# TECHNIQUES TO IMPROVE SAFETY AND OPERATIONS AT SIGNALIZED DIAMOND INTERCHANGES IN NEVADA

**FINAL REPORT**


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## ABSTRACT

Similar to other states in the U.S., signalized diamond interchanges are one of the most common interchange types on Nevada's urban highways. The primary objective of this research was to develop strategies and techniques for improving traffic operations at urban diamond interchange locations in Nevada. In addition to conducting a comprehensive literature review of the state-of-the-art research on operating diamond interchanges, a nationwide survey of transportation agencies that are responsible for managing diamond interchanges was also conducted, from which the best practices on managing diamond interchanges were obtained. Based on the strategies and techniques identified through the literature review and the agency survey, two case studies were conducted in the Reno-Sparks area to demonstrate the strategies. In consideration of the specific traffic and geometric characteristics at the study sites, innovative signal phasing schemes and operational strategies were implemented. Before and after studies at the case study sites showed significant improvements over the existing signal control and timing. With the proposed signal control and timing, about 30% reduction in travel time and 25% reduction in stops were achieved at the test sites. The research results indicated that operations and perhaps the safety at most Nevada's urban diamond interchanges could be significantly improved by further developing and implementing such strategies and techniques.

Key Words: Diamond Interchange, Signal Timing, Strategies

## EXECUTIVE SUMMARY

Similar to other states in the U.S., signalized diamond interchanges are one of the most common interchange types on Nevada's urban highways. Due to high traffic demands and relatively close spacing between the two signals, diamond interchange locations are often major sources of congestion and crashes in urban highway systems. One of the major operational concerns in Nevada is the vehicle stops and queuing within a diamond interchange resulting from inefficient signal controls. The primary objective of this research was to develop strategies and techniques for improving traffic operations at urban diamond interchange locations in Nevada.

Major research tasks accomplished through this research include: (1) a comprehensive literature review and a nationwide agency survey; (2) development of strategies and techniques for operating diamond interchanges; (3) case studies to implement and test the effectiveness of the strategies in the Reno-Sparks area.

The research resulted in the following major findings and recommendations.

### *Findings*

- Based on the agency survey, most agencies prefer using one controller to operate a diamond interchange, although most diamond interchanges in Nevada are controlled by two controllers and no specific diamond phasing strategies are considered.

- Most agencies do not have specific guidelines on whether and when one controller or two controllers should be used for a diamond interchange. It seems that there is a continued debate on the advantages and disadvantages of either choice.

- It is apparent that the specific signal timing strategies for operating diamond interchanges are still not widely known to many traffic engineers. This is reflected by the lack of efficient signal operations at most of Nevada's urban diamond interchanges.

- TTI-4 phase (by itself or with some modification) proved to be most efficient in reducing the number of stops at an interchange, although it may result in longer delays when the traffic demands are high. However, using longer overlap phases can gain some efficiency with the tradeoff of some stops.

- As demonstrated in one of the case studies, innovative signal control strategies can be developed based on diamond interchange signal control principles for controlling closely-spaced paired signals. Such strategies are generally specific to the traffic flow and geometric characteristics at a site.

***Recommendations***

- Diamond interchange signal control strategies should be further implemented and evaluated at Nevada's urban diamond interchanges to improve their operations and safety.

- Further research is needed to address the issues related to using one controller versus two controllers for operating a diamond interchange. The research should address both efficiency and maintenance issues.

## INTRODUCTION

In the United States, approximately 70% of all freeway interchanges are diamond interchanges. In urban areas, the majority of diamond interchanges are signalized, which typically involve two closely spaced traffic signals with the distance ranging between 250 ft and 600 ft (see Figure 1).

As shown in Figure 1, a diamond interchange serves as a major interface between a freeway and a surface street arterial. High traffic demands and high turning traffic volumes are often observed at diamond interchange locations. Unlike other types of intersections, a diamond interchange also has unique traffic flow patterns. For example, the two left-turn movements on the arterial cannot be served simultaneously (i.e., they are not interlocking). The cross streets are one-way streets. Because of the close spacing and the unique traffic patterns at such locations, managing the operations of diamond interchanges has always been a challenge. One of the major safety and operational concerns is the queuing between the two signals, where queue spillbacks normally result in blockage of the interchange, imposing safety hazards and excessive delays to the roadway users. Traffic safety records often depict diamond interchange locations as being high crash locations, creating operational bottlenecks for urban roadway networks.

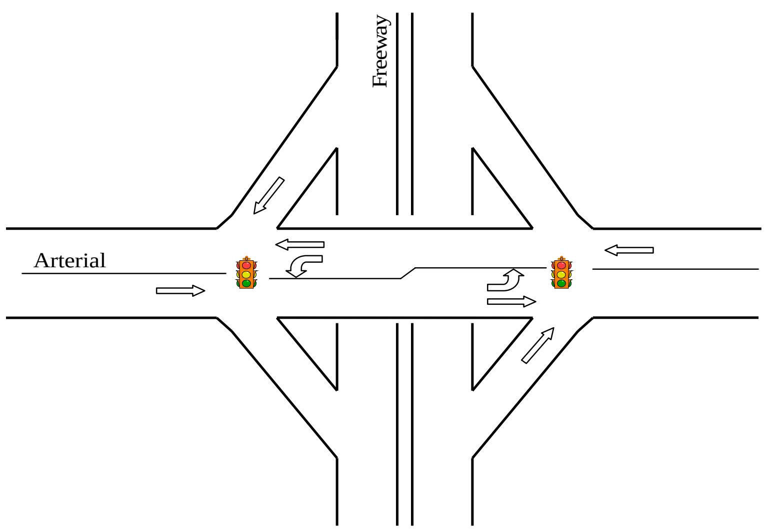



Figure 1 A Typical diamond interchange layout

Research efforts have been conducted in the past to address the operational concerns at diamond interchange locations. Pioneering studies date back to the mid 70's and research continues to be refined to date. Messer and Berry (1975) developed methodologies of optimizing pre-timed diamond phasing and timing for the two commonly used diamond phasing schemes, namely the four-phase and three phase operation. These two phasing schemes were developed based on the use of a single 8-phase NEMA controller. The four-phase scheme, also called TTI four-phase, is suitable for tight urban diamond interchanges (e.g., spacing of less than 350 ft). TTI four-phase can eliminate all vehicle stops within a diamond interchange when operated appropriately. The three-phase scheme is suitable when the spacing is relatively large (e.g., greater than 350 ft) and where enough storage space is available for the arterial left-turn vehicles. These two phasing schemes were later adopted by the Texas Department of Transportation as required specifications for any signal controllers installed at diamond interchange locations in Texas. Currently, only the Eagle controller (EPA 300) by Siemens and the Naztec controller by Naztec Inc. meet these specifications, (i.e., these controllers have the diamond phasing schemes built-in). With developments in signal control technologies, many advanced features have been added to modern signal controllers. As a result, major research efforts have also been conducted recently to improve diamond interchange operations using these advanced controller features. Other phasing schemes, such as lead-lag, lead-lead, lag-lead and lag-lag left turns, can also be used depending on the level of congestion and the available storage between the two intersections forming the diamond interchange.

Urban diamond interchanges in Nevada, particularly the Reno-Sparks metropolitan area, are often treated as two separate signalized intersections controlled by two traffic controllers. The signal timing schemes used to operate the two signals does not take into account the unique traffic characteristics that a diamond interchange poses. This research aims at addressing such operational deficiencies and improving traffic flow and safety at diamond interchange locations.

This research project involved the following specific objectives:

1. Development of strategies/techniques for improving existing urban diamond interchange operations in Nevada, particularly in the Reno-Sparks area; and

2. Implementation and testing of the strategies/techniques at selected diamond interchange locations.

The remainder of this report is organized as follows. First, a background section provides a summary of the literature related to designing and operating signalized diamond interchanges. This section also includes information obtained from a comprehensive agency survey regarding the state-of-the-art practices on operating diamond interchanges. Second, two case studies are presented to demonstrate the strategies developed through this research. Finally, the findings, conclusions and recommendations from the research are provided.

## BACKGROUND

This section includes a comprehensive literature review and an agency survey regarding the state-of-the-art and the state-of-the-practice in the area of diamond interchange operations. A particular focus is on the theories, policies and guidelines for designing and operating signalized diamond interchanges.

### *Literature Review*

Diamond interchanges are characterized by two one-way roads separated by a relatively small distance. The primary operational difference between diamond and regular intersections is that the path of opposing left turns at a diamond interchange interlock, so they cannot be served simultaneously. Although a diamond interchange includes two traffic signals, each signal has only a limited number of traffic movements; therefore, a typical 8-phase signal controller can control both signals at a diamond interchange.

De camp (1993) provided a general overview of different signal phasing schemes/sequences developed over the years to operate diamond interchanges. Each phasing scheme has its unique applications under specific traffic flow and geometric conditions. The key factor in selecting a phasing scheme is the volume per cycle for the four main left-turn movements relative to the available storage between the two signals. Among a variety of phasing schemes that can be used at a diamond interchange, TTI-4 phase, three phase, and four-phase lead-lag operation seem to be the ones better known to traffic engineers and have been used more often.

