNAL SYSTEM

ASSIGNMENT OF SYSTEM DETECTORS

The Naztec system uses three directional parameters in calculating the timing plan selection parameters (*15*). These directional parameters are used to measure as the amount of traffic flow in the inbound, outbound, and cross-street directions. System detectors need to be assigned that permit these traffic parameters to be measured in the system. A maximum of ten system detectors can be assigned to each directional parameter. It is recommended that system detectors on one side of the main arterial street be assigned to the Inbound detector group, the detectors on the other side of the main arterial street be assigned to the Outbound detector group, and the side-street system detectors approaching the critical intersection(s) be assigned to the cross-street detector group.

In the Naztec system, two detectors, a primary detector and a secondary (or backup) detector, can be assigned to each system detector (*15*). The secondary detector is used in calculating the timing plan selection parameters if the primary detector has failed. These detectors can be either local detectors that have been designated for system detector duty or regular system detectors. Any local controller which is part of the system can have some or all of its detectors utilized as system detectors by the master controller.

SCALING FACTORS

Naztec uses a scaled volume and occupancy value in computing the timing plan selection parameters (*15*). The scaled volume and occupancy values vary between 0 and 100%. To scale the volume measurements from the system detectors, a scaling factor, in terms of vehicles per minute, needs to be entered into each local controller. The scaling factor in the Naztec system can range from 0 to 255 vehicles per minute. If 0 is entered, the volume measurement from the system detector will not be included in the calculations of the timing plan selection parameters.

For volume, the scaling factor should represent the maximum minute flow rate expected over the system detector. It is recommended that the saturation flow rate (in vehicles per minute) for each approach where the system detectors are located be used as the scaling factor. Naztec representatives suggest a scaling factor of 20 vehicles per minute per lane (equivalent to 1200 vehicles per hour per lane saturation flow rate) as an appropriate scaling factor; however, this may be low for some urban applications. Historical data from the system detectors should be consulted to ensure that the measured volume levels do not exceed the entered scaling factor for any system detector.

The occupancy measurements from the system detectors also need to be scaled to represent the maximum occupancy expected over a system detector. For example, if the maximum expected occupancy is 25% over a system detector, a scaling factor of 0.25 can be used to scale the occupancy measurements to 100%. Again, historical occupancy data should be

consulted to determine the appropriate scaling factor for each system detector. In cases where the historical data show that occupancy levels are generally low (i.e., less that 25%), it is recommended that the occupancy scaling factor be set to 25% or 30%.

SMOOTHING FACTORS

The Naztec system uses smoothed volume and occupancy measures in computing the timing plan selection parameters (*15*). The equation used to smooth these data is as follows:

$$SV = \frac{New\ Value \times (100 - SF) + Old\ Value \times SF}{100}$$

where,

SV = the smoothed volume or occupancy measurement from the system detector,

New Value = the current volume or occupancy measurement from the system detector,

Old Value = the previously smoothed volume or occupancy measurement from the system detector, and

SF = an user-defined smoothing factor

The same smoothing factor is applied to both the volume and occupancy measures for a detector. The smoothing factors are entered by the user, and their values can range from 0 to 100. An entry of 0 implies that only new data will be used in the directional computations while an entry of 100 results in no new data being included in the directional computations. The higher the smoothing factor, the longer it takes for rapid changes in volume and occupancy to be detected. It is recommended that in the initial implementation of the system, the smoothing factor be set to 50. Setting the smoothing factor to 50 causes the old and new volume and occupancy measures to be weighted equally.

WEIGHTING FACTORS

The next step in setting up the Naztec system to operate in a traffic responsive mode is to determine the appropriate weighting factors for the volume and occupancy measures. The Naztec system uses three directional parameters in selecting a timing plan: an Inbound, an Outbound, and a Cross-Street directional parameter. As shown in the equation below, these parameters are the weighted average of the sum of the volume and occupancy measurements from each of the system detectors assigned to that particular directional parameter. The equation Naztec used to weight the volume and occupancy measurements is as follows (*15*):

$$Directional \; Factor \; = \; \frac{\sum\limits_{i=1}^{10} (c_i VOL_i + k_i OCC_i)}{\sum\limits_{i=1}^{10} (c_i + k_i)}$$

where,

VOL_i = Smoothed volume measurement from the ith system detector,
OCC_i = Smoothed occupancy measurement from the ith system detector,
c_i = volume weighting factor for the ith system detector, and
k_i = occupancy weighting factor for the ith system detector.

