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16. Abstract Most modern traffic signal controllers contain “advanced” features that are often not used but may improve traffic operations under certain conditions. This report documents the research conducted in investigating how diamond interchange operations can be improved by using advanced controller features. The project evaluated the features of traffic signal controllers meeting the current TxDOT traffic signal controller specification. The effectiveness of the advanced features provided by these controllers was evaluated using traffic simulation with real traffic control hardware. Eight potentially useful controller features were identified: (1) separate intersection mode, (2) diamond phasing sequence change by time of day, (3) conditional service, (4) dynamic maximum green times, (5) dynamic split, (6), volume-density control, (7) alternate maximum green and passage times, and (8) adaptive protected-permissive left turns. The research addressed the applicability of these features under different geometric and demand conditions and investigated the effect of detector technology and human factors issues on implementation. Guidelines for improving diamond interchange operations using advanced controller features are included in the report as an Appendix . The Appendix describes the concept of operation of each feature and then provides detailed application guidelines, including applicability under different geometric and demand conditions, as well as compatibility with various detection technologies. Programming instructions are also provided.					
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**RESEARCH REPORT ON IMPROVING
DIAMOND INTERCHANGE OPERATIONS
USING ADVANCED CONTROLLER FEATURES**

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CHAPTER I

INTRODUCTION

Most modern traffic signal controllers contain certain “advanced” features that are often not used but may improve traffic operations at signalized diamond interchanges under certain conditions. The goal of this research project was to improve the state-of-the-practice in diamond interchange control in Texas through providing guidance in the optimal use of existing controller features. In particular, this research project identified useful advanced controller features and determined under which conditions the use of a particular controller feature will improve diamond interchange operations.

The researchers investigated the feature sets of the two controllers that meet the Texas Department of Transportation (TxDOT) traffic signal controller specification (1) in the latter half of 2001: Eagle Traffic Control Systems’ EPAC300 (2) and Naztec Incorporated’s Model 980 controller with Version 50 software (3). These controllers are shown in Figure 1 and Figure 2, respectively. Although many of the features addressed in this research technically exceed the TxDOT specification, these features are available in controllers currently being deployed and thus can be used to improve diamond interchange operations.

Chapter II of this report outlines the research methodology used. Chapter III lists and describes the advanced controller features that have the potential of improving diamond interchange operations. Chapter IV describes the geometric, demand, and other conditions that affect the successful implementation of the features described in Chapter III. Chapter V describes the evaluation of some of the controller features at a number of interchanges in Texas. Chapter VI contains recommendations for improving traffic operations at signalized diamond interchanges by using advanced controller features. Finally, the Appendix contains guidelines for improving traffic operations at signalized diamond interchanges by using advanced controller features.



Figure 1. Eagle EPAC300 Controller.



Figure 2. Naztec 980 Controller.

CHAPTER II

RESEARCH METHODOLOGY

The hypothesis of this research project was that “advanced” controller features have the potential to improve traffic operations at signalized diamond interchanges under certain conditions, if applied correctly. Therefore, the objective of this research project was twofold: (i) to determine under which conditions the use of a particular controller feature will improve diamond interchange operations, and (ii) to ensure that the feature is implemented correctly to achieve the desired effect. To achieve the first objective, it was necessary to:

- identify and understand the available controller features;
- determine which features are applicable to diamond interchange control;
- evaluate the applicable features under a variety of geometric and demand conditions; and
- distill the evaluation results into easy-to-use guidelines.

The second objective was needed to ensure the successful implementation of the research findings. To achieve the second objective, guideline documentation was developed which included:

- description of the useful controller features from an implementation viewpoint;
- implementation guidelines to identify which features are applicable under which conditions; and
- detailed programming instructions.

RESEARCH TASKS

The research objectives were achieved by performing a number of research tasks. Each of these tasks is described in more detail below.

Task 1: Identifying and understanding the available controller features

This task included a study of the TxDOT traffic signal controller specification and the Eagle EPAC300 and Naztec Model 980 controller manuals. In addition, the Naztec Cross-Platform NTCIP Based Controller Simulator was used (4). The purpose was to identify and distinguish between the controller features required by the TxDOT specification and the vendor-specific features exceeding the specification. Candidate controller features were evaluated on real Eagle and Naztec traffic signal controllers provided by TxDOT Bryan District to ensure that they operate as understood from the documentation.

The evaluation was conducted in the TransLink[®] Research Center Laboratory, a state-of-the-art facility at the Texas Transportation Institute that is designed and equipped for advanced research into traffic signal control equipment. The laboratory includes, among others, traffic signal controllers from multiple vendors, a variety of controller assemblies (cabinets), traditional and next-generation controller testing equipment, and the TransLink Hardware-in-the-Loop Traffic Simulation System (5). [Figure 3](#) shows a researcher using the TransLink Hardware-in-the-Loop Traffic Simulation System to evaluate a controller feature on the Eagle controller. [Task 3](#) describes hardware-in-the-loop traffic simulation in more detail.



Figure 3. Controller Feature Evaluation Using the TransLink Hardware-in-the-Loop Traffic Simulation System.

The computer screen in front of the researcher in [Figure 3](#) shows the computerized testing application that was used to send detector calls and other control signals to the controller and view the current controller phasing and other status information. [Figure 4](#) shows the application in more detail.

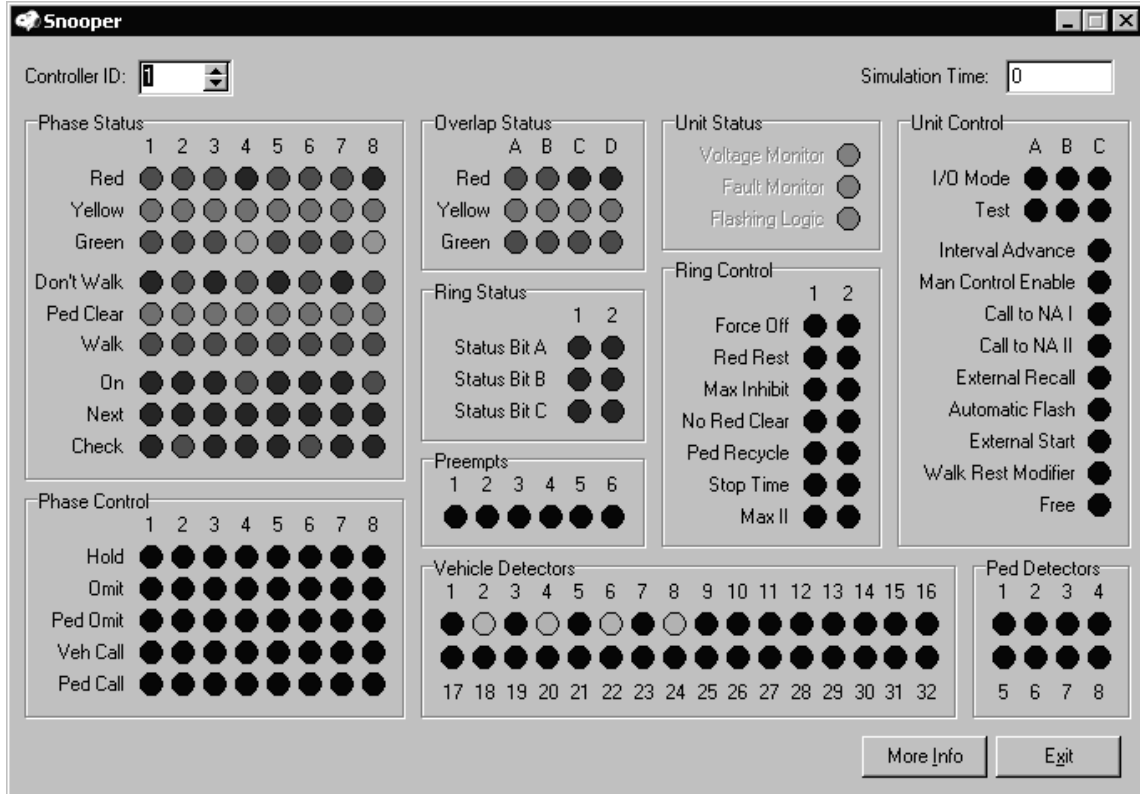


Figure 4. Testing Application Used for Controller Feature Evaluation.

The application screen contains simulated lights and buttons that allow the user to interact with the controller, similar to a NEMA TS 1 testing suitcase. The lights and buttons are arranged in groups. The phase status, overlap status, ring status, and unit status groups of lights display the current phase, overlap, ring, and unit status, respectively. The phase control, ring control, and unit control button groups allow the user to send control signals to the controller. Examples of control signals include phase holds, phase omits, and ring force offs. The screen also contains button groups that represent vehicle detectors, pedestrian detectors, and preempt inputs. These buttons can be activated to send vehicle and pedestrian detector actuations and preempt requests to the controller. This testing application proved invaluable in evaluating controller features in a precise and efficient manner.

Task 2: Determining which features are applicable to diamond operations

Not all the controller features identified in [Task 1](#) are applicable to diamond interchange control under all geometric and demand conditions. The purpose of Task 2 was to determine which features are compatible with the diamond control mode, and to consider the general geometric and demand conditions that may affect the successful implementation of these features. The project team considered the following geometric scenarios:

- variable ramp-terminal spacing;
- presence or absence of U-turn lanes;
- dual and shared arterial left-turn lanes; and
- detector technology and placement (inductive loops, VIVDS).

In addition, the following demand scenarios were considered:

- highly variable demand conditions due to incident rerouting or nearby schools, theaters, or plants with shift changes;
- heavy U-turn demand;
- unbalanced frontage road demand;
- high truck-traffic demand;
- oversaturated conditions;
- low-volume (e.g. night time) conditions; and
- low-volume left-turn movements onto the freeway.

The evaluation was based on previous theoretical and empirical analyses (6, 7, 8), documented experience from traffic engineers (9), and new analyses performed specifically for this research project.

Task 3: Evaluating the applicable features under a variety of geometric and demand conditions

Once candidate controller features were identified, the operational effects of those features were evaluated under a variety of geometric and demand conditions using hardware-in-the-loop traffic simulation. Hardware-in-the-loop traffic simulation is a relatively new technology where a microscopic traffic simulation model is connected to one or more real traffic signal controllers that interact with the simulation model. The connection is established through a controller interface device (CID). The simulation model operates in real time and simulates the movement of vehicles over detectors. The resulting detector actuations are then sent to the signal controller(s) through the CID. The controller reacts to the detector inputs in the same way as if controlling a real interchange, by changing signal phases as needed. The phase status is then returned from the controller to the simulation model, where the simulated vehicles react to the phase indications by stopping or going as appropriate. Figure 5 shows the flow of data between the simulation model and the traffic signal controller, while Figure 6 shows a typical hardware-in-the-loop simulation setup used for evaluating controller features.

The CORSIM simulation model was used for this research project (10). The traffic signal controller emulation provided by CORSIM does not implement the diamond interchange control specified by the TxDOT traffic signal controller specification. Using the TransLink Hardware-in-the-Loop Traffic Simulation System allowed the internal CORSIM signal control logic to be replaced with the actual controller hardware on which the features to be tested were implemented.

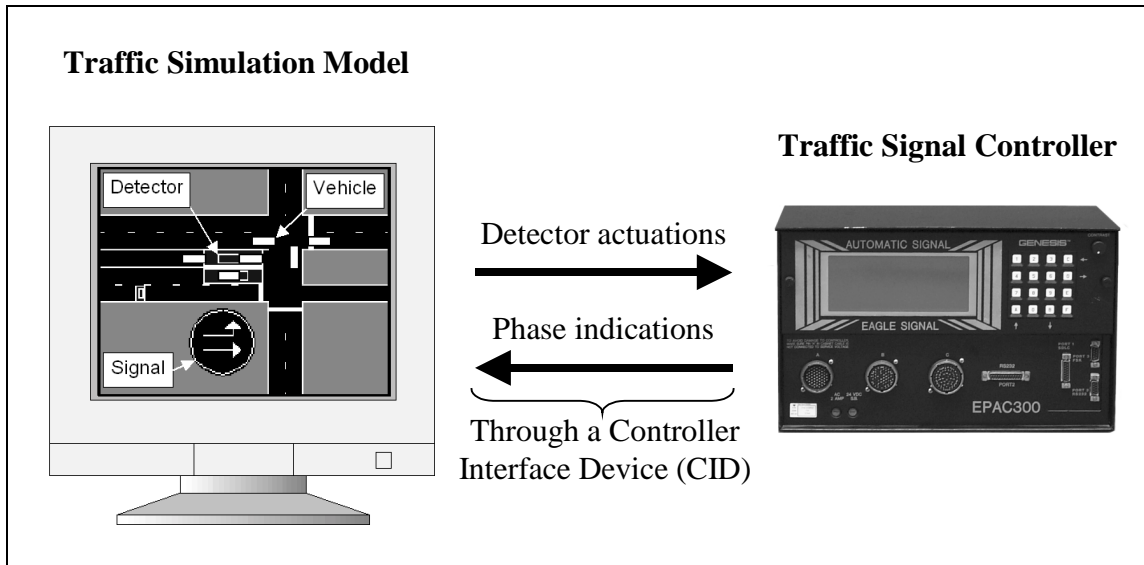


Figure 5. Flow of Data Between the Simulation Model and the Traffic-Actuated Signal Controller.

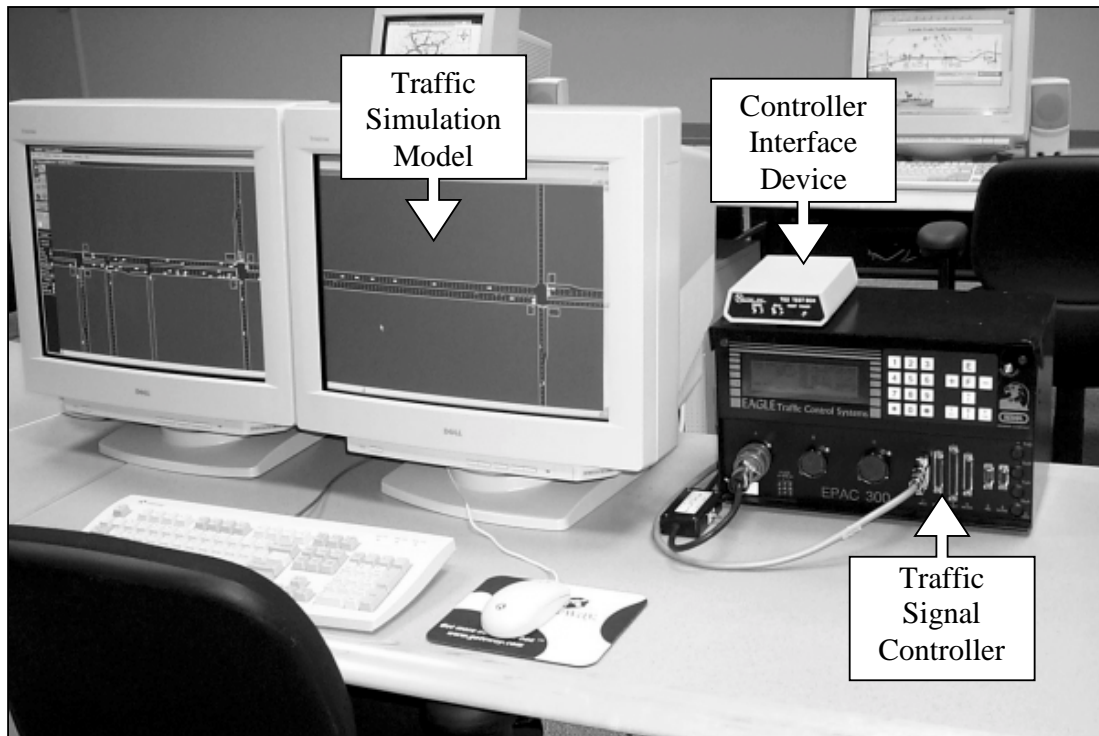


Figure 6. Typical Hardware-in-the-Loop Simulation Setup.

As a result, the researchers could use the extensive measures of effectiveness reported by the simulation model together with the reproducibility of simulated results to very efficiently evaluate the operational effects of a particular controller feature. For a specific combination of geometry and demand, the same simulation could be run with and without the controller feature under consideration. Since the simulation model could reproduce vehicle demand exactly, it was possible to isolate the effect of the control feature from normal day-to-day variations in traffic demand, which is impossible to do in a field evaluation where the variation in traffic volumes cannot be controlled.

Researchers evaluated applicable controller features under generic but representative interchange geometry and demand conditions. Interchange geometry was selected to be representative of the diamond interchange geometries currently in use in Texas. The resulting geometric scenarios were combined with different demand scenarios to form the operating conditions under which the controller features were evaluated. To reduce the number of evaluations, researchers evaluated features only under conditions where they were deemed potentially beneficial, as determined in [Task 2](#).

Task 4: Collect geometric, demand, and control data at trial interchanges

In addition to the evaluation under generic geometry and demand conditions in [Task 3](#), researchers evaluated the candidate controller features at actual interchanges in Texas. The evaluation was based on real geometric, demand, and control data collected at three interchanges:

- the Briarcrest Drive interchange on Texas 6 in Bryan, Texas;
- the Bagby Avenue interchange on Texas 6 in Waco, Texas; and
- the Del Mar Boulevard interchange on I.H. 35 in Laredo, Texas.

Researchers obtained geometric data from as-built drawings and site measurements. Traffic demand data in the form of turning movement counts were obtained from a video camera survey performed by the researchers or from recent turning movement counts conducted by TxDOT or their consultants. The traffic signal controller plans were also obtained to allow them to be used in the real control hardware during the evaluation in [Task 5](#).

Task 5: Evaluate the applicable features at the trial interchanges

In this task, applicable controller features were evaluated at the actual interchanges where data was collected in [Task 4](#). The evaluation was conducted with hardware-in-the-loop simulation using CORSIM, but the geometry and demand of the actual interchanges were used in the simulation. In addition, the actual traffic signal controller settings were used in the real controller controlling the simulation. First, simulations were conducted to determine the baseline operation before the implementation of advanced features. Then, after the implementation of one or more features in the controller, another set of simulations was conducted with exactly the same traffic demand as before. The effect of the feature(s) could then be quantified by comparing the measures of effectiveness produced by the simulation before and after the implementation of

the feature(s). The statistical significance of any changes was determined with a “paired t” test (11). Task 5 served as a verification of the results obtained in Task 3 and provided the opportunity to refine the results previously obtained.

Task 6: Implement useful features at the trial interchanges

During the hardware-in-the-loop simulation evaluation of the operations at the three actual interchanges, researchers identified controller features that improved the operation at some of the interchanges. TxDOT personnel were notified of these possible improvements, and details were provided on how to implement the changes in the controller. TxDOT was responsible for the actual implementation, with support from the project research team.

Task 7: Prepare guidelines for use of available traffic controller features

An important factor limiting the implementation of advanced controller features is the absence of good implementation guidelines. For this reason, guidelines were prepared in Task 7 to assist traffic engineers and technicians in selecting and implementing the controller features that can improve diamond interchange traffic operations under specific geometric and demand conditions. For each feature, the guidelines contain a description of the concept of operation as well as the following implementation guidance:

- a discussion on the applicability of the feature under different geometric, demand, and other conditions;
- a section on the compatibility of the feature with specific controllers, detection technologies, and coordination modes; and
- detailed instructions for programming the feature into the Eagle and Naztec controllers.

The guidelines are included in this report as [Appendix A](#).

Task 8: Prepare a research report

In this task the researchers prepared this research report that documents the research conducted in this project, describes findings, and makes recommendations for implementation of the findings.

Task 9: Develop a project summary report

A project summary report was prepared in the final task (12). The project summary report summarizes the research, describes the findings, and provides implementation recommendations.

CHAPTER III

ADVANCED CONTROLLER FEATURES

At the time the research was completed (mid 2001) only two controllers met the TxDOT traffic signal controller specification: the EPAC300 controller from Eagle Traffic Control Systems and the Model 980 controller with Version 50 software from Naztec Incorporated. However, not all of the advanced diamond interchange traffic control features are available on both the Eagle and Naztec controllers, since the different vendors provide different feature sets. At the same time, not all of the potentially useful features are compatible with all detection technologies, geometric layouts, and traffic demand conditions.

Through Tasks 1, 2, 3, and 5 the research identified the following controller features that are compatible with the diamond operational mode and can potentially improve diamond interchange operations:

- separate intersection mode,
- diamond phasing sequence change by time of day,
- conditional service,
- dynamic maximum green times,
- dynamic split,
- volume-density control,
- alternate maximum green and passage times, and
- adaptive protected-permissive left turns.

These features are described in the following sections. [Figure 7](#) indicates the phase numbering scheme that will be used throughout the descriptions.

SEPARATE INTERSECTION MODE

The TxDOT controller specification defines three diamond interchange control modes: (i) four-phase mode, (ii) three-phase mode, and (iii) separate intersection mode. The four-phase and three-phase modes are well known and often used in field deployments. The separate intersection mode, on the other hand, is less well known, not used as often, and is the topic of this description. The phase sequence and ring structure of the four-phase, three-phase, and separate intersection modes are shown in [Figure 8](#), [Figure 9](#), and [Figure 10](#), respectively.

The phase sequences are simplified in that they do not include phases 3 and 7 and their related clearance and phases defined in the TxDOT specification. The phase sequences resulting from skipped phases are also not shown. The Eagle and Naztec user manuals show the full phase sequences.

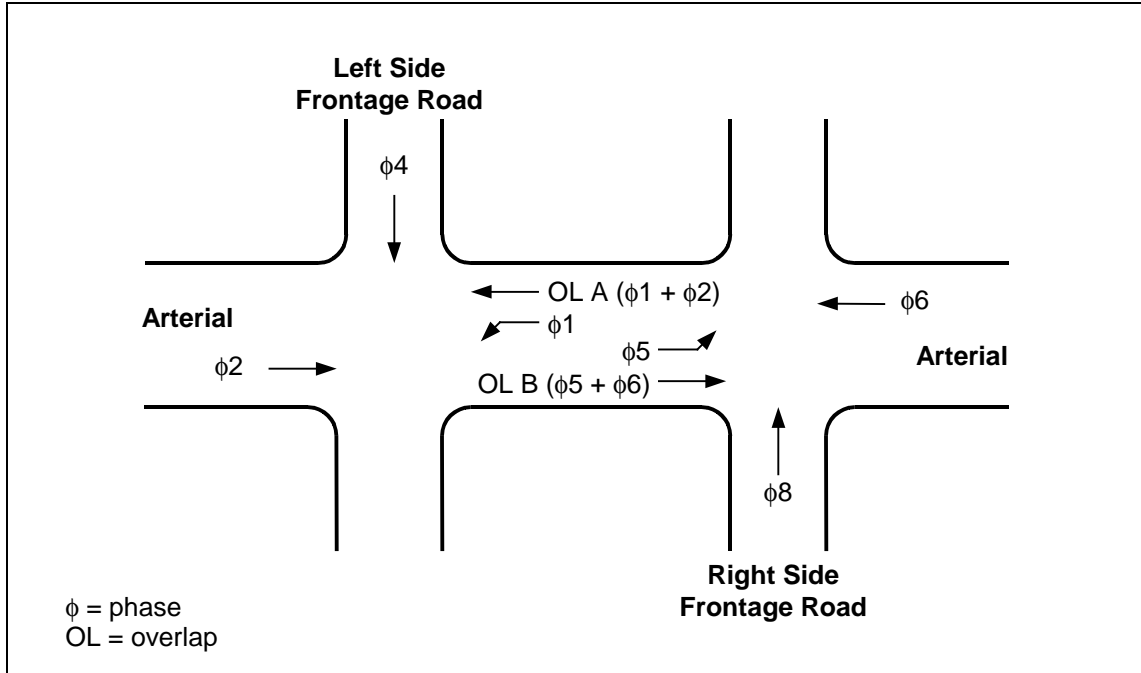


Figure 7. Signal Phase Numbering Scheme for Diamond Interchanges.

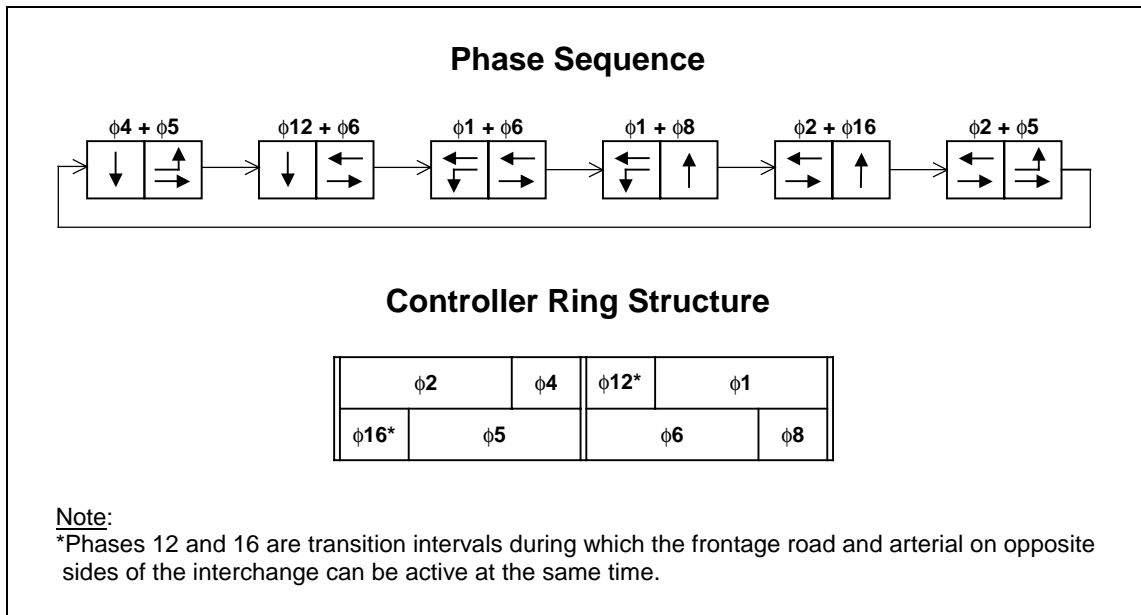


Figure 8. Simplified Four-Phase Diamond Interchange Phasing.

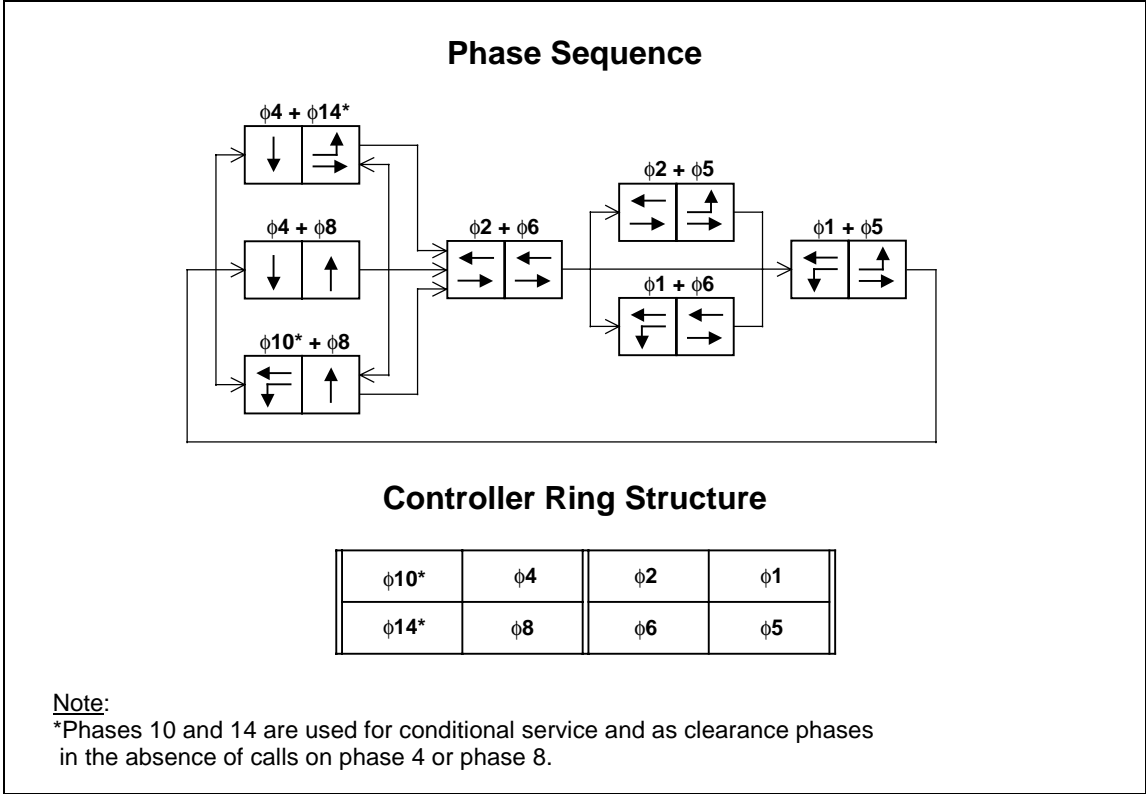


Figure 9. Simplified Three-Phase Diamond Interchange Phasing.

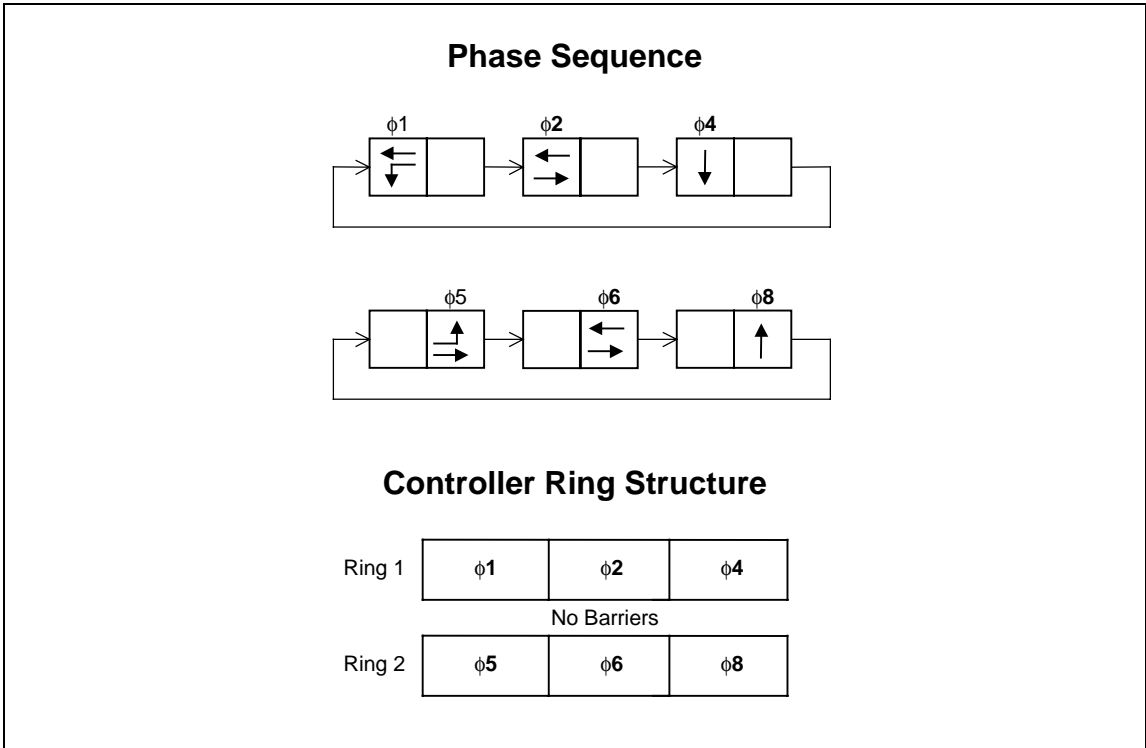


Figure 10. Simplified Separate Intersection Diamond Interchange Phasing.

In the separate intersection mode, interior left turns (phases 1 and 5) lead the external arterial through movements (phases 2 and 6). One ring controls each side of the diamond interchange, and no barriers exist between rings. Under free (noncoordinated) control, the two rings operate independently of each other, and there is no internal offset to provide progression through the interior of the interchange. If progression through the interchange is required, the controller can be run in coordinated mode. The controller does not need to be coordinated with any other controllers; coordination is only used to provide the structure required to create a fixed relationship (offset) between the rings. The separate intersection diamond control mode is valuable under both free and coordinated mode.

Free Separate Intersection Mode

The free separate intersection mode is very effective in handling low-volume conditions. For example, this mode can be used to control an interchange during the late night and early morning hours when traffic volumes are low. Under low-volume conditions the progression provided by four-phase or three-phase control is typically not needed, since traffic streams consist of single vehicles rather than platoons of vehicles. If permissive internal left-turn movements are allowed, detector switching can be used to switch detector actuations from the internal left-turn phase (phase 1 or 5) to the opposing arterial phase (phase 2 or 6) to avoid unnecessary activation of the internal left-turn phases. The internal left-turn phases can also be omitted by time-of-day control if there is no doubt that the permissive left-turn movements would have sufficient capacity for the time the left-turn phases are omitted. If recalls are placed on the arterial phases (2 and 6) and the left turns are treated as described above, the controller will only leave the arterial phases to service frontage road demands. The free separate intersection mode is efficient in serving low frontage road demand in the absence of high arterial demand for two reasons:

1. The controller does not need to wait for the current phase at other side of the interchange to terminate before a frontage road phase can be serviced.
2. When the controller changes to the frontage road requiring service, the arterial phase on the other side of the interchange remains green. This operation is in contrast to the three-phase mode, where the other side of the interchange changes to the internal left-turn phase (phase 10 or 14) when only one frontage road has a call, even if there is no interior left-turn demand on the other side of the interchange.

Coordinated Separate Intersection Mode

Under low-flow conditions it may be acceptable to operate without any guaranteed progression through the interchange, but for higher volumes it is desirable to provide progression. The lack of progression in the separate intersection diamond mode can be addressed by running the controller in coordination. The internal offset is established between the coordinated phases in each ring. The Eagle EPAC300 controller provides a useful “ring-lag” feature that can be used to specify the offset between the coordinated phases, as shown in the top part of [Figure 11](#). The Naztec series 980 controller with the current Version 50 software does not provide a “ring-lag” feature, so the offset between the coordinated phases on the current version

of the Naztec controller and software will always be zero, as shown in the bottom part of [Figure 11](#).

By running the separate intersection diamond mode in coordination with the appropriate ring lag, it is possible to implement nonstandard diamond phasing schemes in the diamond control mode. These nonstandard phasing schemes may be appropriate under nonstandard geometric or demand conditions. The PASSER III (13), Synchro (14), and TRANSYT-7F (15) traffic signal optimization models can be used to generate such nonstandard diamond phasing schemes. For example, the PASSER III lead-lead phasing sequence lends itself well to implementation with the coordinated separate intersection diamond mode with ring lag.