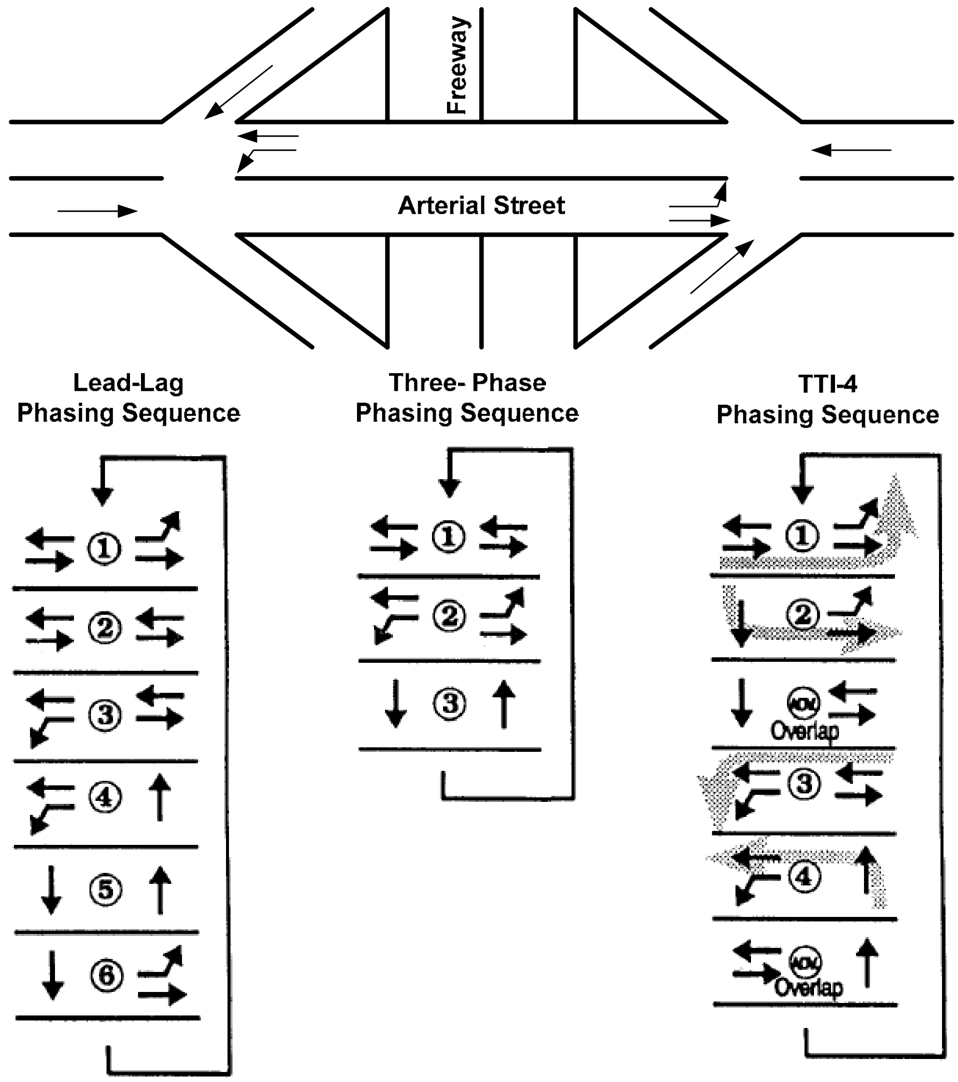



Figure 2 Diamond Interchange Popular Phasing Sequences

TTI-4 phase is characterized by serving the external movements sequentially and clockwise, such that vehicles going through a green at the first intersection receive a green at the second intersection (except for U-turns). This operation entails the use of leading left turns in the interior of the diamond. Another significant characteristic of the

TTI-4 phase is that the arterial street phase on one side can begin before the off-ramp phase on the other side terminates. This overlap is allowed because of the travel time through the interior of the diamond and can increase operational efficiency by compensating for some of the lost times. TTI-4 phase is extremely helpful when the left turns are heavy and the storage space of the diamond interior is small, as it keeps the interior of the diamond empty at all times. It also better meets drivers' expectancy as it always progresses drivers through the two signals without stopping in the middle of the interchange. However, TTI-4 phase can seriously limit the external splits by dividing the cycle length into four separate external phase splits. Hence, when the external movements have heavy volumes, TTI-4 phase is not preferable as queues may build up and spillback at those external approaches to block nearby intersections on the arterial street.

Three-phase operation is characterized by serving the off-ramps simultaneously, followed by the arterial street through movements, and then the interior left turns. At both intersections of the diamond the only difference from a regular intersection will be providing an additional phase to serve the interior left turn. Since the cycle length is divided into only three phases, Three-phase operation provides more flexibility when assigning green times and generally results in a shorter cycle length. Three-phase operation also works better when the traffic volumes of the two off-ramps are of similar magnitude. From a capacity point of view, Three-phase operation is more efficient than TTI-4 phase when the interior storage is adequate and internal queue spillback is less likely to occur. A lead-lag operation comes into play when the external approach volumes are too heavy to use TTI-4 Phase and the diamond interior storage is inadequate for the use of Three-phase operation.

It can be clearly seen from the above discussions that each of these phasing sequences should be applied under specific conditions in order to achieve the best performance, but none is better overall.

Messer and Berry (1975) examined the effects of minimum phase length and variations in the spatial arrangement of the diamond interchange ramp intersections on the capacity of diamond interchanges operated with TTI-4 phase. They calculated signal timings for a given set of geometric and traffic inputs under both unconstrained and constrained (minimum pedestrian crossing time) phase lengths. Two measures of the quality of traffic service afforded motorists–delay and load factor–were calculated for all the tested scenarios. The following are the major findings from their study:

- Signal performance depends on both the proportion of effective green time per cycle and the phase flexibility available to allocate the total green time in proportion to the demand-to-capacity ratios.
- Increasing the overlap for a fixed cycle increases the proportion of effective green time per cycle while tending to reduce phase flexibility between intersections.
- Longer minimum green times reduce phase flexibility, as do shorter cycles.
- Unbalanced demand volumes usually calls for considerable phase flexibility, but their effects can be reduced by judicious selection of the number of approach lanes.
- The proportion of effective green time per cycle will be greater than 1.0 if the total overlap is greater than the lost time. When this exists, the proportion of effective green time per cycle increases as the cycle length is reduced.
- Signal performance is rarely improved by decreasing cycle length below 70 seconds during rush-hour conditions.
- There is an indication that cycle length selection usually depends more on phase flexibility than on total external approach capacity of the interchange.
- For most practical cases, there will be a minimum delay cycle length.
- Phase overlaps of 10 seconds appear to be near to optimal phase overlap for a wide range of conditions. However a phase overlap of 7 seconds will operate effectively at rush-hour cycle lengths.

In selecting a design alternative, the sum of the ratios of average demands to saturation flow rates on the external approaches should not exceed 0.75, 0.80, and 0.85 for phase overlaps of 12, 16 and 20 seconds, respectively.

Messer et al. (1977) developed a computer program that can determine the best strategy to operate a pre-timed signalized diamond interchange to minimize the average delay per vehicle. The program is PASSER III and was originally developed by the Texas Transportation Institute for the Texas Department of Transportation. The program evaluates all possible basic interchange signal phasing sequences, including Three-phase, TTI-4 phase, Lead-lag, Lead-Lead, Lag-Lead, and Lag-Lag. A variety of interchange volume and geometry scenarios were tested using PASSER III and it was found that while TTI-4 phase and Three-phase normally provide good operations, other signal phasing sequences may produce even better operation under certain conditions.

Lee (1994) provided a review of diamond interchange analysis techniques. The paper presented and compared various methods to estimate capacity and other performance measures at diamond interchanges. The paper focused on practical day-to-day approaches to the problem for use mainly in planning applications. As illustrated by the author, efforts to evaluate the capacity of diamond interchanges started in the early 1960's when Capelle and Pinnell (1961) concluded that it is necessary to consider the two signalized intersections of the diamond interchange as a single unit when evaluating their capacity. This is due primarily to the requirements of signalization which should perform two basic functions: (a) all high-volume conflicting movements at both intersections must be separated, and (b) storing of vehicles between the two intersections must be kept at a minimum due to limited interchange interior spacing. To achieve these functions, they selected a phasing plan that has since become known as a four phase with overlap operation (i.e., TTI-4 Phase).

Furthermore, Lee (1994) discussed both the planning and the operational analyses of the Highway Capacity Manual (HCM), as they are the most widely used methods for capacity analysis by traffic engineers. The current HCM procedures still inappropriately analyze the two signalized intersections of a diamond interchange as two separate intersections.

Another method illustrated by Lee (1994) for the diamond interchange analysis is the CHURCH (CALTRANS district 4) method. It considers storage requirements between the two closely spaced intersections of the diamond and then establishes a signal timing to progress those movements with inadequate storage. The method used is intersection lane vehicle (ILV), which is equivalent to the sum of critical volumes specified in the planning method in the HCM. The entire interchange is treated as one operational unit with an assumed phasing, and the sum of ILV is computed for the entire interchange. In arriving at the ILV sum, the procedure considers the travel time between the signalized intersections by increasing the ILV sum by a penalty called the "equivalent ILV". The author concluded that there is an urgent need to develop acceptable analytical techniques for capacity analysis of a diamond interchange as a single unit. In the mean time, guidance should be provided to traffic engineers and practitioners as to how to evaluate the capacity of these facilities. Lee further stated that, at a minimum, the HCM should caution the users as to the possible overestimation of capacity when analyzing diamond interchanges as two separate intersections.