The Naztec system uses different weighting factors for each volume and occupancy measurement from the system detectors. The user is required to enter a value ranging from 0 to 10. An entry of 0 will remove the corresponding volume or occupancy measurement from the traffic responsive calculations. Because the volume and occupancy measurements have already been converted to a percent of the maximum expected value, it is recommended that in the initial installation of the Naztec system, volume and occupancy should be weighted equally (i.e., assigned a weighting factor of 5).

ESTABLISHING THRESHOLDS

The Naztec master controller compares the computed parameters to user-defined thresholds in a table lookup to determine the appropriate cycle length, phase split, and offset level (*15*). The timing plans are selected based upon three traffic parameters (cycle, offset, and split) derived from the directional flow parameters. (See below for determining how the directional parameters are computed.) These parameters are defined as follows:

$$CYCLE = Max \; Inbound \; or \; Max \; Outbound$$

$$OFFSET = \frac{Outbound - Inbound}{Outbound + Inbound} \times 50 + 50$$

$$SPLIT = \frac{Cross - CYCLE}{Cross + CYCLE} \times 50 + 50$$

In the Naztec system, the master controller compares these three parameters to user-defined thresholds to determine the appropriate timing plan. Timing plans are selected using a table lookup procedure. The engineer assigns the appropriate cycle, split, offset parameter that defines the conditions when each particular timing plan is appropriate. As shown in Table A-1, there are six cycle and six split levels that can be used to select timing plans in the Naztec system. A separate timing plan selection matrix is entered for each of the four offset levels.

To correctly set up the Naztec system to operate in a traffic responsive mode, two sets of thresholds are needed for each cycle, phase, and offset level. One set of thresholds applies for increasing parameter values and another set applies for decreasing parameter values. This permits the user to program the controller from oscillating back and forth between different cycle, split, and offset levels. All threshold entries are made in the range of 0 to 100% with the thresholds in the increasing direction being greater than the thresholds in the decreasing direction. An entry of zero will cause a threshold level to be disabled.

Table A-1. Example of Timing Plan Selection Matrix Used at One Offset Level by the Naztec Closed-Loop System

| Cycle Level | Offset Level 1 | | | | | |
	Split Level 1	Split Level 2	Split Level 3	Split Level 4	Split Level 5	Split Level 6
1	Timing Plan 1	Timing Plan 1	Timing Plan 2	Timing Plan 2	Timing Plan 3	Timing Plan 3
2	Timing Plan 4	Timing Plan 4	Timing Plan 5	Timing Plan 5	Timing Plan 6	Timing Plan 6
3	Timing Plan 7	Timing Plan 7	Timing Plan 8	Timing Plan 8	Timing Plan 9	Timing Plan 9
4	Timing Plan 10	Timing Plan 10	Timing Plan 11	Timing Plan 11	Timing Plan 12	Timing Plan 12
5	Timing Plan 13	Timing Plan 13	Timing Plan 14	Timing Plan 14	Timing Plan 15	Timing Plan 15
6	Timing Plan 16	Timing Plan 16	Timing Plan 16	Timing Plan 16	Timing Plan 16	Timing Plan 16

To determine the thresholds for implementing each timing plan, it is recommended that the engineer compute the cycle, offset, and split parameters from system detector data collected during each control condition. This can be done by entering the raw volume and occupancy data for each control condition along with the appropriate scaling, weighting, and smoothing factors into a computer spreadsheet, and calculating the cycle, offset, and split parameters using the equations above. Once the timing plan selection parameters have been computed for each control condition, they can be plotted as a function of time. Since individual timing plans have been developed for specific periods where the traffic conditions are known, the timing plan selection parameters are directly correlated to the traffic conditions that would typically be experienced during the control situation. By plotting the timing plan selection parameters as a function of time, the engineer can quickly see the range of each parameter likely to occur during the control period. Using this graph, the engineer can extract the appropriate thresholds for entering and exiting a given timing.