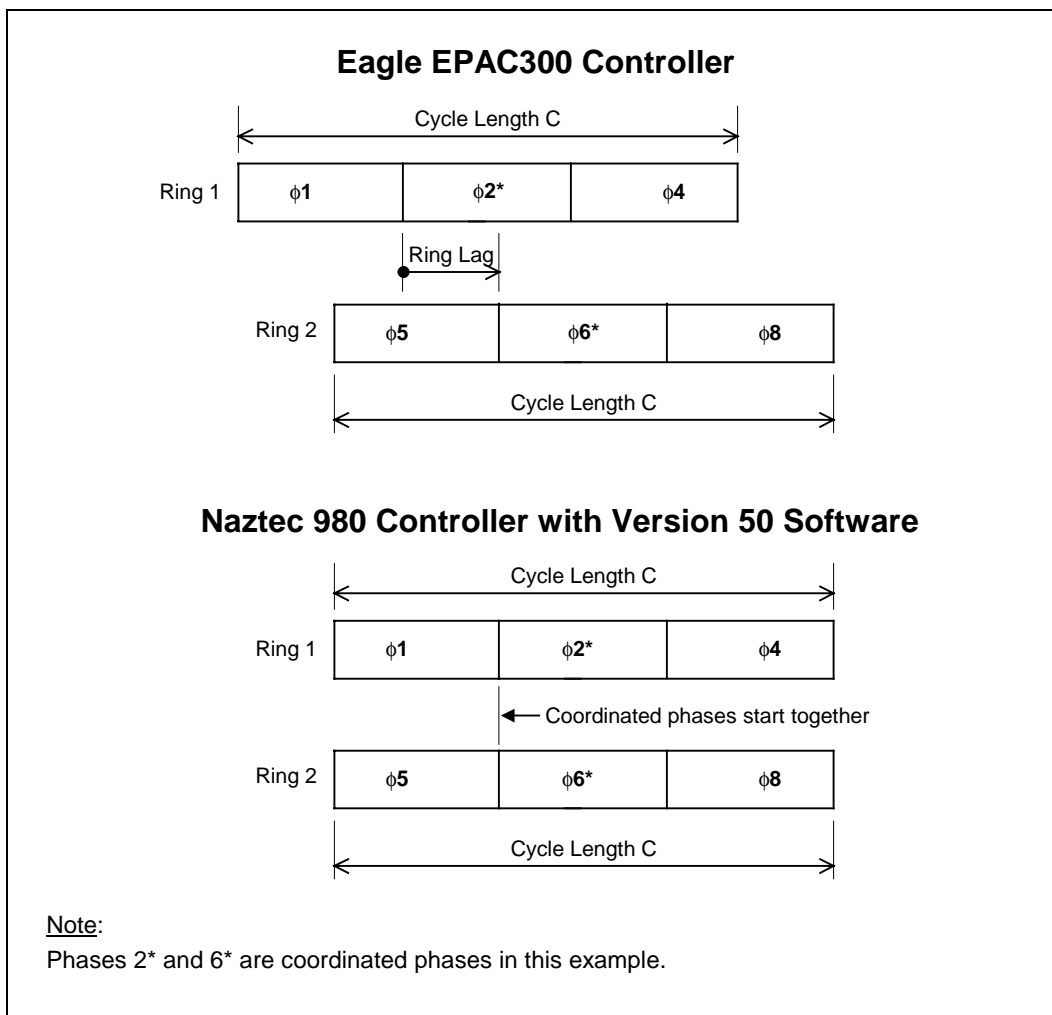


Figure 11. Coordinated Separate Intersection Mode Diamond Interchange Phasing.

Any phase in a ring can be selected as the coordinated phase, but selection of the coordinated phase must take into account the fact that all “unused” green time in the ring typically reverts to the coordinated phase. This operation may result in “early return” problems under coordination, where the upstream signal returns early to the coordinated phase and discharges vehicles that will be stopped at the downstream signal if it did not also return early to the coordinated phase.

DIAMOND CONTROL SEQUENCE CHANGE BY TIME OF DAY

Both the Eagle and Naztec controllers provide the capability of changing the diamond control sequence by time-of-day control. This is a convenient feature, since traffic demand changes during the day and different diamond phasing schemes may be optimal at different times of the day. For example, peak period traffic may perform optimally under coordinated four-phase operation, off-peak day and evening traffic may perform optimally under free (noncoordinated) three-phase operation, and late-night traffic may perform optimally under the free separate intersection mode.

If periods of similar traffic demand can be identified, the controller can be programmed to change to the most appropriate diamond control sequence at the start of each period. Typically, practitioners use turning movement counts to identify periods of similar traffic demand, and then use a PASSER III or Synchro analysis to determine the optimal diamond control sequence for each period.

Timely changes in the diamond control sequence have the potential to optimize traffic flow through the interchange by providing the best possible diamond phasing type for any particular demand condition.

CONDITIONAL SERVICE IN THREE-PHASE SEQUENCE

Conditional service is an alternative method of phase selection that allows the controller to activate phases outside their place in the ring structure. According to the National Electrical Manufacturers Association (NEMA) TS 2-1992 standard, if two concurrent phases are timing and a call exists on the other side of the barrier while one of the phases is prepared to terminate (due to gap out or max out), conditional service allows the ring containing the terminating phase to revert to the preceding phase in that ring, provided that the following four conditions are met (16):

1. A call exists on the preceding phase.
2. The terminating phase is programmed for conditional service.
3. There is sufficient time available before the maximum time of the phase in the other ring elapses.
4. The controller is not running in coordinated mode. (This requirement is relaxed by the Naztec controller, since it supports conditional service under coordination.)

The criterion for determining if sufficient time remains to conditionally service the preceding phase is that the terminating vehicle phase clearance times plus the minimum green time of the conditionally serviced phase must be less than the time remaining on the max timer of the non terminating phase. This requirement is shown graphically in [Figure 12](#).

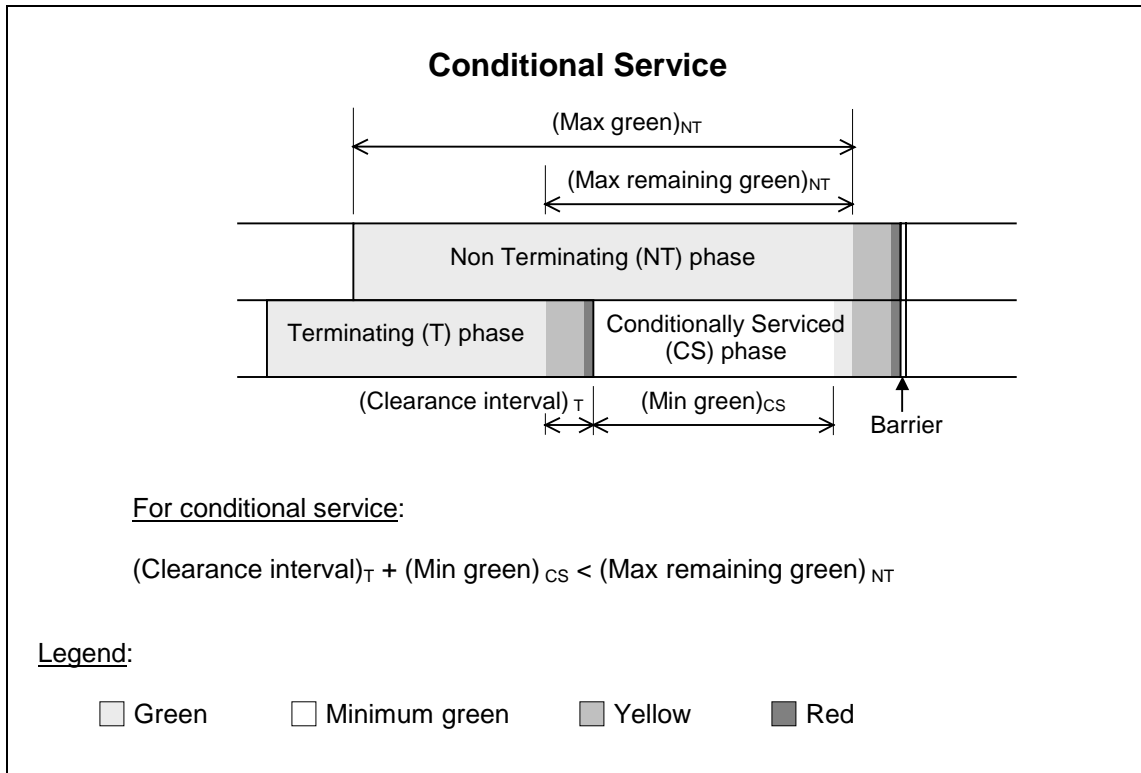


Figure 12. Criteria for Conditional Service.

Conditional service is available on both the Eagle and Naztec controllers. Under the NEMA definition of conditional service, the barrier will not be crossed until the minimum green time of the conditionally serviced phase has expired and the non terminating phase has gapped or reached its maximum time. The effect is that the conditionally serviced phase will operate as a nonactuated phase, since it does not have the capability of extending or terminating on its own. The Eagle controller implements this approach. On the Naztec controller, however, the conditionally serviced phase is actuated, and the barrier will only be crossed when both the conditionally serviced and the non terminating phases have gapped or maxed out.

Conditional service is only compatible with the three-phase diamond control sequence. In the three-phase mode, the frontage road phases (phases 4 and 8) can be programmed for conditional service. The ring structure of the three-phase control mode (see [Figure 9](#)) allows phases 4 and 8 to conditionally service special internal left-turn phases (phases 10 and 14). The interior through movement is serviced at the same time through an overlap with the interior left-turn phase. Conditional service allows the three-phase control mode to adapt to unequal frontage road demand, since the frontage road with less demand can gap out and conditionally service the

internal left-turn and through movement while the other frontage road is still being serviced, as shown in Figure 13.

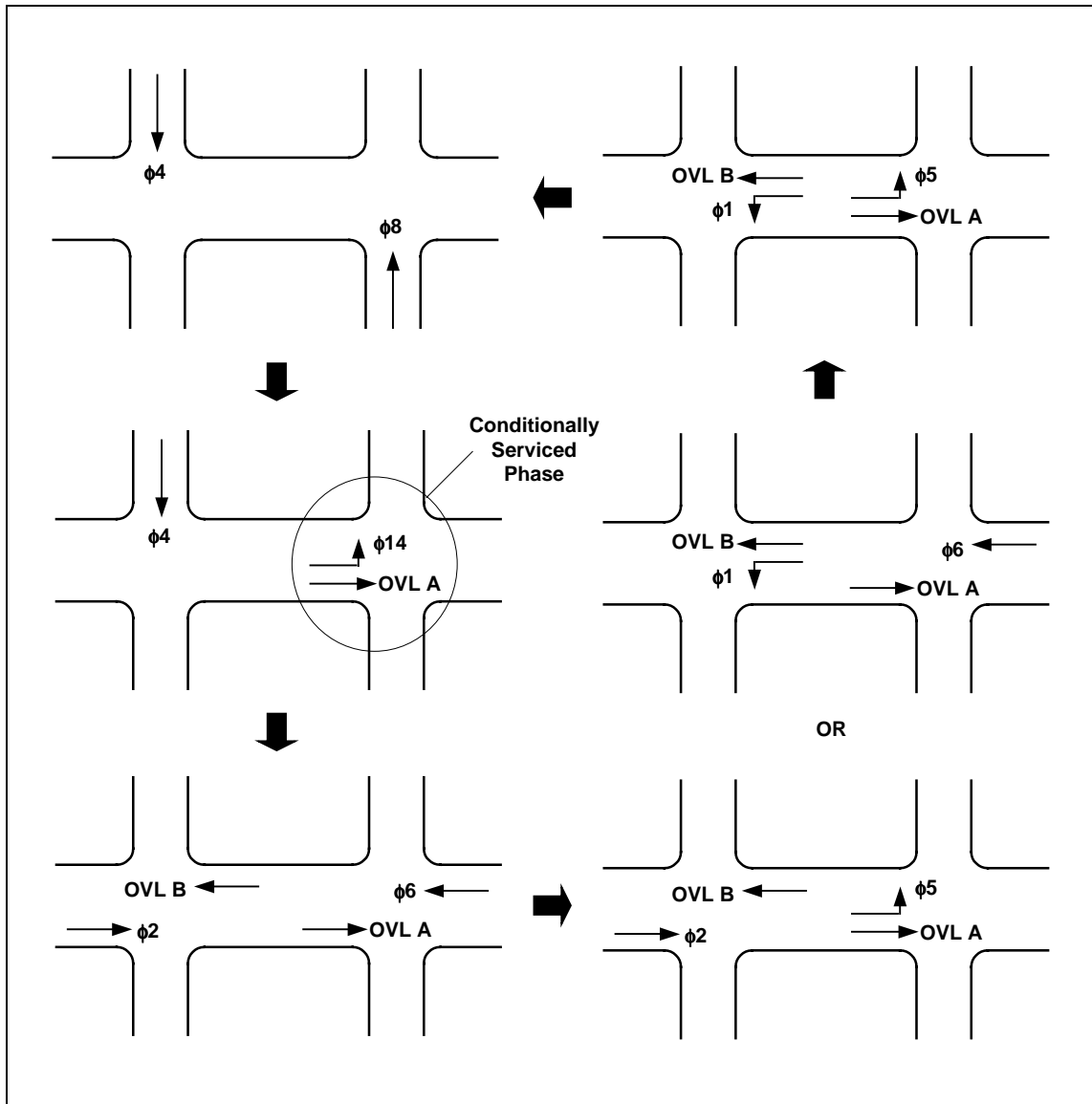


Figure 13. Effect of Conditional Service on Three-Phase Diamond Control.

The effects of conditional service on the three-phase diamond control sequence are as follows:

1. early gap out or max out of one of the frontage road phases (phase 4 or 8);
2. an out-of-sequence (leading as opposed to the usual lagging) service of the internal left-turn movement (phase 10 or 14); and

3. the early start of the interior through movement, since it overlaps with the internal left-turn phase.

DYNAMIC MAXIMUM GREEN TIMES

The NEMA TS 3.5-1996 standard for actuated signal controllers defines “dynamic max” as an alternative mode of phase termination (17). Under dynamic max operation the maximum green time is variable and is controlled by the following parameters:

1. the normal phase maximum (Max 1 or Max 2), which serves as an upper or lower bound for the dynamic maximum green time;
2. the “dynamic max limit,” which serves as the other bound for the dynamic maximum green time. If this value is larger than the normal maximum, it becomes the upper limit, and if it is lower than the normal maximum, it becomes the lower limit; and
3. the “dynamic max step,” which specifies how the dynamic maximum green time varies between the normal phase maximum (Max 1 or Max 2) and the dynamic max limit.

Under dynamic max control the maximum green time of a phase can vary and the current maximum green time is referred to as the “running max.” The running max starts with the normal phase maximum (Max 1 or Max 2). When a phase maxes out twice in a row and on each successive max out thereafter, one dynamic max step value is added to the running max until such an addition would mean that the running max is greater than the larger of the normal maximum green time or the dynamic max limit. When a phase gaps out twice in a row and on each successive gap out thereafter, one dynamic max step value is subtracted from the running max until such subtraction would mean that the running max becomes less than the smaller of the normal maximum green time or the dynamic max limit. If a phase gaps out in one cycle and maxes out in the next cycle, or vice versa, the running max will not change (17).

Figure 14 shows an example of dynamic max operation. The graph shows the running max green times and actual green times for a phase through 13 cycles. In this example the normal maximum is Max 1 with a value of 25 seconds. The dynamic max limit is set to 40 seconds with a dynamic max step of 5 seconds. Cycle 1 starts with a running max equal to Max 1 (25 seconds). In cycle 1 the phase gaps out, so no change is made to the running max. The phase maxes out in both cycles 2 and 3, so the running max is increased by 5 seconds (the dynamic max step) to 30 seconds for cycle 4. In cycle 4 the phase gaps out, so no change is made to the running max. Cycles 5 and 6 see the phase max out twice, so the running max is increased to 35 seconds in cycle 7. The phase also maxes out in cycle 7, so the running max for cycle 8 is increased to 40 seconds, which is the maximum value based on the dynamic max limit. In both cycles 8 and 9, the phase gaps out so the running max for cycle 10 is decreased to 35 seconds. Each successive cycle gaps out, so the running max is decreased by 5 seconds each cycle until it reaches the minimum of 25 seconds (Max 1) in cycle 12.

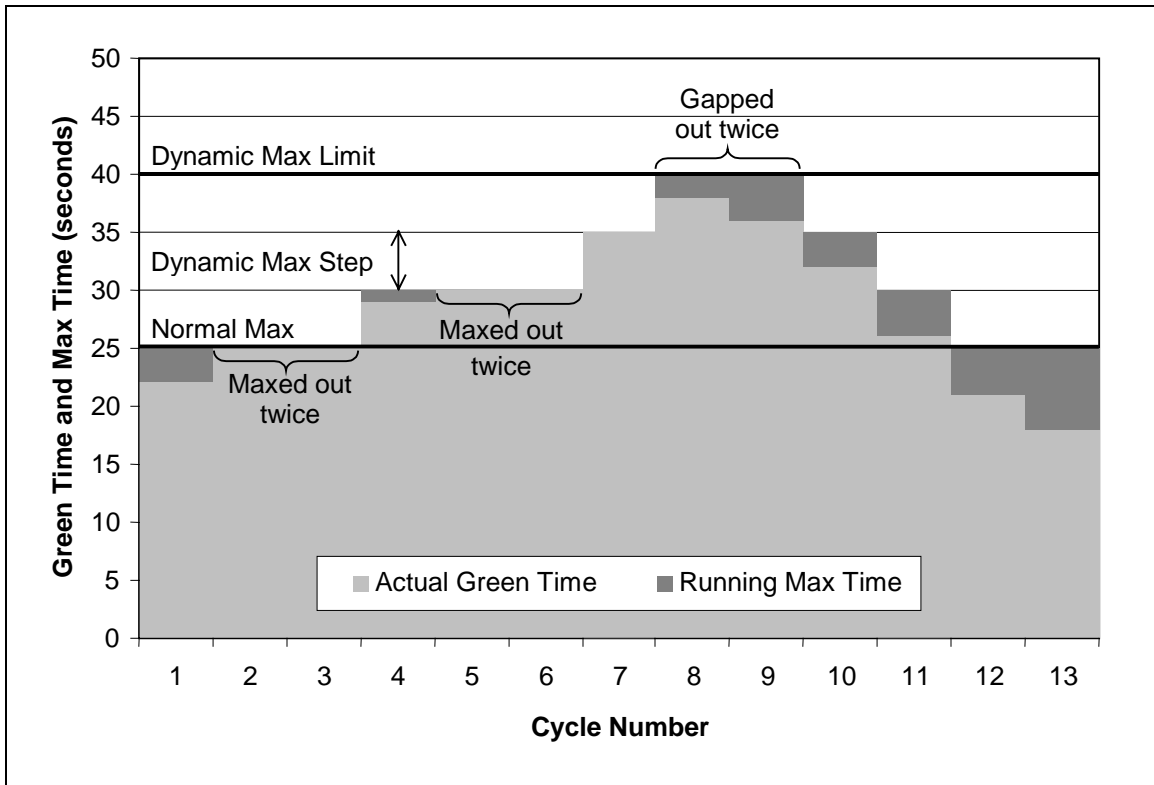


Figure 14. Example of Dynamic Maximum Operation.

The dynamic maximum feature has the ability to adapt to unexpected increases in demand that could be the result of special events or rerouting due to incidents. One potential use of the dynamic maximum feature would be to use it on the frontage road phases to be more responsive to unexpected increases in frontage road demand due to rerouting as a result of freeway incidents.

DYNAMIC SPLIT

The dynamic split feature does for coordinated control what the dynamic maximum green time feature (described above) does for actuated control. The Eagle controller implements dynamic splits through the Coordination Adaptive Splits (CAS) feature, which is compatible with the diamond control mode. The Critical Intersection Control (CIC) feature of the Naztec controller also provides dynamic split but is not compatible with the diamond control mode and will consequently not be described further.

According to the Eagle controller manual the goal of the CAS feature is to dynamically find and use the most advantageous split possible (2). This is done for all noncoordinated phases, since the coordinated phases are not adjusted. Adaptive split is achieved by monitoring the termination of each noncoordinated phase to determine whether the phase gapped out or was

forced off. CAS monitors the time usage of each phase under coordination. If, for two consecutive cycles, a phase is forced off by coordination while not already in the yellow or red clearance interval, the phase becomes a candidate for an additional increment of split. Conversely, if, for two consecutive cycles, a phase becomes ready to terminate with more than 1 second of time left on its coordination timer, the phase becomes a candidate for giving up an increment of split. Split time is taken away from the phases marked as candidates for giving up split and added to the phases marked as candidates for increasing split. Split times are typically changed in 1 second increments. If a phase gaps out in one cycle and is forced off in the next, the adaptive split will not change. Time is never subtracted from a phase split except to give to another phase, so the cycle length stays the same.

Figure 15 shows an example of the operation of the dynamic split feature. It shows only the first ring (phases 1, 2, and 4) of a controller in coordinated separate intersection mode. The cycle length is 120 seconds with an initial 20:60:40 split between phases 1, 2, and 4. Phase 2 is the coordinated phase. Phases 1 and 4 have a minimum green time of 5 seconds and 5 seconds of clearance time, for a minimum phase time of 10 seconds. Phase 1 only requires the minimum phase time, but phase 4 has a significant demand (perhaps due to a freeway incident) that requires more than the default 40/120 split. The controller operates in the permitted mode (so that all unused time goes to the start of the coordinated phase) with plan force offs (so that the phase is forced off a fixed time after it becomes active).

Initially, phase 4 has a 40 second split and phase 1 uses 10 seconds of the available 20 seconds, so that phase 2 starts 10 seconds early. In the third cycle, after phase 4 was forced off twice and phase 1 gapped out twice, the splits of phases 4 and 1 are increased and decreased by 1 second. Phase 4 now has a 41 second split, phase 1 uses 10 seconds of the available 19 seconds, and phase 2 starts 9 seconds early. The reallocation of splits continues until cycle 12, when the split of phase 1 has been reduced to the minimum phase time of 10 seconds, and the split of phase 4 has increased to 50 seconds. Since phase 1 runs to the new split time of 10 seconds, phase 2 does not start early any more and has a duration of 60 seconds.

The adaptive split feature is useful in redistributing time between the noncoordinated phases based on the actual demand. It is also useful for reclaiming some of the “unused” time in that cycle that normally goes back to the coordinated phase. The coordination mode and force mode play an important role in how the adaptive split feature operates, since it controls how and when phases are forced off. It should be kept in mind, however, that a maximum recall on any phase (placed as a default, by time of day, or as the result of a failed detector) will disable the adaptive split feature.

VOLUME-DENSITY CONTROL

Volume-density control has been part of the NEMA actuated traffic signal controller standard since the NEMA TS 1 standard of 1989 (18). Volume-density control provides two features: (i) variable initial timing and (ii) gap reduction timing. Each of these features is described separately below.

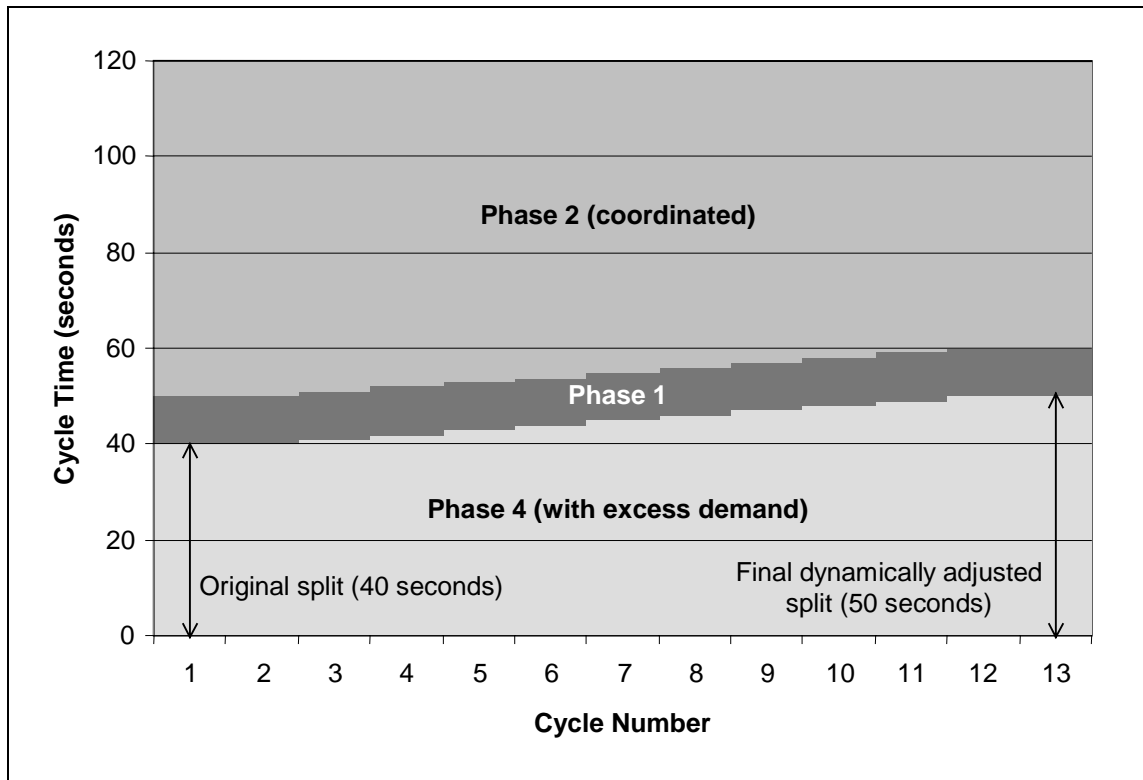


Figure 15. Example of Dynamic Split Operation.

Variable Initial Timing

Under variable initial timing the duration of the initial portion of the green (the first timed portion of the green interval) can increase dependent on the number of vehicle actuations stored on the phase while its signal is displaying yellow or red (16). The variable initial timing period operates like a “variable minimum green” and is determined by the following three parameters:

1. minimum green time, which determines the minimum variable initial time period;
2. seconds per actuation, which determines the time by which the variable initial time will be increased (starting from zero) with each vehicle actuation received during the yellow and red intervals of the phase; and
3. maximum initial, which is the maximum of the variable initial timing period.

Figure 16 shows the effect of these parameters on the variable initial timing period. The figure shows how the initial timing starts with the minimum green time. Once the number of vehicle actuations multiplied by the seconds per actuation becomes larger than the minimum green time, the initial timing takes on the former value, until it reaches the maximum initial value which acts as an upper limit.

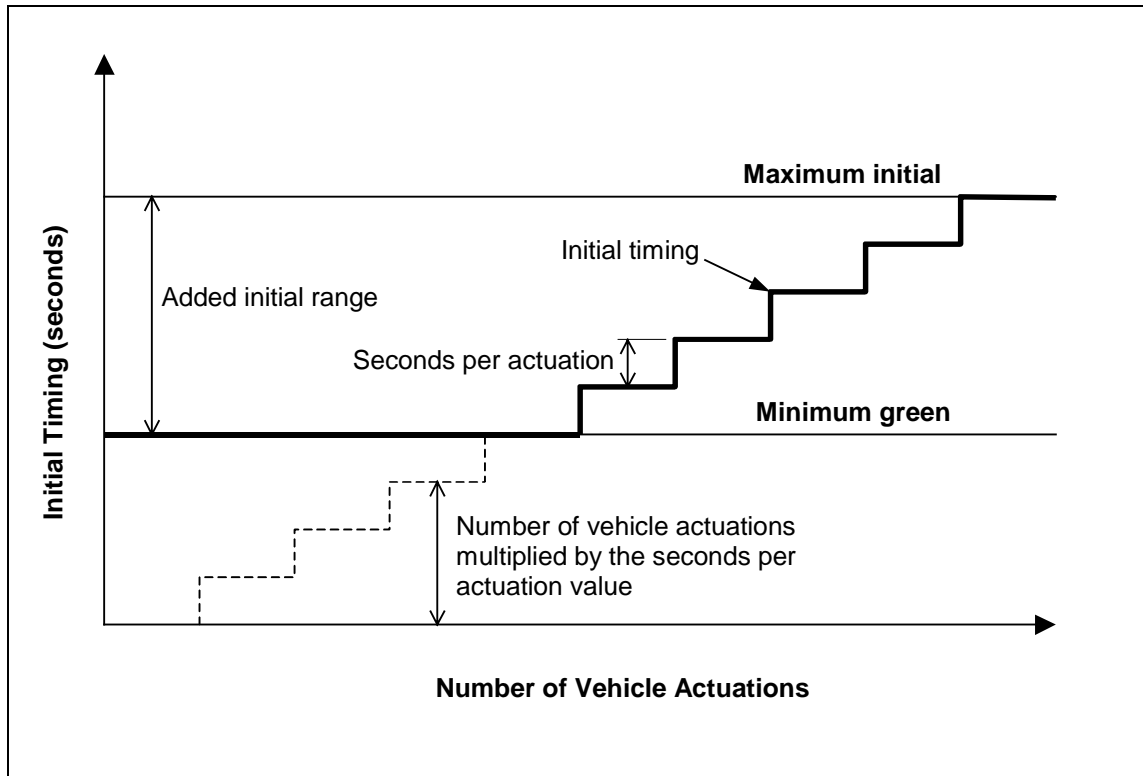


Figure 16. Variable Initial Timing.

Variable initial timing is most effectively used when setback detectors are provided without any stop-bar detection, so that the initial timing can be incremented to the appropriate value required to service vehicles that queue between the stop line and the setback detector. Variable initial timing is compatible with the diamond control mode, and can be useful in the four-phase control mode, where setback detectors are often used. Variable initial timing requires point detection to operate, so it may not be appropriate to use with the zone detection provided by video detection.

Gap Reduction Timing

Gap reduction timing is typically used with setback detectors on high-speed approaches and is used to control the size of the allowable gap. With setback detectors, the time allowed for a vehicle to pass from the detector to the intersection, the passage time, is usually longer than the gap that would normally be required to retain the right of way (19). The gap reduction feature compensates for this difference by reducing the allowable gap from the passage time to a minimum allowable gap that equals the required gap for right-of-way retention. Gap reduction is available in both the Eagle and Naztec controllers and is affected by the following five parameters:

1. passage time, the initial value of the allowable gap;
2. minimum gap, the minimum value of the allowable gap;

3. time before reduction, the amount of time that must expire before gap reduction can start, measured from when there is a serviceable conflicting call. If the conflicting call occurs while the phase is red, the time before reduction starts at the beginning of green. If the conflicting call is removed, this timer is reset;
4. cars before reduction, the number of vehicle actuations that must occur before gap reduction can start; and
5. time to reduce, which begins timing after the time before reduction and during which the allowable gap is reduced from the passage time to the minimum gap.

Figure 17 shows the relationship between these parameters and the allowable gap.

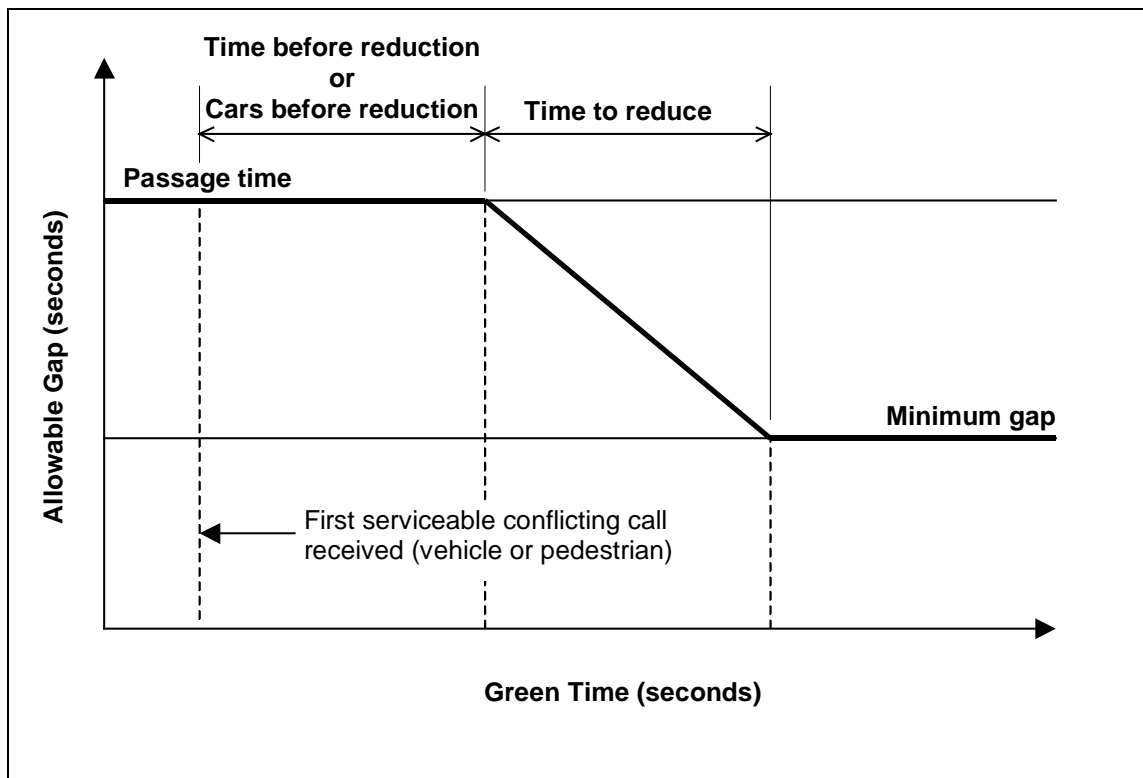


Figure 17. Gap Reduction.

Typically, the last vehicle to maintain the allowable gap should receive the full passage time to clear the intersection. However, during the period between the expiration of the allowable gap and expiration of the passage time, the phase operates as nonactuated. Any vehicle crossing the detector during this period would not be guaranteed the full passage time and may potentially be exposed to the dilemma zone.

ALTERNATE MAXIMUM GREEN AND PASSAGE TIMES

“Rule-of-thumb” guidelines state that the maximum phase green times should be set as low as possible, but still high enough to serve queues approximately 1.3 times the average queue length (in vehicles) for the peak volume during the period the maximum green will be in effect (19). Alternatively, the maximum green time can be set equal to the optimal fixed-time green time, as determined by traffic signal optimization software such as PASSER III or Synchro, provided that the volume-to-capacity ratio is not greater than 0.85 (20).

Since traffic volumes (and hence queue lengths) vary through the day, traffic signal control efficiency can be improved by using different maximum green values throughout the day to reduce the amount of time that the signal controller operates with nonoptimal maximum green times. The NEMA TS 2-1992 standard requires that a traffic signal controller provide two maximum green time values (16). In the Eagle and Naztec controllers these two maximum green times (Max 1 and Max 2) are selected either by time-of-day control or by external input. Even though the use of two maximum green times are better than the use of only one maximum green time, two maximum green times are not enough to accurately “track” the optimal maximum green time as it typically varies through the day, as Figure 18 illustrates.

The Eagle EPAC300 controller addresses this shortcoming by providing up to three additional maximum green times (Max 3, Max 4, and Max 5), as well as three additional passage times that can be selected by special function or by time-of-day setting. The additional passage times can be used to provide more “snappy” operation at certain times of the day (perhaps under high traffic volumes), while the additional maximum green times can be used to more closely “track” the optimal maximum green times, as shown in Figure 19.

The Naztec 980 controller provides an “Alternate Programs” feature that can be used to change the maximum green times and passage times on a time-of-day basis. In addition, other phase-related settings such as minimum green times can also be set by time of day by using the Alternate Programs feature of the Naztec controller.

Even though the use of the alternate maximum green feature has the potential to improve traffic operations, it may be challenging to implement successfully. Proper implementation requires knowledge of traffic demand variation through the day, as well as the ability to determine when alternate maximum green times should be in effect and the appropriate value of those maximum green times.

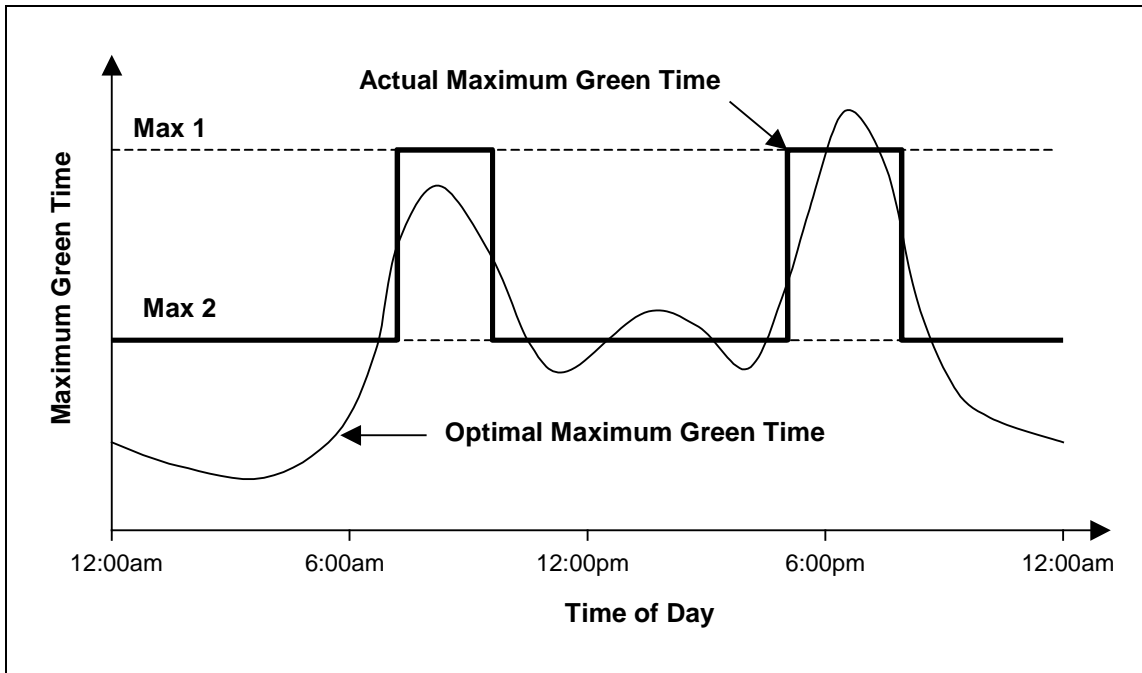


Figure 18. Actual and Optimal Maximum Green Times with Max 1 and Max 2.