Lee et al. (2006) conducted a simulation study to evaluate actuated signal operations of congested diamond interchanges. Both Three-phase and TTI-4 phase were employed with four ramp spacings and traffic patterns. The major measures of effectiveness used in the study are throughput, average delay, and total stops. According to the study, TTI-4 phase gave less or comparable average delays (higher throughputs) for most traffic patterns at ramp spacings of 250 ft or more. Three-phase control gave less or comparable average delay (more throughputs) when the interchange had a balanced traffic pattern from all the external approaches. As for the number of stops, TTI-4 phase operation gave fewer stops than Three-phase for all the congested conditions investigated.

Engelbrecht et al. (2001) conducted a comprehensive study on improving diamond interchange operations using advanced controller features. They identified eight potentially useful controller features. The effectiveness of those advanced features was evaluated using traffic simulation with real traffic control hardware. Their study was specific to a one-controller operation of both signals at a diamond interchange. The advanced controller features evaluated included: (1) separate intersection mode, (2) diamond phasing sequence change by time of day, (3) conditional service, (4) dynamic minimum 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 human factors issues on implementation. One of the main findings of the research was that the realization of the potential usefulness of the separate intersection diamond control mode which is not commonly used. It was found that if used judiciously, it can provide more efficient control than Three-phase or TTI-4 phase. The separate intersection mode was found to 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.

Nelson et al. (2000) provided a synthesis of current practice and proposed guidelines for implementing both Three-phase and TTI-4 phase using some common features equipped with modern traffic signal controllers.

### *Agency Survey*

As one of the major tasks of this research, a nationwide agency survey was conducted regarding the policies and practices related to designing and operating diamond interchanges. The primary objective of the survey was to gather additional information that was not available in the published literature. Many experienced traffic engineers may have developed strategies and techniques for operating diamond interchanges, but such techniques may have been kept in-house without adequate publicity to other agencies. Adopting some of these little-known techniques could help in addressing the issues encountered in this research.

The survey was posted on-line and the web link was sent through email to over 100 contact persons representing different agencies working in the field of traffic operations and management (e.g. state transportation departments, traffic consultants and universities). About 24 responses were received, representing 13 states throughout the nation. Figure 3 shows the geographical distribution of the states that participated in the survey.

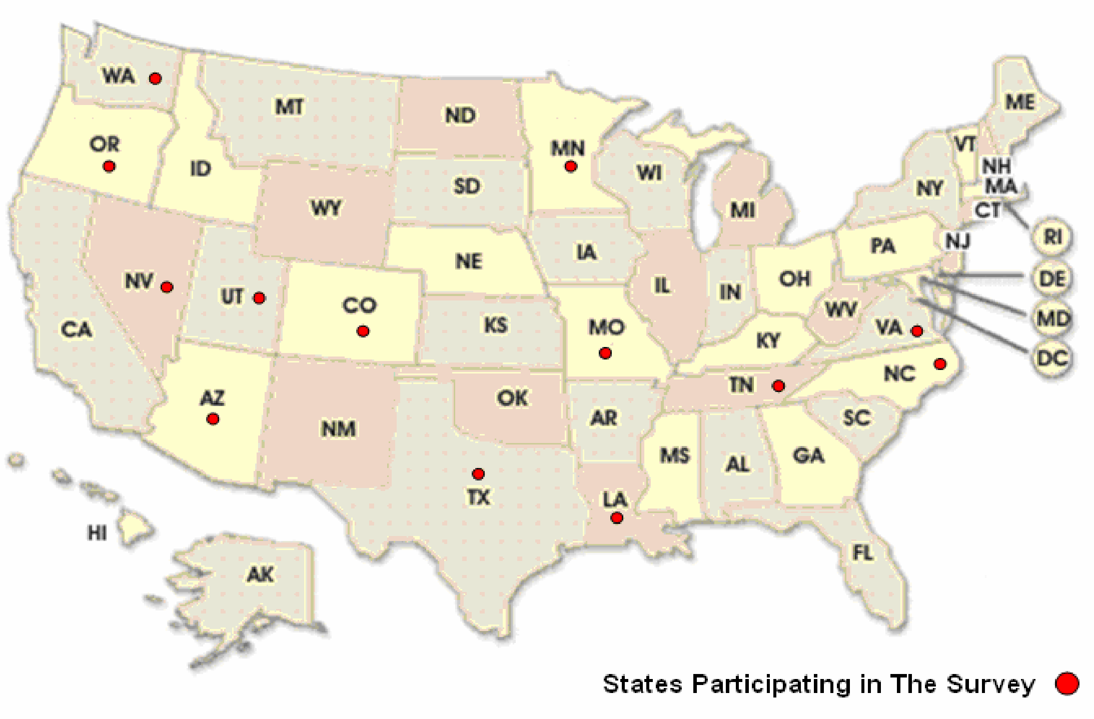



Figure 3 Geographical distribution of states participating in the survey

The following is a summary of the survey results organized by question. A brief summary is given after each question, representing the current practice and the surveyed expert's opinion with respect to the question. Appendix I includes the original responses from each respondent for each surveyed question and Appendix II provides a list of the persons who responded along with their organization and contact information.

*Main Considerations and Issues Regarding Safety and Operations at a Diamond Interchange*

Almost all the states surveyed, including Texas, Oregon, Colorado, Utah and Missouri, indicated that the main safety and operations issues at diamond interchanges are queue management and interaction related. When the spacing between the two intersections is too short (Tight Diamond), TTI 4-phase operation is preferred since it eliminates queues between the two intersections. On the other hand, when the spacing between the two intersections is relatively large, other operational strategies such as traditional 3-phase operations and lead-lag could be considered. In Texas, a tight diamond interchange has 250 ft of spacing or less between the intersections.

Other important issues were related to excessive delays, off-ramp queues and off-ramps right turn treatment in heavy traffic areas.

*The Number of Controllers Used and Agencies Preference*

The Survey results show that a high number of states are using one controller to operate a diamond interchange. Such states include Texas, Arizona, Utah, Louisiana and Colorado. The distance or the travel times between the two intersections are the main issues of consideration; if the diamond is tight (travel time less than 7 seconds) one controller operations is preferred. The major issue of using one controller is related to maintenance. Signal technicians feel single controller installations have too much input and wiring for a single cabinet. Technicians often complain that it is too hard to monitor both intersections at the same time while working a service call, especially when the intersection is far from the cabinet. Some traffic engineers also feel that one controller operation does not provide the same flexibility to change and manipulate the interchange signal operations. Some sight distance problems are also of concern when the distance between the two intersections is longer than 800 ft. This is related to the fact that it is preferred that motorists in the upstream signal should be able to see the downstream signal. The main advantage of using one controller to operate a diamond interchange is that it ensures coordination of all movements between the two intersections at all times, whereas using two controllers can result in signals easily going out of coordination and causing high level of service degradation at the interchange. In general, as long as the distance between the two intersections is not too large and no sight distance issues exist, it is preferred to use a single controller to operate the two intersections to maintain coordination at all times.

*Use of a Special Timing Plan*

The survey results show that the three most popular diamond interchange signal operation strategies are TTI 4-Phase, Traditional 3-Phase, and 3-phase with Lead-Lag operation. Selecting the suitable operation for each interchange is mainly dependent on the distance between the two intersections and the intensity of the different traffic movements. However, minor phasing adjustments are indicated as an operational requirement in some cases to deal with special situations, such as in Oregon, where a right-turn phase is added in some situations to accommodate heavy off-ramp right-turn movements. It is also worth mentioning that most of the responses agree that it is not recommended to switch the type of operations used at a diamond interchange frequently unless necessary, due to driver expectation issues.

*Type of Controller (Manufacturer, Model, and Software)*

As indicated by the survey results, the major manufacturers for the controllers and software are Eagle, Naztec, Wapiti, Econolite, and Safetran. The corresponding models are shown in Appendix 1 (see Question 4).

*Existing Guidelines*

Based upon the survey results, it became clear that no specific written guidelines exist for diamond interchange operations in any of the surveyed states. Texas, however, has a guideline for timing and coordinating diamond interchanges with adjacent traffic signals produced by the Texas Transportation Institute in the year 2000. In most cases the type of operations selected for a diamond interchange is dictated by a combination of analysis and the judgment and experience of the city traffic engineer.

*Special Treatments*

A number of special treatments are advised by some of the experts in the survey, including;

- Design with plenty of lane capacity and enough distance between two intersections to provide future operational flexibility. (Texas)
- Off-ramp right-turn signalization at heavy traffic areas. (Oregon)
- Reconstruction of Diamond Interchanges into Single-Point Urban Interchanges. (Utah)
- Double serving some heavy left-turn movements in the same cycle. (Texas)
- Studying the effect of U-turn movements on the capacity and safety of Diamond Interchanges. (Texas)
- Applying maximum recalls on left-turn movements to prevent premature gap-outs. (Utah)

In summary, the survey revealed the following major findings regarding agency practice in managing diamond interchange operations:

- Using one controller to operate a diamond interchange is preferred by most agencies, as it is more efficient in progression than using two controllers.
- Signal technicians and maintenance crews do not like using one controller, mainly because of excessive controller cabinet wiring and sight obstruction issues when the spacing is large (e.g., 800 ft).
- TTI-4-phase is preferred by most agencies due to perfect progression between the two signals.
- Almost all the surveyed agencies have no specific written guidelines available for operating diamond interchanges. The type of control and phasing are determined on a case-by-case basis.