APPENDIX B:

**GUIDELINES FOR IMPLEMENTING TRAFFIC
RESPONSIVE MODE WITH AN ECONOLITE
CLOSED-LOOP SIGNAL SYSTEM**

ASSIGNMENT OF SYSTEM DETECTORS

In the Econolite system, up to 32 system detectors can be used in a traffic responsive mode (*16*). Each system detector is assigned to one of the following eight detector groups:

- Level,
- Direction 1 Traffic,
- Direction 2 Traffic,
- Split Demand A,
- Split Demand B,
- Arterial Demand,
- Non-Arterial Demand, and

The Level detector group is used to provide an indication of the overall amount of traffic in the system. Data from this group are directly responsible for determining the appropriate cycle length to be used by the system. As the name implies, the Direction 1 and Direction 2 detector groups provide an indication of the flow in each direction in the system, and are used to determine the appropriate offset pattern (e.g., inbound, outbound, or average) to be used by the system. The Split Demand A and Split Demand B detector groups are used by the master controller to determine whether to implement special split plans or phasing, while the Arterial and Non-Arterial Demand detector groups are used to determine whether or not to implement a timing plan that favors cross-street traffic over the main arterial street traffic. Of these detector groups, the Level, the Direction 1, and the Direction 2 detector groups are most critical. The most basic configuration of the Econolite system requires data from these three detectors groups only. Data from the Split Demand and the Arterial/Non-Arterial detector groups are needed only if the operator wishes to implement special split patterns or provide preference treatment for cross-street phasing.

Up to four detectors can be assigned for each group (*16*). The user must decide whether to use the highest value, the second highest value, or an average value from all of the detectors assigned to each detector group. To guard against random fluctuation in traffic causing unnecessary timing plan changes, it is recommended that the Econolite system be set up to use the average value of the data from the each detector group.

SCALING FACTORS

The Econolite system also uses scaling factors to convert volume and occupancy measurements to scaled values (*16*). The volume scaling factor is entered as vehicles per hour per 100 while the occupancy scaling factor is entered as a percent. The scaling factors for both of these traffic parameters should be chosen so as that the volume or occupancy measurements at saturation produce a scaled volume and occupancy of 100%.

SMOOTHING FACTORS

Once the system detectors and traffic functions have been assigned to each detector group, the volume and occupancy from each detector group is smoothed. A smoothed data value is generated by taking the current data and relating it with a smoothing factor to the previously sampled data from each detector. The smoothed values are then used in the timing plan selection process. The equation used by the Econolite system to smooth the data is as follows (*16*):

$$S_n = S_{n-1} + \frac{SMF \times (S - S_{n-1})}{100}$$

where,

S_n = Current smoothed data (%),
S_{n-1} = Previous smoothed data (%),
S = Current selected detector group data (%), and
SMF = Smoothing factor (a whole number ranging from 0 to 99)

The smoothing factor is entered by the user and is a whole number ranging from 0 to 99. In general, the higher the smoothing value, the more influence current volume and occupancy measurement will have on the smoothed data. As with the Naztec controller, it is recommended that the smoothing factor be set to 50 in the initial implementation of the Econolite system.

WEIGHTING FACTORS

The Econolite system does not have a method of directly assigning weighting factors to the system detector data. First, the user must decide which traffic parameter [i.e., volume, occupancy, or concentration (which is a maximum of either the volume and occupancy measurements at a system detector)] to use in the calculations (*16*). It is recommended that concentration be used because it would result in the highest value of the volume and occupancy measures at a system detector being used in the calculations.

The user then must decide whether to use the highest value encountered by any one of the detector groups, the second highest value, or an average value calculated using the data from all the detectors for the timing plan selection parameter (*16*). It is recommended that, at least initially, the system be set up to use average values from the system detectors. This will keep random fluctuations in traffic over particular system detectors from causing unexpected timing plan changes.