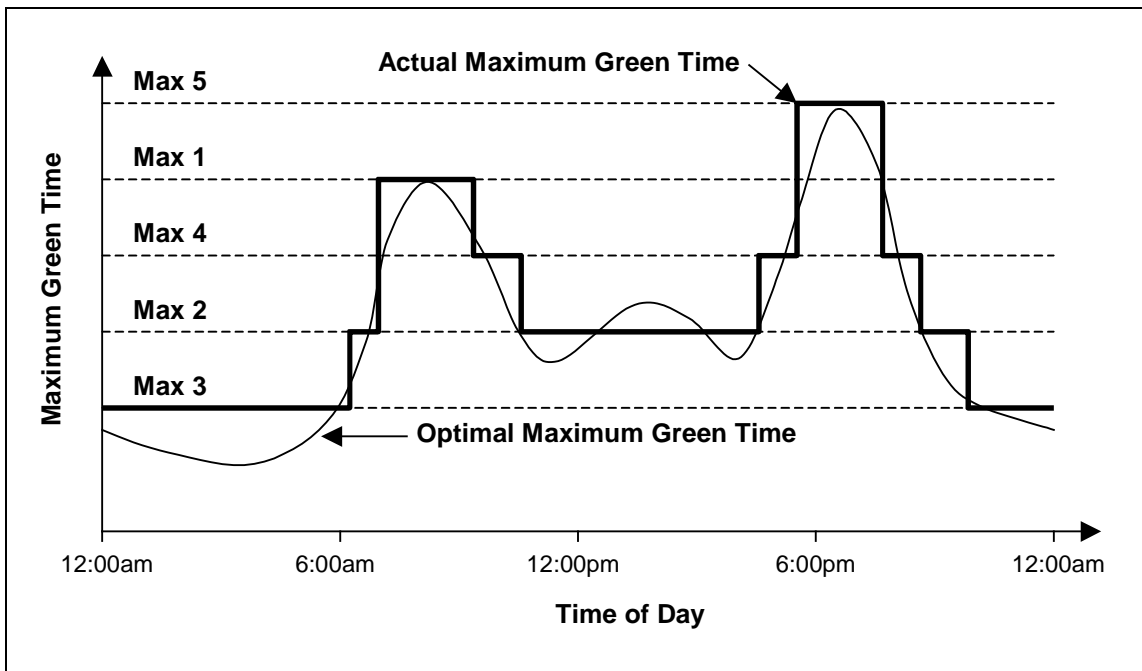


Figure 19. Actual and Optimal Maximum Green Times with Alternate Max Greens.

The dynamic maximum feature described previously also has the ability to “track” the optimal maximum green times and can, therefore, automatically select a reasonably optimal maximum green time for any demand, as long as it lies between the normal max and the dynamic max limit. This approach requires less data and is easier to maintain, since it automatically adapts to long-term changes in time-dependent traffic demand. The disadvantage of the dynamic maximum feature is that it results in frequent max outs, since the feature tries to minimize the maximum green time and only increases the maximum green time when the phase maxes out twice in succession. These frequent max outs may be problematic, since the controller operates as nonactuated when maxing out and will terminate the green regardless of any traffic approaching, potentially leaving approaching vehicles in the dilemma zone.

ADAPTIVE PROTECTED-PERMISSIVE LEFT TURNS

The Eagle EPAC300 controller provides a useful feature called Adaptive Protected-Permissive operation. This feature measures the volume of left-turn traffic and the number of available gaps in the opposing through vehicle traffic to determine whether the left turn should operate as protected or permissive (2). Permissive operation is achieved by omitting the left-turn phase. The user sets the following variables to control the operation of the Adaptive Protected-Permissive feature:

- Minimum Turn Volume (MTV). If the left-turn volume is less than this value, the left-turn phase will be omitted and left-turn operation will be permissive.
- Minimum Vehicle Gap (MVG). Gaps measured in the opposing through movement detector calls have to be greater than this value to act as a “through gap window” that can accommodate a permissive left-turn vehicle. Larger gaps can accommodate multiple gap windows.
- Gap Percentage (GP). This variable represents the percentage of gap windows that left-turn vehicles utilize.
- Maximum Constant Call (MCC). If there has been a constant turn detector call for more than this time, the omit on the left-turn phase will be lifted and left-turn operation will be protected.

The measured left-turn volume and number of through gap windows during green are smoothed over a period of 5 minutes to yield the Smoothed Turn Volume (STV) and Smoothed Gap Windows (SGV) variables.

Permissive operation is provided when

$$STV < MTV \tag{1}$$

or

$$SGV \times (GP \div 100) > STV \tag{2}$$

Protected operation is provided when there has been a constant left-turn detector call longer than the Maximum Constant Call.

The Minimum Vehicle Gap and Gap Percentage values need to be set taking into account the lane and detector layout on the approach opposing the left-turn movement. With multiple detectors per lane (for example where multiple-detector dilemma zone protection is provided), it may be difficult to determine appropriate MVG and GP settings to assure proper operation.

Adaptive Protected-Permissive operation can only be used on the internal left-turn movements (phases 1 and 5) in the separate intersection control mode, since left-turn movements cannot be omitted in the three-phase and four-phase control modes.

Adaptive Protected-Permissive operation should only be used at locations suitable for protected-permissive left-turn operation. In addition, the detection layout must be able to provide accurate traffic counting and gap measurement, and for this reason, video detection may not be an appropriate detection technology to use with this feature.

Note that use of Adaptive Protected-Permissive operation does create inconsistencies in the left-turn control provided in the interior of a diamond interchange. The effects of these inconsistencies on driver expectation must be thoroughly analyzed at each candidate site before such features are implemented. And, as permissive turns are allowed in certain situations, adequate sight distance must be present so that left-turning motorists can judge whether or not an adequate gap exists in the opposing traffic stream to accommodate their left-turn maneuver.

CHAPTER IV

FACTORS AFFECTING IMPLEMENTATION

A number of factors affect the successful implementation of any of the controller features described in the previous [chapter](#). These factors can be divided into five different categories:

1. traffic demand,
2. geometry,
3. controller technology,
4. detection technology and layout, and
5. human factors.

Each of these categories is described in detail in the sections below. The guidelines prepared as part of this research project contain more specific implementation guidance and can be found in [Appendix A](#) of this report.

TRAFFIC DEMAND

Traffic demand is a very important factor that affects the successful implementation of many of the advanced features identified in this research project.

Operators should use the free separate intersection where traffic volumes are low enough to be essentially random, since progression through the interchange is typically not expected under these conditions. The research identified “rule-of-thumb” guidelines can be used to identify the traffic demand conditions under which the noncoordinated (free) separate intersection mode will be applicable. The guidelines are based on the assumption that random, non-platooned traffic conditions occur when:

- on the frontage roads, two or fewer vehicles are typically served at one time by a frontage road phase in separate intersection mode; and
- on the arterial, three or fewer arterial vehicles are typically stopped while the frontage road is being served in separate intersection mode.

A Monte-Carlo simulation was conducted in a Microsoft[®] Excel spreadsheet to translate these conditions into equivalent traffic volumes, assuming the following representative traffic controller settings (21):

- 12 seconds of minimum green on the arterial phase;
- 7 seconds of minimum green on the frontage road phase;
- 3 seconds passage time on the arterial and frontage road phases; and
- a total of 5 seconds of yellow change and red clearance time on the arterial and frontage road phases.

The Monte-Carlo simulation determined, as a function of the arterial and frontage road traffic volumes, (i) the proportion of phases during which three or fewer vehicles are stopped on the arterial while the frontage road phase is active and (ii) the proportion of phases during which two or fewer vehicles are served by the frontage road phase. [Figure 20](#) and [Figure 21](#) show the results of the analysis.

[Figure 20](#) shows the proportion of phases with three or fewer arterial vehicles stopped as a function of the two-way arterial traffic volume. The 95th percentile value in the graph corresponds to an arterial traffic volume of approximately 300 vehicles an hour. Therefore, at volumes of less than 300 arterial vehicles an hour, three or fewer arterial vehicles will typically be stopped while moderate frontage road volumes are being served in the free separate intersection mode. [Figure 21](#) shows the proportion of phases with two or fewer frontage road vehicles serviced per phase as a function of the two-way arterial traffic volume and the frontage road volume. The 95th percentile value in the graph is largely independent of the arterial volume and corresponds to a frontage road volume of approximately 125 vehicles an hour when the arterial demand is less than 300 vehicles an hour. Therefore, at less than 300 arterial vehicles an hour and less than 125 frontage road vehicles per hour, two or fewer frontage road vehicles per phase will typically be served in the free separate intersection mode.

Traffic demand also dictates how the diamond control sequence can be changed by time-of-day control. Diamond sequence changes are typically made to match the traffic signal control to the prevailing traffic conditions to achieve the best operation. The decision on when to change the diamond control sequence should depend, amongst others, on how traffic characteristics change throughout the day, in both demand and directional distribution ([19](#)). Typically, turning movement counts are needed to determine how traffic demand changes throughout the day. These traffic demands can then be analyzed using a software tool such as PASSER III to determine the optimal control mode at different times during the day.

The successful application of conditional service depends strongly on traffic demand, specifically on how frontage road traffic demand translates to green time demand for the frontage road phases. The use of conditional service depends on a threshold time equal to the sum of the change interval of the terminating (low demand) frontage road phase and the green time of the conditionally serviced interior left-turn phase. The operator should not use conditional service when the average green time demand on the two frontage roads differs by less than the threshold time. When the green time demand on the two frontage roads differs by more than the threshold time, conditional service should only be used when more vehicles are served by the conditionally serviced left-turn phase than would have been served by the terminating (lower demand) frontage road phase, had it not terminated. These requirements ensure that conditional service reduces the average queue length at the interchange, which will reduce total delay and improve traffic operations.

The dynamic maximum green time feature is most useful under unexpected or highly variable traffic demand conditions. One potential application of this feature would be to use it on the frontage road phases to be more responsive to unexpected increases in frontage road demand due to rerouting as a result of freeway incidents. The dynamic split feature operates on the same principle as dynamic maximum green times by dynamically adjusting the split under coordination in response to an imbalance of demand on the noncoordinated phases.

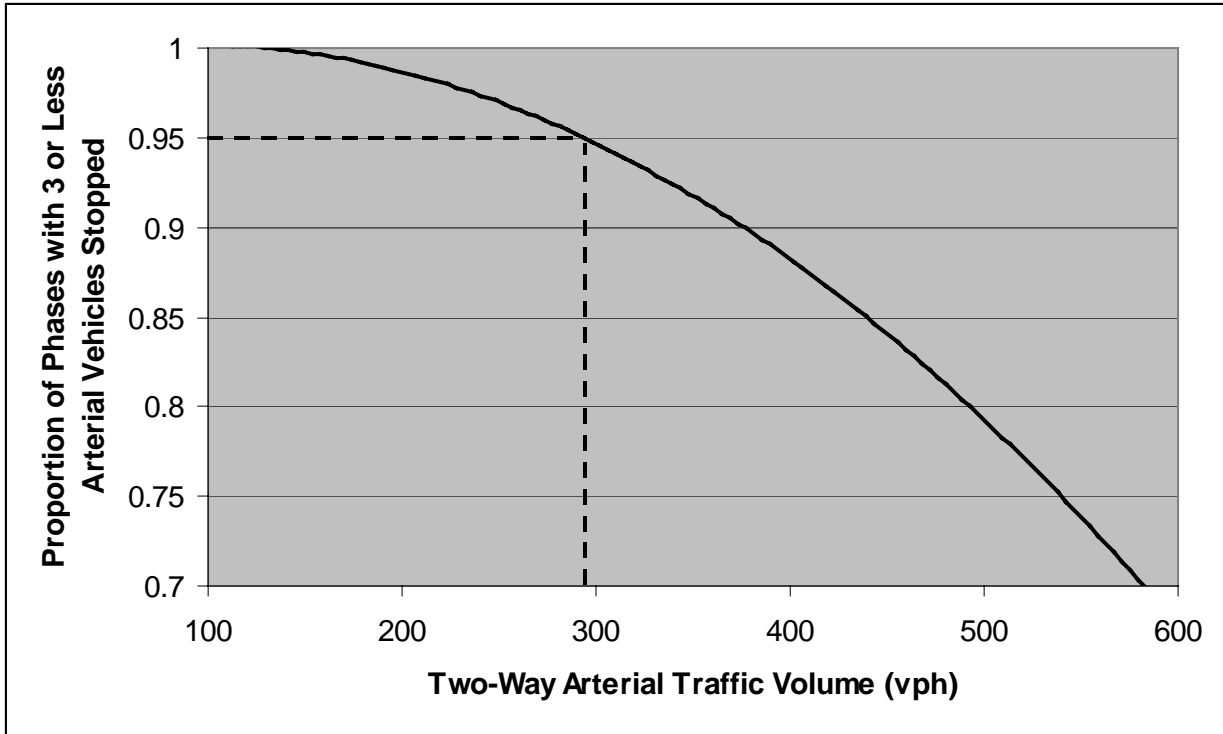


Figure 20. Arterial Stops as a Function of Arterial Traffic Volume.

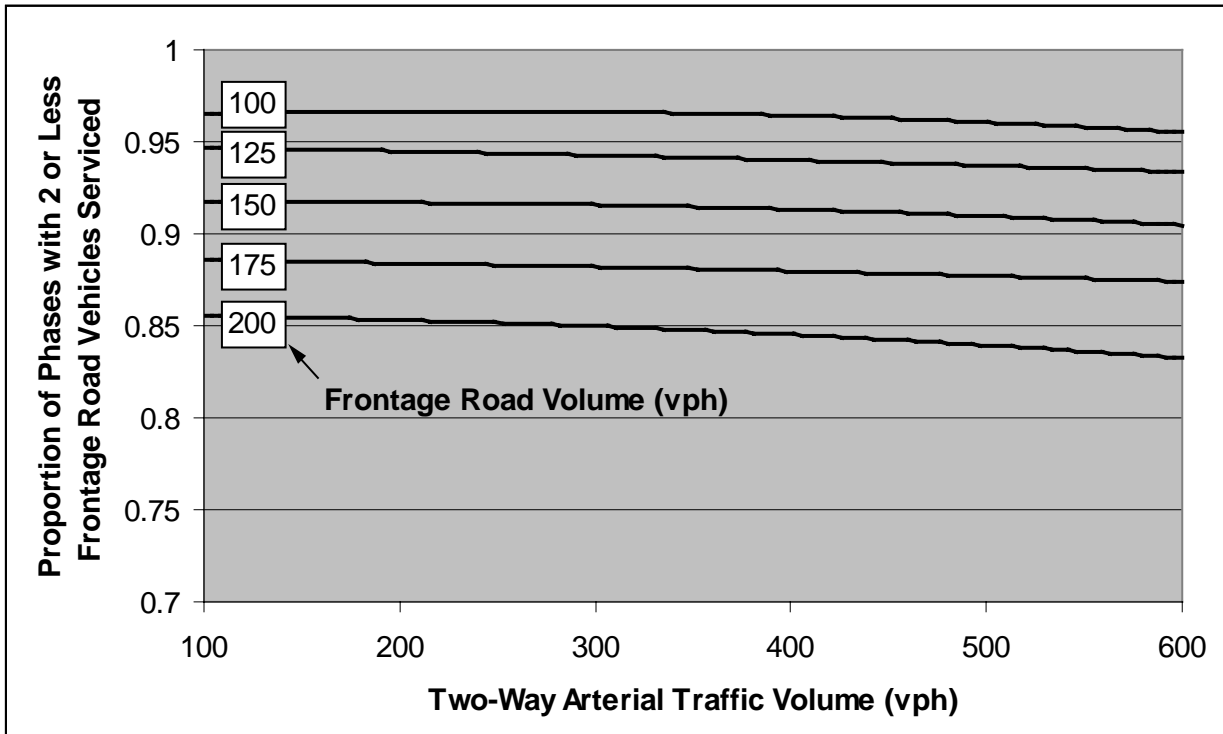


Figure 21. Frontage Road Stops as a Function of Arterial and Frontage Road Traffic Volume.

The gap reduction feature of volume-density control is typically intended for isolated operations and depends on free traffic flow and should therefore not be used where oversaturated conditions are expected (19).

Alternate maximum green and passage times can be used to manually adapt the actuated traffic control settings to changing traffic flows through the day. Alternate maximum green times can be used to provide the most appropriate maximum green time for a period of relatively constant traffic flow. There is usually no need to change passage times by time of day. An exception would be during high-demand periods, where the passage times may be reduced to provide “snappier” operation at the interchange.

GEOMETRY

Interchange geometry plays an important role in the successful implementation of many of the advanced features identified in this research project. Specifically, the interaction of geometry and traffic demand should be considered since it can lead to undesirable operations such as queue spillback and sluggish operation due to unequal lane utilization.

Interchange geometry typically determines if the diamond control sequence can be changed by time-of-day control. For example, the three-phase diamond control is typically not used at narrow interchanges where the internal travel time is less than the frontage road phase duration. If this is the case, the first left-turning vehicle in the frontage road queue will reach the downstream intersection while the other frontage road phase is still active, since both frontage road phases (phases 4 and 8, see Figure 7) are serviced simultaneously in the three-phase sequence. Left-turning frontage road traffic will, therefore, have to stop at the downstream intersection, which can create the interlocked condition shown in Figure 22.

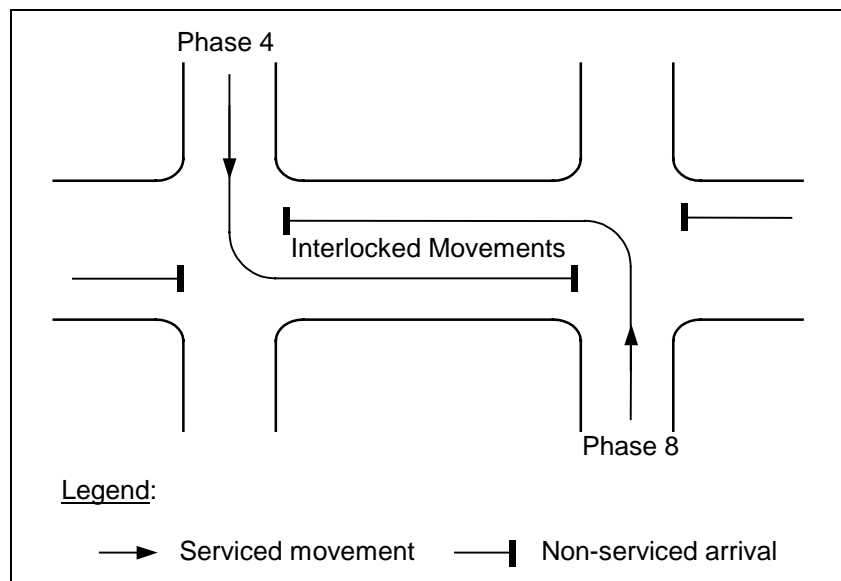


Figure 22. Interlock with Three-Phase Operation at Narrow Diamond Interchanges.

In the free separate intersection mode, interior left-turn movements should operate under protected and permissive phasing to minimize the number of arterial traffic stops. Interchange geometry, in particular lane layout, controls whether permissive interior left-turn phasing can be used. Permissive interior left-turn phasing is typically not used where the interior left-turn lanes are shared with through movements, as is the case at some older narrow diamond interchanges. Geometric conditions where more than two opposing through lanes have to be crossed by the left-turn movement, where dual interior left-turn lanes are provided, or where insufficient sight distance exists will also typically require protected-only interior left-turn phasing.

CONTROLLER TECHNOLOGY

Not all control features discussed in [Chapter III](#) are available on both the Eagle and Naztec controllers. Therefore, the available controller technology can restrict the implementation of a particular feature. [Table 1](#) shows which features are available on which controllers in which control modes; however, since both the Eagle and Naztec controllers conform to the NEMA TS 1 and TS 2 standards it is possible to interchange controllers from the two manufacturers to provide a required controller feature for implementation.

Table 1. Compatibility of Features with Eagle and Naztec Controllers.

Feature	Compatible with Eagle?	Compatible with Naztec?
Separate intersection mode	Yes	Yes (coordinated only with zero ring lag)
Diamond phasing sequence change by time of day	Yes	Yes
Conditional service	Yes (three-phase free operation only)	Yes (three-phase control only)
Dynamic maximum green times	Yes	Yes (not on phases 1 and 5 in four-phase mode)
Dynamic split	Yes	No
Volume-density control	Yes	Yes
Alternate maximum green and passage times	Yes	Yes
Adaptive protected-permissive left turns	Yes (only in separate intersection mode)	No

DETECTION TECHNOLOGY AND LAYOUT

Detection technology and layout affects the applicability of the controller features described in [Chapter III](#). Video detection is very suitable for zone detection, but may not be sufficiently accurate to serve as input to controller features that rely on the accurate point detection of vehicles, such as volume-density control and adaptive protected-permissive left turns. Potential shortcomings of video detection include irregular gap measurement and occlusion of vehicles by other larger vehicles.

[Figure 23](#) illustrates the issue of irregular gap measurement. Because of the camera angle and resulting parallax error, vehicle lengths observed by the video detection system are longer than actual vehicle lengths by a factor that varies with the height of the rear of the vehicle traversing the detection zone. Therefore, the measured gap between vehicles is always less than the actual gap and the difference depends on the height of the rear of the leading vehicle. Since the heights of vehicles in the traffic stream vary randomly, measured gaps will vary randomly and controller functions that rely on accurate vehicle gap measurement—such as the adaptive protected-permissive left-turn feature that uses measured gap sizes to determine left-turn capacity—may not operate correctly.

[Figure 24](#) shows the related problem of vehicle occlusion. As shown, it is possible for a larger vehicle to obscure a smaller vehicle following behind it, resulting in the smaller vehicle not actuating the video detector. This occlusion may lead to problems in controller features that depend on accurate vehicle counting, such as the added initial feature of volume-density control and the adaptive protected-permissive left-turn feature that uses left-turn vehicle counts to determine left-turn demand.

Increasing distance between the camera and the detection zone exacerbates the irregular gap measurement and vehicle occlusion problems if the camera height does not increase in the same ratio. Since there is typically a maximum height at which a camera can be mounted, setback detectors often used for diamond interchange control will be more susceptible to these types of errors. Relocating the camera to a location closer to the setback detector is one potential solution.

Detection layout affects the applicability of the volume-density feature. The application of variable initial timing is appropriate when setback detectors are provided without stop-bar detectors, or in the case where setback detectors are combined with stop-bar detectors that operate in a calling (nonextending) mode only. The variable initial timing feature should generally not be used with stop-bar detectors with an extending function.

For the successful implementation of the adaptive protected-permissive left-turn feature it is critical that the detection system is able to provide accurate traffic counting for the left-turn movement as well as accurate gap measurement for the through movement. Ideally, a single set of detectors crossing all lanes should be used for gap measurement on the opposing movement. If multiple detectors are used on the opposing movement, for example for dilemma-zone protection, gaps cannot be measured accurately since each vehicle actuates multiple detectors. In

this case, an additional set of detectors may need to be installed and connected to the signal cabinet on a separate lead-in.

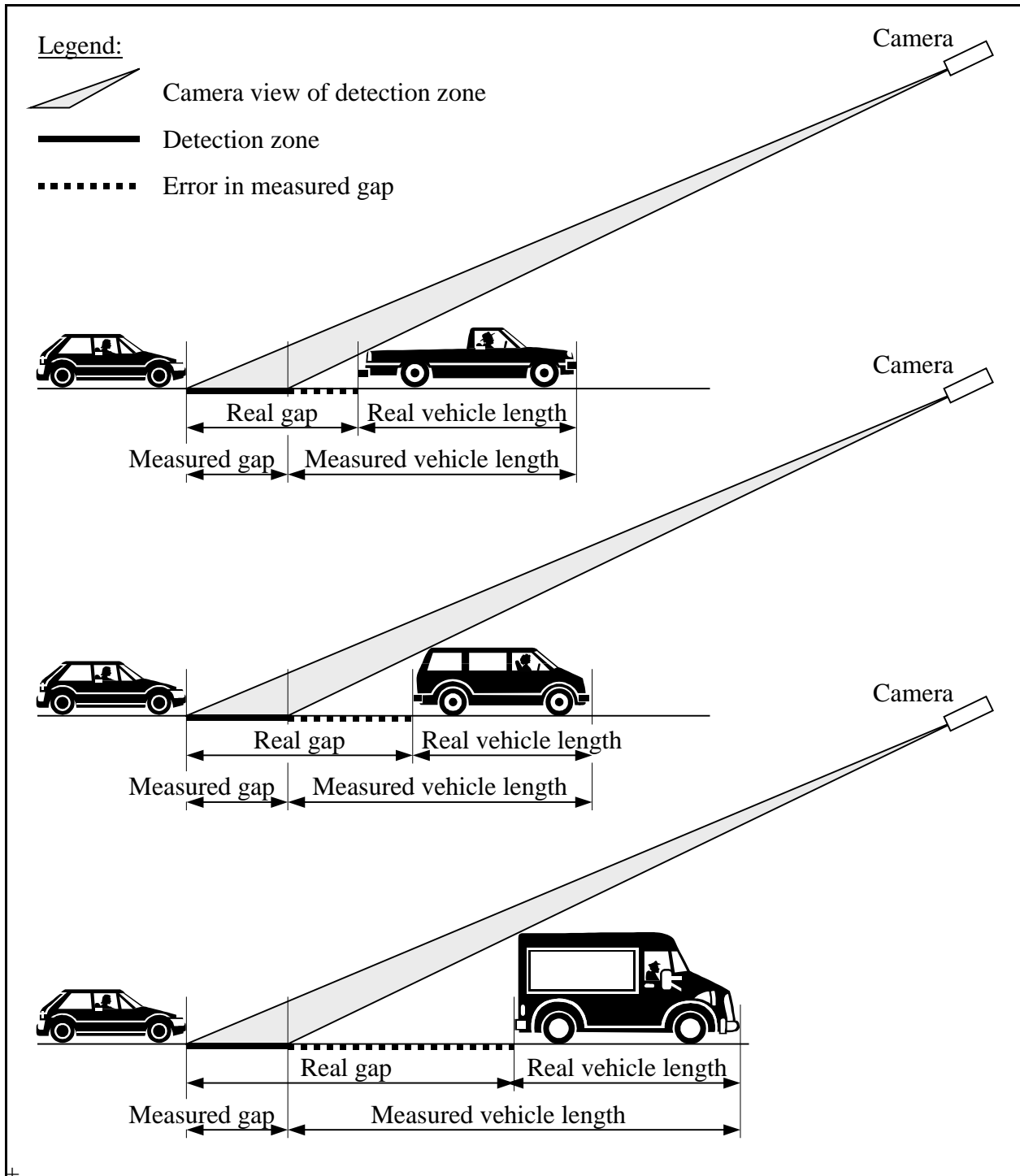


Figure 23. Irregular Gap Measurement with Video Detection.

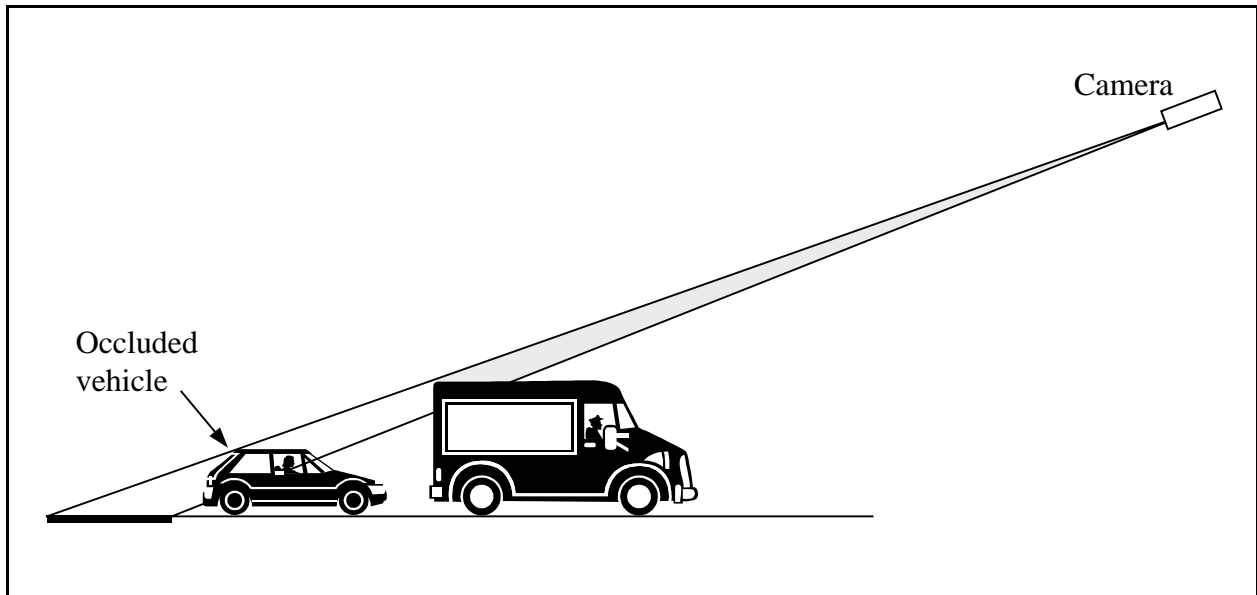


Figure 24. Vehicle Occlusion with Video Detection.

HUMAN FACTORS

Human factors are probably the most important factors that affect the implementation of the advanced controller features identified in this study. Specifically, the engineer should give careful attention to driver expectancy and related safety issues when implementing any feature.

For example, the free separate intersection mode should not be used where driver expectancy of three-phase or four-phase operation may compromise safety. Drivers used to three-phase control may expect lagging interior left turns, while the separate intersection mode provides leading left turns, if left turns are provided at all. Conversely, drivers familiar with four-phase control will still be provided with leading interior left turns, but may not expect the absence of interior progression that is always provided by four-phase control. The engineer should decide whether driver expectancy problems preclude the use of the free separate intersection mode at the interchange.

The engineer should also take into account driver expectancy when considering changing the diamond control sequence by time of day. Drivers moving through the upstream intersection of an interchange may expect the downstream intersection to be green, especially if the intersections are closely spaced or if a bridge or other structure obscures the traffic signal of the downstream intersection. A change in diamond control sequence may violate this expectancy and create a potential safety hazard. The engineer should decide on the appropriateness and safety implications of changing the diamond control sequence by time of day.

When dealing with setback detectors, the engineer should be careful not to inadvertently disable dilemma zone protection. This may happen when activating the gap reduction feature of volume-density control. Typically, the last vehicle to maintain the allowable gap should receive

the full passage time to clear the intersection. However, during the period between the expiration of the allowable gap and expiration of the passage time, the phase operates as nonactuated. Any vehicle crossing the detector during this period would not be guaranteed the full passage time and may potentially be exposed to the dilemma zone.

The use of the dynamic maximum feature may also lead to an increase in the number of vehicles that are exposed to the dilemma zone. If not used correctly the dynamic maximum feature can result in frequent max outs, since the feature tries to minimize the maximum green time and only increases the maximum green time when the phase maxes out twice in succession. These frequent max outs may be problematic, since the controller operates as nonactuated when maxing out and will terminate the green regardless of any traffic approaching, potentially leaving approaching vehicles in the dilemma zone.

CHAPTER V

EVALUATION AND IMPLEMENTATION

Research Tasks 4, 5, and 6 comprised the evaluation and implementation of the controller features at actual interchanges in Texas. The evaluation was based on geometric, demand, and control data that were collected at three interchanges:

- the Briarcrest Drive interchange on Texas 6 in Bryan, Texas;
- the Bagby Avenue interchange on Texas 6 in Waco, Texas; and
- the Del Mar Boulevard interchange on I.H. 35 in Laredo, Texas.

Researchers obtained geometric data from as-built drawings and site measurements. Demand data in the form of turning movement counts were obtained from a video camera survey performed by the researchers, or from recent turning movement counts conducted by TxDOT or their consultants. The traffic signal controller plans were also obtained to allow them to be programmed into the controllers used in the hardware-in-the-loop simulation.

BRIARCREST/TEXAS 6 INTERCHANGE

Evaluation

The CORSIM simulation network consisted of an east-west arterial section (Briarcrest Drive) containing the diamond interchange and three adjacent intersections, two with minor street stop control, and one with signal control (Freedom Boulevard). The spacing between the two diamond interchange terminals is a relatively wide 1150 feet. In the simulation, the two interchange terminals were controlled with a real Eagle EPAC300 signal controller in actuated-coordinated diamond control mode, while the other signalized intersection was controlled with CORSIM's emulated fixed-time controller. A NEMA TS 2 controller interface device was used to integrate the real controller hardware into the simulation, as shown in Figure 4.

In this evaluation, the coordinated separate intersection diamond control mode was compared to the coordinated three-phase diamond control mode during the afternoon peak hour. The interchange currently operates under coordinated separate intersection mode control during the afternoon peak period.

Researchers conducted traffic counts at the Briarcrest interchange on April 4, 2001. The afternoon peak hour was found to be between 4:45 PM and 5:45 PM. Table 2 shows the 15-minute demand volumes during the afternoon peak hour.

Table 2. Briarcrest Interchange Demand.

15 Minute Time Ending	West Terminal								
	Eastbound Arterial Movements			Southbound Frontage Rd. Movements				Westbound Interior Movements	
	Thru & Left	Thru & Thru	Right	U-Turn	Left	Through	Right	Left	Through
5:00 PM	146	115	137	9	8	50	82	72	198
5:15 PM	188	162	157	8	12	53	112	89	241
5:30 PM	169	161	176	9	17	66	97	121	292
5:45 PM	180	176	162	8	13	34	120	93	261
Total	683	614	632	34	50	203	411	375	992
15 Minute Time Ending	East Terminal								
	Westbound Arterial Movements			Northbound Frontage Rd. Movements				Eastbound Interior Movements	
	Thru & Left	Thru & Thru	Free Right	U-Turn	Left	Through	Right	Left	Through
5:00 PM	36	63	18	36	140	13	58	155	107
5:15 PM	42	69	21	47	153	14	54	196	180
5:30 PM	65	84	17	56	219	16	62	178	181
5:45 PM	39	90	21	54	139	11	45	188	198
Total	182	306	77	193	651	54	219	717	666

The 15-minute traffic volumes were entered into the simulation model to accurately represent the peaking characteristics during the peak hour. A fixed initialization period of 3 minutes was selected, and a 5-minute period of no demand was added at the end of the simulation to flush all traffic from the network to allow for accurate measurements.

Since the simulation contained an emulated controller that had to run in coordination with the real controller, trial-and-error was used to determine the local cycle timer value on the real controller at which the simulation had to be started to achieve the required offset between the real and emulated controller.

Researchers performed 10 paired evaluation runs, each pair consisting of two runs with the same traffic demand and random number seed, but with a different diamond interchange control strategy (separate intersection vs. three-phase). Only the random number seed varied between evaluation pairs, the overall traffic demand and turning movements remained the same. The simulation runs determined four performance measures:

1. overall network delay,
2. maximum queue length;
3. delay on the eastbound internal left-turn movement of the interchange, and
4. delay on the east-bound external approach to the interchange.

Table 3 shows the results from the 10 paired simulation runs.

Table 3. Briarcrest Interchange Simulation Results.