- A unique application of TTI-4 phase is to use overlaps for controlling heavy right-turn movements at the ramp approaches. As it is common to have heavy right-turn volumes on the off-ramp approaches at diamond interchanges, further exploration of this operational technique is of significance to advance the state-of-the-art research and practice in the area of diamond interchange operations.

## CASE STUDIES

This section documents two case studies, illustrating the applications of the advanced strategies and techniques identified in this research. The case study sites were selected in the Reno-Sparks area, where operational problems existed due to the lack of diamond interchange control strategies. The case study sites included: (1) six signals near I-80 and Virginia Street; and (2) the US 395/Moana Lane diamond interchange.

### *Case Study 1: I-80 and Virginia Street Signals*

#### Site Description

The study site includes six closely spaced signalized intersections on the south side of the University of Nevada, Reno (UNR) campus. Before implementation of the new signal timing, the same signal control and signal phases were used for the AM, PM, mid-day and off peak periods. Only the phase splits and offsets were different during the four time periods. A cycle length of 90 seconds was used during all time periods.

Figure 4 through Figure 6 show the existing AM, Midday and PM peak hour traffic volumes and lane configurations. The before signal control and signal phases are shown in Figure 7. The six signalized intersections were controlled by six individual signal controllers. Although the signals were coordinated with time-of-day plans, significant queuing and stops were observed due to the lack of consideration of the unique traffic flow patterns within the network.

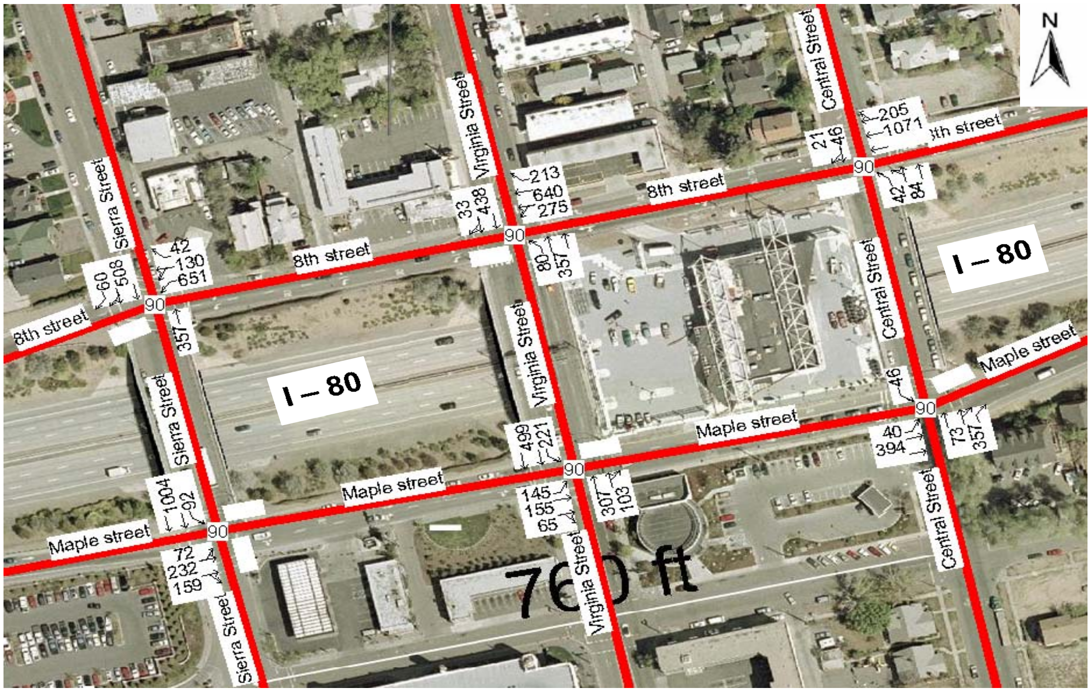


Figure 4 Existing traffic volumes, lane configuration and cycle length, AM Peak

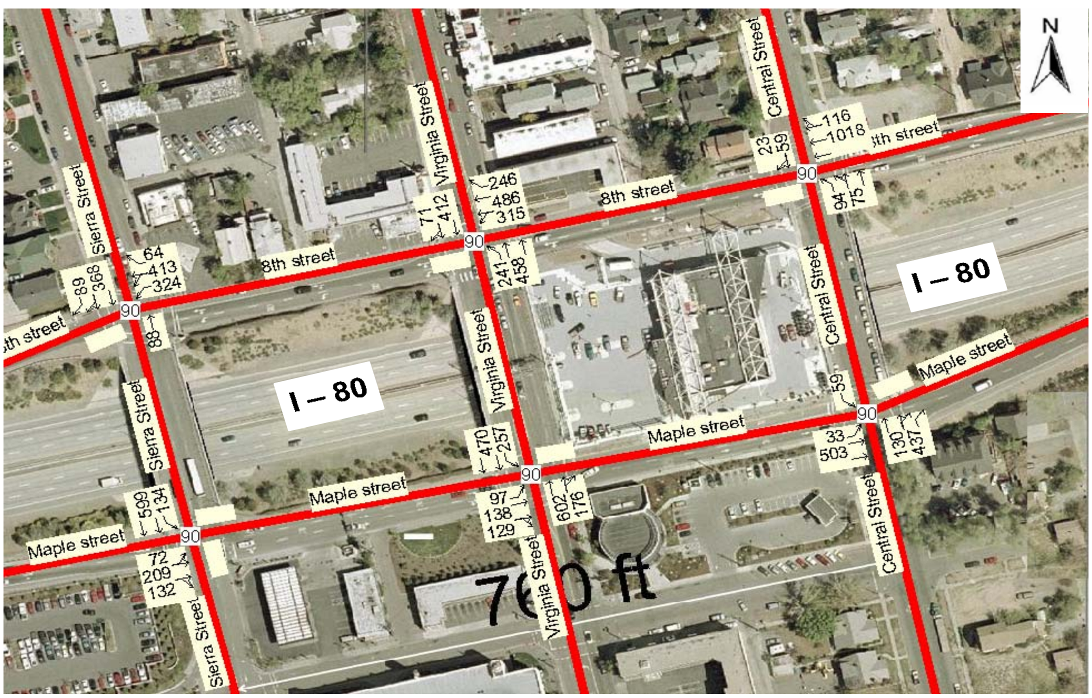


Figure 5 Existing traffic volumes, lane configuration and cycle length, Midday Peak