ESTABLISHING THRESHOLDS

The Econolite system uses the following four traffic parameters to select timing plans in a traffic responsive mode (*16*):

- the *Computed Level* Parameter,
- the *Computed Offset* parameter,
- the *Non-Arterial Preference* parameter, and
- *the Computed Split/Special Function* parameter.

Of these four parameters, only the *Computed Level* and *Computed Offset* parameters are required to operate the Econolite system in a traffic responsive mode at its most basic level. Using only these two parameters, up to 15 different timing plans can be implemented. The other two parameters are used to provide special control during specific traffic situations.

The *Computed Level* parameter is used to assess the overall demand level in the system. (It can be thought of as a cycle length selection parameter). As shown in Figure B-1, the user has the option of using up to five *Computed Levels* to classify demand in the Econolite system. The first level (Level 1) corresponds to the lowest anticipated demand level in the system, while the fifth level (Level 5) corresponds to the highest. The user has to assign thresholds which define the amount of demand anticipated for each *Computed Level*. Two sets of thresholds are required, one for increasing levels of demand and a second for decreasing levels of demand. To prevent constant switching between adjacent levels, the threshold sets must overlap, with the thresholds for increasing levels being greater than the thresholds for declining levels of demand. A threshold entry of 101 is used to inhibit access to a given demand level.

The *Computed Offset* is the other parameter that is needed to select timing plans in the most basic traffic responsive mode of the Econolite system. The *Computed Offset* parameter is used to assess the need to implement a timing plan that favors a particular direction of traffic. It compares the data from the Direction 1 (DR1) system detector group to the data from the Direction 2 (DR2) system detector group to determine the need for preferential treatment in a particular direction. For example, if the traffic over the DR1 detector group is greater than traffic over the DR2 detector group, then a timing plan that favors the DR1 direction should be implemented. Conversely, if traffic over the DR2 detector group is greater than traffic over DR1 detector group, then a timing plan that favors the DR2 traffic should be implemented. If DR1 and DR2 are equal, then a timing plan for balanced traffic flow (called AVG in the Econolite system) is required. (See above for information about system detector groups.)

Table B-1. Timing Plan Matrix for Econolite System

Non-Arterial Preference *	Computed Offset	Computed Cycle Level				
		1	2	3	4	5
Arterial	DR1	Timing Plan 1	Timing Plan 2	Timing Plan 3	Timing Plan 4	Timing Plan 5
	AVG	Timing Plan 6	Timing Plan 7	Timing Plan 8	Timing Plan 9	Timing Plan 10
	DR2	Timing Plan 11	Timing Plan 12	Timing Plan 13	Timing Plan 14	Timing Plan 15
Non-Arterial		Timing Plan 16	Timing Plan 17	Timing Plan 18	Timing Plan 19	Timing Plan 20

* Shade area represents optional contol. Non-shade area represents required control.

Like the *Computed Level* parameters, thresholds are used to define when different directional preference levels are reached. The *Computed Offset* parameter is computed using the following equation:

$$Computed\ Offset\ (\%)\ =\ |DR1\ -\ DR2|$$

Two sets of thresholds are needed to define the directional preference levels: one set for traffic flow transitioning from Direction 1 to a balanced traffic flow to Direction 2 (the Direction 1 thresholds) and another set for traffic transitioning from Direction 2 to a balanced flow to Direction 1 (the Direction 2 thresholds). The appropriate offset level is determined by the magnitude of the *Computed Offset* parameter and the predominant flow of traffic. If traffic in Direction 1 is greater than the Direction 2, then the *Computed Offset* parameter is compared to the Direction 1 thresholds. If Direction 2 traffic is greater than Direction 1 traffic, then the *Computed Offset* parameter is compared to the Direction 2 thresholds.

To set the thresholds, it is recommended that the user calculate the *Computed Level* and the *Computed Offset* parameters for each of the control conditions using the system detector data collected in Step 2. They can be plotted as a function of time. The thresholds can then be set by evaluating the range of parameters that exist during each of the control conditions.