Run	Overall Network Delay (seconds/vehicle)			Maximum Eastbound Internal Left-Turn Queue Length (vehicles)		
	Separate Intersection Mode	Three-Phase Mode	Difference	Separate Intersection Mode	Three-Phase Mode	Difference
1	57.0	59.4	2.4	28	24	-4
2	55.2	61.2	6.0	28	13	-15
3	53.4	58.2	4.8	27	11	-16
4	53.4	58.8	5.4	27	14	-13
5	55.2	59.4	4.2	29	15	-14
6	57.6	61.2	3.6	30	10	-20
7	58.2	61.8	3.6	35	30	-5
8	55.8	57.6	1.8	30	11	-19
9	55.2	57.0	1.8	31	23	-8
10	57.0	55.8	-1.2	32	22	-10
Sample Mean	55.8	59.0	3.2	29.7	17.3	-12.4
Standard Deviation	1.65	1.96	2.12	2.50	6.90	5.52
Run	Maximum Eastbound Internal Left-Turn Delay (seconds/vehicle)			Maximum Eastbound External Delay (seconds/vehicle)		
	Separate Intersection Mode	Three-Phase Mode	Difference	Separate Intersection Mode	Three-Phase Mode	Difference
1	51.2	25.0	-26.2	22.0	25.7	3.7
2	49.6	20.2	-29.4	17.2	28.5	11.3
3	46.6	19.0	-27.6	14.7	25.5	10.8
4	46.5	20.1	-26.4	15.0	29.7	14.7
5	51.3	20.4	-30.9	18.1	30.5	12.4
6	53.9	18.2	-35.7	22.9	34.0	11.1
7	63.5	33.2	-30.3	18.0	30.6	12.6
8	51.4	20.5	-30.9	20.1	24.9	4.8
9	57.2	26.9	-30.3	15.3	22.4	7.1
10	55.4	23.5	-31.9	18.9	22.1	3.2
Sample Mean	52.7	22.7	-30.0	18.2	27.4	9.1
Standard Deviation	5.13	4.61	2.82	2.84	3.88	4.12

The paired sample means and standard deviations can be used to determine if the separate intersection mode and the three-phase mode result in significantly different performance. Performance differences are identified by testing the null hypothesis that the performance is the same, in other words, that the mean of the paired sample differences is zero, or $H_0 : \mu_1 - \mu_2 = 0$ (11). The test statistic, t , is calculated as follows:

$$t = \frac{\bar{d}}{s_d / \sqrt{n}}, \quad (3)$$

where \bar{d} and s_d are the sample mean and standard deviation of the n (10 in this case) differences. The null hypothesis can be rejected (implying that the performance is different) if $|t| > t_{\alpha/2}$, where α is the probability of erroneously rejecting the null hypothesis. For this analysis, a value of 0.01 was chosen for α , which means that we want to be 99 percent confident that the performance is different if the null hypothesis is rejected. The threshold value $t_{\alpha/2}$ can be determined as 3.250 from statistical tables for $\alpha = 0.01$ and $n - 1$ (9 in this case) degrees of freedom.

Table 4 displays the results from the hypothesis test for the four measures of effectiveness. From the table it can be seen that the null hypothesis is rejected for all four performance measures, indicating that the difference between the separate intersection mode and the three-phase mode have a statistically significant effect on all four performance measures.

Table 4. Briarcrest Interchange Hypothesis Test Results.

	Overall Network Delay	Maximum Eastbound Internal Left-Turn Queue Length	Maximum Eastbound Internal Left-Turn Delay	Maximum Eastbound External Delay
\bar{d}	3.2	-12.4	-30.0	9.1
s_d	2.12	5.52	2.82	4.12
n	10	10	10	10
$ t $	4.584	6.737	31.910	6.680
$t_{\alpha/2}$	3.250	3.250	3.250	3.250
$ t > t_{\alpha/2}$?	True	True	True	True
Null Hypothesis?	Reject	Reject	Reject	Reject

The differences in performance measures between the separate intersection mode and the three-phase mode can be calculated from the $100(1 - \alpha)$ percent (99 percent for $\alpha = 0.01$ in this case) confidence interval:

$$\bar{d} \pm \frac{t_{\alpha/2} s_d}{\sqrt{n}}. \quad (4)$$

From the calculated confidence intervals the following conclusions can be drawn:

- On average, the separate intersection mode results in an overall network delay 0.9 to 5.5 seconds per vehicle *less* than the three-phase mode.
- On average, the separate intersection mode results in an eastbound external approach delay 4.7 to 13.6 seconds per vehicle *less* than the three-phase mode.
- On average, the separate intersection mode results in a maximum eastbound interior left-turn queue length 6.4 to 18.4 vehicles *more* than the three-phase mode.
- On average, the separate intersection mode results in a maximum eastbound interior left-turn delay 26.9 to 33.0 seconds per vehicle *more* than the three-phase mode.

In summary, the analysis indicated that the coordinated separate intersection mode is more efficient in handling the afternoon peak-hour traffic at the Briarcrest interchange than the three-phase mode. Specifically, the analysis indicated that on average, the separate intersection mode results in an overall delay reduction of 2 to 9 percent over the three-phase mode. There are some trade-offs involved, however. The analysis indicated that the eastbound interior left-turn queues and delays are significantly higher under the separate intersection mode than under the three-phase mode, but that the delays on the eastbound exterior approach are significantly less under the separate intersection mode. At this particular interchange this trade-off was not problematic because of the large interchange spacing allowing enough interior storage space to handle the longer interior queue lengths resulting from the separate intersection mode.

Implementation

The following implementation guidance was developed during the hardware-in-the-loop analysis of the Briarcrest interchange:

1. The separate intersection mode is more efficient than three-phase in the afternoon peak, so no change is necessary.
2. Do not use volume-density settings. They are not compatible with video detection.
3. Consider a longer “constant call” detector diagnostic time on the external approaches. Under high volumes the long detection zones on the external approaches may have a constant call of more than 5 minutes, and thus fail the diagnostic.
4. Consider detector switching on the permissive interior left turn movements. This would minimize the activation of the left-turn phase when gaps exist in the opposing through movement. This approach may be an alternative to omitting phases 1 and 5 by time-of-day control.

5. Do not enter splits for phases 9 to 16 in separate intersection mode, and phases 9 to 11 and 13 to 15 for four-phase. These are “non-primary” phases, and should therefore not be entered. If entered, they could interfere with the Coordinated Adaptive Splits (see below).
6. Consider using Coordinated Adaptive Splits when running coordinated to be more tolerant of imperfect splits. You can activate this feature by time of day through Auxiliary events.
7. Consider using Dynamic Maximum Greens when running free to be more tolerant of unexpected heavy movements. You can activate this feature by time of day through Auxiliary events.

This information was conveyed to Mr. Kirk Barnes, TxDOT Traffic Engineer for the Bryan District.

BAGBY/TEXAS 6 INTERCHANGE

Evaluation

The CORSIM simulation network for the Bagby Interchange consisted of a north-south arterial section (Bagby Avenue) containing the diamond interchange. The spacing between the two diamond interchange terminals is 560 feet. In the simulation, the two interchange terminals were controlled with a real Eagle EPAC300 signal controller operating in free diamond control mode. A NEMA TS 2 controller interface device integrated the real controller hardware into the simulation, as shown in [Figure 4](#).

At the request of Mr. Larry Coclosure from the TxDOT Waco District, the evaluation specifically focused on low-volume operations at the interchange. At the time of the evaluation, the interchange operated in the three-phase sequence at all times except during the morning and afternoon peak period, when it operated in the four-phase sequence. The evaluation compared the use of the free separate intersection mode to the three-phase mode under low-volume conditions. To test the guidelines developed as part of this study, traffic counts were not conducted at this interchange; instead, traffic demand volumes were selected to fall within the thresholds stipulated by the guidelines for free separate intersection control:

- a combined arterial volume of 300 vehicles per hour or less, and
- a volume of 125 vehicles per hour or less on each frontage road.

[Figure 25](#) shows the traffic volumes used in the evaluation of the Bagby interchange under low volume conditions.

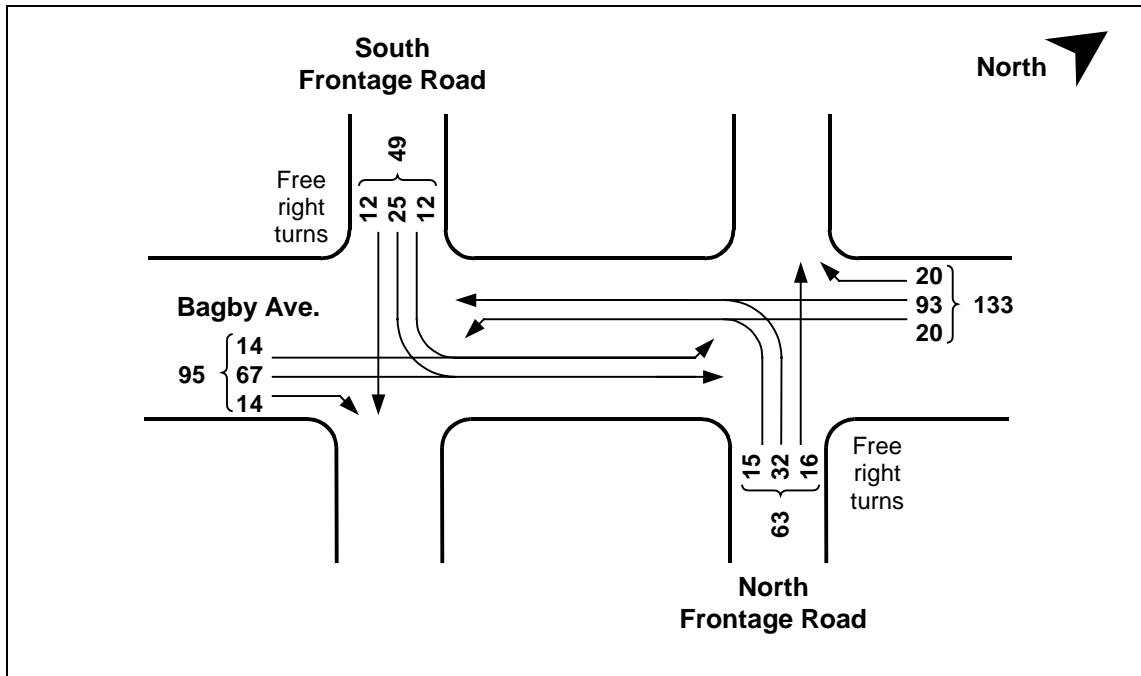


Figure 25. Bagby Interchange Demand.

The researchers performed four grouped evaluation runs, each group consisting of four runs with the same traffic demand and random number seed, but with a different diamond interchange control strategy. The following control strategies were evaluated:

- three-phase mode (the existing control mode),
- separate intersection mode without detector switching,
- separate intersection mode with detector switching on the internal left-turn detectors, and
- separate intersection mode with internal left-turn phases omitted.

The researchers only varied the random number seed between evaluation pairs; the overall traffic demand and turning movements were kept the same. The evaluation compared the percentage of stops at the interchange under the different control strategies since delay and queue lengths are less sensitive quality-of-service indicators under low-volume conditions. The results of the evaluation are shown in [Table 5](#) and [Figure 26](#).

The leftmost bar in [Figure 26](#) indicates the percentage of stops when using the three-phase sequence. The other bars show reduced stops using the free separate intersection mode with different left-turn phasing treatments. The rightmost bar represents the free separate intersection mode with the interior left turns omitted, which results in a 34 percent reduction in stops compared to the three-phase sequence.

Table 5. Individual Bagby Interchange Simulation Results.

Run	Percentage of Vehicles Stopping at the Interchange			
	Three-Phase Mode	Separate Intersection Mode No Detector Switching	Separate Intersection Mode With Detector Switching	Separate Intersection Mode Internal Left Turns Omitted
1	50.6	40.5	34.9	33.7
2	56.3	46.9	39.3	34.1
3	50.1	48.2	41.5	37.4
4	55.4	42.4	38.9	33.3
Sample Mean	53.1	44.5	38.7	34.6
Standard Deviation	3.2	3.6	2.7	1.9

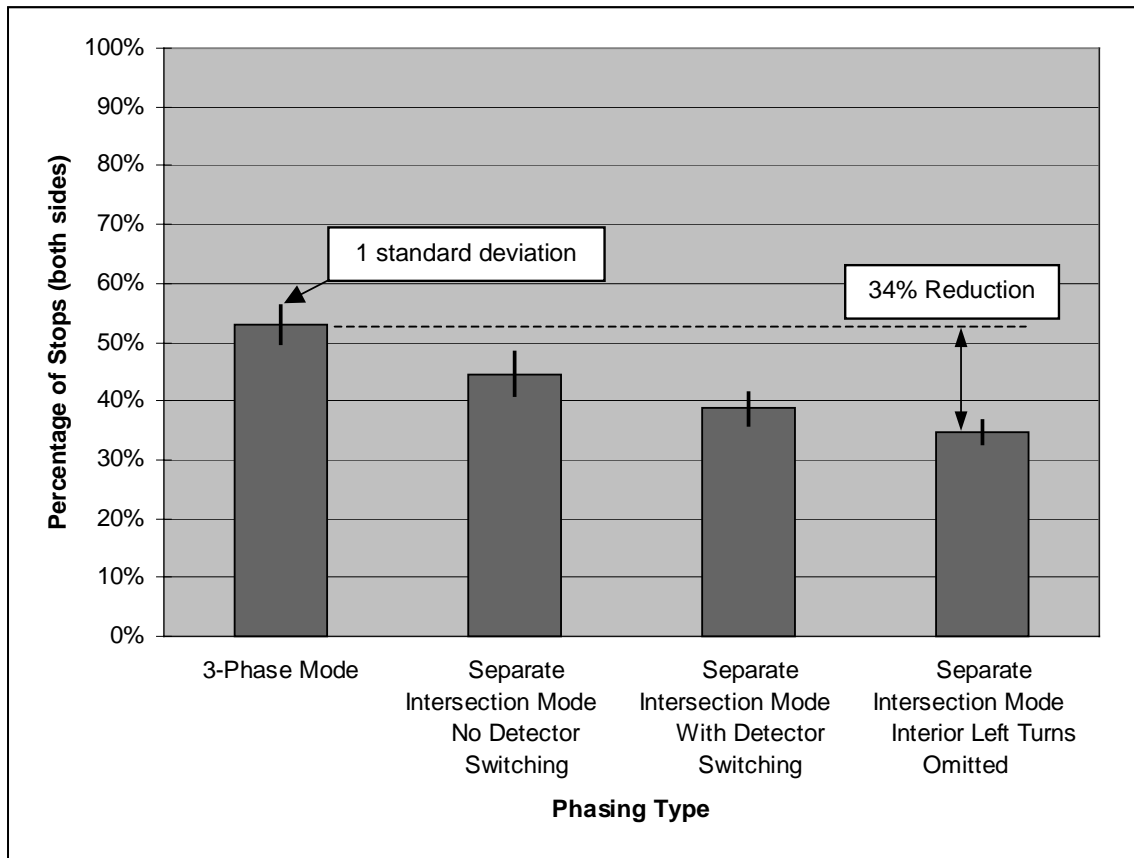


Figure 26. Summarized Bagby Interchange Simulation Results.

Implementation

The evaluation indicated that the separate intersection mode could significantly reduce stops under low-volume conditions compared to the three-phase mode. The researchers conveyed this information to Mr. Larry Coclosure of the TxDOT Waco District and Mr. Rick Charlton of the City of Waco. The City of Waco is responsible for the maintenance of the signal. The implementation guidelines and programming instructions in the following sections were also provided to Mr. Charlton.

Implementation guidelines

The free separate intersection mode does not guarantee progression through the interchange. Therefore, operators should only use it where traffic volumes are low enough to be essentially random, since progression through the interchange is typically not expected under these conditions. As volumes increase, the random flow will change to nonrandom, platooned flow, which can be served more efficiently by providing progression through the interchange.

The following “rule-of-thumb” guideline can be used to identify the traffic demand conditions under which the noncoordinated (free) separate intersection mode will be applicable.

Use the noncoordinated (free) separate intersection mode when both the following conditions are met:

1. On the frontage roads, two or fewer vehicles are typically served by a frontage road phase at one time. This will typically occur at traffic volumes less than 120 vehicles per hour.
2. On the arterial, three or fewer arterial vehicles are typically stopped while the frontage road is being served. This will typically occur at two-way arterial traffic volumes less than 300 vehicles per hour.

Minimum phase recalls should be placed on the arterial phases (2 and 6) to allow the interchange to dwell in the arterial phases and so decrease the number of stops required by arterial traffic.

If conditions permit, interior left-turn movements should operate under protected and permissive phasing to achieve maximum benefit. The activation of the internal left-turn phases (phases 1 and 5) should be minimized under free separate intersection control to minimize the number of arterial traffic stops. This can be achieved by the following:

- Omitting the internal left-turn phases (phases 1 and 5) by time-of-day control, resulting in two-phase control. This should only be done during the times where sufficient capacity is available to efficiently operate the internal left-turn movement without protected phasing.
- Skipping the internal left-turn phases when not required, through the use of detector delays, detector switching, and nonlocking detector memory. For example, a delay of 4 to 8 seconds can be placed on the left-turn detectors to provide the opportunity for left-

turners to accept gaps in the opposing traffic before the protected left-turn phase is called. In addition, the left-turn detector can be switched to the opposing through phase while the through phase is green so that left turns extend the opposing through phase and increase the probability that the left-turn maneuver can thus be serviced in permissive mode during the green time of the opposing through phase. Also, nonlocking detector memory should be used to minimize the activation of the interior left-turn phases in the absence of actual left-turn demand.

- Using the Adaptive Protected-Permissive feature of the Eagle controller to automatically decide whether to omit the interior left-turn phase, based on the left-turn demand and the number of gaps in the opposing through movement.

The noncoordinated (free) separate intersection mode should not be used where driver expectancy of three-phase or four-phase operation may compromise safety. Drivers used to three-phase control may expect lagging interior left turns, while the separate intersection mode provides leading left turns, if left turns are provided at all. Conversely, drivers used to four-phase control will still be provided with leading interior left turns, but may not expect the absence of interior progression that is always provided by four-phase control. The engineer should decide whether driver expectancy problems would preclude the use of the free separate intersection mode at the interchange.

Setback detectors on the frontage roads (typically provided for four-phase operation) can significantly improve operation in the noncoordinated separate intersection mode. Since the frontage road phase is called when the vehicle crosses the setback detector, the frontage road phase would typically be green or turn green shortly after the vehicle reaches the intersection, depending on the setback distance and vehicle speed. If setback detectors are used on the frontage roads, the minimum green times of the frontage road phases (phases 4 and 8) should be set considering the travel time from the setback detector to the stop line. Specifically, care should be taken to ensure that the frontage road green does not expire before the vehicle reaches the stop line. In the case where frontage road detectors are set back a significant distance from the intersection, the sluggish operation resulting from the long frontage road minimum green times required may negate the advantages of the noncoordinated separate intersection mode.

Programming instructions

The internal left-turn phases (phases 1 and 5) can be omitted using the TBC (Time Base Control) Phase Function Mapping feature of the Eagle controller. This is done as follows:

1. Press “6” from the MAIN MENU to show the TIME BASE MENU.
2. Press “9” to show the TIME BASE PHS FUNC MAPPING screen.
3. Scroll down and assign the PHS-01 PHS OMIT and PHS-05 PHS OMIT functions to unused phase functions by entering a “1” in the appropriate FUNC SEL column. In most cases the default phase function mapping of Phase Function 9 for Phase 1 Omit and Phase Function 13 for Phase 5 Omit is appropriate.
4. Press “3” from the TIME BASE MENU to show the TRAFFIC EVENTS screen.

5. Enter one or more new events into the Traffic Events database, or change existing events, using the procedure described in the Eagle EPAC300 Product Manual (2), section 4.2.4. Activate the appropriate phase function (9 and 13 for the default mapping) by entering “1” into the appropriate P1-16 column. In the default phase function mapping, a “1” will be entered in the P9 and P13 columns to activate phase function 9 and 13, thereby omitting phases 1 and 5, respectively.
6. Make sure that the new event(s) in the Traffic Events database are called at the appropriate time by using the TIME BASE DAY EQUATE/TRANSFER screen (Press “6” from the TIME BASE MENU), as described in the Eagle EPAC300 Product Manual (2), section 4.2.7.

Under nonactuated (free) operation the diamond control sequence can be set via special functions tied to a time-based auxiliary event. This is done using the following procedure:

1. Press “6” from the MAIN MENU to show the TIME BASE MENU.
2. Press “0” to show the TIME BASE SPC FUNC MAPPING screen.
3. Scroll down and assign each of the diamond modes (TX DIAMOND–FOUR PHASE, TX DIAMOND–THREE PHASE, and TX DIAMOND–SEPARATE) to an unused special function (say special function 6, 7, and 8), by entering a “1” in the appropriate SPC FUNC column (the 6th, 7th, and 8th columns in this example).
4. Press “4” from the TIME BASE MENU to show the AUXILIARY EVENTS screen.
5. Enter one or more new events into the Auxiliary Events database, or change existing events, using the procedure described in the Eagle EPAC300 Product Manual (2), section 4.2.5. Activate the appropriate special function (6, 7, or 8 in this example) by entering “1” into the appropriate S1-8 column. In this example, a “1” will be entered in the S6 column to activate special function 6 and call the four-phase mode, a “1” will be entered in the S7 column to activate special function 7 and call the three-phase mode, and “1” will be entered in the S8 column to activate special function 8 and call the separate intersection mode.
6. Make sure that the new event(s) in the Auxiliary Events database are called at the appropriate time by using the TIME BASE DAY EQUATE/TRANSFER screen (Press “6” from the TIME BASE MENU), as described in the Eagle EPAC300 Product Manual (2), section 4.2.7.

DEL MAR/I.H. 35 INTERCHANGE

Evaluation

The CORSIM simulation network for the Del Mar Interchange is shown in [Figure 27](#). The spacing between the interchange terminals—San Bernardo Avenue and San Dario Avenue—is approximately 320 feet, which represents a fairly narrow diamond interchange. A U-turn lane (not shown in [Figure 27](#)) is provided to the south of the interchange to service traffic demand from San Dario Ave. to San Bernardo Ave, but this facility was not included in the simulation model since it is not controlled by the interchange traffic signals.

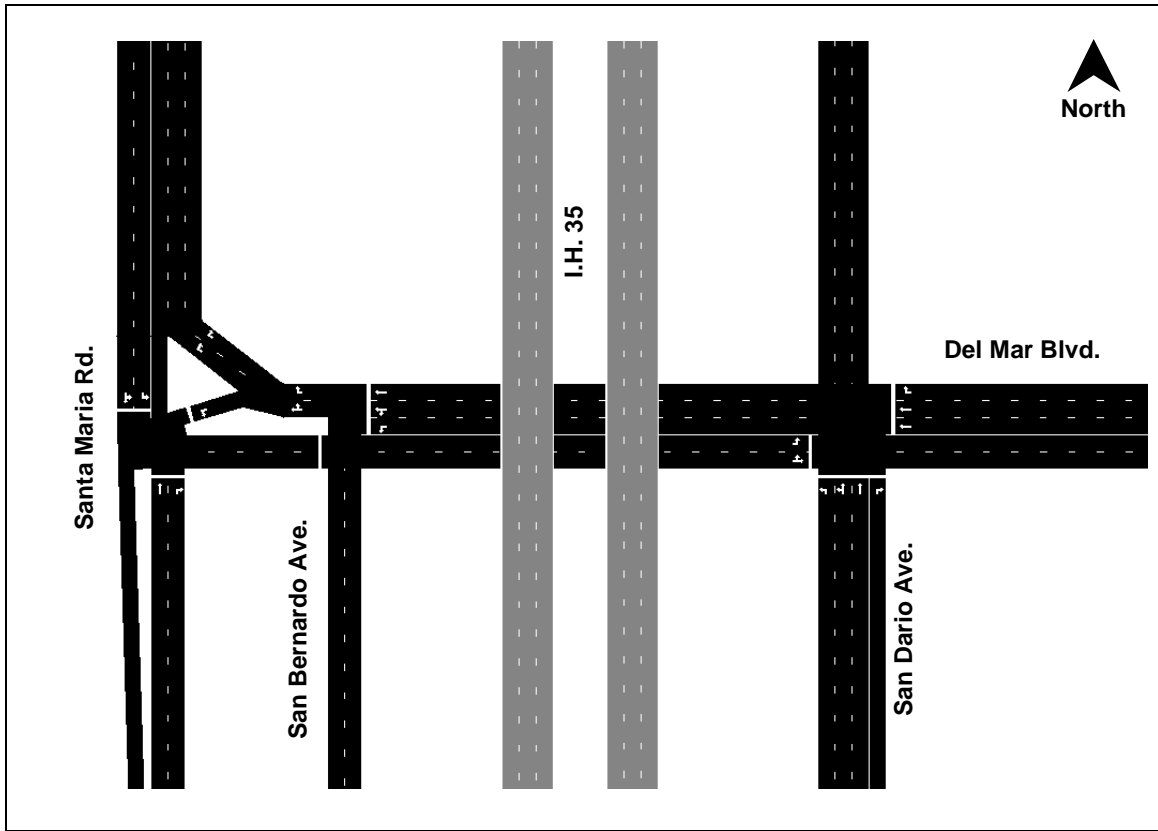


Figure 27. Del Mar Interchange Layout.

At the time of the evaluation, a Naztec 980 controller with Version 50 software was controlling the Del Mar interchange. Although the geometric layout is not a standard diamond interchange, a standard four-phase sequence is used to control the interchange through the innovative use of overlaps and sharing of phases between movements. The phase and overlap numbering scheme is shown in [Figure 28](#).

The narrow spacing of the interchange and the many potentially conflicting movements require the use of the four-phase sequence at all times to ensure that the interior of the interchange is kept clear. Video detection is used at the Del Mar interchange. The combination of the Naztec controller, four-phase operation at all times, and video detection restricts the implementation of advanced features at this interchange. Consequently, the only advanced features that are suitable for implementation at this interchange are dynamic maximum green times and alternate maximum green times. Since both these features have the same objective—to adapt the signal timing to variable demand—the researchers only evaluated the dynamic maximum green time feature. The feature was only used on phase 8, which controls the northbound traffic on San Dario Avenue that acts as the northbound frontage road of I.H. 35.

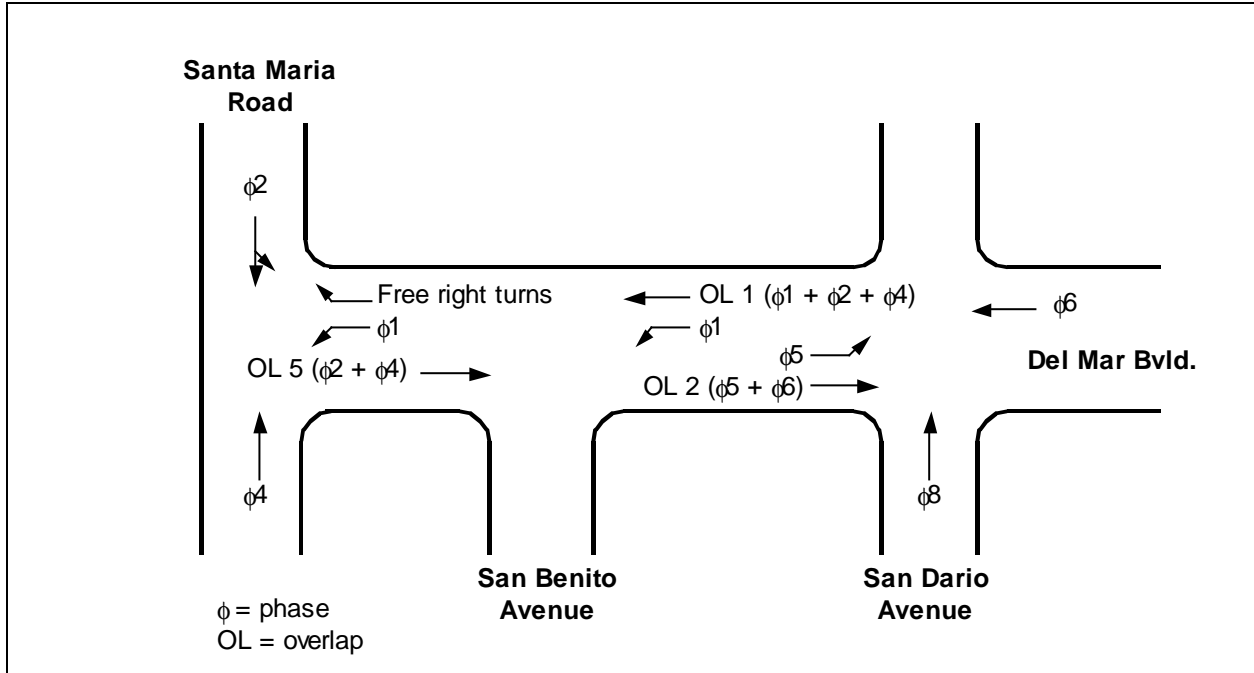


Figure 28. Del Mar Interchange Phase Numbering Scheme.

At the time of the evaluation, TxDOT Laredo District personnel were in the process of retiming the Del Mar interchange. Consequently, TTI researchers used PASSER III to calculate new four-phase minimum and maximum green times for the afternoon peak hour traffic demand at the interchange. The resulting phase times are shown in [Table 6](#). The dynamic maximum green time feature was programmed on phase 8 as follows:

- dynamic maximum limit: 40 seconds, and
- dynamic maximum step: 5 seconds.

Table 6. Del Mar Interchange Phase Times.

Phase	Minimum Green Time (seconds)	Minimum Green Time (seconds)
1	7	25
2	7	15
4	0	15
5	7	25
6	7	15
8	0	10
12	0	5
16	0	5

The evaluation tested the ability of the dynamic maximum green time feature on phase 8 to handle a sudden increase in demand due to traffic rerouting from I.H. 35 to San Dario Avenue, possibly due to an incident on the freeway. The evaluation used the afternoon peak hour (5:00 PM to 6:00 PM) traffic demand determined previously by the Texas Transportation Institute and augmented by turning movement counts conducted by contractors for the TxDOT Laredo district (22). To simulate the sudden increase in demand, researchers increased the simulated demand on San Dario Avenue (phase 8) by 1,200 vehicles per hour between 5:15 PM and 5:30 PM.

Table 7 shows the evaluation results obtained from four simulation replications. The table shows the average delay per vehicle at the interchange and the maximum queue length on San Dario Avenue, without and with the dynamic maximum green time feature activated on phase 8.

Table 7. Del Mar Interchange Simulation Results.

Run	Overall Network Delay (seconds/vehicle)			Maximum Queue Length on San Dario Ave. (vehicles)		
	Without Dynamic Max	With Dynamic Max	Difference	Without Dynamic Max	With Dynamic Max	Difference
1	66.6	51.0	15.6	144	50	94
2	71.4	60.0	11.4	147	68	79
3	69.0	60.6	8.4	152	50	102
4	66.6	50.4	16.2	146	89	57
Sample Mean	68.4	55.5	12.9	147.3	64.3	83.0
Standard Deviation	2.30	5.55	3.68	3.40	18.55	19.78

Table 8 shows the results of a hypothesis test to determine if the dynamic maximum green time feature has a statistically significant effect on the interchange delay and the maximum queue length on San Dario Avenue. From the table it can be seen that the null hypothesis is rejected for both performance measures, indicating that the dynamic maximum green time feature indeed has a statistically significant effect on the two performance measures. Calculating confidence intervals with Equation 4 yields the following results:

- On average, use of the dynamic maximum green time feature results in an overall network delay 2.1 to 50.6 seconds per vehicle *less* than if the feature was not used.
- On average, use of the dynamic maximum green time feature results in a maximum queue length on San Dario Avenue 25.2 to 325.4 vehicles *less* than if the feature was not used.

Table 8. Del Mar Interchange Hypothesis Test Results.

	Overall Network Delay	Maximum Queue Length on San Dario Ave.
\bar{d}	12.9	83.0
s_d	3.68	19.78
n	4	4
$ t $	7.01	8.39
$t_{\alpha/2}$	5.84	5.841
$ t > t_{\alpha/2}?$	True	True
Null Hypothesis?	Reject	Reject

Implementation

The evaluation indicated that the dynamic maximum green time feature can reduce delays and queues significantly when used on a phase controlling traffic subject to demand variations. The researchers relayed this information, together with the phase times in [Table 6](#), to Messrs. Jimmy Deliganis and Oscar Matel of the TxDOT Laredo District, who are responsible for the implementation of any new traffic signal controller settings at the Del Mar interchange.

In addition, the researchers suggested that TxDOT consider methods of providing setback detection on San Dario Avenue and Santa Maria Road. If setback detection can be provided on the frontage roads to yield between 7 and 10 seconds of travel time between the setback detector and the stop line, interchange operations can be improved through better utilization of the transition intervals (phases 12 and 16). With the absence of setback detection—as was the case with the video detection layout at the time of the evaluation—the controller services the transition intervals after gapping out on phase 4 or 8, resulting in low flow rates across the frontage road stop lines during the transition intervals. If setback detection is provided on the frontage roads, a high-density traffic stream will still be located between the setback detector and the stop line at the start of the transition interval, resulting in significantly higher flow rates across the frontage road stop lines during the transition intervals. However, for the reasons described in [Chapter IV](#) of this report, the video detection provided at the Del Mar interchange is not suitable for providing setback detection, limiting TxDOT’s options of providing setback detection.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

This research project identified the following eight controller features that can be used to improve diamond interchange operations under certain conditions:

- separate intersection mode,
- diamond phasing sequence change by time of day,
- conditional service,
- dynamic maximum green times,
- dynamic split,
- volume-density control,
- alternate maximum green and passage times, and
- adaptive protected-permissive left turns.

The guidelines developed as part of this project describe the concept of operation of each of these features and provide detailed application guidelines, including applicability under different geometric and demand conditions and compatibility with various detection technologies. The guidelines, found in [Appendix A](#) of this report, also provide detailed programming instructions to guide engineers and technicians in implementing these features on the Eagle and Naztec controllers.

One of the main findings of this project was a realization of the potential usefulness of the separate intersection diamond control mode. The separate intersection diamond control mode is not commonly used, but if applied judiciously it has the potential to provide more efficient control than the three-phase or four-phase sequences that are typically used for diamond interchange control in Texas. The separate intersection mode can be used in both free and coordinated mode.

The free separate intersection mode can significantly reduce stops at interchanges under low-volume conditions, especially if the interior left turns can operate as permissive left turns and steps are taken to reduce the activation of the interior left-turn phases. The coordinated separate intersection mode has the potential to provide more efficient operation than the three-phase or four-phase sequence under certain conditions that can be determined with signal optimization software such as PASSER III and Synchro. The “ring lag” feature provided by the Eagle controller can be used to specify the offset between the coordinated phases, allowing the separate intersection mode to provide progression through the interchange under a wide range of geometric and demand conditions.

RECOMMENDATIONS

1. Since the coordinated separate intersections mode with “ring lag” proved very useful, the researchers recommend that the TxDOT specification be extended to include the “ring lag” or “individual ring offset” feature that is required to implement the coordinated separate intersections mode in the most flexible manner. The Eagle controller already implements the ring-lag feature, but the Naztec controller does not.
2. The researchers recommend that the potential drawbacks of video detection, as discussed above, should be taken into account when deciding on the vehicle detection technology to use at new signalized diamond interchanges, or when a change in existing detection technology is considered.
3. The researchers recommend that the guidelines developed in this research be used when reevaluating existing diamond interchange operation or when developing timing for new interchanges. The controller features identified in this project should be implemented, as appropriate according to the guidelines, but in all cases driver expectation and other safety issues should be taken into account.