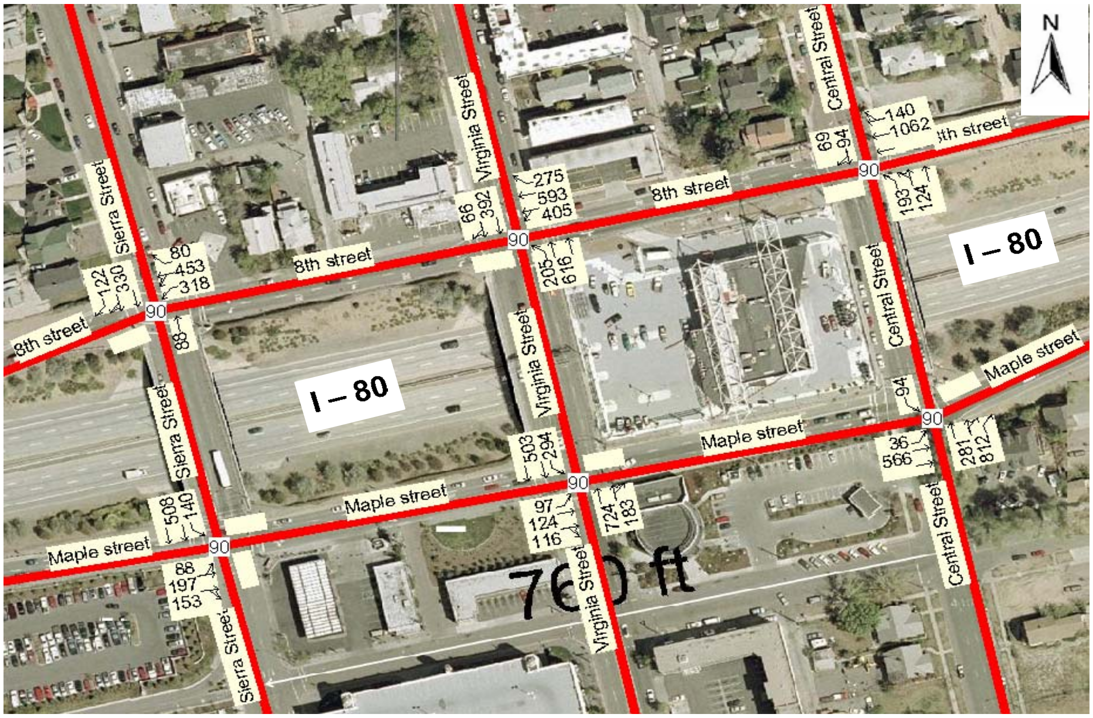



Figure 6 Existing traffic volumes, lane configuration and Cycle length, PM Peak

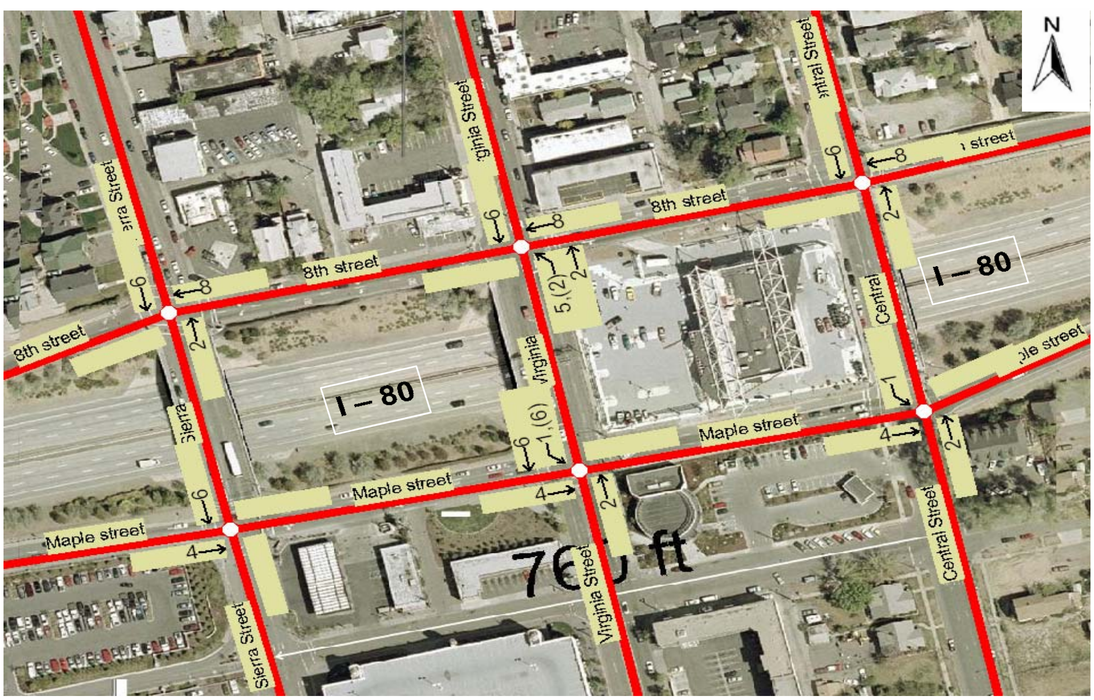



Figure 7 Existing control and signal phasing numbers – All Periods

Both 8th Street and Maple Street are one-way streets, serving traffic flow exiting and entering the I-80 freeway. The approximate distance between 8th Street and Maple Street is 300 feet. Virginia Street is a two-way four lane arterial, serving major traffic flow between the UNR campus and downtown Reno. As can be seen, the two signals on Virginia Street form a standard tight diamond interchange. Center Street and Sierra Street are partial one-way/two-way arterials, mainly serving downtown Reno traffic exiting and entering the I-80 freeway. The signals on these two streets do not form standard diamond interchanges because of the absence of certain traffic movements. For example, the signals on Sierra Street do not have the northbound left-turn movement at 8th Street and the northbound through movement at Maple Street. The signals on Center Street do not have the through movement at Maple Street, and split phasing was used for the north/south directions at both signals. No left-turn traffic is allowed for the westbound approach at the Center Street/8th Street intersection. Despite such differences, these signals do have traffic flow patterns and signal spacing that closely resembles a tight diamond interchange. We later refer to the signals on the three arterial streets as paired signals, where a single controller will be proposed to control each pair of signals.

As shown in Figure 4 Figure 5 Figure 6, major traffic flow movements at the study site include the I-80 westbound off-ramp (i.e., the westbound approach at Center Street/8th Street) to southbound Virginia Street and southbound Sierra Street, as well as southbound Virginia Street to I-80 eastbound. The "before" timing plan focused on progression of traffic along 8th street; however, the lack of efficient phasing and coordination often resulted in stops and queues between the paired signals on Virginia Street and on Sierra Street.

**Proposed Control**

The proposed "After" control calls for using three controllers to control the six intersections (see Figure 8 and Figure 9): one for the paired signals on Virginia Street using the standard TTI-4-phase scheme, one for the signals on Center Street and one for the signals on Sierra Street. The signal control schemes for Center Street and Sierra Street were derived based on similar concepts of diamond interchange control schemes.

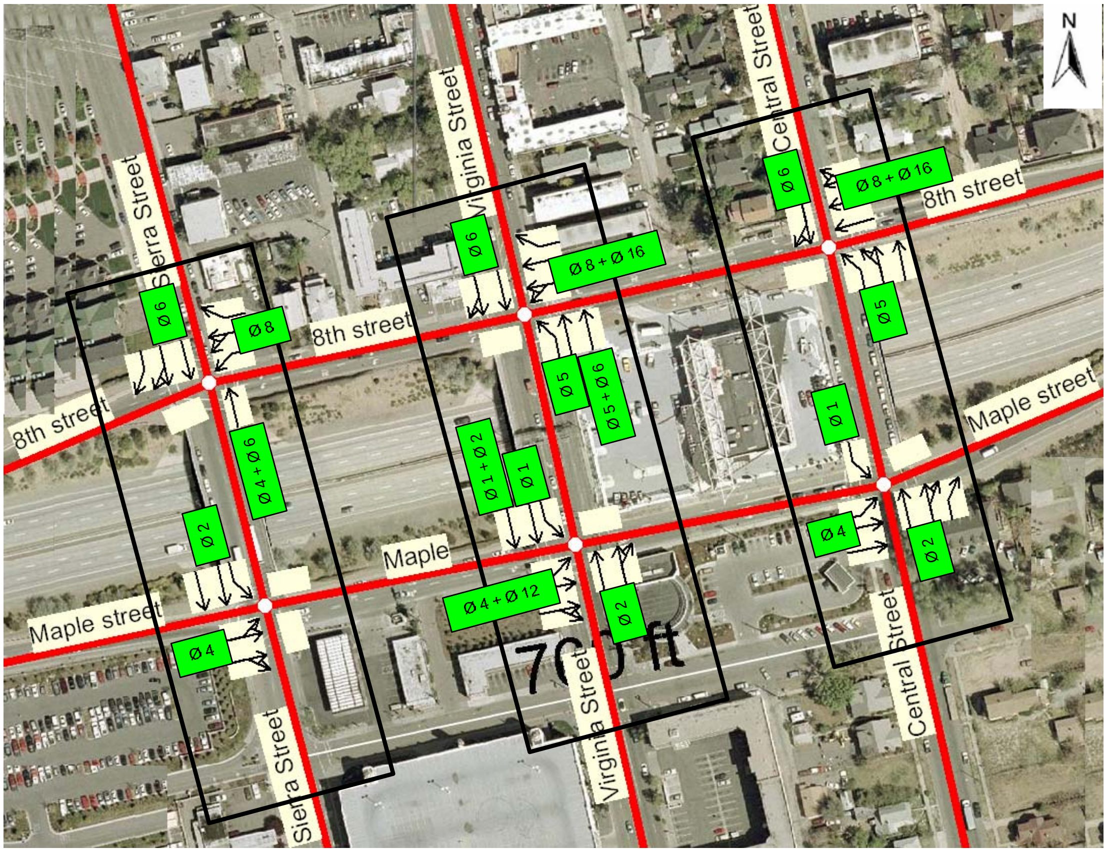



Figure 8 Proposed signal control scheme

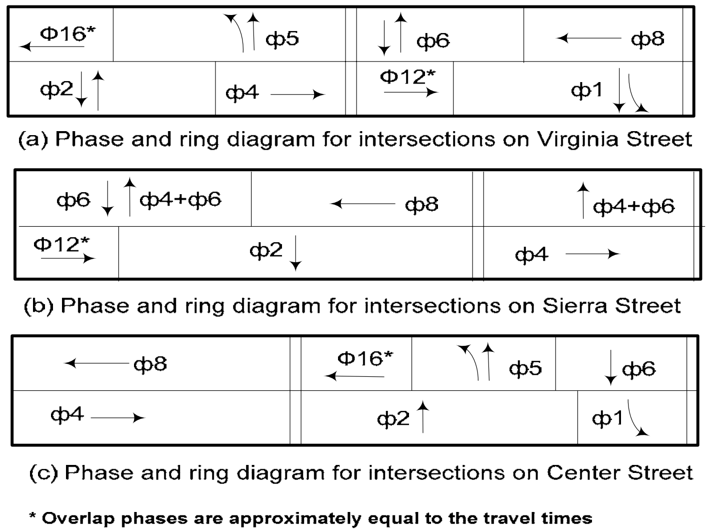



Figure 9 Proposed phase and ring structure

Similar to the overlap phases used in standard diamond interchanges, overlap phases are also used for the signals on Center Street (Φ16) and Sierra Street (Φ12). The duration of these two overlap phases is approximately the travel time between the paired signals, which provide added efficiency while allowing vehicles progress through without having to stop. With the proposed signal control, vehicle stops and queues can be eliminated almost completely between the two signals on Virginia Street, except for a small number of internal U-turn vehicles (i.e., westbound on 8$^{th}$ Street turning south on Virginia Street and then heading eastbound on Maple Street). Such U-turn traffic is relatively minor, and most of these are missed turns. Major vehicle stops are also eliminated between the signals on Sierra Street. Occasional vehicle stops and queues may occur for those arriving during the last portion of phase 8 (the westbound movement at 8$^{th}$ Street). On Center Street, vehicles coming from the west on Maple Street and heading north on Center Street will stop, but the effect is considered minor due to low traffic demand for this movement (no more than 40 vph during any peak periods). Vehicles may also experience stops if they arrive during the last portion of the signal phase for the northbound traffic.