In addition to the basic configuration, the Econolite system has two programmable options that can be used to implement timing plans for special control situations. With the programmable options, the engineer can implement the following optional controls:

- five additional timing plans can be called that provide preferential treatment to cross-street traffic, and
- up to four special phase splits/ special functions for each *Computed Level / Computed Offset* matrix entry.

To provide preferential treatment for cross-street traffic, the Econolite system uses a *Non-Arterial Preference* parameter. It is computed by comparing the data from the assigned Arterial Demand detector group (ART) to the data from the Non-Arterial Demand detector group (NRT). The following logic rules are used for determining whether to provide preferential treatment for the cross-street:

- If the smoothing factor for the Arterial Demand detector group is set to zero, then the decision to provide preferential treatment is based solely on the data from the Non-Arterial Demand detector group.
- If the value from the Non-Arterial Demand detector group is greater than the value from the Arterial Demand detector group, the decision to provide preferential treatment to the cross street is computed by taking the difference between the value of the Non-Arterial Demand detector group and the Arterial Demand detector group (i.e., NRT - ART). The result of this difference is compared to a user-defined threshold to determine whether or not to implement a timing plan that favors a cross-street timing plan. The actual selection of the timing plan is then based on the *Computed Level* parameter.
- If the value from the Arterial Demand detector group is greater than the value from the Non-Arterial detector group, then the selection of the timing plan is based on the *Computed Level* and *Computed Offset* parameters.

To set the threshold, the engineer must determine what level of cross-street traffic would warrant the use of a special timing plan that favors cross-street traffic. To do this, the user should compute the *Non-Arterial Preference* parameter for the situations where a cross-street timing plan would be needed. The *Non-Arterial Preference* parameter is computed using the following equation:

$$SNRT = NRT - ART$$

where,

      SNRT = Non-Arterial Preference parameter,

      NRT = Volume, occupancy, or concentration data from the Non-Arterial Demand detector group, and

     ART =   Volume, occupancy, or concentration data from he Arterial Demand detector group.

Note that only two threshold values are required to implement the cross-street preferential treatment option: one for transitioning into cross-street preferential control, and another for transitioning out of cross-street preferential control. If more than one situation exists where cross-street preferential control might be implemented, the engineer needs to set the thresholds so that this option is implemented in every case. A careful analysis of the Non-Arterial Preference parameter in all situations where preferential treatment to the cross-street might be desired should provide a clear indication of the appropriate threshold values.

The user also has the option of implementing a special split function that calls different split plans for each *Computed Level* and *Computed Offset* combination. One of four Split/Special Function commands can be selected to operate with each *Computed Level/Computed Offset* combination. If this option is used to select the split plans in a traffic responsive mode, the appropriate split level is determined by comparing the data from the Split Demand A detector group to the data from the Split Demand B detector group. The results of the evaluation are compared thresholds to determine which of four split/special functions to implement. The comparison occurs only when Split Demand A and B traffic functions are assigned for use in selecting plans in the traffic responsive mode.

In order the set the thresholds to use the Split/Special Function, the user must know before hand under what conditions the optional split/special functions will be used. This makes establishing the thresholds a matter of determining the range of parameters that is likely to occur when the special control condition is present in the field. This can be done by computing the *Special/Split* parameter using the data collected in step 2 from those detectors assigned to the Split Demand A and Split Demand B detector groups. The *Special/Split* parameter is computed as follows:

$$SSPL = SPA - SPB$$

where,
     SSPL =   Special/Split parameter,
     SPA =   Volume, occupancy, or concentration from the Split Demand A detector group, and
     SPB =   Volume, occupancy, or concentration from the Split Demand B detector group.

APPENDIX C:

**GUIDELINES FOR IMPLEMENTING TRAFFIC
RESPONSIVE MODE WITH AN EAGLE
CLOSED-LOOP SIGNAL SYSTEM**

ASSIGNMENT OF SYSTEM DETECTORS

The architecture of the Eagle closed-loop system is somewhat different than the other two TxDOT approved closed-loop systems. In the Eagle system, the local intersection controller receives volume and occupancy data from eight special detectors as well as the normal detectors used to provide actuated control (*17,18*). The user can assign any of these detectors to be system detectors for operating the system in the traffic responsive model. Unlike the other controller manufacturers, the Eagle local intersection controller unit processes (i.e., converts to full scale, smooths the data, and computes a volume plus occupancy parameter) the detector data <u>before</u> it is transmitted to the master controller. (With the other controller manufacturers, the processing of the system detector data takes place at the master controller.)