REFERENCES

1. Texas Department of Transportation. *Departmental Specification TO-4048: Full Actuated Solid State Controller Unit (TS-2) with Diamond, TBC, Preempt, and Closed Loop Operation; and Base-Mounted TS-2 Cabinet Assembly*. Traffic Operations Division, Traffic Management Section, Austin, TX, 1998.
2. Eagle Traffic Control Systems. *EPAC300 Actuated Controller Unit Product Manual*. Austin, TX, 1997.
3. Naztec Incorporated. *Intersection Control Software, TS-2 Version 50.x*. Sugarland, TX, 2001.
4. Naztec Incorporated. *Naztec Cross-Platform NTCIP Controller Simulator Version 1.1*. On the Internet at http://www.naztec.com/training/virtual_controller/mm-start.htm. Link valid October 2001.
5. Engelbrecht, Roelof J., Christopher M. Poe, and Kevin N. Balke. *Development of a Distributed Hardware-In-The-Loop Simulation System for Transportation Networks*. Presented at the Transportation Research Board 78th Annual Meeting, Washington D.C., 1999.
6. Herrick, G. Curtis. *Strategies for Improving Traffic Operations at Oversaturated Diamond Interchanges*. M.S. Thesis, Texas A&M University, College Station, TX, 1992.
7. Engelbrecht, Roelof J. *Coordinating Diamond Interchange and Arterial Street Signal Control*. M.S. Thesis, Texas A&M University, College Station, TX, 1997.
8. Koonce, Peter J. V. *Evaluation of Traffic Operations at Diamond Interchanges Using Advanced Actuated Control*. M.S. Thesis, Texas A&M University, College Station, TX, 1998.
9. De Camp, G.B. *A Primer on Diamond Interchanges*. In *TexITE News*, Texas Section of Institute of Transportation Engineers, Houston, TX, Spring 1993, pp. 3-4, 11.
10. ITT Systems & Sciences Corporation. *CORSIM User's Manual*. Version 1.04. FHWA, U.S. Department of Transportation, Washington D.C., March 1998.
11. Ott, R.L. *An Introduction to Statistical Methods and Data Analysis*. Fourth Edition. Duxbury Press, Belmont, CA, 1992.
12. Engelbrecht, Roelof J., Steven P. Venglar, and Zong Z. Tian. *Summary Report on Improving Diamond Interchange Operations Using Advanced Controller Features*. Report 4158-S, Texas Transportation Institute, College Station, TX, October 2001.
13. Venglar, Steven P. and Peter J.V. Koonce. *PASSER III-98 Application and User's Guide*. Texas Transportation Institute, College Station, TX, 1999.
14. Trafficware Corporation. *Synchro Users Guide Version 5*. Albany, CA, 2000.
15. Courage, K.G., C.E. Wallace, and M.A. Hadi. *TRANSYT-7F Users Guide*. U.S. Department of Transportation, Washington D.C., December 1991.
16. National Electrical Manufacturers Association. *Traffic Controller Assemblies*. NEMA Standards Publication No. TS 2-1992. Washington D.C., 1992.
17. National Electrical Manufacturers Association. *National Transportation Communications for ITS Protocol (NTCIP) Object Definitions for Actuated Traffic Signal Controller Units*. NEMA Standards Publication No. TS 3.5-1996. Washington D.C., 1996.
18. National Electrical Manufacturers Association. *Traffic Control Systems*. NEMA Standards Publication No. TS 1-1989. Washington D.C., 1989.

19. Orcutt, F.R., Jr. *The Traffic Signal Book*. Prentice Hall, Englewood Cliffs, NJ, 1993.
20. Venglar, S.P., P. Koonce, and T. Urbanik II. *PASSERTM III-98 Application and User's Guide*. Texas Transportation Institute, Texas A&M University, College Station, TX, 1998.
21. Freund, J.E., F.J. Williams, and B.M. Perles. *Elementary Business Statistics*. Fifth Edition. Prentice Hall, Inc., Englewood Cliffs, NJ, 1988.
22. Texas Transportation Institute. *Analysis Of The Del Mar / Mines Road Interchange With Interstate Highway 35*. San Antonio, TX, July 1996.

**APPENDIX:
GUIDELINES FOR IMPROVING
DIAMOND INTERCHANGE OPERATIONS USING
ADVANCED CONTROLLER FEATURES**

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CHAPTER A-I

INTRODUCTION

Most modern traffic signal controllers contain certain “advanced” features that are often not used but may improve traffic operations at signalized diamond interchanges under certain conditions. The objective of this guideline document is to assist traffic engineers and technicians in selecting and implementing the controller features that can improve diamond interchange traffic operations under specific geometric and demand conditions.

These guidelines are based on the feature sets of the two controllers that meet the Texas Department of Transportation (TxDOT) traffic signal controller specification (1) in the latter half of 2001: Eagle Traffic Control Systems’ EPAC300 (2) and Naztec Incorporated’s Model 980 controller with Version 50 software (3). Although many of the features that will be addressed in these guidelines technically exceed the TxDOT specification, these features are available in controllers currently being deployed and thus can be used to improve diamond interchange operations. These guidelines are restricted to advanced features that are compatible with the diamond operational mode, since it is assumed that the diamond mode will be used for controlling the diamond interchange.

Users of this guideline document should keep in mind that the recommendations incorporated herein are general in nature and that in all cases, engineers should use their judgment in selecting and implementing specific controller features for diamond interchange control. Specifically, attention should be given to driver expectancy and related safety issues when changing traffic signal control based on the guidelines contained in this document. Also, it should be kept in mind that the controller features addressed in these guidelines are not the only features that can be used to improve diamond intersection control. In many cases, special or nonstandard geometric or demand conditions will provide the opportunity to apply other controller features in an innovative manner.

Finally, it should be noted that additional features with the potential of improving diamond operations may become available when controllers from other manufacturers become compliant with the TxDOT specification or when the control software of the EPAC300 or Model 980 controllers are upgraded or improved. As a result, these guidelines will most likely become outdated and should therefore be updated on a regular basis.

CHAPTER A-II

ADVANCED CONTROLLER FEATURES

At the time these guidelines were developed (mid 2001) only two controllers met the TxDOT traffic signal controller specification: the EPAC300 controller from Eagle Traffic Control Systems and the Model 980 controller with Version 50 software from Naztec Incorporated. However, not all of the advanced diamond interchange traffic control features are available on both the Eagle and Naztec controllers, since the different vendors provide different feature sets. At the same time, not all of the potentially useful features are compatible with all detection technologies, geometric layouts, and traffic demand conditions.

FEATURE LIST

The following controller features, which are all compatible with the diamond operational mode on either the Eagle, Naztec, or both, could potentially improve diamond interchange operations and will be addressed in these guidelines:

- separate intersection mode,
- diamond phasing sequence change by time of day,
- conditional service,
- dynamic maximum green times,
- dynamic split,
- volume-density control,
- alternate maximum green and passage times, and
- adaptive protected-permissive left turns.

[Chapter A-III](#) provides a short description of the concept of operation of each of the eight features listed above. [Chapter A-IV](#) then provides detailed guidelines on the application of each feature, including geometric and demand conditions and programming procedures. [Chapter A-IV](#) also provides decision flow charts to determine if a particular feature is compatible with a specific controller, detection technology, or coordination mode.

CHAPTER A-III

CONCEPT OF OPERATION

Figure A-1 indicates the phase numbering scheme that will be used throughout this document.

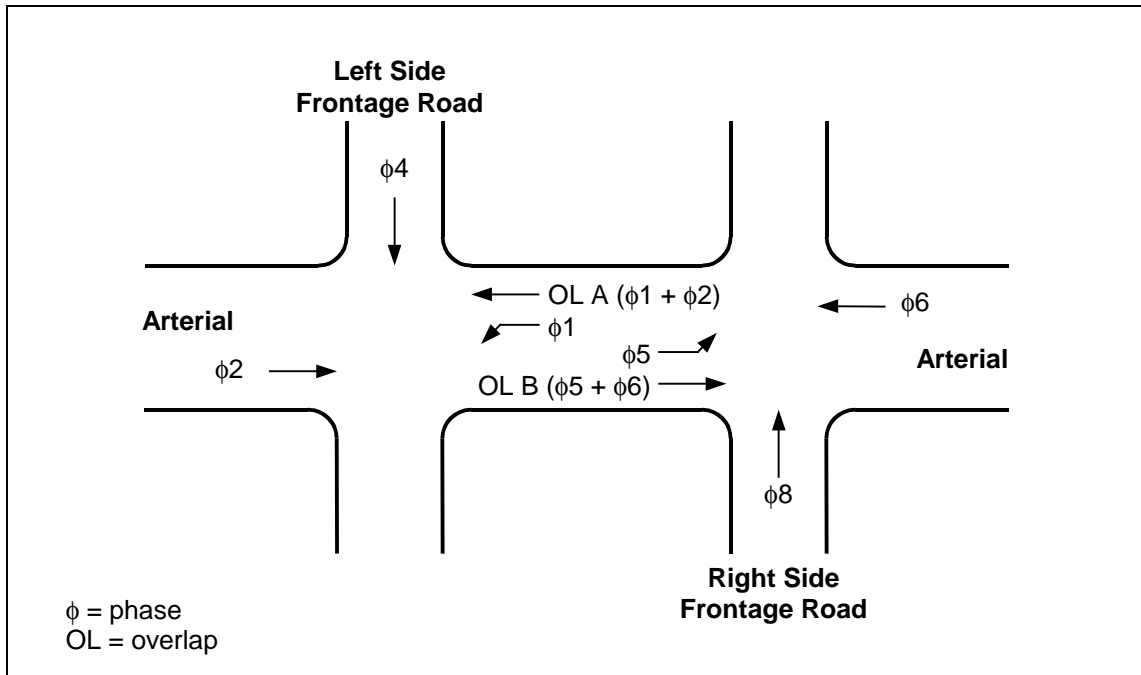


Figure A-1. Signal Phase Numbering Scheme for Diamond Interchanges.

SEPARATE INTERSECTION MODE

The TxDOT controller specification defines three diamond interchange control modes: (i) four-phase mode, (ii) three-phase mode, and (iii) separate intersection mode. The four-phase and three-phase modes are well known and often used in field deployments. The separate intersection mode, on the other hand, is less well known and not used as often, and is the topic of this description. The phase sequence and ring structure of the four-phase, three-phase, and separate intersection modes are shown in Figure A-2, Figure A-3, and Figure A-4, respectively.

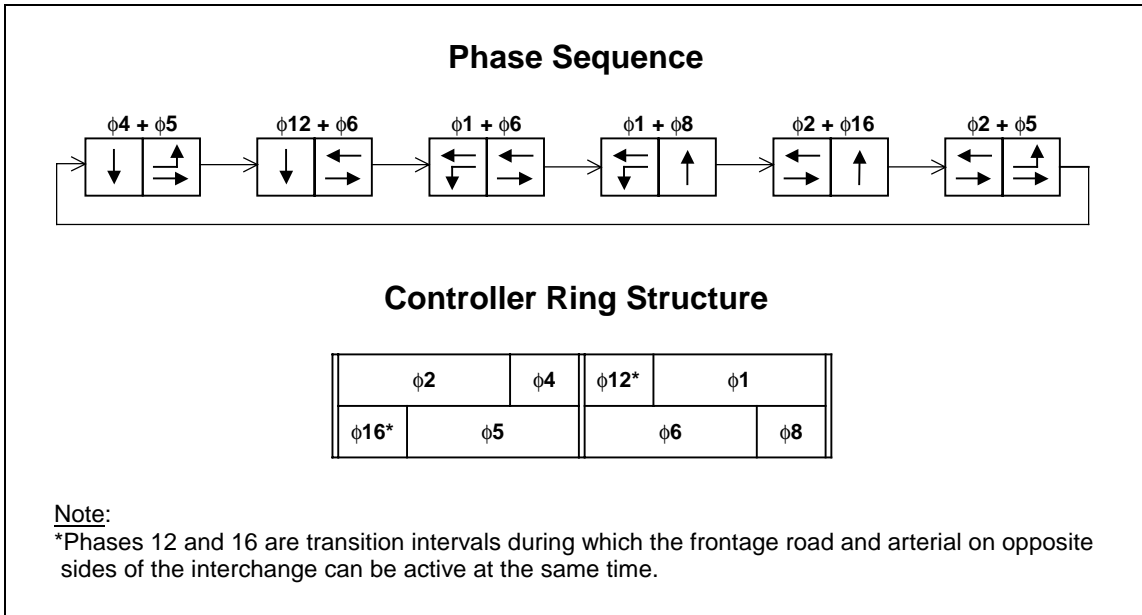


Figure A-2. Simplified Four-Phase Diamond Interchange Phasing.

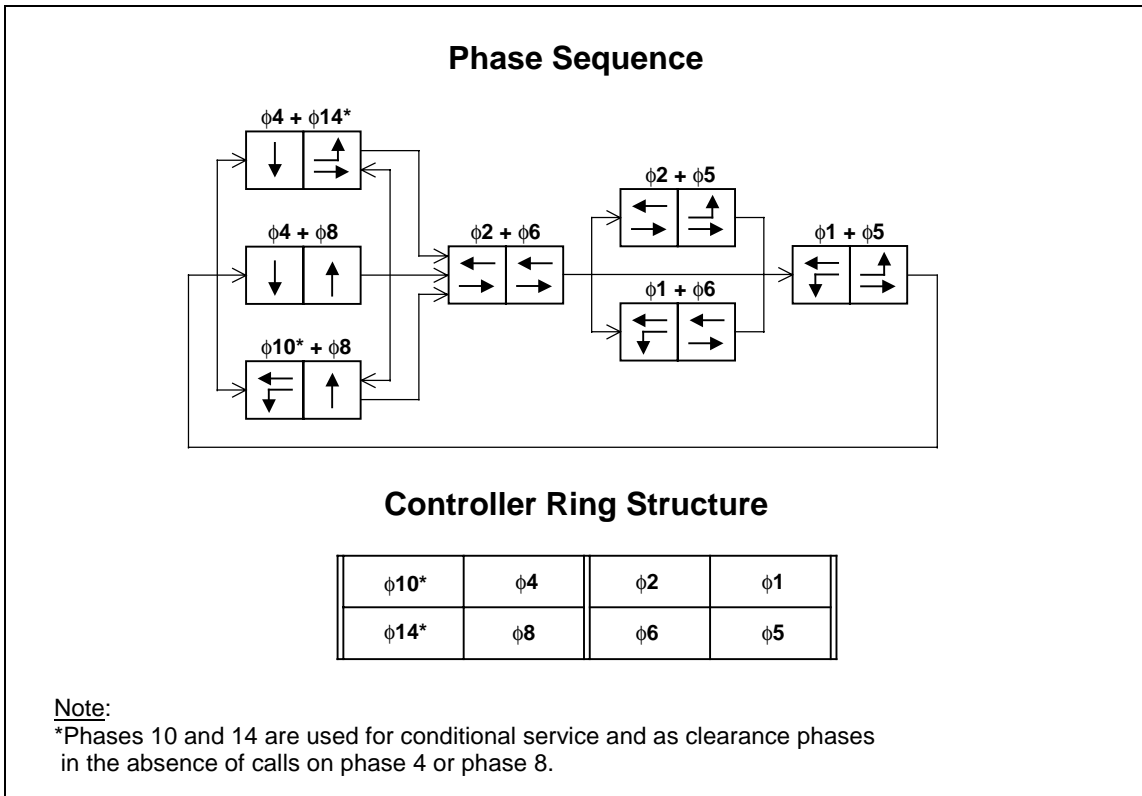


Figure A-3. Simplified Three-Phase Diamond Interchange Phasing.

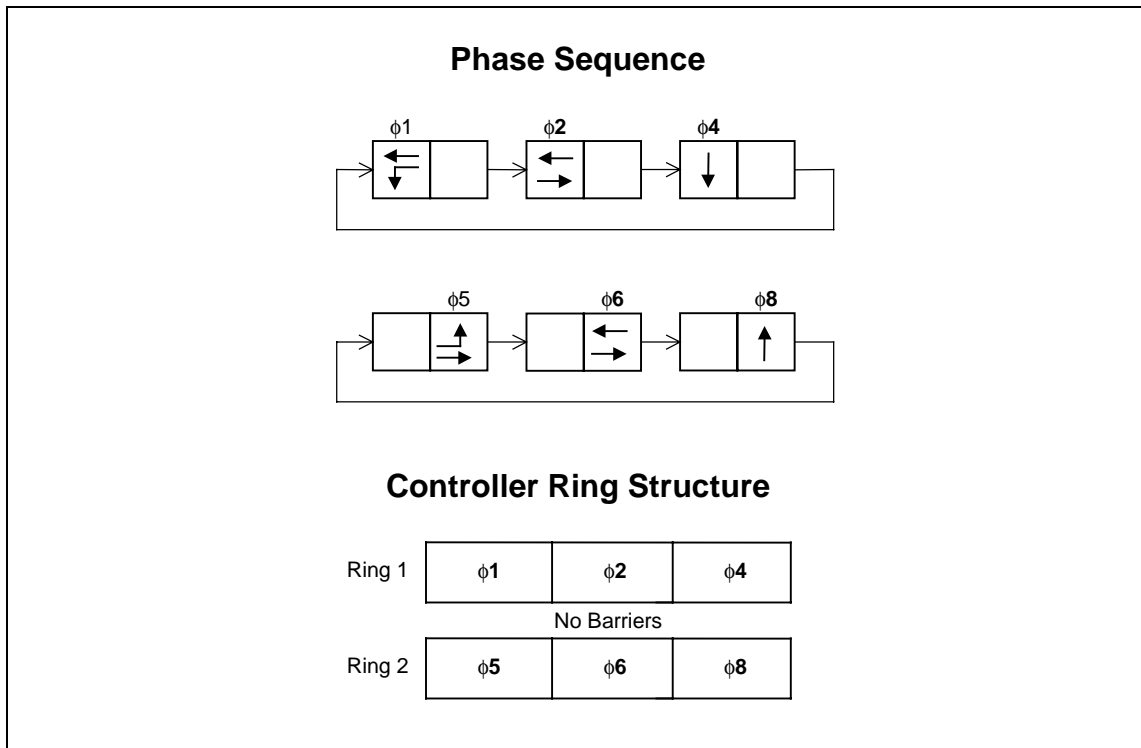


Figure A-4. Simplified Separate Intersection Diamond Interchange Phasing.

The phase sequences are simplified in that they do not include phases 3 and 7 and their related clearance and phases defined in the TxDOT specification. The phase sequences resulting from skipped phases are also not shown. The Eagle and Naztec user manuals show the full phase sequences.

In the separate intersection mode, interior left turns (phases 1 and 5) lead the external arterial through movements (phases 2 and 6). One ring controls each side of the diamond interchange and no barriers exist between rings. Under free (noncoordinated) control, the two rings operate independently of each other and there is no internal offset to provide progression through the interior of the interchange. If progression through the interchange is required, the controller can be run in coordinated mode. The controller does not need to be coordinated with any other controllers; coordination is only used to provide the structure required to create a fixed relationship (offset) between the rings. The separate intersection diamond control mode is valuable under both free and coordinated mode.

Free Separate Intersection Mode

The free separate intersection mode is very effective in handling low-volume conditions. For example, this mode can be used to control an interchange during the late night and early morning hours when traffic volumes are low. Under low-volume conditions the progression provided by four-phase or three-phase control is typically not needed, since traffic streams consist of single vehicles rather than platoons of vehicles. If permissive internal left-turn movements are allowed, detector switching can be used to switch detector actuations from the internal left-turn phase (phase 1 or 5) to the opposing arterial phase (phase 2 or 6) to avoid unnecessary activation of the internal left-turn phases. The internal left-turn phases can also be omitted by time-of-day control if there is no doubt that the permissive left-turn movements would have sufficient capacity for the time the left-turn phases are omitted. If recalls are placed on the arterial phases (2 and 6) and the left turns are treated as described above, the controller will only leave the arterial phases to service frontage road demands. The free separate intersection mode is efficient in serving low frontage road demand in the absence of high arterial demand for two reasons:

1. The controller does not need to wait for the current phase at other side of the interchange to terminate before a frontage road phase can be serviced.
2. When the controller changes to the frontage road requiring service, the arterial phase on the other side of the interchange remains green. This is in contrast to the three-phase mode, where the other side of the interchange changes to the internal left-turn phase (phase 10 or 14) when only one frontage road has a call, even if there is no interior left-turn demand on the other side of the interchange.

Coordinated Separate Intersection Mode

Under low-flow conditions it may be acceptable to operate without any guaranteed progression through the interchange, but for higher volumes it is desirable to provide progression. The lack of progression in the separate intersection diamond mode can be addressed by running the controller in coordination. The internal offset is established between the coordinated phases in each ring. The Eagle EPAC300 controller provides a useful “ring-lag” feature that can be used to specify the offset between the coordinated phases, as shown in the top part of [Figure A-5](#). The Naztec series 980 controller with the current Version 50 software does not provide a “ring-lag” feature, so the offset between the coordinated phases on the current version of the Naztec controller and software will always be zero, as shown in the bottom part of [Figure A-5](#).

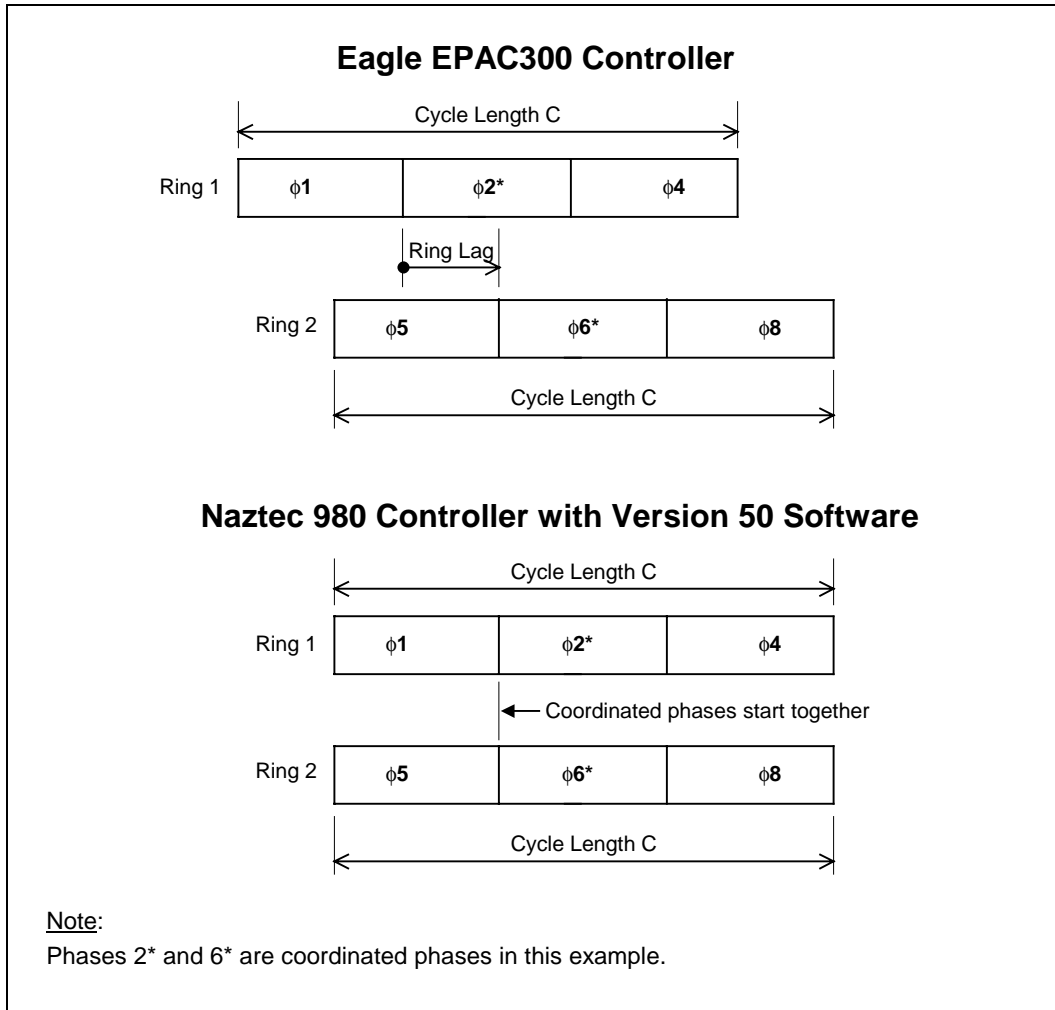


Figure A-5. Coordinated Separate Intersection Mode Diamond Interchange Phasing.

By running the separate intersection diamond mode in coordination with the appropriate ring lag, it is possible to implement nonstandard diamond phasing schemes in the diamond control mode. These nonstandard phasing schemes may be appropriate under nonstandard geometric or demand conditions. The PASSER III (4), Synchro (5), and TRANSYT-7F (6) traffic signal optimization models can be used to generate such nonstandard diamond phasing schemes. For example, the PASSER III lead-lead phasing sequence lends itself well to implementation with the coordinated separate intersection diamond mode with ring lag.

Any phase in a ring can be selected as the coordinated phase, but selection of the coordinated phase must take into account the fact that all “unused” green time in the ring typically reverts to the coordinated phase. This may result in “early return” problems

under coordination, where the upstream signal returns early to the coordinated phase and discharges vehicles that will be stopped at the downstream signal if it did not also return early to the coordinated phase.

DIAMOND CONTROL SEQUENCE CHANGE BY TIME OF DAY

Both the Eagle and Naztec controllers provide the capability of changing the diamond control sequence by time-of-day control. This is a convenient feature, since traffic demand changes during the day and different diamond phasing schemes may be optimal at different times of the day. For example, peak period traffic may perform optimally under coordinated four-phase operation, off-peak day and evening traffic may perform optimally under free (noncoordinated) three-phase operation, and late-night traffic may perform optimally under the free separate intersection mode.

If periods of similar traffic demand can be identified, the controller can be programmed to change to the most appropriate diamond control sequence at the start of each period. Typically, turning movement counts are used to identify periods of similar traffic demand, and a PASSER III or Synchro analysis can be used to determine the optimal diamond control sequence for each period.

Timely changes in the diamond control sequence have the potential to optimize traffic flow through the interchange by providing the best possible diamond phasing type for any particular demand condition.

CONDITIONAL SERVICE IN THREE-PHASE SEQUENCE

Conditional service is an alternative method of phase selection that allows the controller to activate phases outside their place in the ring structure. According to the National Electrical Manufacturers Association (NEMA) TS 2-1992 standard, if two concurrent phases are timing and a call exists on the other side of the barrier while one of the phases is prepared to terminate (due to gap out or max out), conditional service allows the ring containing the terminating phase to revert to the preceding phase in that ring, provided that the following four conditions are met (7):

1. a call exists on the preceding phase;
2. the terminating phase is programmed for conditional service;
3. there is sufficient time available before the maximum time of the phase in the other ring elapses; and
4. the controller is not running in coordinated mode. (This requirement is relaxed by the Naztec controller, since it supports conditional service under coordination.)

The criterion for determining if sufficient time remains to conditionally service the preceding phase is that the terminating vehicle phase clearance times plus the minimum green time of the conditionally serviced phase be less than the time remaining on the max timer of the non terminating phase. This is shown graphically in [Figure A-6](#).

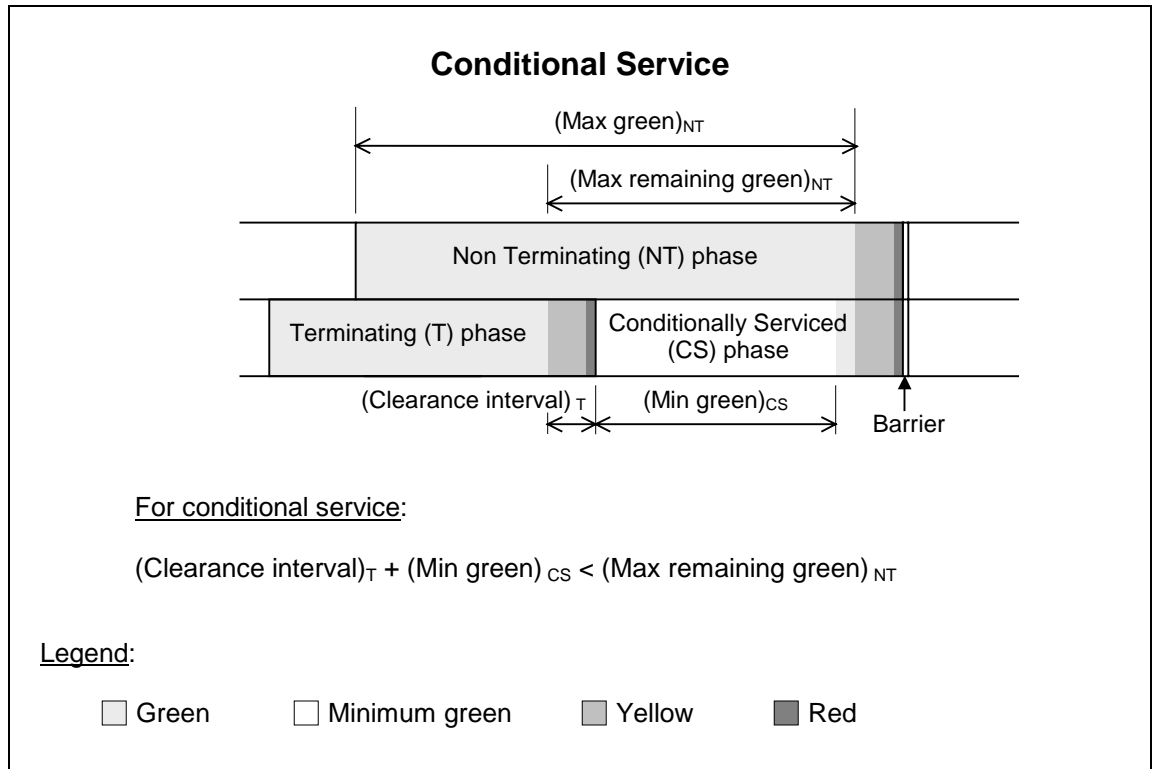


Figure A-6. Criteria for Conditional Service.

Conditional service is available on both the Eagle and Naztec controllers. Under the NEMA definition of conditional service, the barrier will not be crossed until the minimum green time of the conditionally serviced phase has expired and the non terminating phase has gapped or reached its maximum time. The effect is that the conditionally serviced phase will operate as a nonactuated phase, since it does not have the capability of extending or terminating on its own. The Eagle controller implements this approach. On the Naztec controller, however, the conditionally serviced phase is actuated, and the barrier will only be crossed when both the conditionally serviced and the non terminating phases have gapped or maxed out.

Conditional service is only compatible with the three-phase diamond control sequence. In the three-phase mode, the frontage road phases (phases 4 and 8) can be programmed for conditional service. The ring structure of the three-phase control mode

(see [Figure A-3](#)) allows phases 4 and 8 to conditionally service special internal left-turn phases (phases 10 and 14). The interior through movement is serviced at the same time through an overlap with the interior left-turn phase. Conditional service allows the three-phase control mode to adapt to unequal frontage road demand, since the frontage road with less demand can gap out and conditionally service the internal left-turn and through movement while the other frontage road is still being serviced, as shown in [Figure A-7](#).

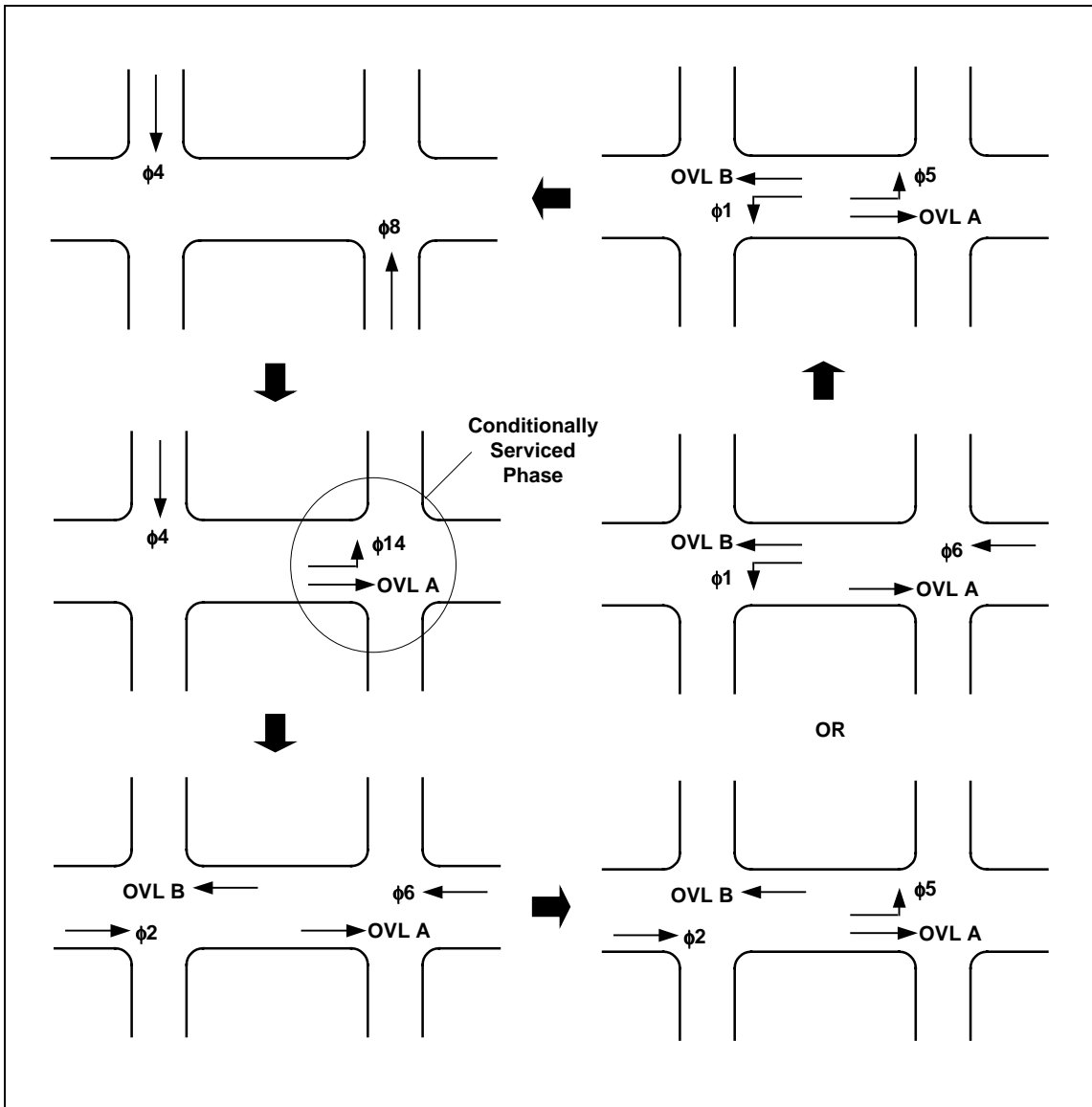


Figure A-7. Effect of Conditional Service on Three-Phase Diamond Control.

The effects of conditional service on the three-phase diamond control sequence can be summarized as follows:

1. early gap out or max out of one of the frontage road phases (phase 4 or 8);
2. an out-of-sequence (leading as opposed to the usual lagging) service of the internal left-turn movement (phase 10 or 14); and
3. the early start of the interior through movement, since it overlaps with the internal left-turn phase.

DYNAMIC MAXIMUM GREEN TIMES

The NEMA TS 3.5-1996 standard for actuated signal controllers (8) defines “dynamic max” as an alternative mode of phase termination. Under dynamic max operation the maximum green time is variable and is controlled by the following parameters:

1. the normal phase maximum (Max 1 or Max 2), which serves as an upper or lower bound for the dynamic maximum green time;
2. the “dynamic max limit,” which serves as the other bound for the dynamic maximum green time. If this value is larger than the normal maximum, it becomes the upper limit, and if it is lower than the normal maximum, it becomes the lower limit; and
3. the “dynamic max step,” which specifies how the dynamic maximum green time varies between the normal phase maximum (Max 1 or Max 2) and the dynamic max limit.

Under dynamic max control the maximum green time of a phase can vary and the current maximum green time is referred to as the “running max.” The running max starts with the normal phase maximum (Max 1 or Max 2). When a phase maxes out twice in a row and on each successive max out thereafter, one dynamic max step value is added to the running max until such an addition would mean that the running max is greater than the larger of the normal maximum green time or the dynamic max limit. When a phase gaps out twice in a row and on each successive gap out thereafter, one dynamic max step value is subtracted from the running max until such subtraction would mean that the running max becomes less than the smaller of the normal maximum green time or the dynamic max limit. If a phase gaps out in one cycle and maxes out in the next cycle, or vice versa, the running max will not change (8).

Figure A-8 shows an example of dynamic max operation. The graph shows the running max green times and actual green times for a phase through 13 cycles. In this example the normal maximum is Max 1 with a value of 25 seconds. The dynamic max limit is set to 40 seconds with a dynamic max step of 5 seconds. Cycle 1 starts with a

running max equal to Max 1 (25 seconds). In cycle 1 the phase gaps out, so no change is made to the running max. The phase maxes out in both cycles 2 and 3, so the running max is increased by 5 seconds (the dynamic max step) to 30 seconds for cycle 4. In cycle 4 the phase gaps out, so no change is made to the running max. Cycles 5 and 6 see the phase max out twice, so the running max is increased to 35 seconds in cycle 7. The phase also maxes out in cycle 7, so the running max for cycle 8 is increased to 40 seconds, which is the maximum value based on the dynamic max limit. In both cycles 8 and 9, the phase gaps out so the running max for cycle 10 is decreased to 35 seconds. Each successive cycle gaps out, so the running max is decreased by 5 seconds each cycle unit it reaches the minimum of 25 seconds (Max 1) in cycle 12.