Since the signals within the study network are controlled by three signal controllers, the timing strategy focuses on providing maximum progression for the major traffic movements. Once the offsets are set to progress the major movements, progression for the other non-major movements is fixed. For example, the offsets are set in a way that favors traffic progression along 8th Street, because it involves two major traffic movements within the network (westbound 8th Street to southbound Virginia Street and westbound 8th Street to southbound Sierra Street).

The same 90-sec cycle length was used to develop the new coordination plan under the proposed signal control. There are three particular reasons to use a 90-sec cycle. A 90-sec cycle was found to be adequate enough to accommodate pedestrian crossing times at various locations in the network. Using a 90-sec cycle is also consistent with the previous cycle length, producing compatible performance measures for comparison purposes. A 90-sec cycle was also found to provide optimal progression for the three major traffic movements as indicated in the time-space diagrams in Figure 10. The time-space diagram in the upper half of Figure 10 shows that a perfect progression is achieved along 8th Street. It should also be realized that once the traffic progresses through the signals at Virginia Street and Sierra Street, the traffic turning south to downtown Reno can also progress through the next signals without stopping due to the proposed special phasing and single controller operation. The time-space diagram in the lower part of Figure 10 shows that the major movement coming from the north on Virginia Street and going east to I-80 can progress through the entire study network without stopping. With the proposed timing, progression is greatly improved for the majority of the movements.

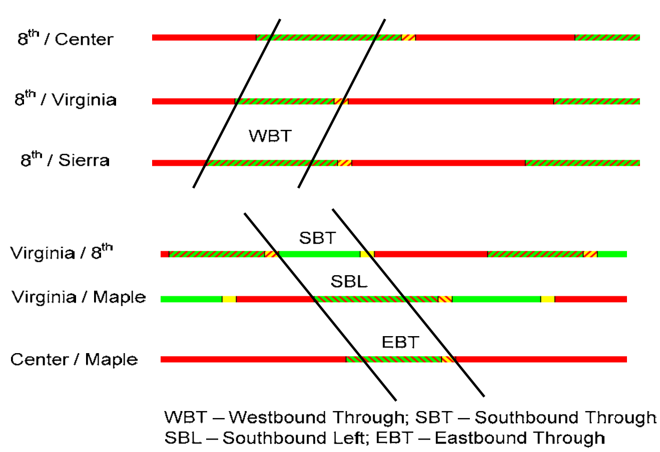



Figure 10 Time-space diagrams for major traffic movements

## Simulation Results

The proposed signal control and timing was evaluated against the existing signal control. The evaluation was conducted using *SimTraffic* (Husch, D. and Albeck, 2003) simulation model. Two traffic control scenarios were evaluated. The first scenario was with the existing control and phasing, using individual controllers for each of the six signals. The second scenario was the proposed control using three signal controllers.

Two performance measures were compared for the three scenarios: the network-level travel time and the network-level stops. The reason for selecting travel time as a performance measure is that travel time is directly related to other major performance measures such as speed and delay. However, stops do not always directly reflect travel time and delay. A signal timing solution could result in the same amount of travel time and delay but with different number of stops, as in the cases illustrated in

Figure 11. The figure shows one case of two timing solutions where a vehicle experiences the same amount of delay but with different number of stops. In (a), the vehicle is stopped and delayed at Intersection #1, but not at Intersection #2. In (b), the vehicle is stopped and delayed at both intersections. The vehicle experienced the same amount of total delay in (a) and (b), but the vehicle in (b) has more stops than that in (a). The situation in (b) could be a result of an improper signal offset setting or a phase early release. An early phase release is common if the phase is designated as the coordinated phase and the non-coordinated phases terminate earlier due to lack of demand during excessive phase split allocation, as in the case of timing based on pedestrian crossings. One of the major objectives of signal timing practice is to minimize stops, especially to avoid vehicles from making consecutive stops.

*SimTraffic* was used to conduct the simulation analyses for the three scenarios. Ten simulation runs were conducted for each scenario, with each run lasing 15 minutes with a 5-miniute warm-up time. Ten simulation runs is generally considered sufficient to provide statistically valid results under low degree of saturation conditions (*1*). The intersections within the study network all have adequate capacities to handle the simulated traffic demands.

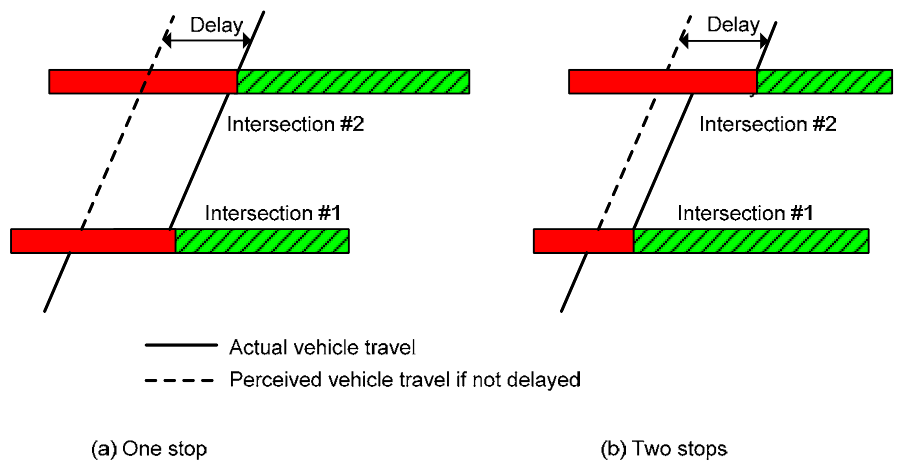



Figure 11 Timing solutions with same delay but different stops

Figure 12 shows the network level travel time and Figure 13 shows the network-level stops. Both figures include the average results from 10 simulation runs. The figures also include the p-values from the results of analysis of variance (ANOVA) and the 95% confidence interval for identification of significant differences.

Figure 12 shows that statistically different travel time results were found for the two scenarios as indicated by the p-value of 0.001, 0.014 and 0.040 for the AM, Midday and PM peaks, respectively. Also, Figure 13 indicates that a statistically different number of network-level stops were obtained between the two scenarios as indicated by the p-value of 0.000, 0.000 and 0.000 for the AM, Midday and PM peaks, respectively. An ANOVA p-value of less than 0.05 indicates that there is evidence that the results are statistically different from each other at the 5% significance level. Based on the 95% confidence intervals, it can be seen that the proposed signal control and timing resulted in significantly lower travel time and number of stops than the existing scenario. It can be concluded from this result that the proposed signal control strategy will result in a significant reduction in travel time, delay and number of stops, which would be a considerable improvement over the existing control. Drivers will generally face slightly longer delays on the external approaches, but once they depart the signal, they can generally traverse the network with minimal delays and stops. However, the three major traffic movements identified earlier can typically progress through the entire network without stopping.