The master controller for the Eagle system has the ability to receive output data from eight system detectors for each intersection (*17*). The maximum number of system detectors that can be used by the Eagle master controller is 64. Any eight of these detectors can be assigned to the following ten computational channels:

- Cycle Select One (CS1),
- Cycle Select Two (CS2),
- Directionality One (DR1),
- Directionality Two (DR2),
- Non-Arterial One (NA1),
- Non-Arterial Two (NA2),
- Queue One (Q1),
- Queue Two (Q2),
- Occupancy One (OC1), and
- Occupancy Two (OC2)

The Cycle Select computational channels are used by the Eagle master controller to determine the appropriate cycle length for the system (*18*). It is recommended that the engineer assign the system detectors approaching the critical intersection(s) on both the main street and the cross street to the Cycle Select computational channels.

The Eagle master controller uses the Directionality computational channels to determine which one of three offset levels (Inbound, Average, and Outbound) to implement (*18*). It is recommended that the system detectors in one direction of flow be assigned to the Directionality One (DR1) computational channel and the system detectors in the opposite direction to the Directionality Two (DR2) computational channel.

The Non-Arterial computational channels, along with data from the Directionality or Cycle Select channels, are used by the Eagle master controller to determine the appropriate split plan in a traffic responsive mode (*18*). The Non-Arterial computational channels provide the

engineer with a mechanism for monitoring cross-street demands; therefore, it is recommended that only those system detectors on the cross street(s) approaching the critical intersection(s) be included in the Non-Arterial computational channels.

The Eagle system can also select up to eight additional timing plans using the Queue 1, Queue 2, Occupancy 1, and Occupancy 2 computational channels (*18*). These computational channels can be used to measure special traffic conditions that may warrant the use of special timing plans. Note that these computational channels are not required to operate the Eagle system in its most basic traffic responsive mode, but are required if timing plans for special conditions will be used. In this case, the system detectors assigned to these computational channels must directly measure the traffic condition requiring the special timing plan. Therefore, the engineer must determine what conditions are needed to implement a special timing plan and then determine which system detectors can best measure these specific traffic conditions.

SCALING FACTORS

Unlike the Naztec and Econolite systems which scale the volume and occupancy measurements at the master controller, the local controllers in an Eagle closed-loop system convert both the volume and occupancy to a percent of full scale before sending them to the Master controller. To convert volume measurements to full scale, the user must enter the estimated lane capacity (in vehicles per hour) for each system detector. The local controller converts the volume measurement to a percentage using the following equation (*17*):

$$VOL\% = \frac{Volume \times 60 \times 100}{VPHR}$$

where,
$\quad$ VOL% = Percent of full-scale volume,
$\quad$ Volume = 1 minute volume measurement from system detector, and
$\quad$ VPHR = Estimated lane capacity for system detector (in vehicle per hour)

Similarly, occupancy measurements are also converted to a percent of full scale at the local controller before it is passed on to the master. It is computed by taking the raw one minute occupancy count, multiplying by a correction factor (initially set to one), multiplying by one hundred to convert the final result to a percentage, and dividing by the maximum occupancy count over the system detector in one minute (*17*). Therefore, to scale occupancy in the Eagle system, the user needs to enter the maximum number of times the controller is likely to find a vehicle occupying the detector in a one minute period. This number is a function of the sampling rate of the detector. The Eagle system samples each detector 60 times per second. If the detector was occupied 100% of the time, the maximum occupancy count at the system detector would be 3600. To enter a scaling factor other than 100% (as recommended above when no