The dynamic maximum feature has the ability to adapt to unexpected increases in demand that could be the result of special events or rerouting due to incidents. One potential use of the dynamic maximum feature would be to use it on the frontage road phases to be more responsive to unexpected increases in frontage road demand due to rerouting as a result of freeway incidents.

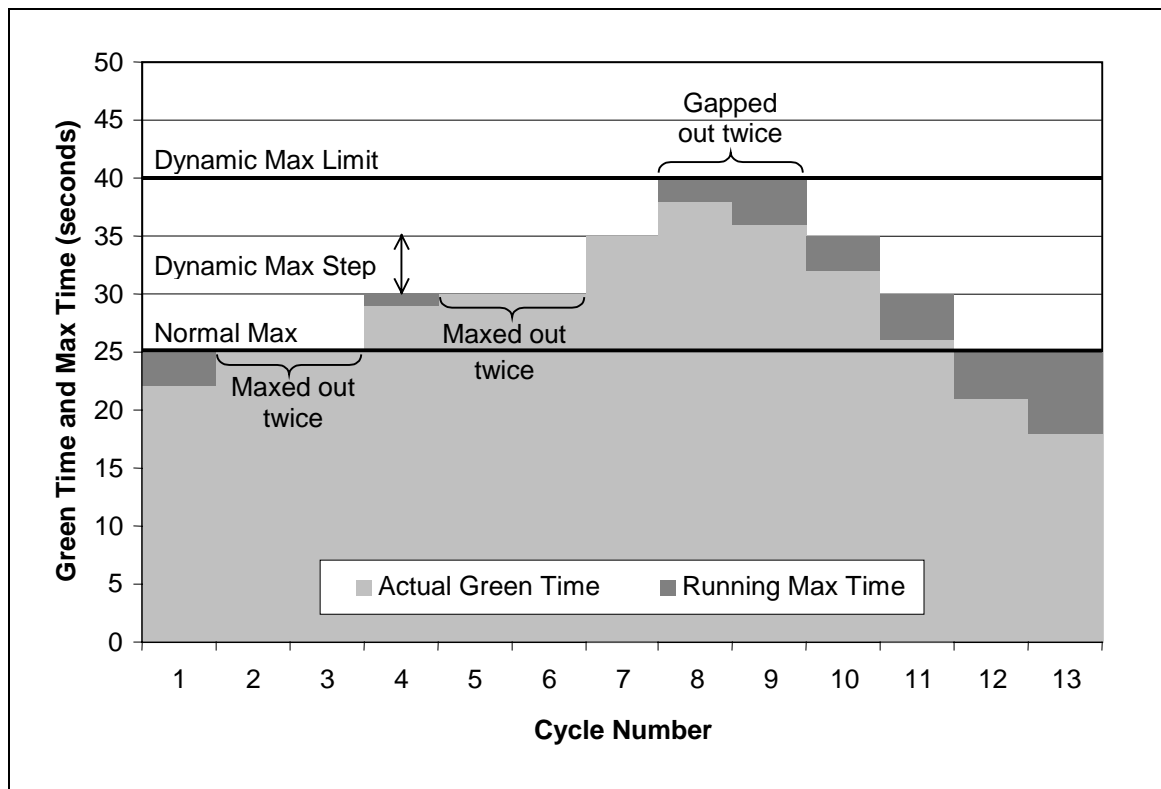


Figure A-8. Example of Dynamic Maximum Operation.

DYNAMIC SPLIT

The dynamic split feature does for coordinated control what the dynamic maximum green time feature (described above) does for actuated control. The Eagle controller implements dynamic splits through the Coordination Adaptive Splits (CAS) feature, which is compatible with the diamond control mode. The Critical Intersection Control (CIC) feature of the Naztec controller also provides dynamic split but is not compatible with the diamond control mode and will consequently not be described further.

According to the Eagle controller manual (2) the goal of the CAS feature is to dynamically find and use the most advantageous split possible. This is done for all noncoordinated phases, since the coordinated phases are not adjusted. Adaptive split is achieved by monitoring the termination of each noncoordinated phase to determine whether the phase gapped out or was forced off. CAS monitors the time usage of each phase under coordination. If, for two consecutive cycles, a phase is forced off by coordination while not already in the yellow or red clearance interval, the phase becomes a candidate for an additional increment of split. Conversely, if, for two consecutive cycles, a phase becomes ready to terminate with more than one second of time left on its coordination timer, the phase becomes a candidate for giving up an increment of split. Split time is taken away from the phases marked as candidates for giving up split and added to the phases marked as candidates for increasing split. Split times are typically changed in 1 second increments. If a phase gaps out in one cycle and is forced off in the next, the adaptive split will not change. Time is never subtracted from a phase split except to give to another phase, so the cycle length stays the same.

Figure A-9 shows an example of the operation of the dynamic split feature. It shows only the first ring (phases 1, 2, and 4) of a controller in coordinated separate intersection mode. The cycle length is 120 seconds with an initial 20:60:40 split between phases 1, 2, and 4. Phase 2 is the coordinated phase. Phases 1 and 4 have a minimum green time of 5 seconds and 5 seconds of clearance time, for a minimum phase time of 10 seconds. Phase 1 only requires the minimum phase time, but phase 4 has a significant demand (perhaps due to a freeway incident) that requires more than the default 40/120 split. The controller operates in the permitted mode (so that all unused time goes to the start of the coordinated phase) with plan force offs (so that the phase is forced off a fixed time after it becomes active).

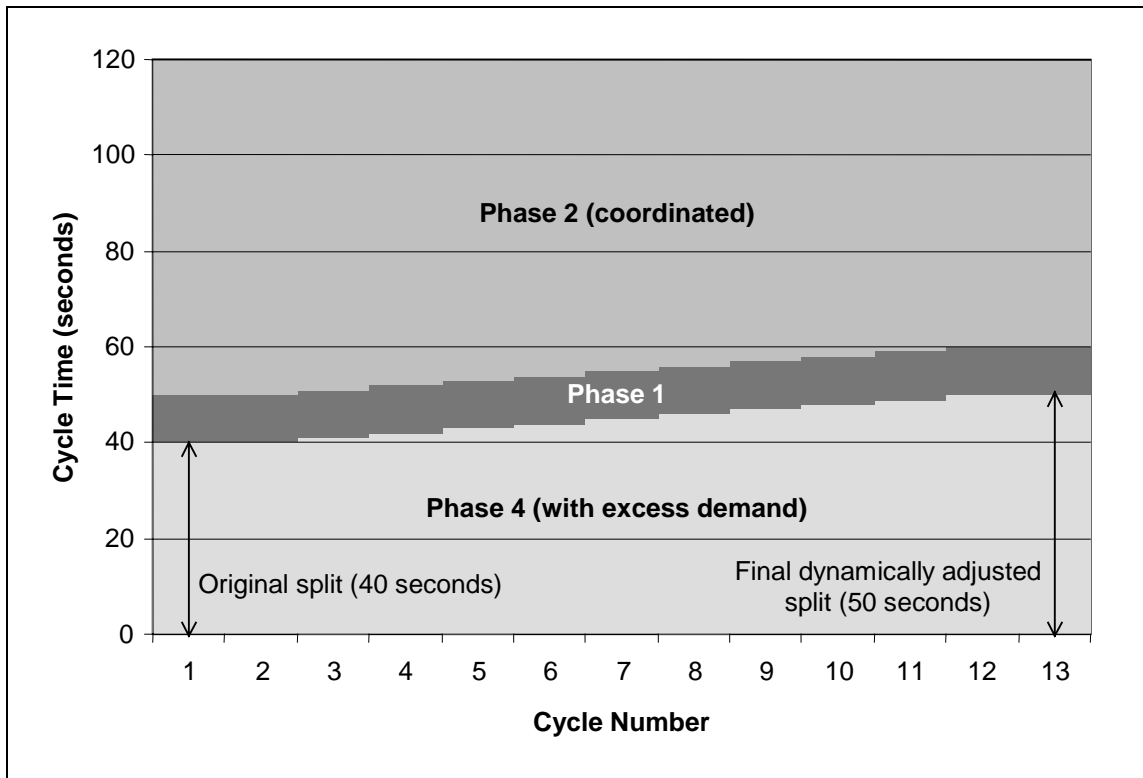


Figure A-9. Example of Dynamic Split Operation.

Initially, phase 4 has a 40 second split and phase 1 uses 10 seconds of the available 20 seconds, so that phase 2 starts 10 seconds early. In the third cycle, after phase 4 was forced off twice and phase 1 gapped out twice, the splits of phases 4 and 1 are increased and decreased by 1 second. Phase 4 now has a 41 second split, phase 1 uses 10 seconds of the available 19 seconds, and phase 2 starts 9 seconds early. The reallocation of splits continue until cycle 12, when the split of phase 1 has been reduced to the minimum phase time of 10 seconds and the split of phase 4 has increased to 50 seconds. Since phase 1 runs to the new split time of 10 seconds, phase 2 does not start early any more and has a duration of 60 seconds.

The adaptive split feature is useful in redistributing time between the noncoordinated phases based on the actual demand. It is also useful for reclaiming some of the “unused” time in that cycle that normally goes back to the coordinated phase. The coordination mode and force mode play an important role in how the adaptive split feature operates, since it controls how and when phases are forced off. It should be kept in mind, however, that a maximum recall on any phase (placed as a default, by time of day, or as the result of a failed detector) will disable the adaptive split feature.

VOLUME-DENSITY CONTROL

Volume-density control has been part of the NEMA actuated traffic signal controller standard since the NEMA TS 1 standard of 1989 (9). Volume-density control provides two features: (i) variable initial timing and (ii) gap reduction timing. Each of these will be described separately below.

Variable Initial Timing

Under variable initial timing the duration of the initial portion of the green (the first timed portion of the green interval) can increase dependent on the number of vehicle actuations stored on the phase while its signal is displaying yellow or red (7). The variable initial timing period can be thought of as a “variable minimum green” and is determined by the following three parameters:

1. minimum green time, which determines the minimum variable initial time period;
2. seconds per actuation, which determines the time by which the variable initial time will be increased (starting from zero) with each vehicle actuation received during the yellow and red intervals of the phase; and
3. maximum initial, which is the maximum of the variable initial timing period.

Figure A-10 shows the effect of these parameters on the variable initial timing period. The figure shows how the initial timing starts with the minimum green time. Once the number of vehicle actuations multiplied by the seconds per actuation becomes larger than the minimum green time, the initial timing takes on the former value, until it reaches the maximum initial value which acts as an upper limit.

Variable initial timing is most effectively used when setback detectors are provided without any stop-bar detection, so that the initial timing can be incremented to the appropriate value required to service vehicles that queue between the stop line and the setback detector. Variable initial timing is compatible with the diamond control mode, and can be useful in the four-phase control mode, where setback detectors are often used. Variable initial timing requires point detection to operate, so it may not be appropriate to use with the zone detection provided by video detection.

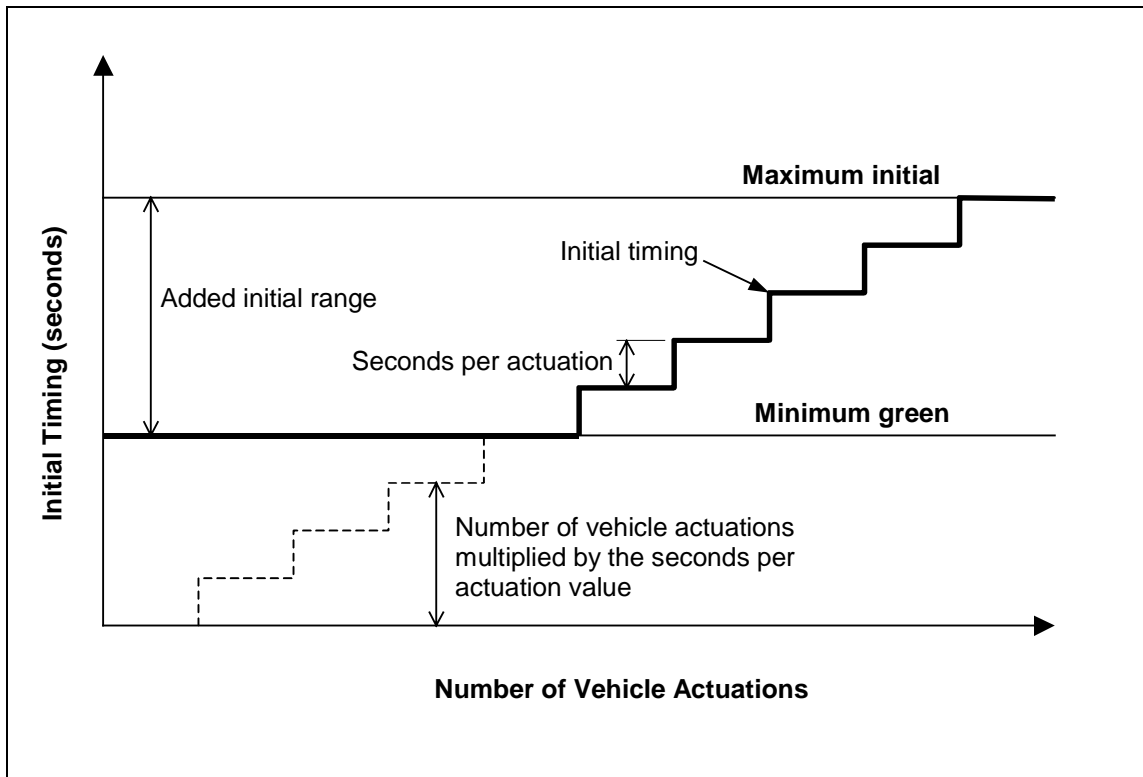


Figure A-10. Variable Initial Timing.

Gap Reduction Timing

Gap reduction timing is typically used with setback detectors on high-speed approaches and is used to control the size of the allowable gap. With setback detectors, the time allowed for a vehicle to pass from the detector to the intersection, the passage time, is usually longer than the gap that would normally be required to retain the right of way (10). The gap reduction feature compensates for this by reducing the allowable gap from the passage time to a minimum allowable gap that equals the required gap for right-of-way retention. Gap reduction is available in both the Eagle and Naztec controllers and is affected by the following five parameters:

1. passage time, the initial value of the allowable gap;
2. minimum gap, the minimum value of the allowable gap;
3. time before reduction, the amount of time that must expire before gap reduction can start, measured from when there is a serviceable conflicting call. If the conflicting call occurs while the phase is red, the time before reduction starts at the beginning of green. If the conflicting call is removed, this timer is reset;
4. cars before reduction, the number of vehicle actuations that must occur before gap reduction can start; and

5. time to reduce, which begins timing after the time before reduction and during which the allowable gap is reduced from the passage time to the minimum gap.

Figure A-11 shows the relationship between these parameters and the allowable gap.

Typically, the last vehicle to maintain the allowable gap should receive the full passage time to clear the intersection. However, during the period between the expiration of the allowable gap and expiration of the passage time, the phase operates as nonactuated. Any vehicle crossing the detector during this period would not be guaranteed the full passage time and may potentially be exposed to the dilemma zone.

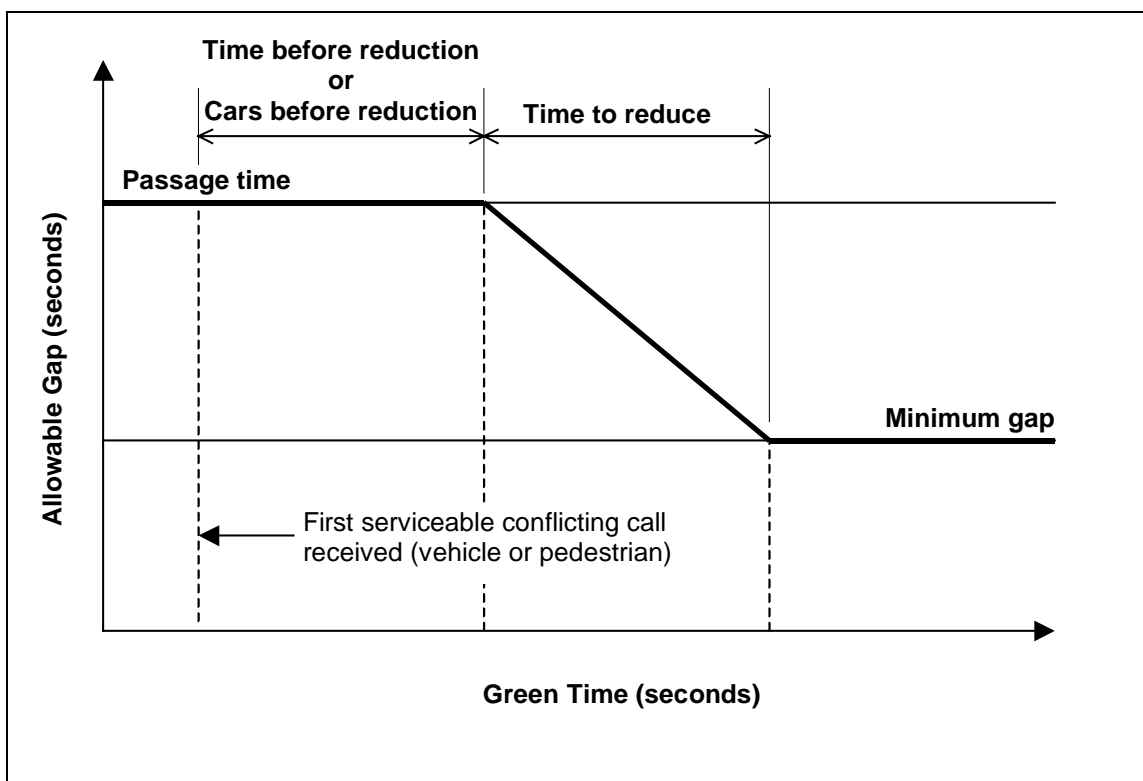


Figure A-11. Gap Reduction.

ALTERNATE MAXIMUM GREEN AND PASSAGE TIMES

“Rule-of-thumb” guidelines state that the maximum phase green times should be set as low as possible, but still high enough to serve queues approximately 1.3 times the average queue length (in vehicles) for the peak volume during the period the maximum green will be in effect (10). Alternatively, the maximum green time can be set equal to the optimal fixed-time green time, as determined by traffic signal optimization software such as PASSER III or Synchro, provided that the volume-to-capacity ratio is not greater than 0.85 (11).

Since traffic volumes (and hence queue lengths) vary through the day, traffic signal control efficiency can be improved by using different maximum green values throughout the day to reduce the amount of time that the signal controller operates with nonoptimal maximum green times. The NEMA TS 2-1992 standard (7) requires that a traffic signal controller provide two maximum green time values. In the Eagle and Naztec controllers these two maximum green times (Max 1 and Max 2) can be selected either by time-of-day control or by external input. Even though the use of two maximum green times are better than the use of only one maximum green time, two maximum green times are not enough to accurately “track” the optimal maximum green time as it typically varies through the day, as Figure A-12 illustrates.

The Eagle EPAC300 controller addresses this shortcoming by providing up to three additional maximum green times (Max 3, Max 4, and Max 5), as well as three additional passage times that can be selected by special function or by time-of-day setting. The additional passage times can be used to provide more “snappy” operation at certain times of the day (perhaps under high traffic volumes), while the additional maximum green times can be used to more closely “track” the optimal maximum green times, as shown in Figure A-13.

The Naztec 980 controller provides an “Alternate Programs” feature that can be used to change the maximum green times and passage times on a time-of-day basis. In addition, other phase-related settings such as minimum green times can also be set by time of day by using the Alternate Programs feature of the Naztec controller.

Even though the use of the alternate maximum green feature has the potential to improve traffic operations, it may be challenging to implement successfully, since proper implementation requires knowledge of how traffic demand varies through the day, as well as the ability to determine when alternate maximum green times should be in effect and what the value of these maximum green time values should be.

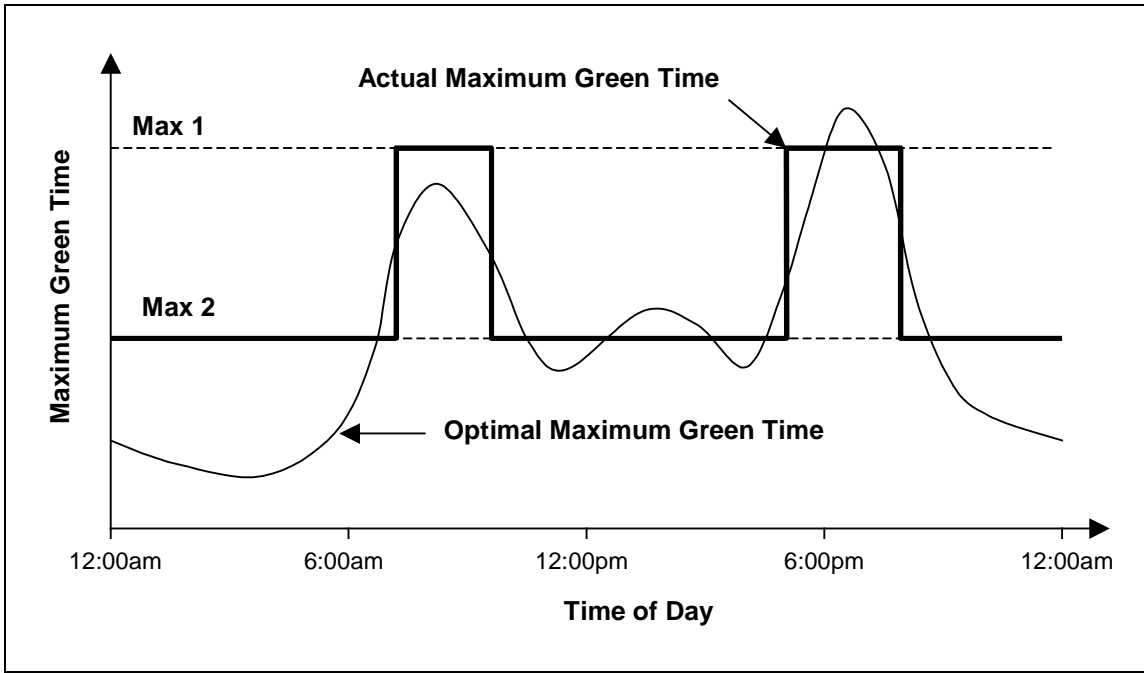


Figure A-12. Actual and Optimal Maximum Green Times with Max 1 and Max 2.

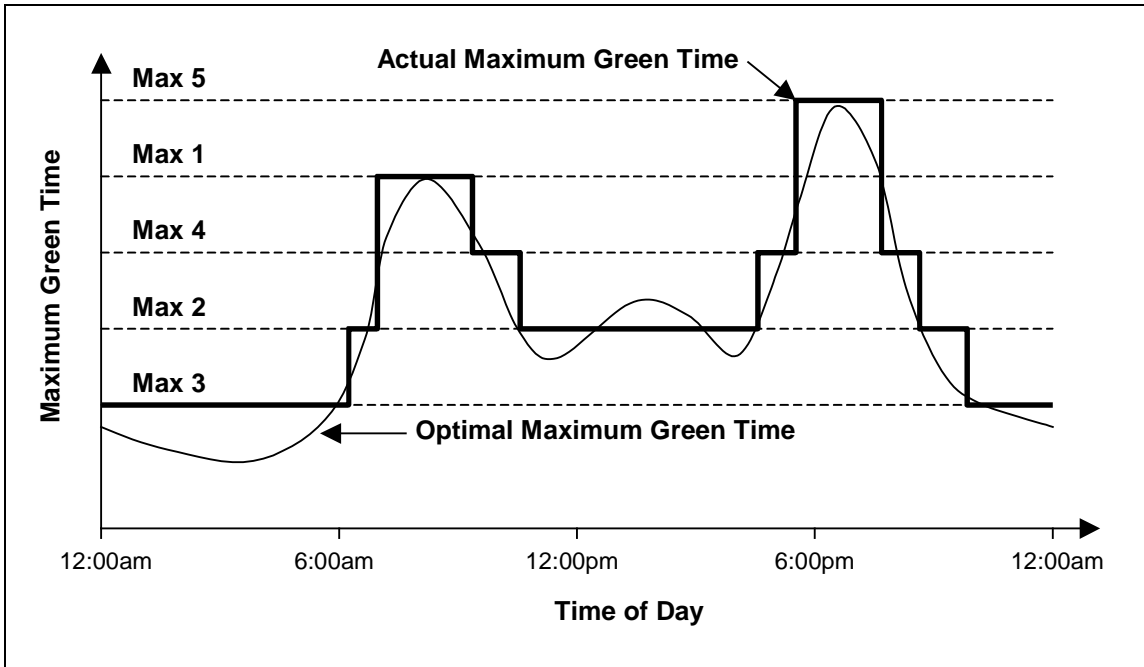


Figure A-13. Actual and Optimal Maximum Green Times with Alternate Max Greens.

The dynamic maximum feature described previously also has the ability to “track” the optimal maximum green times and can therefore automatically select a reasonably optimal maximum green time for any demand, as long as it lies between then normal max and the dynamic max limit. This approach requires less data and is easier to maintain, since it automatically adapts to long-term changes in time-dependent traffic demand. The disadvantage of the dynamic maximum feature is that it results in frequent max outs, since the feature tries to minimize the maximum green time and only increases the maximum green time when the phase maxes out twice in succession. These frequent max outs may be problematic, since the controller operates as nonactuated when maxing out and will terminate the green regardless of any traffic approaching, potentially leaving approaching vehicles in the dilemma zone.

ADAPTIVE PROTECTED-PERMISSIVE LEFT TURNS

The Eagle EPAC300 controller provides a useful feature called Adaptive Protected-Permissive operation. This feature measures the volume of left-turn traffic and the number of available gaps in the opposing through vehicle traffic to determine whether the left turn should operate as protected or permissive (2). Permissive operation is achieved by omitting the left-turn phase. The user sets the following variables to control the operation of the Adaptive Protected-Permissive feature:

- Minimum Turn Volume (MTV). If the left-turn volume is less than this value, the left-turn phase will be omitted and left-turn operation will be permissive.
- Minimum Vehicle Gap (MVG). Gaps measured in the opposing through movement detector calls have to be greater than this value to act as a “through gap window” that can accommodate a permissive left-turn vehicle. Multiple gap windows can be accommodated by larger gaps.
- Gap Percentage (GP). This variable represents the percentage of gap windows that left-turn vehicles utilize.
- Maximum Constant Call (MCC). If there has been a constant turn detector call for more than this time, the omit on the left-turn phase will be lifted and left-turn operation will be protected.

The measured left-turn volume and number of through gap windows during green are smoothed over a period of 5 minutes to yield the Smoothed Turn Volume (STV) and Smoothed Gap Windows (SGV) variables.

Permissive operation is provided when

$$STV < MTV \tag{1}$$

or

$$SGV \times (GP \div 100) > STV \tag{2}$$

Protected operation is provided when there has been a constant left-turn detector call longer than the Maximum Constant Call.

The Minimum Vehicle Gap and Gap Percentage values need to be set taking into account the lane and detector layout on the approach opposing the left-turn movement. With multiple detectors per lane (for example where multiple-detector dilemma zone protection is provided), it may be difficult to determine appropriate MVG and GP settings to assure proper operation.

Adaptive Protected-Permissive operation can only be used on the internal left-turn movements (phases 1 and 5) at a diamond interchange and is only compatible with the separate intersection control mode, since left-turn movements cannot be omitted in the three-phase and four-phase control modes.

Adaptive Protected-Permissive operation can only be used at locations suitable for protected-permissive operation. In addition, the detection layout must be able to provide accurate traffic counting and gap measurement, and for this reason, video detection may not be an appropriate detection technology to use with this feature.

It must be noted that use of Adaptive Protected-Permissive operation does create inconsistencies in the left-turn control provided in the interior of a diamond interchange. The effects of these inconsistencies on driver expectation must be thoroughly analyzed at each candidate site before such features are implemented. And, as permissive turns are allowed in certain situations, adequate sight distance must be present so that left-turning motorists can judge whether or not an adequate gap exists in the opposing traffic stream to accommodate their left-turn maneuver.

CHAPTER A-IV

APPLICATION GUIDELINES

This chapter provides implementation guidelines for the controller features identified in [Chapter A-II](#) and described in [Chapter A-III](#). For each controller feature, three sections will be provided:

1. a section on the applicability of the feature under different geometric, demand, and other conditions;
2. a section on the compatibility of the feature with specific controllers, detection technologies, or coordination modes; and
3. a section on programming the feature into the Eagle and Naztec controllers.

For all programming instructions, the controller is assumed to be in the diamond control mode. Please note that the programming instructions are intended to supplement the instructions in the Eagle and Naztec controller manuals (2, 3), and where any discrepancies exist, the controller manuals shall govern.

SEPARATE INTERSECTION MODE

Application

As described in [Chapter A-III](#), the separate intersection mode provides independent signal control at the two sides of the interchange. Separate guidelines are provided for the application of the separate intersection mode under free (i.e., noncoordinated) and coordinated conditions.

Free Separate Intersection Mode

The free separate intersection mode does not guarantee progression through the interchange. Therefore, operators should only use it where traffic volumes are low enough to be essentially random, since progression through the interchange is typically not expected under these conditions. As volumes increase, the random flow will change to nonrandom, platooned flow, which can be served more efficiently by providing progression through the interchange.

The following “rule-of-thumb” guideline can be used to identify the traffic demand conditions under which the noncoordinated (free) separate intersection mode will be applicable.

Use the noncoordinated (free) separate intersection mode when both the following conditions are met:

1. On the frontage roads, two or fewer vehicles are typically served by a frontage road phase at one time. This will typically occur at traffic volumes less than 120 vehicles per hour.
2. On the arterial, three or fewer arterial vehicles are typically stopped while the frontage road is being served. This will typically occur at two-way arterial traffic volumes less than 300 vehicles per hour.

Minimum phase recalls should be placed on the arterial phases (2 and 6) to allow the interchange to dwell in the arterial phases and so decrease the number of stops required by arterial traffic.

If conditions permit, interior left-turn movements should operate under protected and permissive phasing to achieve maximum benefit. The activation of the internal left-turn phases (phases 1 and 5) should be minimized under free separate intersection control to minimize the number of arterial traffic stops. This can be achieved by the following:

- Omitting the internal left-turn phases (phases 1 and 5) by time-of-day control, resulting in two-phase control. This should only be done during the times where sufficient capacity is available to efficiently operate the internal left-turn movement without protected phasing.
- Skipping the internal left-turn phases when not required, through the use of detector delays, detector switching, and nonlocking detector memory. For example, a delay of 4 to 8 seconds can be placed on the left-turn detectors to provide the opportunity for left-turners to accept gaps in the opposing traffic before the protected left-turn phase is called. In addition, the left-turn detector can be switched to the opposing through phase while the through phase is green so that left turns extend the opposing through phase and increase the probability that the left-turn maneuver can thus be serviced in permissive mode during the green time of the opposing through phase. Also, nonlocking detector memory should be used to minimize the activation of the interior left-turn phases in the absence of actual left-turn demand.
- Using the Adaptive Protected-Permissive feature of the Eagle controller to automatically decide whether to omit the interior left-turn phase, based on the left-turn demand and the number of gaps in the opposing through movement.

The noncoordinated (free) separate intersection mode should not be used where driver expectancy of three-phase or four-phase operation may compromise safety. Drivers used to three-phase control may expect lagging interior left turns, while the separate intersection mode provides leading left turns, if left turns are provided at all. Conversely, drivers used to four-phase control will still be provided with leading interior left turns, but may not expect the absence of interior progression that is always provided by four-phase control. The engineer should decide whether driver expectancy problems would preclude the use of the free separate intersection mode at the interchange.

Setback detectors on the frontage roads (typically provided for four-phase operation) can significantly improve operation in the noncoordinated separate intersection mode. Since the frontage road phase is called when the vehicle crosses the setback detector, the frontage road phase would typically be green or turn green shortly after the vehicle reaches the intersection, depending on the setback distance and vehicle speed. If setback detectors are used on the frontage roads, the minimum green times of the frontage road phases (phases 4 and 8) should be set considering the travel time from the setback detector to the stop line. Specifically, care should be taken to ensure that the frontage road green does not expire before the vehicle reaches the stop line. In the case where frontage road detectors are set back a significant distance from the intersection, the sluggish operation resulting from the long frontage road minimum green times required may negate the advantages of the noncoordinated separate intersection mode.

Coordinated Separate Intersection Mode

Under certain volume and geometric conditions, the use of the coordinated separate intersection control mode may be more efficient than three-phase or four-phase control. However, the wide range of volume and geometric conditions that can be in effect at an interchange precludes the development of generic guidelines to determine when the coordinated separate intersection will be more efficient than the three-phase or four-phase modes. For this reason, it is suggested that an analytical comparison of the different control modes should be performed, using a software tool such as PASSER III.

If the PASSER III analysis indicates an efficient non-three-phase or four-phase “lead-lead” solution, the ring-lag feature of the Eagle EPAC300 controller provides enough flexibility for implementation. This is done by selecting appropriate coordinated phases and setting the ring lag to the appropriate value. If the interchange does not form part of a larger coordinated signal system, operators should generally select coordinated phases to service a particular movement as it progresses through the interchange. If the interchange does form part of a larger coordinated signal system, the coordinated phases can be selected to service the coordinated movement phases on the arterial. In general, however, the coordinated phases should be selected based on the demand for progression. For example, the progression of the U-turns may not be useful if turnaround lanes are provided.

Coordinated phases and coordination parameters should also be chosen to minimize the probability of early return to the upstream coordinated phase, since this could disrupt progression through the interchange. Operators can minimize early return problems by:

- Selecting an appropriate coordination mode. For example, the “yield” coordination mode adds unused green time to the start of the coordinated phase, while the “permissive” mode adds unused green time to the end of the coordinated phase.
- Selecting the appropriate force off mode. For example, the “fixed force off” mode will force off phases at fixed points in the cycle, allowing unused split time to revert to the following phase, while the “floating force off” mode will force off phases after their assigned split, so that unused split time will revert to the coordinated phase.
- Using minimum phase recalls where appropriate. Minimum recalls will ensure that noncoordinated phases are not skipped, resulting in more predictable splits and offsets.

Typically, a combination of the “permissive” coordination mode and “fixed force offs” with minimum recalls will minimize early returns to the coordinated phase.

Unlike the Eagle controller, the Naztec controller does not provide a ring-lag feature and is therefore generally not suited for implementing the coordinated separate intersection mode. However, the Naztec controller may be used where a zero offset between the coordinated phases is appropriate.

Compatibility

Figure A-14 provides a flow chart of the compatibility of the separate intersection mode on the Eagle and Naztec controllers. As indicated, the coordinated separate intersection mode is available on both the Eagle and Naztec controllers, but only the Eagle controller provided a “ring-lag” feature at the time this guideline document was prepared.