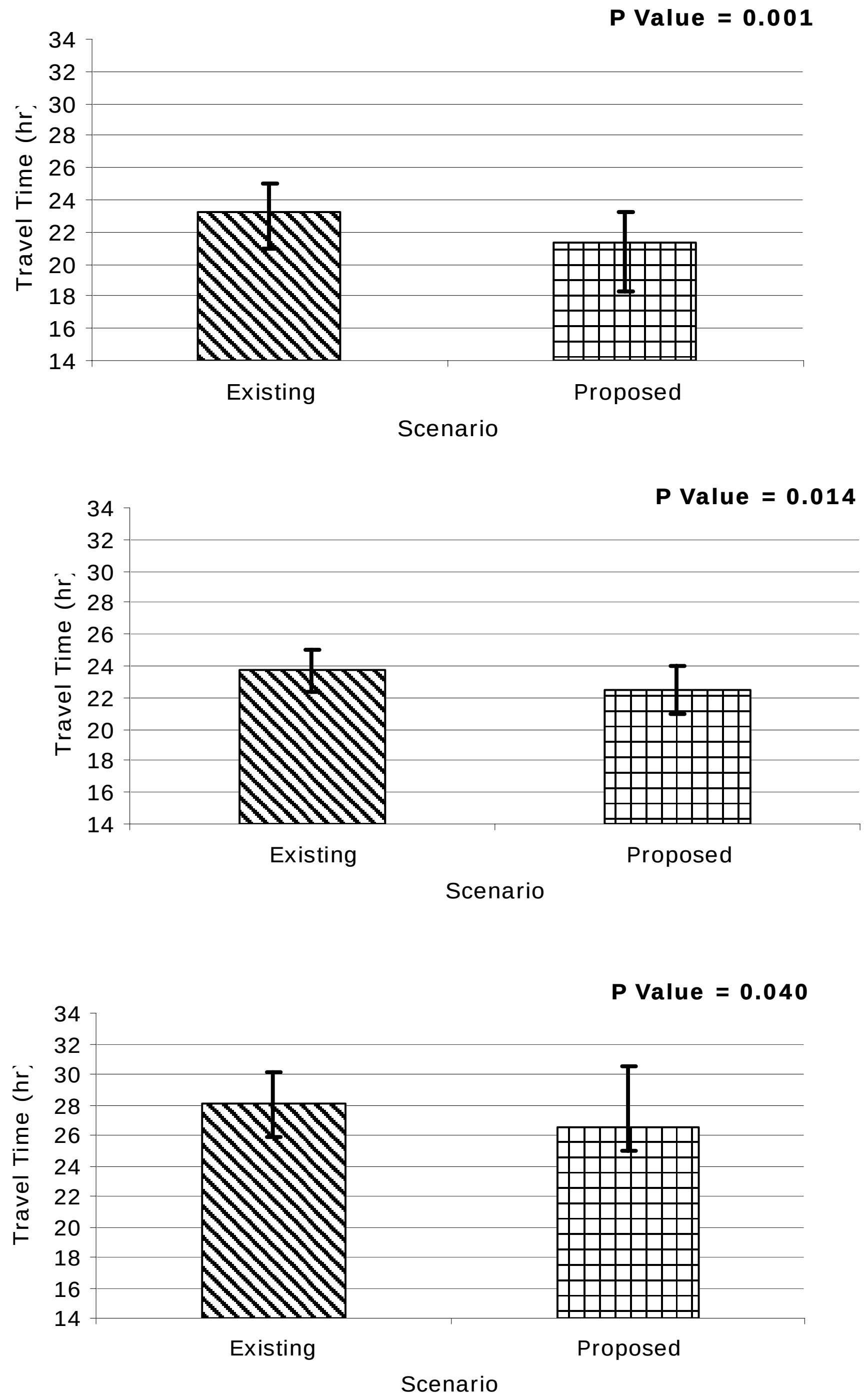



Figure 12 Comparison of Network-level travel time for the AM, Midday and PM peaks respectively

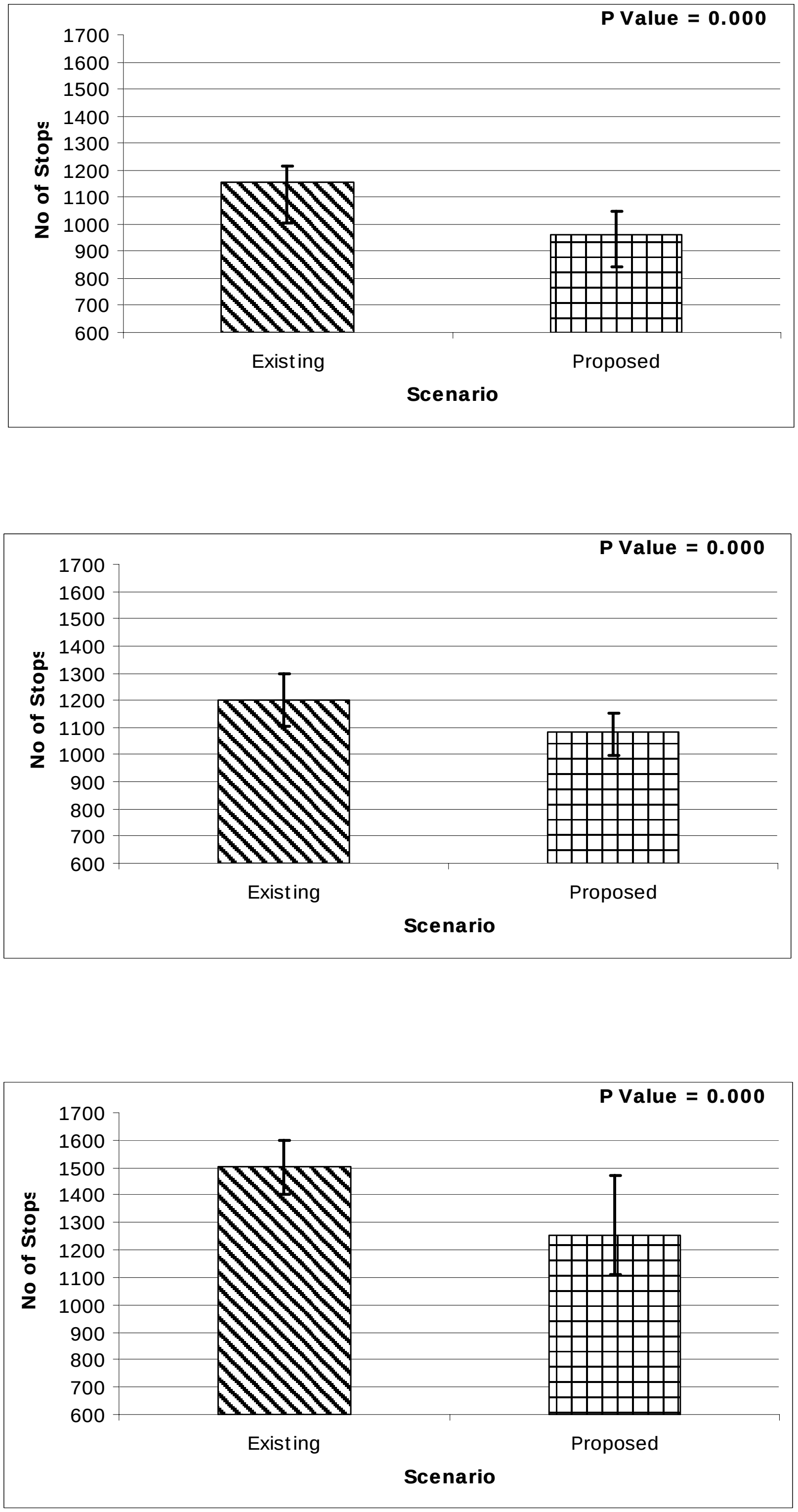
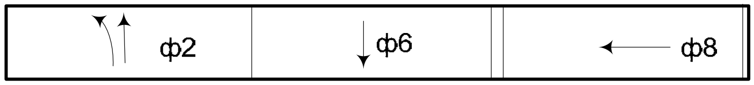



Figure 13 Comparison of Network-level stops for the AM, Midday and PM peaks respectively

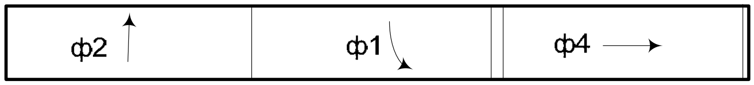
## Field Implementation

As significant reductions in stops and travel time were achieved in simulation, field implementation of the proposed signal control was conducted. Because the City of Reno did not have immediate plans to modify the existing signal controllers and re-wire the cabinets to implement the proposed single-controller strategies, the signal timing was implemented using the existing signal control hardware utilizing fixed-time settings. Since the six signals form a small grid network similar to some downtown networks, where intersection spacing are equal and fixed-time operation is generally preferred for progression purposes. Thus, fixed-time coordination was considered adequate to in order to achieve the desired offsets and progression and was expected to perform similarly to the single controller scenario. Figure 14 shows the proposed phase and ring structures when using a single signal controller for each of the six intersections.

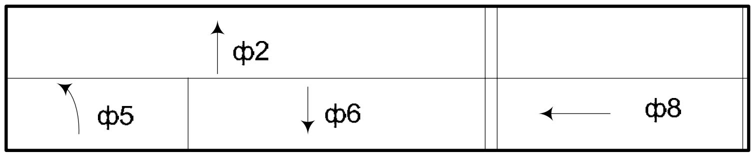
During the implementation of the PM Peak timing plan, it was noticed that significant queuing existed on the southbound approach at the intersection of Virginia Street and $8^{th}$ Street. The queues were caused by the loss of capacity when using the standard TTI-4 phasing scheme. To reduce the queues at this location, the southbound phase was released ten seconds earlier to increase the phase split (it was essentially using a longer overlap as in the standard TTI-4 phasing scheme). However, such an early release resulted in a short stop at Maple Street. To reduce the time of the stop, the eastbound phase was set to run as activated with a minimum recall and a minimum green. Hence, the eastbound phase can gap-out after running its minimum split to provide more green time for the southbound phases. The minimum green is to ensure that eastbound Maple Street vehicles coming from the upstream signal at Sierra Street can reach Virginia Street before the phase gaps out.