congestion is present on an approach), the user needs to multiply 3600 by the desired scaling factor. Therefore, entries of 900 and 1080 for the expected maximum occupancy count would be required to achieve a scaling factor of 25% and 30%, respectively. The formula for converting occupancy measurements to percentage of full scale is as follows:

$$OCCP\% = \frac{OCCP \times CTFC \times 100}{MXOCC}$$

where,

$\quad$ OCCP% = $\quad$ Percent of full-scale occupancy,
$\quad\quad$ OCCP = $\quad$ 1 minute occupancy count for system detector,
$\quad\quad$ CTFC = $\quad$ User-defined correction factor (initially set to 1), and
$\quad$ MXOCC = $\quad$ The expected maximum occupancy count over the system detector.

SMOOTHING FACTORS

The Eagle system smooths the volume and occupancy measurements before they are sent to the master controller. Both volume and occupancy are smoothed by summing a portion of the old average percent values and the new measurements (*17*). The portion of the old percent volume/occupancy value used in the calculations is based on the averaging time (a user-defined parameter varying between 1 and 99 minutes) for the detector. The equation used to smooth volume and occupancy measurements in the Eagle system is as follows:

$$SA\% = \frac{(AVGT - 1) \times OA\% + NA\%}{AVGT}$$

where,

$\quad$ SA% = $\quad$ Smoothed averaged volume or occupancy percentage,
$\quad$ OA% = $\quad$ Old average volume or occupancy percentage,
$\quad$ NA% = $\quad$ New average volume or occupancy percentage, and
$\quad$ AVGT = $\quad$ User defined averaging time (in minutes).

Note that an averaging time of one minute results in the only new volume or occupancy data being used to compute the timing plan selection parameters. After the volume and occupancy measures are smoothed, they are added together and sent to the master controller.

WEIGHTING FACTORS

With the Eagle system, the user has the option of providing both direct and indirect weighting of the volume plus occupancy parameters coming in to the master controller from the

local controllers. The Eagle system permits the user to assign a weighting factor (ranging from 0 to 100) to each detector group (*18*). Volume plus occupancy measurements are multiplied by the weighting factor before they enter to timing plan selection processes. For the initial installation of the Eagle system, it is recommended that the volume plus occupancy parameter in each computational channel be weighted equally using a weighting factor of 50.

The user can also indirectly weight data from particular system detectors by deciding whether to use the average of all volume plus occupancy measurements from the detectors assigned to a computational channel or to use just the highest volume plus occupancy measurements of all the detectors assigned to the computational channel. For the initial implementation, it is recommended that volume plus occupancy measurements from the system detectors assigned to each computational channel be averaged.

ESTABLISHING THRESHOLDS

In the Eagle system, timing plans are selected by comparing the processed volume plus occupancy measurements from the designated computational channels to the thresholds entered by the operator. Oscillations between timing plans are controlled by requiring the user to set different thresholds for increasing or decreasing selection parameters (*18*).

A total of seven routines are available for use in selecting a timing plan (*18*); however, only three of the seven selection routines are required to operate the Eagle system in a traffic responsive mode. These three routines include the following:

- the cycle selection routine,
- the offset selection routine, and
- the split plan selection routine.

Using these three routines, a total of 48 different timing plans (i.e., combination of dials, offsets, split plans) can be implemented by the system..

The cycle selection routine is used to determine the appropriate dial in which to operate the system (*18*). A total of seven different Cycle Levels, ranging from 0 to 6, are used in the cycle selection routine. Each Cycle Level corresponds to a specific dial plan. To determine the appropriate Cycle Level, the volume plus occupancy (V+O) parameters from either the *Cycle Select* computational channels (CS1 or CS2) or the *Directionality* computational channels (DR1 and DR2) are compared to established thresholds for each Cycle Level. (The user has to decide which of these computational channels are to be used in determining the cycle level). Two sets of thresholds are required for each Cycle Level: one for increasing Cycle Levels, and another for decreasing Cycle Levels.