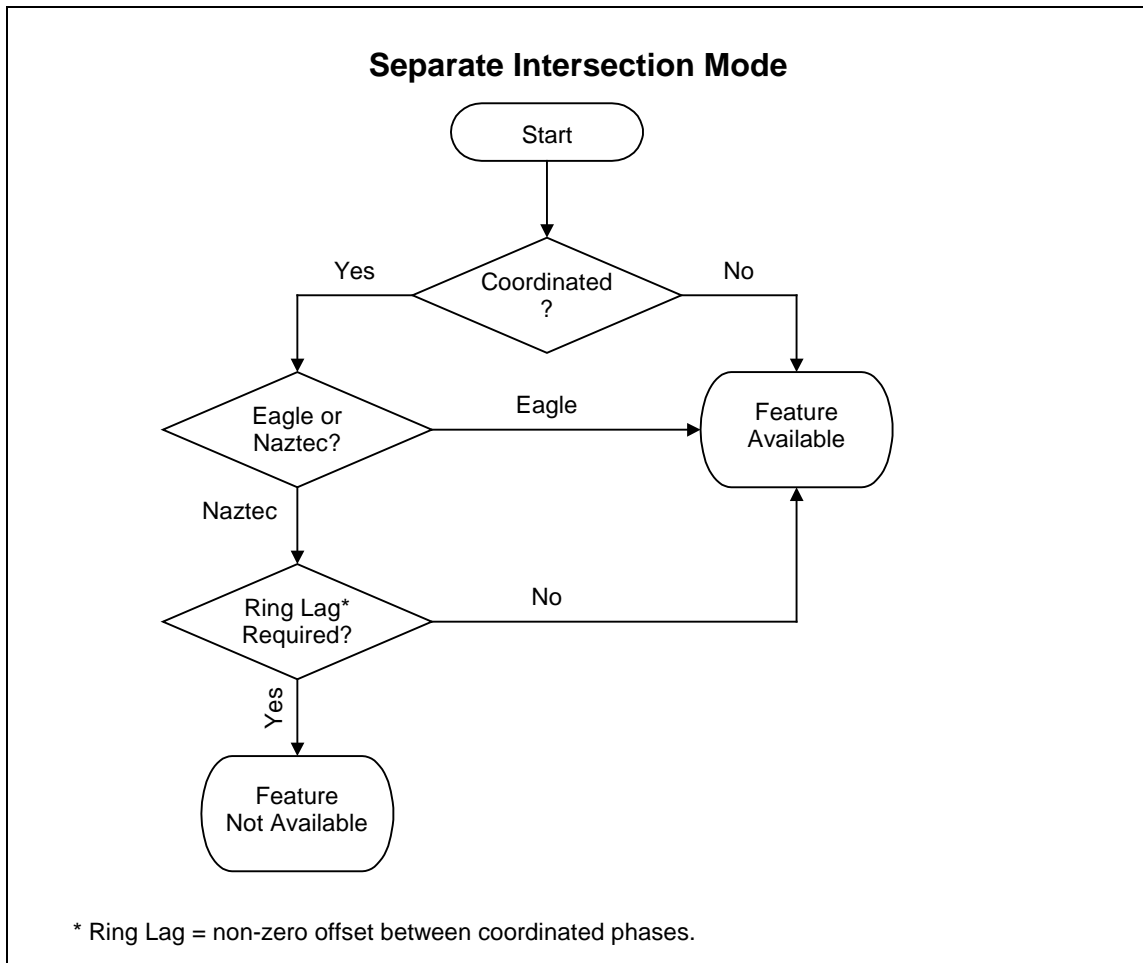


Figure A-14. Availability of Coordinated Separate Intersection Mode.

The separate intersection control mode is compatible with video and inductive loop detection. Detection is required on the interior left-turn movements, except where the interior left-turn phases (phases 1 and 5) can be omitted and the interior left-turn movements serviced as permissive movements.

Programming

Eagle EPAC300 Controller

On the Eagle EPAC300 controller, the separate intersection mode can be selected as the default diamond control sequence using the following steps:

1. Press “4” from the MAIN MENU to show the UNIT MENU.
2. Press “1” from the UNIT MENU to show the STARTUP & MISC MENU.
3. Set the ALT SEQUENCE field to “18” to select the separate intersection mode as the default diamond control sequence.

The internal left-turn phases (phases 1 and 5) can be omitted using the TBC (Time Base Control) Phase Function Mapping feature of the Eagle controller. This is done as follows:

1. Press “6” from the MAIN MENU to show the TIME BASE MENU.
2. Press “9” to show the TIME BASE PHS FUNC MAPPING screen.
3. Scroll down and assign the PHS-01 PHS OMIT and PHS-05 PHS OMIT functions to unused phase functions by entering a “1” in the appropriate FUNC SEL column. In most cases the default phase function mapping of Phase Function 9 for Phase 1 Omit and Phase Function 13 for Phase 5 Omit is appropriate.
4. Press “3” from the TIME BASE MENU to show the TRAFFIC EVENTS screen.
5. Enter one or more new events into the Traffic Events database, or change existing events, using the procedure described in the Eagle EPAC300 Product Manual (2), section 4.2.4. Activate the appropriate phase function (9 and 13 for the default mapping) by entering “1” into the appropriate P1-16 column. In the default phase function mapping, a “1” will be entered in the P9 and P13 columns to activate phase function 9 and 13, thereby omitting phases 1 and 5, respectively.
6. Make sure that the new event(s) in the Traffic Events database are called at the appropriate time by using the TIME BASE DAY EQUATE/TRANSFER screen (Press “6” from the TIME BASE MENU), as described in the Eagle EPAC300 Product Manual (2), section 4.2.7.

Naztec 980 Controller

On the Naztec 980 controller, the separate intersection mode can be set as the default diamond control sequence as follows:

1. Press “1” from the MAIN MENU to show the CONTROLLER screen.
2. Press “2” to show the UNIT/RING screen.
3. Press “1” to show the UNIT PARAMETERS screen.
4. Scroll down and toggle the Diamond Mode to “SEP,” selecting the separate intersection mode as the default diamond control sequence.

The next [section](#) contains information on changing the diamond control sequence by time-of-day.

DIAMOND CONTROL SEQUENCE CHANGE BY TIME OF DAY

Application

Both the Eagle and Naztec controllers provide the ability to change the diamond control sequence by time-of-day control. This is usually done to match the traffic signal control to the prevailing traffic conditions to achieve the best operation.

The decision on when to change the diamond control sequence should depend on the following factors (10):

- how traffic characteristics change throughout the day, in both demand and directional distribution;
- the quality of service that can be provided by the various diamond control sequences, in both free and coordinated mode; and
- how transition between the different control modes would affect traffic operations.

Typically, turning movement counts are needed to determine how traffic demand changes throughout the day. These traffic demands can then be analyzed using a software tool such as PASSER III to determine the optimal control mode at different times during the day. Usually, turning movement counts are only available during peak periods, for example, the morning peak period and the afternoon peak period. Diamond control sequence changes by time of day can be best evaluated if turning movement counts are available for more periods, including the noon peak period and perhaps an evening off-peak count as well.

Changes in the diamond control sequence should not take place too often, however. Diamond control sequence changes typically result in periods of transition that can be disruptive to traffic flow. For example, some movements may receive longer reds or shorter greens than usual, resulting in traffic backup under heavy volumes. Also, the controller may drop out of coordination when changing diamond control sequence, requiring a transition sequence to return to coordination. This transition period may also impact traffic flow adversely. Due to these inefficiencies, the diamond control sequence should not be changed more than once every 15 minutes (10).

Ideally, changes between different diamond control sequences should be kept to a minimum, since any change in the diamond control sequence has the potential to violate driver expectancy and thus lead to unsafe conditions. Wherever possible, diamond interchange control should first be optimized by maintaining the same diamond control sequence and changing cycle lengths, offsets, and splits in the case of coordinated control or actuated traffic control parameters such as maximum green times

in the case of free operation. Changes in the diamond control sequence should only be considered if this approach does not achieve the desired operation. However, changing the diamond control sequence by time of day, especially changing to the free separate intersection mode during off-peak periods with very low demand, could potentially be beneficial to diamond interchange operations.

The following issues should be taken into account when considering changing the diamond control sequence:

- Driver expectancy. Drivers moving through the upstream intersection of an interchange may expect the downstream intersection to be green, especially if the intersections are closely spaced or if a bridge or other structure obscures the downstream intersection signal. A change in diamond control sequence may violate this expectancy and create a potential safety hazard. The engineer should decide on the appropriateness and safety implications of changing the diamond control sequence by time of day.
- Detector layout. Detector layout and location may restrict which diamond control sequences are compatible with each other. For example, four-phase control can operate with detection only on the external approaches to the interchange, but three-phase and separate intersection control require detection on the internal left turns as well. Also, four-phase control operates most efficiently when the frontage road detectors are set back a significant distance, but three-phase control typically requires stop-bar detection to operate efficiently. Diamond control sequence changes can only be effective if the detector layout is compatible with the all the modes that it is desirable to switch between.
- Controller settings. Different controller settings may be required when operating in different diamond control sequences. Examples are: minimum green times, maximum green times, split times, etc. A change in the diamond control sequence would only be practical if the same controller settings can be used or if the controller settings can be changed by time of day in the same manner as the diamond control sequence is changed.

Compatibility

Both the Eagle and Naztec controllers support switching between four-phase, three-phase, and separate intersection mode, in both free and coordinated operation, by time-of-day control. However, as described previously, the Naztec controller does not offer the “ring-lag” feature required for optimal coordinated separate intersection mode.

Programming

Eagle EPAC300 Controller

Under nonactuated (free) operation the diamond control sequence can be set via special functions tied to a time-based auxiliary event. This is done using the following procedure:

1. Press “6” from the MAIN MENU to show the TIME BASE MENU.
2. Press “0” to show the TIME BASE SPC FUNC MAPPING screen.
3. Scroll down and assign each of the diamond modes functions (TX DIAMOND–FOUR PHASE, TX DIAMOND–THREE PHASE, and TX DIAMOND–SEPARATE) to an unused special function (say special function 6, 7, and 8), by entering a “1” in the appropriate SPC FUNC column (the 6th, 7th, and 8th columns in this example).
4. Press “4” from the TIME BASE MENU to show the AUXILIARY EVENTS screen.
5. Enter one or more new events into the Auxiliary Events database, or change existing events, using the procedure described in the Eagle EPAC300 Product Manual (2), section 4.2.5. Activate the appropriate special function (6, 7, or 8 in this example) by entering “1” into the appropriate S1-8 column. In this example, a “1” will be entered in the S6 column to activate special function 6 and call the four-phase mode, a “1” will be entered in the S7 column to activate special function 7 and call the three-phase mode, and “1” will be entered in the S8 column to activate special function 8 and call the separate intersection mode.
6. Make sure that the new event(s) in the Auxiliary Events database are called at the appropriate time by using the TIME BASE DAY EQUATE/TRANSFER screen (Press “6” from the TIME BASE MENU), as described in the Eagle EPAC300 Product Manual (2), section 4.2.7.

The different coordinated diamond control sequences can be set as coordinated plans that can be called by manual control or time-of-day control. This can be done as follows:

1. Press “5” from the MAIN MENU to show the COORD DATA MENU.
2. Press “3” to show the DIAL/SPLIT screen.
3. Select Level 1 on the DIAL/SPLIT screen for the DIAL and SPLIT you want to use for the coordinated separate intersection mode.
4. Set the ALT SEQ field for the appropriate offsets to “16,” “17,” or “18” to respectively activate the four-phase, three-phase, or separate intersection mode. For the separate intersection mode (ALT SEQ 18), be sure to set the appropriate ring lag by entering the offset between the coordinated phases in the R2 LAG field.

5. Select Level 2 on the DIAL/SPLIT screen for the appropriate DIAL and SPLIT and enter the split times and phase modes for the primary phases of the particular diamond control mode, using the diamond operation rules in section 19.7 of the Eagle EPAC300 Product Manual (2).
6. For manual control, select the appropriate Dial, Split, and Offset containing the coordinated separate intersection plan from the COORD MANUAL CONTROL screen (Press “2” from the COORD DATA MENU).
7. For time-of-day control, select the appropriate Dial, Split, and Offset from the TRAFFIC EVENTS screen (Press “3” from the TIME BASE MENU), as would be done for any other coordinated plan.

Naztec 980 Controller

On the Naztec 980 controller with Version 50 software, the diamond control sequence can be activated by time-of-day control using the following steps:

1. Press “2” from the MAIN MENU to show the COORD PARMS/PATTERN screen.
2. Press “6” to show the ALTERNATE TABLES screen.
3. In the row of the pattern number (PAT#) that will be used for the free separate intersection mode, scroll to the right and select either the “4 ϕ ,” “3 ϕ ,” or “SEP” entry under the “DIA” column to respectively select the four-phase, three-phase, or separate intersection mode.
4. Press “4” from the MAIN MENU to show the TIME BASED SCHEDULER screen.
5. Press “5” to show the action screen and enter the pattern number corresponding to the separate intersection mode (as defined in step 3) to an appropriate action (ACTN) number.
6. Press “4” from the TIME BASED SCHEDULER screen and enter the day plan to be used.
7. On the DAY PLAN screen, set up the times and the action number(s) defined in step 5.
8. Using either the Easy Schedule or the Advanced Schedule feature of the TIME BASED SCHEDULER, set up an appropriate schedule to use the day plan set up in the previous step, as described in Chapter 7 of the Naztec controller manual (3).

The above steps apply to both the free and coordinated modes of the Naztec controller. If coordination is required, set up the coordinated plan parameters as described in Chapter 6 of the Naztec controller manual (3), while taking into account the special requirements for coordination in the diamond mode, as described in section 11.3 of the Naztec controller manual.

CONDITIONAL SERVICE IN THREE-PHASE SEQUENCE

Application

Conditional service is only of value when operating in the three-phase diamond control sequence. And, even though conditional service is a potentially useful controller feature, it may not always improve traffic operation at an interchange.

Relatively simple application guidelines can be developed for the use of conditional service if the total intersection delay is used as the measure of effectiveness. Embedded in traffic analysis theory is a direct correlation between average intersection delay (in vehicle-hours per hour) and average queue length (in vehicles) at the intersection. Extending this concept to an entire interchange, we can argue that if conditional service (or any other controller feature) reduces the average queue length at an interchange, total delay will be reduced and traffic operations will improve.

Operators should consider two cases of conditional service, as shown in [Figure A-15](#). In the first case, the conditionally serviced interior left-turn phase is completely “shadowed” by the non terminating (high-demand frontage road) phase in the other ring, so that the barrier is crossed when the non terminating phase terminates normally, by either gapping or maxing out. Therefore, the conditionally serviced interior left-turn phase does not delay the termination of the non terminating phase, and consequently, the *non terminating phase controls*. In the second case, the conditionally serviced interior left-turn phase delays the normal termination of the non terminating phase. In this case, the non terminating phase, having gapped out in the absence of demand, has to wait for the conditionally serviced interior left-turn phase to terminate before the barrier can be crossed. Consequently, the *conditionally serviced phase controls*.

- Non terminating phase controls. This occurs when the green time demand on the two frontage roads differs by more than the sum of change interval of the terminating (low demand) frontage road phase and the green time of the following conditionally serviced left-turn phase. In this case, conditional service will improve traffic operations if the reduction in the average interior queue length due to conditional service is less than the increase in the average queue length on the low-demand frontage road due to conditional service. In general, this occurs when more vehicles are served by the conditionally serviced left-turn phase (including the interior through movement serviced by the associated overlap) than would have been served by the terminating frontage road phase, had it not terminated. If we assume that traffic arrivals on the frontage road are random, the following guideline can be used to determine if conditional service should be used when the non terminating phase controls.

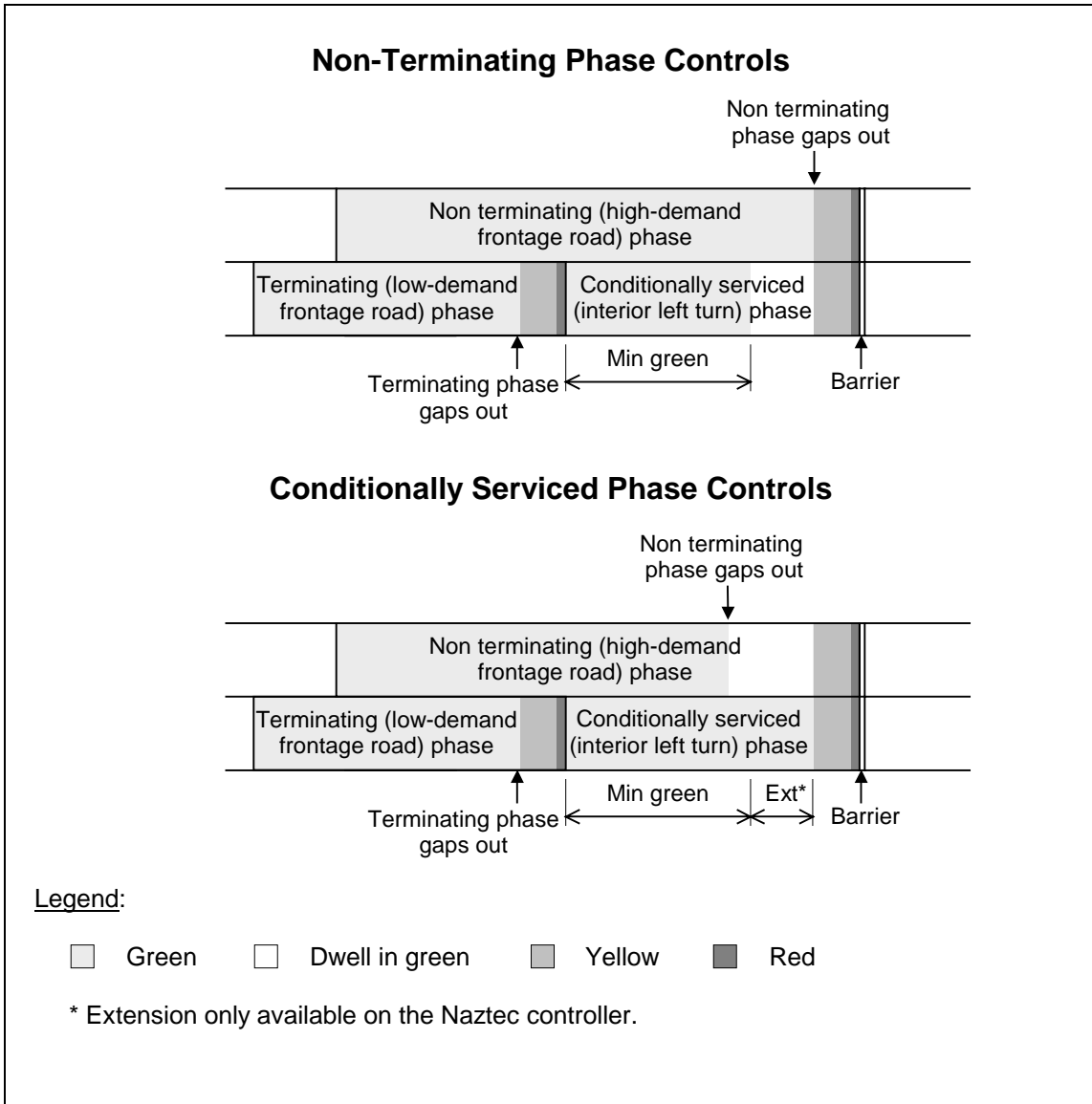


Figure A-15. Two Cases of Conditional Service.

When the non terminating phase controls, use conditional service if

$$V_{CS} > N_{CS} \times (V_{FR} \div 3600) \times [CIT_T + AGT_{CS}], \quad (3)$$

where:

V_{CS} = hourly traffic volume served by the conditionally serviced phase;
 N_{CS} = number of conditional service phase activations per hour;

V_{FR} = hourly traffic volume on the frontage road with lower demand;
 CIT_T = clearance time of the terminating (low demand) frontage road phase, in seconds; and
 AGT_{CS} = average green time of the conditionally serviced interior left-turn phase, in seconds.

The equality in [Equation 3](#) can be evaluated by a traffic survey while the interchange is operating with conditional service, or by using a technology such as hardware-in-the-loop traffic simulation ([12](#)). With hardware-in-the-loop traffic simulation, the same traffic demand conditions can be analyzed with and without conditional service using a traffic simulation model controlled by a real traffic signal controller.

- Conditionally serviced phase controls. The conditionally serviced phase will control when the barrier is crossed in the case where the required green times of the frontage roads are approximately equal, but not so high that the frontage roads routinely max out. In this case, the conditionally serviced interior left-turn phase will keep the non terminating frontage road phase from terminating even after it has gapped out. Under conditional service, the duration of the non terminating frontage road phase could be artificially extended by as much as the sum of the change interval of the terminating (low demand) frontage road phase and the green time of the following conditionally serviced interior left-turn phase. During this additional time, arriving traffic will join the queues on four approaches (two arterials, one frontage road, and one internal approach), while traffic is only served on two approaches (one frontage road and one internal approach), as shown [Figure A-16](#). The imbalance between arriving and served traffic makes it unlikely that the average queue length at the interchange will be reduced due to the conditional service. Consequently, conditional service should normally not be applied when the conditionally serviced phase would control, except if a detailed analysis or field observation indicates that it would indeed be beneficial.

In summary, the following “rule-of-thumb” application guidelines can be used to determine when conditional service should be used:

- The use of conditional service depends on a threshold time equal to the sum of the change interval of the terminating (low demand) frontage road phase and the green time of the conditionally serviced interior left-turn phase. Assuming a 5 to 7 second green time on the conditionally serviced phase and a 5 second change interval on the terminating phase, this threshold time is typically about 10 to 12 seconds.
- Do not use conditional service when the average green time demand on the two frontage roads differs by less than threshold time.

- When the green time demand on the two frontage roads differs by more than the threshold time, conditional service should only be used when more vehicles are served by the conditionally serviced left-turn phase than would have been served by the terminating (lower demand) frontage road phase, had it not terminated. If enough information exists, [Equation 3](#) can be used to determine if conditional service should be used.

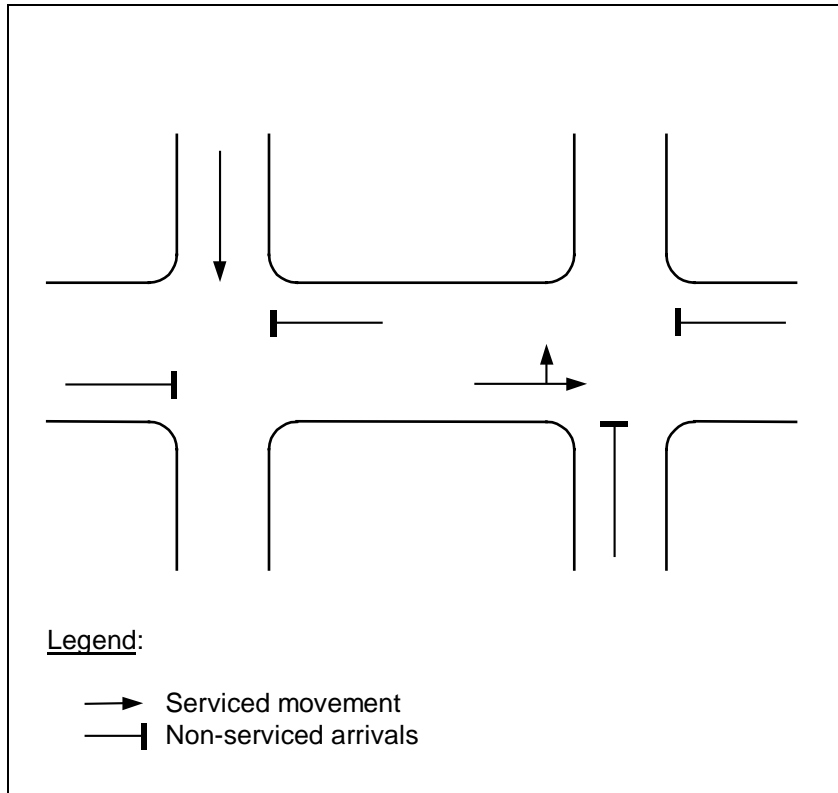


Figure A-16. Serviced Movements and Nonserved Arrivals during Conditional Service with the Conditionally Serviced Phase Controlling.

In practice, conditional service is independently activated on each side of the interchange. These application guidelines dictate that conditional service, if used at all, will only be active at one side of the interchange, so either phase 4 or 8 (or neither) will be selected for conditional service, except where conditional service can be selectively disabled on a time-of-day basis.

Since the applicability of conditional service depends on the threshold time presented above, shorter threshold times will increase the potential applicability of conditional service. Therefore, it is important that the minimum green time of the conditionally serviced phases (phases 10 and 14) be set to a relatively low value, such as 5 seconds.

A subtle difference exists in the operation of conditional service on the Eagle and Naztec controllers. Since the Naztec controller is designed for conditional reservice, the conditionally serviced phases (phases 10 and 14) are actuated, whereas on the Eagle controller the conditionally serviced phases are nonactuated. Therefore, it is important to set an appropriate maximum green time for the conditionally serviced phases on the Naztec controller to ensure that the non terminating phase controls when the barrier is crossed. Based on the guidelines presented above, the maximum green time of the conditionally serviced phase should be set slightly lower than the difference in the expected green time demand on the two frontage roads minus the duration of the change interval of the terminating frontage road phase.

When using conditional service, operators should use nonlocking detector memory on the interior left-turn phases (phases 10 and 14) to keep frontage road vehicles that may “cut the corner” and drive over the interior left-turn detectors from placing calls for conditional service when no real demand exists.

With the appropriate maximum green times or split times, conditional service can also be used to provide “unconditional” twice-per-cycle interior left turns, which can be useful in clearing a congested interchange interior. As with regular conditional service, unconditional twice-per-cycle interior left turns works best where there is a significant difference in the average green times required by the two frontage roads. By setting the maximum green times of the frontage roads so that they differ by more than the sum of clearance time of the shorter frontage road and the minimum green time of the interior left turn (the criterion for conditional service shown in [Figure A-6](#)), the conditional serviced phase can be forced to activate after the frontage road with the lower demand terminates, provided there is demand for conditional service. [Figure A-17](#) shows the resulting phase sequence. The need for and effect of twice-per-cycle left turns are best evaluated with a traffic simulation model such as CORSIM ([13](#)) or VISSIM ([14](#)) or with hardware-in-the-loop simulation.

Compatibility

[Figure A-18](#) provides a flow chart of the compatibility of conditional service on Eagle and Naztec controllers. Conditional service is available on Naztec controllers in both free and coordinated mode, while Eagle controllers provide conditional service only in free mode.

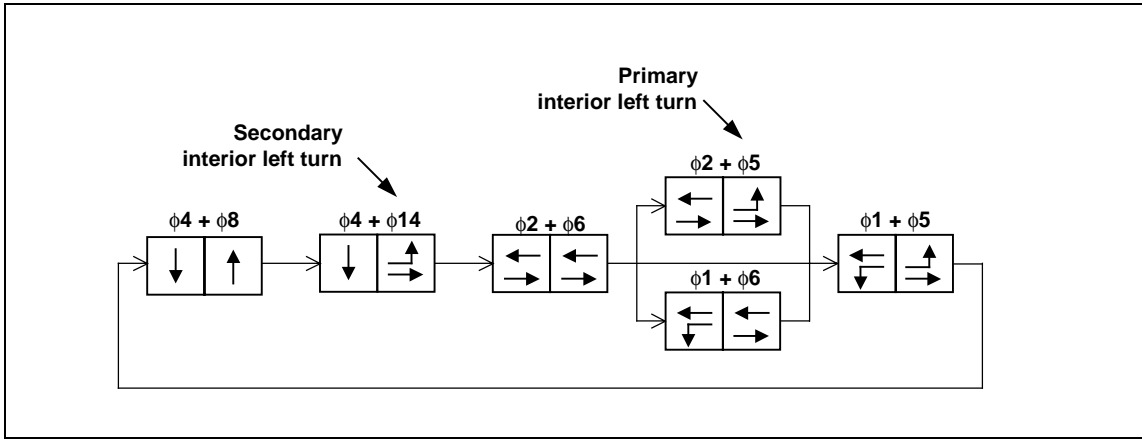


Figure A-17. Diamond Interchange Phasing with Twice-Per-Cycle Interior Left Turns.

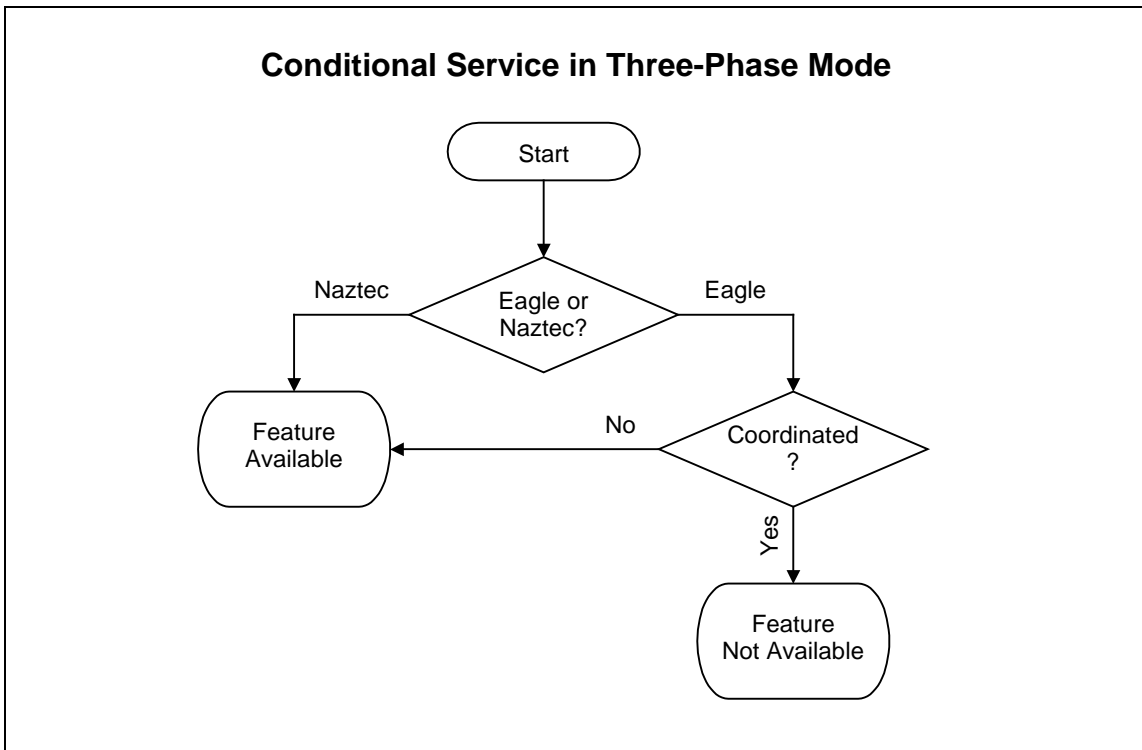


Figure A-18. Availability of Conditional Service in Three-Phase Mode.

Programming

Eagle EPAC300 Controller

By default, the conditional service feature is disabled on the Eagle EPAC300 controller in the diamond control mode. The following procedure can be used to enable or disable the conditional service feature:

1. Press “3” from the MAIN MENU to show the PHASE MENU.
2. Press “6” to show the N.LOCK & MISC screen.
3. To disable conditional service, enter “0” in the CON SER field for phases 4 and/or 8. To enable conditional service, enter “1” in the CON SER field for phases 4 and/or 8. Normally, if used at all, conditional service will only be used on one side of the interchange, and therefore will only be activated on phase 4 or phase 8.

Conditional service cannot be enabled or disabled by time of day on the Eagle controller. The decision whether conditional service should be used must take into account traffic operations throughout the day, but will usually depend on whether conditional service will improve operations during the peak periods.

Since the conditional service phases are nonactuated, it is important to set an appropriate minimum green time for the conditionally serviced phases (phases 10 and 14). This is done on the PHASE TIMES screen under the PHASE MENU.

Naztec 980 Controller

The Naztec 980 controller with Version 50 software also has the conditional service feature disabled by default. The following procedure can be used to enable or disable the conditional service feature:

1. Press “1” from the MAIN MENU to show the CONTROLLER screen.
2. Press “1” to show the PHASES screen.
3. Press “2” to show the OPTIONS screen.
4. Scroll down to the CONDIT’L SERVICE row.
5. To enable conditional service, toggle the CONDIT’L SERVICE entry for phases 4 and/or 8 to “X.” To disable conditional service, toggle the CONDIT’L SERVICE entry for phases 4 and/or 8 to “.” Normally, if used at all, conditional service will only be used on one side of the interchange, and therefore will only be activated on phase 4 or phase 8.

The conditional service feature can also be enabled and disabled on a time-of-day basis on the Naztec controller. This is helpful if conditional service is only needed at certain times of the day or if conditional service is needed at different sides of the interchange at different times of the day. The following procedure can be used to enable or disable conditional service on a time-of-day basis:

1. Press “1” from the MAIN MENU to show the CONTROLLER screen.
2. Press “1” to show the PHASES screen.
3. Press “6” to show the ALTERNATE PHASE PROGRAMS screen.
4. Press “2” and enter an existing or new Alternate Set number.
5. Enter the phases that will have conditional service enabled or disabled in the ASSIGNED ϕ row, starting from the left. These will typically be phases 4 and 8.
6. Scroll down to the CONDIT’L SERVICE row.
7. To enable conditional service, toggle the CONDIT’L SERVICE entry in the column corresponding to phases 4 and/or 8 to “X.” To disable conditional service, toggle the CONDIT’L SERVICE entry in the column corresponding to phases 4 and/or 8 to “.”
8. Enable all the other phase options you want to be active in this set. If you do not do this, all the other phase options will be disabled when this set is used!
9. Repeat steps 4 to 8 as appropriate.
10. Press “2” from the MAIN MENU to show the COORD PARMS/PATTERN screen.
11. Press “6” to show the ALTERNATE TABLES screen.
12. In the row of each pattern number (PAT#) that will be used, enter the appropriate Alternate Set number entered in step 4 under the “ALT: ϕ OPT” column.
13. Press “4” from the MAIN MENU to show the TIME BASED SCHEDULER screen.
14. Press “5” to show the action screen and enter the pattern numbers defined in step 11 to an appropriate action number (ACTN).
15. Press “4” from the TIME BASED SCHEDULER screen and select the day plan to be used.
16. On the DAY PLAN screen, set up the times and the action number(s) defined in step 14.
17. Using either the Easy Schedule or the Advanced Schedule feature of the TIME BASED SCHEDULER, set up an appropriate schedule to use the day plan set up in the previous step, as described in Chapter 7 of the Naztec controller manual (3).

DYNAMIC MAXIMUM GREEN TIMES

Application

The dynamic maximum green time feature is a traffic-responsive control feature that has the potential of improving traffic operations under unexpected or highly variable traffic conditions. One potential application of this feature would be to use it on the frontage road phases to be more responsive to unexpected increases in frontage road demand due to rerouting as a result of freeway incidents.

It is important to keep in mind that the dynamic maximum green time feature is responsive rather than adaptive in nature. It does not anticipate the need for longer maximum green times; it only reacts to insufficient maximum green times during previous phases. Therefore, the dynamic maximum green time feature is slow to respond to changing traffic conditions compared to adaptive control algorithms. This is not necessarily a bad characteristic, since fast responses based on estimated demand may lead to overcorrections, which in turn may lead to traffic instabilities. Implemented correctly, the dynamic maximum green time feature has the potential to improve traffic operations at diamond interchanges through a stable, responsive control strategy.

In most cases the dynamic maximum green time feature would be used to increase maximum green times from their default (Max 1 or Max 2) values. The feature also has the ability to decrease maximum green times from their default values, but doing so will lead to the phase more frequently maxing out, which could have safety impacts, especially on higher speed approaches where a dilemma zone may exist. However, interior left-turn phases with leading protected-permissive left turns may benefit from a reduction in their default (Max 1 or Max 2) values. In this case, each time the left-turn phase gaps out successively, the running maximum green time will be reduced so that a larger proportion of the left turners will be forced to perform permissive left turns. Conversely, when the left-turn phase maxes successively, the running maximum green will be increased to dissipate any interior left turn that may have formed due to insufficient gaps in the opposing through movement.

The dynamic maximum step should be kept relatively short to ensure a balance between the “responsiveness” of the phase and overall interchange efficiency. A dynamic maximum step size of 5 or 10 seconds will be sufficient in most cases.

Operators must select the dynamic maximum limit based on the application. Dynamic maximum limits should be selected to ensure adequate “cycling” of the interchange when the running maximum green time for one or more phases is equal to the dynamic maximum limit. For example, a higher dynamic maximum limit may be needed to protect frontage road phases from oversaturation due to freeway rerouting than the dynamic maximum limit required for protection against “normal” demand spikes on the arterial movement.

When the dynamic maximum feature is considered for application, it is important to consider the effect of the higher maximum green time on progression through the interchange. For example, under three-phase control, if the frontage road phase time is longer than the travel time through the interchange, left-turning traffic from the frontage road will find the downstream internal approach signal red, except if conditional service is active. Similarly, under four-phase control, dynamic maximums should not be provided on the transition intervals (phases 12 and 16) to avoid extending these phases to the point where interior progression cannot be provided. Care should be taken to fully understand the impacts of the longer green times potentially provided by the dynamic green time feature and how it interacts with the phasing sequence and other features such as conditional service.

The dynamic maximum green time feature is generally not useful under coordinated control, since phase maximums are usually inhibited.

The dynamic maximum green time feature is disabled by a maximum recall on a phase, either programmed as default, activated by time of day, or as the result of a failed detector.

Compatibility

The dynamic maximum feature is supported in both the Eagle and Naztec controllers. However, in the four-phase diamond control mode on the Naztec controller, phases 1 and 5 operate nonactuated, and are therefore not compatible with the dynamic maximum feature, as [Figure A-19](#) shows.