Offset plans are selected using the volume plus occupancy measures from the Directionality computational channels (DR1 and DR2) (*18*). Using these computational channels, three offset plans [one favoring inbound traffic (Inbound), one favoring balanced traffic (Average), and one favoring outbound traffic (Outbound)] can be selected. The appropriate offset plans are chosen based on the difference in the volume plus occupancy measurements from the Inbound and Outbound directional parameters (See Step 1) using the following equation:

$$OP = \frac{DR1}{(DR1 + DR2)} \times 100$$

where,

OP = Offset Plan parameter,

$DR1$ = Smoothed volume plus occupancy measurements from the Directionality 1 computational channel, and

$DR2$ = Smoothed volume plus occupancy measurements from the Directionality 2 computational channel.

"Average" flow conditions are defined when flow is balanced (i.e., $DR1 = DR2$). When flow in one direction exceeds the flow in the other direction by the programmed threshold, a preferential offset (an offset plan favoring either the inbound or outbound direction) will be used. The logic that is used in the Eagle master controller is as follows:

- If the offset plan parameter is less or equal to than the "Inbound" threshold, then an offset plan that favors the "Inbound" direction should be implemented.
- If the offset plan parameter is between the "Inbound" threshold and the "Outbound" threshold, then the "Average" offset plan should be implemented.
- If the offset plan parameter is greater than or equal to the "Outbound" threshold, then an offset plan that favors the "Outbound" direction should be implemented.

The user needs to provide appropriate thresholds depending upon whether the offset plan is transitioning from "Inbound" to "Average" to "Outbound" or vice versa. Therefore, a total of four different offset thresholds need to be provided by the user. The Eagle system requires that the thresholds transitioning from "Inbound" to "Outbound" be greater than the thresholds for transitioning in the opposite direction (i.e., from "Outbound" to "Average" to "Inbound").

Split plans are selected in a similar manner as the offset plan, except that flow on the arterial street is compared to flow on the cross street. The equation for determining the split level is as follows (*18*):

$$SPL = \frac{Art}{Art + NonArt} \times 100$$

where,

SPL = Split plan parameter,

Art = Flow parameter representing traffic the arterial street. It is computed by summing the volume plus occupancy parameters from the Cycle Select computational channels (CS1 + CS2) or from the Directionality computational channels (DR1 + DR2), and

NonArt = Flow parameter representing traffic on the cross street(s). It is computed by summing the volume plus occupancy parameters from the Non-Arterial computational channels (NA1 + NA2).

The four split plans are available for use with the Eagle system and have the following designation: Average, Side Street, Arterial, and Heavy Arterial (18). The Average split plan is intended to be called during "normal" travel conditions. If the side street traffic exceeds the main street traffic, then a split plan favoring the side street traffic can be implemented. The two other split plans, Arterial and Heavy Arterial are used to provide preferential treatment to the main street.

In setting up these thresholds, it is recommended that the engineer compute each of the above mentioned timing plan selection parameters for each of the identified control conditions. The parameters can then be plotted as a function of time. Appropriate thresholds can be determined by identifying when the parameters change for a given control condition.

The Eagle system also has the capability of selecting eight timing plans based on volume and occupancy, or occupancy only measurements from four computational channels: Queue One (Q1), Queue Two (Q2), Occupancy One (OC1), and Occupancy Two (OC2) (18). Each routine has programmable thresholds that must be set by the user. If the thresholds are exceeded, then the master controller calls a pre-programmed pattern, overriding the pattern called for by the analysis of the cycle, split, and offset routines. Different special patterns can be selected with each of the special routines. Priority is given to the first routine to reach threshold Level 1. If more than one routine achieves threshold Level 1, Level 2 will override Level 1. When more than one routine achieves the same level simultaneously, the priority level is as follows:

- Occupancy 1 Routine,
- Occupancy 2 Routine,
- Queue 1 Routine, and
- Queue 2 Routine.

If these special timing plan routines are used in a traffic responsive mode, special care must be taken to ensure that the thresholds established for these special timing plans are different than the ones required to implement the timing plans for normal control conditions. Therefore, the user must have *a priori* knowledge of when special timing plans may be required and how the traffic for these special conditions is distributed over the system detectors. With this knowledge,

the user can select the system detectors and establish thresholds that allow these special timing plans to be implemented.