Programming

Eagle EPAC300 Controller

The dynamic maximum green time feature on the Eagle EPAC300 controller is activated through a special function and is programmed through the special detector data. The following steps are required:

1. Press “6” from the MAIN MENU to show the TIME BASE MENU.
2. Press “0” to show the TIME BASE SPC FUNC MAPPING screen.
3. Scroll down and assign each one or more of the DYNA MAX functions to an unused special function by entering a “1” in the appropriate SPC FUNC column. Three sets of dynamic maximum settings are available: DYNA MX3, DYNA MX4, and DYNA MX5.
4. Press “4” from the TIME BASE MENU to show the AUXILIARY EVENTS screen.

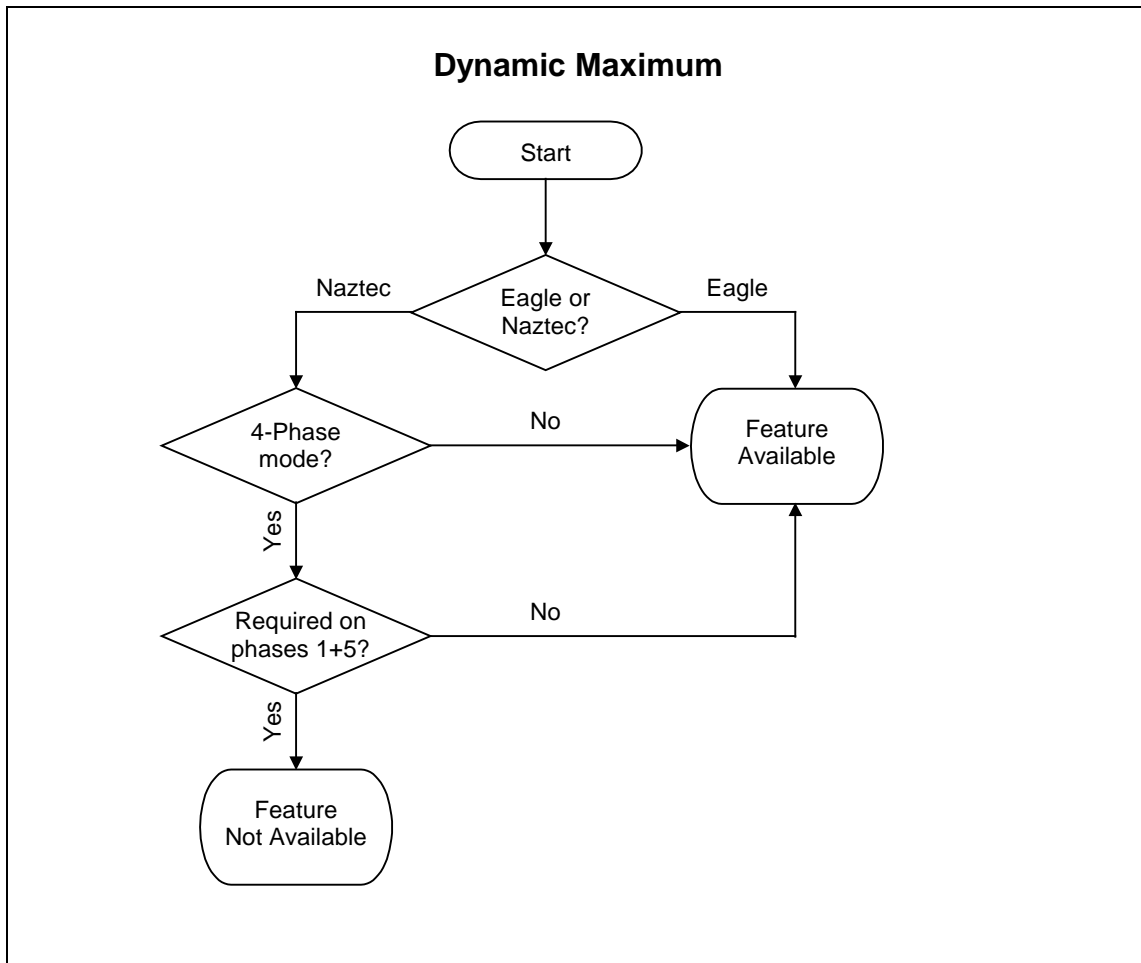


Figure A-19. Availability of the Dynamic Maximum Feature.

5. Enter one or more new events into the Auxiliary Events database, or change existing events, using the procedure described in the Eagle EPAC300 Product Manual (2), section 4.2.5. Activate the appropriate special function programmed in step 3 by entering “1” into the appropriate S1-8 column.
6. Make sure that the new event(s) in the Auxiliary Events database are called at the appropriate time by using the TIME BASE DAY EQUATE/TRANSFER screen (Press “6” from the TIME BASE MENU), as described in the Eagle EPAC300 Product Manual (2), section 4.2.7.
7. Press “3” from the MAIN MENU to show the PHASE MENU.
8. Press “8” to show the SPEC. DETECTOR screen.
9. If necessary, press “A” to select the DETECTOR TIMING DATA mode.
10. Based on the set of dynamic maximum settings programmed in step 3, select either VEH 33-40 and VEH 41-48 for phases 1-8 and 9-16, respectively, for DYNA MX3; or VEH 49-56 and VEH 57-64 for phases 1-8 and 9-16,

respectively, for DYNA MX4; or PED 1-8 and SPC 1-8 for phases 1-8 and 9-16, respectively, for DYNA MX5.

11. On the resulting screens, the detector timings will be mapped to the dynamic step and dynamic maximum values. Enter the dynamic maximum step value (in tenths of seconds) on the DM3STEP, DM4STEP, or DM5STEP line in the column that corresponds to the appropriate phase. Similarly, enter the dynamic maximum limit (in seconds) on the DMX3, DMX4, or DMX5 line in the column that corresponds to the appropriate phase.

Naztec 980 Controller

The dynamic maximum feature on the Naztec 980 controller with Version 50 software is somewhat easier to program than on the Eagle controller. The following procedure can be used to program the default dynamic maximum settings:

1. Press “1” from the MAIN MENU to show the CONTROLLER screen.
2. Press “1” to show the PHASES screen.
3. Press “1” to show the TIMES screen.
4. Scroll down to the DYMAXLIM and MAX STEP rows.
5. Enter the appropriate dynamic maximum limit and dynamic maximum step values in the DYMAXLIM and MAX STEP rows, respectively, under the column that corresponds to the appropriate phase.

The Naztec controller only provides one set of dynamic maximum settings that cannot be changed or deactivated by time of day.

DYNAMIC SPLIT

Application

In addition to dynamic maximum green times, the Eagle controller provides another traffic-responsive feature: dynamic splits, or in Eagle terminology, Coordinated Adaptive Split. This feature operates on the same principle as dynamic maximum green times by dynamically adjusting the split under coordination in response to an imbalance of demand on the noncoordinated phases. The Naztec controller does not provide a similar feature that is compatible with the diamond control mode.

This feature is generally applicable and can be used wherever coordinated control is used. However, a maximum recall, either programmed by the user, activated on a time-of-day basis, or resulting from a failed detector, will disable the dynamic split feature.

One requirement to ensure the correct operation of the dynamic split feature is to only program split times for the primary phases, as explained in the Eagle EPAC300 Product Manual (2), section 19.7. The primary phases for each diamond control sequence are as follows:

- Four-phase diamond mode: 1, 2, 3, 4, 5, 6, 7, 8, 12, and 16.
- Three-phase diamond mode: 1, 2, 3, 4, 5, 6, 7, 8, 9, and 13, but if either 3 or 4 is dark, 13 is not primary; and if either 7 or 8 is dark, 9 is not primary.
- Separate intersection mode: 1, 2, 3, 4, 5, 6, 7, and 8.

Since noncoordinated phase durations can exceed the programmed split times when the dynamic split feature is active, care should be taken to evaluate the effect of potential longer split times on progression through the interchange. For example, under the three-phase sequence, a sufficient increase in the splits for the frontage road phases may result in the lack of progression for left-turning traffic from the frontage road through the downstream signal.

Also, it should be kept in mind that dynamic splits are constrained by the minimum green times of the individual noncoordinated phases, and therefore appropriate minimum green times should be programmed to ensure proper operation.

Compatibility

Under diamond control the dynamic split feature is only compatible with the Eagle EPAC300 controller, as shown in [Figure A-20](#).

Programming

Eagle EPAC300 controller

The operator can use the following sequence to activate the dynamic split feature on the Eagle EPAC300 controller:

1. Press “6” from the MAIN MENU to show the TIME BASE MENU.
2. Press “0” to show the TIME BASE SPC FUNC MAPPING screen.
3. Scroll down to the COORD ADAPTIVE SPLIT function and assign it to an unused special function by entering a “1” in the appropriate SPC FUNC column.
4. Press “4” from the TIME BASE MENU to show the AUXILIARY EVENTS screen.
5. Enter one or more new events into the Auxiliary Events database, or change existing events, using the procedure described in the Eagle EPAC300 Product Manual (2), section 4.2.5. Activate the appropriate special function programmed in step 3 by entering “1” into the appropriate S1-8 column.

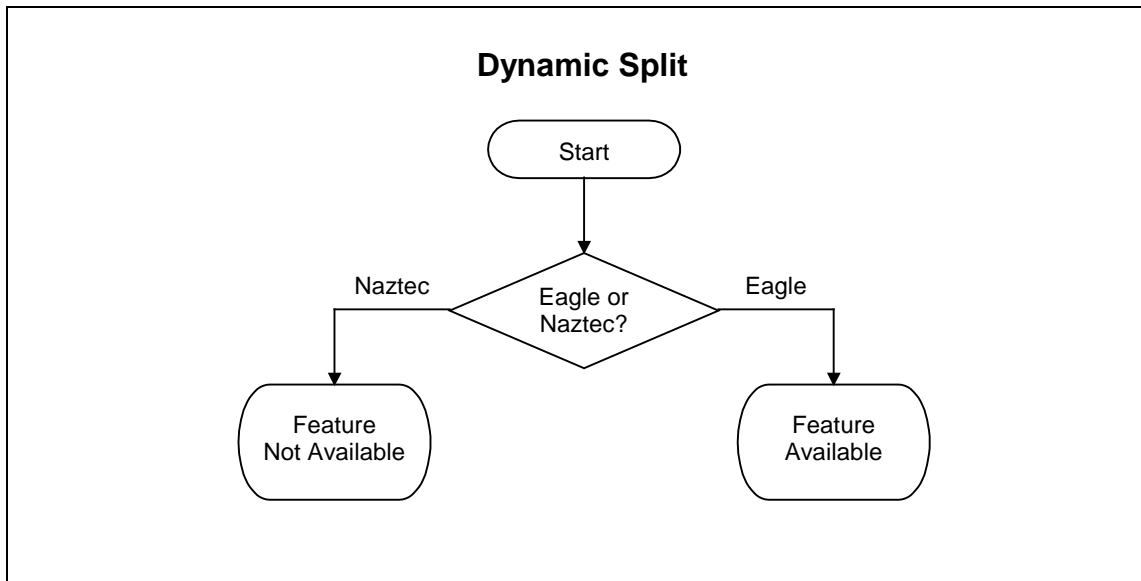


Figure A-20. Availability of the Dynamic Split Feature.

6. Make sure that the new event in the Auxiliary Events database is called at the appropriate time by using the TIME BASE DAY EQUATE/TRANSFER screen (Press “6” from the TIME BASE MENU), as described in the Eagle EPAC300 Product Manual (2), section 4.2.7.

VOLUME-DENSITY CONTROL

Application

Volume-density control provides two features: (i) variable initial timing and (ii) gap reduction timing. Application guidelines for each are provided below.

Variable Initial Timing

The application of variable initial timing is appropriate when only setback detectors are provided, or in the case where setback detectors are combined with stop-bar detectors that operate in a calling (nonextending) mode only. The variable initial timing feature should generally not be used with stop-bar detectors with an extending function.

The added initial value is typically set to $0.025 \times P$ seconds, where P is the percentage of the approach traffic in the critical lane (10). This value needs to be

adjusted when there are multiple detectors per lane on the approach, for example, in the case of multiple-loop dilemma zone protection or if a stop-bar detector is provided with the setback detector. In this case, the added initial can be set to $0.025 \times (P \div Q)$ seconds, where P is the percentage of the approach traffic in the critical lane and Q is the average number of detectors actuated by each vehicle that arrives during red or yellow.

The maximum initial time has to be long enough to service the queue that does not have any detection and can typically be estimated as $2 + 2 \times (D \div 25)$ seconds, where D is the distance from the stop line to the nearest setback detector, in feet.

The successful application of the variable initial timing feature depends on the accurate point detection of vehicles. For this reason, it is suggested that where inductive loop detectors are used, the detector amplifier is set to operate in pulse mode (10). The requirement of accurate point detection of vehicles introduces some challenges when using the variable initial timing feature with video detection. Video detection is more suitable for zone detection and may therefore not provide sufficiently accurate point detection of vehicles to successfully apply variable initial timing. This is especially true for setback detectors, where individual vehicles may be missed due to occlusion by trucks or other large vehicles. In addition, many video detection implementations rely on multiple detectors within the detection zone, which could result in multiple detector actuations per vehicle traveling through the detection zone, complicating the setting of the added initial value.

One potential application of variable initial timing is in the four-phase control mode. The four-phase mode typically features a setback detector some distance away from the frontage road stop line and a calling stop-bar detector that is deactivated whenever a specified gap occurs on green. Operators can use variable initial timing to avoid the need for a long minimum green time on the frontage road phase by providing a sufficiently long initial time to ensure that all queued vehicles on the frontage road are serviced, even if the stop-bar detector is deactivated by a gap while the queue is still being served.

Gap Reduction Timing

Gap reduction provides a mechanism to reduce the size of the allowable gap from the passage time down to a minimum allowable gap. This feature is generally used with setback detectors in conjunction with variable initial timing. This approach has largely been superseded by multiple-detector dilemma zone protection but may still be useful for application at diamond interchanges. One potential use of gap reduction would be to address the problem of inefficient operation due to unequal lane utilization on the external arterial approaches to the interchange. For example, the City of San Antonio has used the gap reduction feature to reduce the allowable gap on a multiple-lane arterial approach to a minimum value that would result in the arterial phase gapping out if only a single lane is being served during the latter part of the phase (15). This leads to the

“compaction” of arterial queues and an overall improvement in diamond interchange operations.

A similar approach can be considered where the diamond interchange operation is sluggish in the latter part of a phase. By reducing the allowable gap after an initial period, the probability of gapping out can be increased, resulting in shorter phase times, a shorter cycle length, and improved operations.

The gap reduction parameters are typically set to the values in [Table A-1](#) (10).

Table A-1. Typical Gap Reduction Parameters.

Parameter	Range (seconds)	Typical Value (seconds)
Minimum Gap	0.5 to 3.0	2.0
Time Before Reduction	0 to 30	0*
Time to Reduce	30 to 90	45

* The Eagle controller requires a minimum Time Before Reduction of 1 second to activate the gap reduction feature.

The values in [Table A-1](#) should always be verified and fine-tuned in the field to make sure they achieve the specific objective of gap reduction.

The Eagle and Naztec controllers also offer a volume-based reduction feature (cars before reduction), but this feature typically yields little in additional benefits to traffic and is difficult to set up correctly (10).

Gap reduction control is typically intended for isolated operations and depends on free traffic flow and should therefore not be used in coordinated systems or where oversaturated conditions are expected (10).

Typically, the last vehicle to maintain the allowable gap should receive the full passage time to clear the intersection. If the allowable gap is less than the travel time from the detector to the stop line, the last vehicle will see a yellow signal before entering the intersection, which may not be desirable. The operator can avoid this by activating the “last car passage” feature on the Eagle controller and the “guaranteed passage” feature on the Naztec controller. However, it should be kept in mind that during the period between the expiration of the allowable gap and expiration of the passage time, the phase operates as nonactuated and any vehicle crossing the detector during this period would not be guaranteed the full passage time and may potentially be exposed to the dilemma zone as the phase terminates.

Compatibility

The variable initial and gap reduction features are compatible with the diamond interchange control mode on both the Eagle and Naztec controllers. However, successful application of these features requires setback detectors with reasonably accurate point detection, which are typically not afforded by video detection. Therefore, the variable initial and gap reduction features are less suited for application at interchanges with video detection.

Programming

Eagle EPAC300 Controller

The variable initial and gap reduction features of the Eagle controller can be programmed using the following procedure:

1. Press “3” from the MAIN MENU to show the PHASE MENU.
2. Press “2” to show the DENSITY TIMES screen.
3. In the appropriate column for each phase, enter the added initial time (in tenths of seconds) in the AINI/10 row, the maximum initial time in the MAX INI row, the time before reduction in the TIM BEF row, the cars before reduction in the CAR BEF row, the time to reduce in the TIME TO row, and the minimum gap (in tenths of seconds) in the MGAP/10 row. The TIM BEF value must be greater than 1 second to activate the gap reduction feature.

If the gap reduction feature is programmed, the last car passage feature can be activated, if required, as follows:

1. Press “3” from the MAIN MENU to show the PHASE MENU.
2. Press “6” to show the N.LOCK & MISC screen.
3. To enable the last car passage feature, enter “1” in the LC PASS field for the appropriate phases. To disable the last car passage feature, enter “0” in the LC PASS field.

Naztec 980 Controller

The following procedure can be followed to program the variable initial and gap reduction features on the Naztec controller:

1. Press “1” from the MAIN MENU to show the CONTROLLER screen.
2. Press “1” to show the PHASES screen.
3. Press “1” to show the TIMES screen.

4. Scroll down, and in the appropriate column for each phase, enter the added initial time in the ADD INIT row, the maximum initial time in the MAX INIT row, the time before reduction in the TIME B4 row, the cars before reduction in the CARS B4 row, the time to reduce in the TIME TO row, and the minimum gap in the MIN GAP row.

If the gap reduction feature is programmed, the last car passage feature can be activated, if required, as follows:

1. Press “1” from the MAIN MENU to show the CONTROLLER screen.
2. Press “1” to show the PHASES screen.
3. Press “2” to show the PHASE OPTIONS screen.
4. To enable the guaranteed passage feature on a phase, scroll down and toggle the GUARANTD PASSAGE field for the phase to “X.” To disable guaranteed passage, toggle the GUARANTD PASSAGE to “.”

If the variable initial feature is programmed, the added initial feature must also be enabled under the detector options for the calling detector. This is done as follows:

1. Press “5” from the MAIN MENU to show the DETECTORS screen.
2. Press “2” to show the VEHICLE OPTIONS screen.
3. To enable the added initial feature on a detector, toggle the ADD.INIT field for the detector to “X.” To disable the added initial feature, toggle the ADD.INIT to “.”

ALTERNATE MAXIMUM GREEN AND PASSAGE TIMES

Application

Alternate maximum green and passage times can be used to manually adapt the actuated traffic control settings to changing traffic flows through the day.

Alternate maximum green times can be used to provide the most appropriate maximum green time for a period of relatively constant traffic flow. Typically, the maximum green time of an actuated phase is set to serve queues approximately 1.3 times the average queue length (in vehicles) for the peak volume during the period the maximum green will be in effect (10). Alternatively, the maximum green time can be set equal to the optimal fixed-time green time as determined by traffic signal optimization software such as PASSER III or Synchro, provided that the volume-to-capacity ratio is not greater than 0.85 (11). If the volume-to-capacity ratio lies between 0.85 and 0.95, the following equation can be used to calculate that maximum green time (11):

$$G_{\max} = G + \frac{X^2}{[(2 \cdot (1 - X))]} \quad (4)$$

where:

- G_{\max} = maximum green time (seconds);
- G = optimal fixed-time green time for the movement (seconds); and
- X = volume-to-capacity ratio for the movement.

There is usually no need to change passage times by time of day. An exception would be during high-demand periods, where the passage times may be reduced to provide “snappier” operation to improve interchange operation. Care must be taken not to introduce a dilemma zone when reducing the passage time.

Compatibility

Both the Eagle and Naztec controllers provide alternate maximum green and passage times.

Programming

Eagle EPAC300 Controller

The alternate maximum green and passage time feature on the Eagle EPAC300 controller is activated through a special function and is programmed through the special detector data. The following steps are required:

1. Press “6” from the MAIN MENU to show the TIME BASE MENU.
2. Press “0” to show the TIME BASE SPC FUNC MAPPING screen.
3. Scroll down and assign each one or more of the PAS+MAX functions to an unused special function by entering a “1” in the appropriate SPC FUNC column. Three sets of alternate maximum green and passage times are available: PAS3+MX3, PAS4+MX4, and PAS5+MX5.
4. Press “4” from the TIME BASE MENU to show the AUXILIARY EVENTS screen.
5. Enter one or more new events into the Auxiliary Events database, or change existing events, using the procedure described in the Eagle EPAC300 Product Manual (2), section 4.2.5. Activate the appropriate special function programmed in step 3 by entering “1” into the appropriate S1-8 column.
6. Make sure that the new event(s) in the Auxiliary Events database are called at the appropriate time by using the TIME BASE DAY EQUATE/TRANSFER screen (Press “6” from the TIME BASE MENU), as described in the Eagle EPAC300 Product Manual (2), section 4.2.7.

7. Press “3” from the MAIN MENU to show the PHASE MENU.
8. Press “8” to show the SPEC. DETECTOR screen.
9. If necessary, press “A” to select the DETECTOR TIMING DATA mode.
10. Based on the set of dynamic maximum settings programmed in step 3, select either VEH 33-40 and VEH 41-48 for phases 1-8 and 9-16 when using PAS3+MX3, or VEH 49-56 and VEH 57-64 for phases 1-8 and 9-16 when using PAS4+MX4, or PED 1-8 and SPC 1-8 for phases 1-8 and 9-16 when using PAS5+MX5.
11. On the resulting screens, the detector timings will be mapped to the alternate passage time and alternate maximum green time. Enter the alternate passage time (in tenth of seconds) on the PAS3, PAS4, or PAS5 line in the column that corresponds to the appropriate phase. Similarly, enter the alternate maximum green time (in seconds) on the MAX3, MAX4, or MAX5 line in the column that corresponds to the appropriate phase. Keep in mind that the alternate passage time is entered in tenths of seconds. Also, consult section 15.1 of the Eagle EPAC300 Product Manual (2) for instructions on specifying only alternate passage times or alternate maximum green times.

If there is no need for alternate passage times, the Max 2 alternate maximum green time can also be activated on a time-of-day basis using the following procedure:

1. Press “6” from the MAIN MENU to show the TIME BASE MENU.
2. Press “9” to show the TIME BASE PHS FUNC MAPPING screen.
3. Scroll down and assign any of the PHS-nn MAX # 2 functions to unused phase functions by entering a “1” in the appropriate FUNC SEL column. In most cases the default phase function mapping of Phase Function 1 for Phase 1 Max 2, Phase Function 2 for Phase 2 Max 2, etc., is appropriate.
4. Press “3” from the TIME BASE MENU to show the TRAFFIC EVENTS screen.
5. Enter one or more new events into the Traffic Events database, or change existing events, using the procedure described in the Eagle EPAC300 Product Manual (2), section 4.2.4. Activate the appropriate phase function (1 to 8, corresponding to Max 2 for phases 1 to 8 for the default mapping), by entering “1” into the appropriate P1-16 column.
6. Make sure that the new event(s) in the Traffic Events database are called at the appropriate time by using the TIME BASE DAY EQUATE/TRANSFER screen (Press “6” from the TIME BASE MENU), as described in the Eagle EPAC300 Product Manual (2), section 4.2.7.

Naztec 980 Controller

The following procedure can be used to program alternate passage times and maximum green times on the Naztec controller on a time-of-day basis:

1. Press “1” from the MAIN MENU to show the CONTROLLER screen.
2. Press “1” to show the PHASES screen.
3. Press “6” to show the ALTERNATE PHASE PROGRAMS screen.
4. Press “1” and enter an existing or new Alternate Set number.
5. Enter the phases that will have alternate passage times and/or maximum green times in the ASSIGN ϕ row, starting from the left.
6. Scroll down to the GAP, EXT and MAX1 rows and enter the alternate passage times and/or maximum green times in the columns corresponding to the phases entered in step 5.
7. Enter all the other phase times you want to use in this set. If you do not do this, all the other phase times will be set to zero when this set is used!
8. Repeat steps 4 to 7 as appropriate.
9. Press “2” from the MAIN MENU to show the COORD PARMS/PATTERN screen.
10. Press “6” to show the ALTERNATE TABLES screen.
11. In the row of each pattern number (PAT#) that will be used, enter the appropriate Alternate Set number entered in step 4 under the “ALT: ϕ TIME” column.
12. Press “4” from the MAIN MENU to show the TIME BASED SCHEDULER screen.
13. Press “5” to show the action screen and enter the pattern numbers defined in step 10 to an appropriate action (ACTN) number.
14. Press “4” from the TIME BASED SCHEDULER screen and select the day plan to be used.
15. On the DAY PLAN screen, set up the times and the action number(s) defined in step 12.
16. Using either the Easy Schedule or the Advanced Schedule feature of the TIME BASED SCHEDULER, set up an appropriate schedule to use the day plan set up in the previous step, as described in Chapter 7 of the Naztec controller manual (3).

ADAPTIVE PROTECTED-PERMISSIVE LEFT TURNS

Application

The adaptive protected-permissive left-turn feature provided by the Eagle EPAC300 controller can automatically determine whether left turns should operate as protected-permissive or permissive only, depending on the left-turn demand and the availability of gaps in the opposing through movement. If sufficient gaps exist in the opposing movement so that left turns can operate as permissive only, the left-turn phase is automatically omitted.

Operators can apply this feature at diamond interchanges, but only for the internal left-turn movements (phases 1 and 5) in the separate intersection control mode, since left-turn movements cannot be omitted from the rigid ring structures of the three-phase and four-phase control modes.

Adaptive protected-permissive operation should only be considered for use at locations suitable for protected-permissive operation. The feature should never be used at locations where protected-only left turns are required due to a left-turn accident history, multiple left-turn lanes, or restricted visibility of oncoming traffic.

It must also be noted that use of adaptive protected-permissive operation does create inconsistencies in the left-turn control provided in the interior of a diamond interchange. The effects of these inconsistencies on driver expectation must be thoroughly analyzed at each candidate site before such features are implemented. And, as permissive turns are allowed in certain situations, adequate sight distance must be present so that left-turning motorists can judge whether or not an adequate gap exists in the opposing traffic stream to accommodate their left-turn maneuver.

It is critical that the detection system be able to provide accurate traffic counting for the left-turn movement as well as accurate gap measurement for the through movement. Ideally, a single set of detectors crossing all lanes should be used for gap measurement on the opposing movement. If multiple detectors are used on the opposing movement, for example for dilemma-zone protection, gaps cannot be measured accurately since each vehicle actuates multiple detectors. In this case, an additional set of detectors may need to be installed and connected to the signal cabinet on a separate lead-in. Again, as with the volume-density features described previously, video detection may not be an appropriate detection technology for the adaptive protected-permissive left-turn feature due to shortcomings such as occlusion by large vehicles and inaccurate gap measurements.

If the detection system is suitable for implementing the adaptive protected-permissive left-turn feature, the following guidelines can be used to set the parameters of the feature:

1. Select the Minimum Turn Volume by estimating the number of cycles per hour, and multiplying this number with the average number of left-turners per cycle that will clear on yellow, typically 1.0 to 1.5.
2. Typically, the Minimum Vehicle Gap should be set to 5 seconds, except where a critical gap analysis indicates otherwise.
3. The Gap Percentage should typically be set to 100. However, this value can be used to “tweak” the adaptive protected-permissive left-turn feature by setting it to a value larger than 100 if the protected phase is activated too often, or to a value smaller than 100 if the protected phase is not activated often enough.
4. The Maximum Constant Call should be set to a value representing the upper limit of the expected delay at a permissive left-turn phase. A value no larger than 2 minutes is recommended.

It is critical that the operator fine-tune these parameters in the field and that signal operation is observed at various times of the day to verify that the adaptive protected-permissive left-turn feature indeed operates as expected. This may be a very time-consuming exercise, but when the adaptive protected-permissive left-turn feature is set up correctly, it should be able to adapt to any changes in traffic demand and typically not require much maintenance, provided that the detection system is operational.

An alternative to this feature may be to use a delay time on the left-turn detector to keep left-turning vehicles from immediately registering a call for service on the left-turn phase. If this is combined with detector switching (where calls for the left-turn phase are switched to the opposing through phase while the through phase is green), left-turn phase activations can be minimized and permissive operation can be used. However, flexibility is maintained in that protected operation will still be activated if there is any queue buildup on the left-turn movement. Another alternative would be to omit the left turn(s) by time-of-day control, as described in the guidelines for the Separate Intersection Mode.

Compatibility

Only the Eagle EPAC300 controller provides adaptive protected-permissive left turns, as [Figure A-21](#) shows.

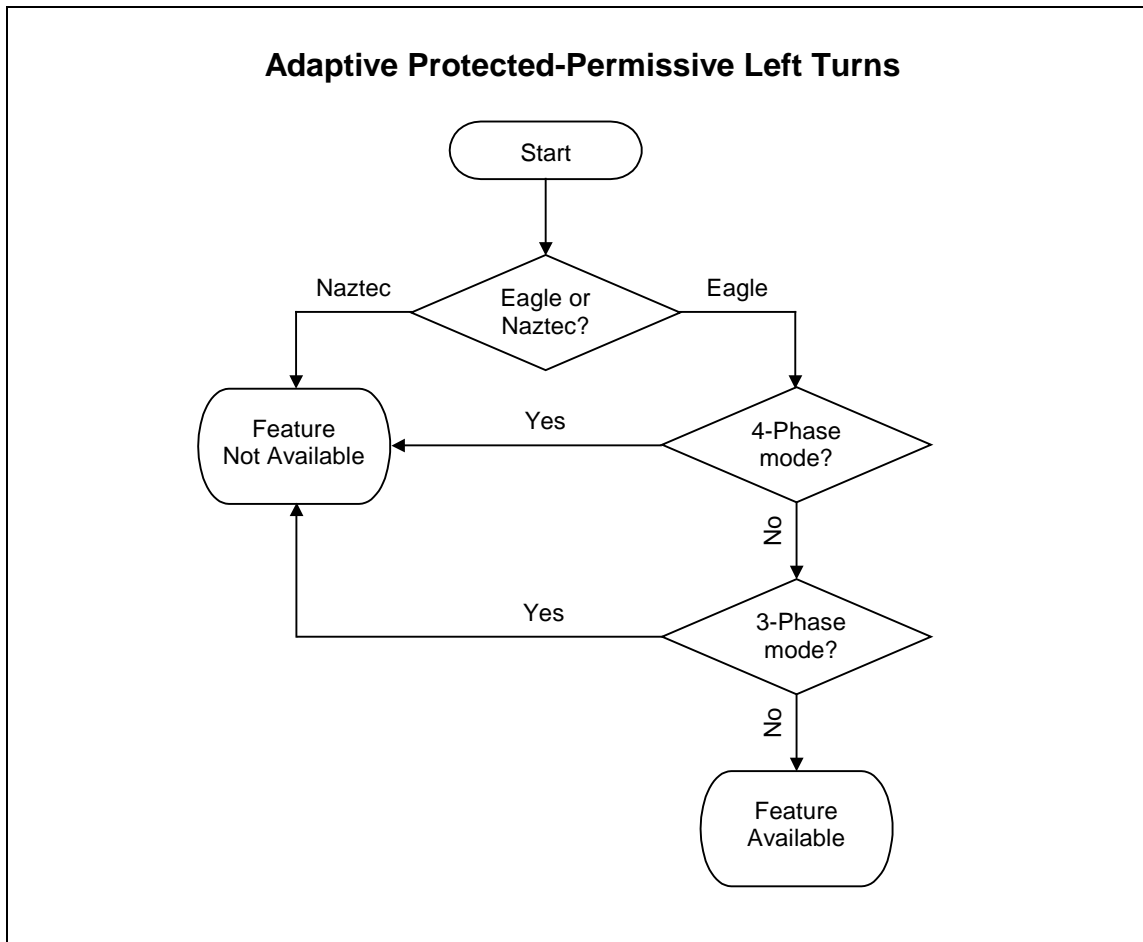


Figure A-21. Availability of the Adaptive Protected-Permissive Left-Turn Feature.

Programming

The following steps can be followed to program the adaptive protected-permissive left-turn feature on the Eagle EPAC controller:

1. Press “3” from the MAIN MENU to show the PHASE MENU.
2. Press “8” to show the DETECTOR CONTROL DATA MENU.
3. Select the appropriate detector group containing the detectors used for left-turn traffic counting and opposing through traffic gap measurement.
4. If necessary, press “A” to select the DETECTOR TIMING DATA mode.
5. In the OPERATION MODE row enter “5” for the left-turn detector and “6” for the opposing through detector. The phase assigned to the detector with Mode 5 will receive the phase omit when permissive left turns are required.

6. In the SWITCHED PHASE row enter the phase number of the left-turn phase under adaptive protected-permissive control for both the Mode 5 (left turn) and Mode 6 (opposing through) detectors.
7. Press “F” to return to the DETECTOR CONTROL DATA MENU.
8. Press “A” to switch to the DETECTOR TIMING DATA mode.
9. Select the appropriate detector group containing the detectors used for left-turn traffic counting and opposing through traffic gap measurement.
10. In the EXTEND row, enter the Maximum Constant Call (in minutes) for the Mode 5 (left turn) detector and the Gap Percentage (in percent) for the Mode 6 (opposing through) detector.
11. In the DELAY row, enter the Minimum Turn Volume (in vehicles per hour) for the Mode 5 (left turn) detector and the Minimum Vehicle Gap (in seconds) under the Mode 6 (opposing through) detector.

It is also possible to deactivate the adaptive protected-permissive left-turn feature by special function time-of-day control, but this should generally not be necessary if the feature is set up correctly to provide protected-permissive control under higher demand and permissive-only control under lower demand. Also, since the feature is only compatible with the separate intersection mode, it need not be disabled when changing to the three-phase or four-phase control modes.

REFERENCES

1. Texas Department of Transportation. *Departmental Specification TO-4048: Full Actuated Solid State Controller Unit (TS-2) with Diamond, TBC, Preempt, and Closed Loop Operation; and Base-Mounted TS-2 Cabinet Assembly*. Traffic Operations Division, Traffic Management Section, Austin, TX, 1998.
2. Eagle Traffic Control Systems. *EPAC300 Actuated Controller Unit Product Manual*. Austin, TX, 1997.
3. Naztec Incorporated. *Intersection Control Software, TS-2 Version 50.x*. Sugarland, TX, 2001.
4. Venglar, Steven P. and Peter J.V. Koonce. *PASSER III-98 Application and User's Guide*. Texas Transportation Institute, College Station, TX, 1999.
5. Trafficware Corporation. *Synchro Users Guide Version 5*. Albany, CA, 2000.
6. Courage, K.G., C.E. Wallace, and M.A. Hadi. *TRANSYT-7F Users Guide*. U.S. Department of Transportation, Washington D.C., December 1991.
7. National Electrical Manufacturers Association. *Traffic Controller Assemblies*. NEMA Standards Publication No. TS 2-1992. Washington D.C., 1992.
8. National Electrical Manufacturers Association. *National Transportation Communications for ITS Protocol (NTCIP) Object Definitions for Actuated Traffic Signal Controller Units*. NEMA Standards Publication No. TS 3.5-1996. Washington, D.C., 1996.
9. National Electrical Manufacturers Association. *Traffic Control Systems*. NEMA Standards Publication No. TS 1-1989. Washington D.C., 1989.
10. Orcutt, F.R., Jr. *The Traffic Signal Book*. Prentice Hall, Englewood Cliffs, NJ, 1993.
11. Venglar, S.P., P. Koonce, and T. Urbanik II. *PASSERTM III-98 Application and User's Guide*. Texas Transportation Institute, Texas A&M University, College Station, TX, 1998.
12. Engelbrecht, Roelof J., Christopher M. Poe, and Kevin N. Balke. *Development of a Distributed Hardware-In-The-Loop Simulation System for Transportation Networks*. Presented at the Transportation Research Board 78th Annual Meeting, Washington D.C., 1999.
13. ITT Systems & Sciences Corporation. *CORSIM User's Manual*. Version 1.04. FHWA, U.S. Department of Transportation, March 1998.
14. PTV Planung Transport Verkehr AG. *VISSIM 3.00 Users Manual*. Karlsruhe, Germany, 1999.
15. Herrick, G. Curtis. *Strategies for Improving Traffic Operations at Oversaturated Diamond Interchanges*. M.S. Thesis, Texas A&M University, College Station, TX, 1992.