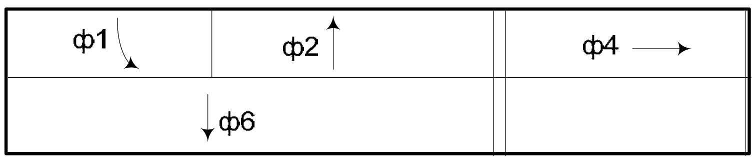

(a) Phase and ring diagram for intersection Center and 8th



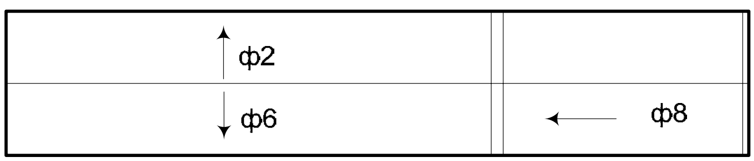

(b) Phase and ring diagram for intersection Center and Maple



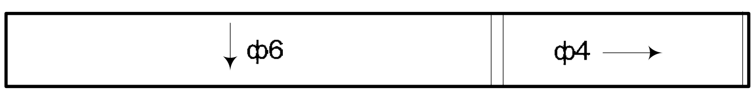

(c) Phase and ring diagram for intersection Virginia and 8th




(d) Phase and ring diagram for intersection Virginia and Maple




(e) Phase and ring diagram for intersection Sierra and 8th




(f) Phase and ring diagram for intersection Sierra and Maple

Figure 14 One Controller Proposed phase and ring structure

## Travel Time Runs

For the purpose of evaluating the effectiveness of the proposed signal timing, travel time runs were conducted once the proposed timing plans were in operation. Travel times were collected for four major routes, which were representative of the various movements along the network. Data were collected on two weekdays and the travel times of each route were collected twice during both the AM peak and the PM peak periods. The AM peak was from 7:00 to 9:00 AM and the PM peak was from 4:30 to 6:30 PM. There are four cases of signal timing plan and operations: the Before Case when signals were running coordination with the before splits and offsets; the Actuated – Non Coordinated Case when signals were off-line during downtown construction; the Coordinated–No Max Recall Case when signals were running coordination with the proposed timing but not having phases placed with max recalls; and the After Case when signals were running coordination with the proposed timing and max recalls on most of the phases (similar to fixed time). The four selected routes were as follows (see Figure 15 and Figure 16).

**Route 1:** (Virginia Street: 8th –Maple – Center and Maple – I80 East)

**Route 2:** (8th Street: Center – Virginia – Sierra –Sierra and Maple – Sierra South)

**Route 3:** (Center Street: Maple – 8th – Virginia and 8th – Sierra and 8th – I80 West)

**Route 4:** (Maple Street: Sierra – Virginia – Center – Center and 8th – Center North)


Figure 15 Travel time Routes – Route 1 and 2

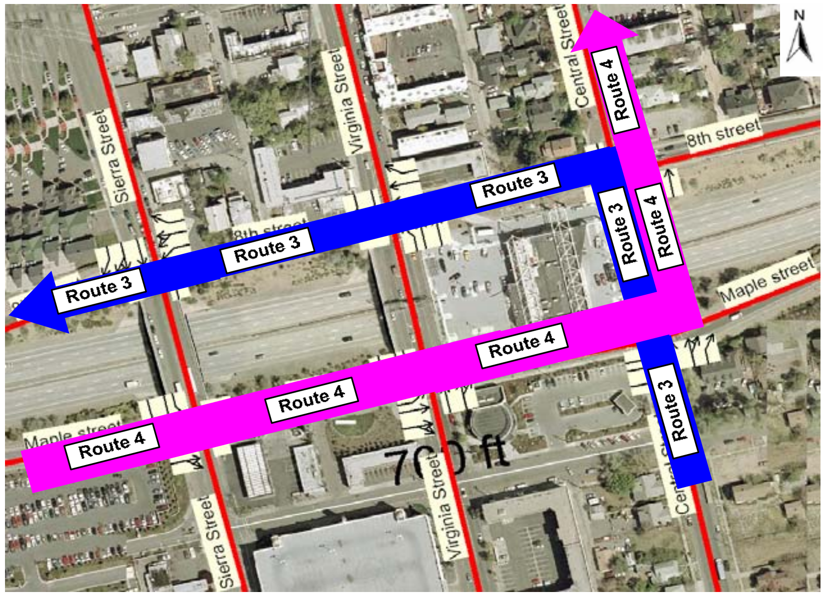



Figure 16 Travel Time Routes – Route 2 and 3

The travel times were collected by driving through the network and video taping the selected routes. Actual travel times of each route were later extracted from the videos. The travel times were measured from the moment the vehicle passed the stop line of the first signal in a route until it reached the stop line of the last signal. Any stops occurring along the route were also recorded. Figure 17 to Figure 20 illustrate the average travel times during the AM and PM peak periods for routes 1 through 4, respectively.

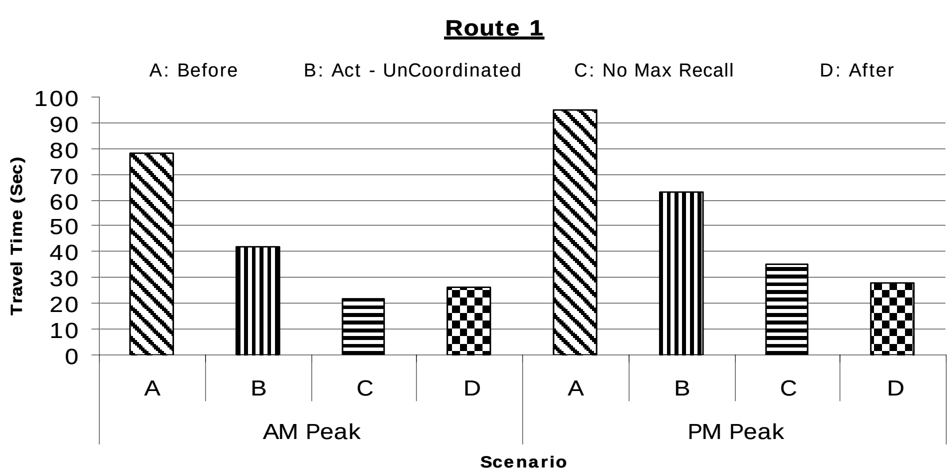



Figure 17 Average Travel Time – Route 1 (AM and PM Peak)

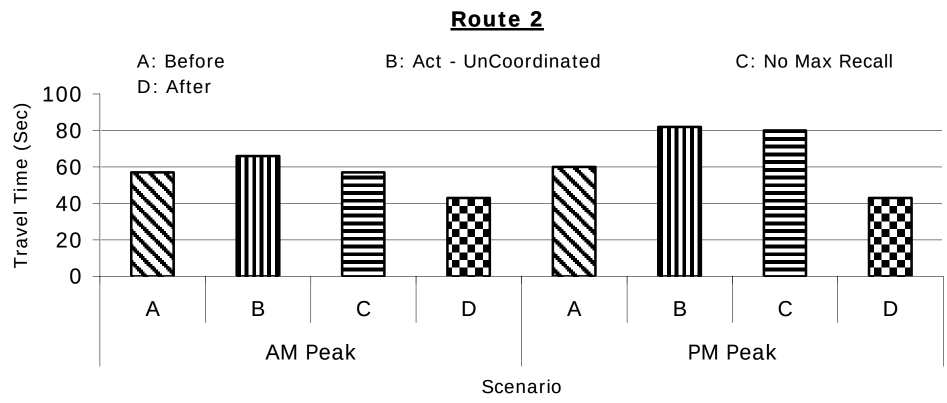



Figure 18 Average Travel Time – Route 2 (AM and PM Peak)

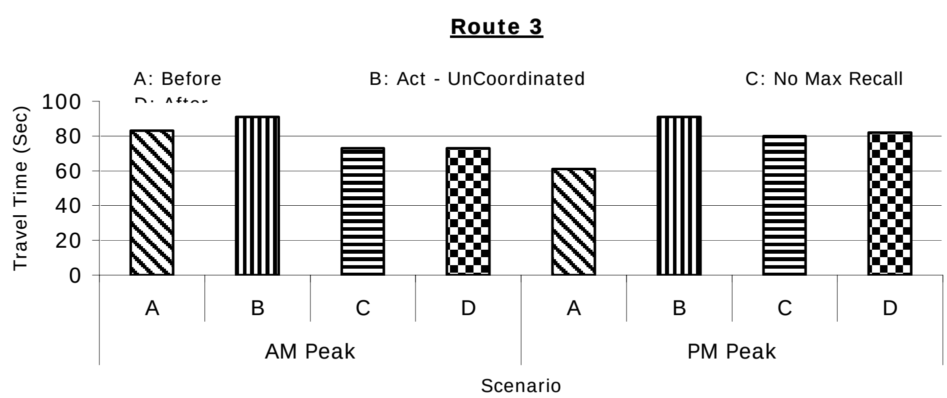



Figure 19 Average Travel Time – Route 3 (AM and PM Peak)

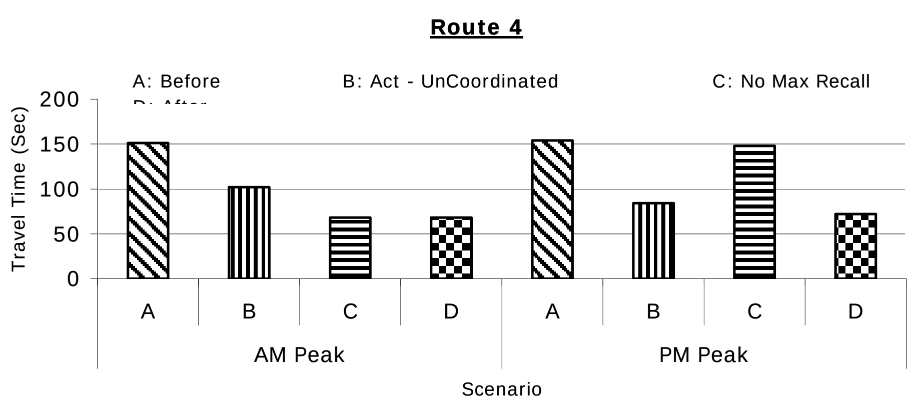



Figure 20 Average Travel Time – Route 4 (AM and PM Peak)

It should be noted that the case study network included about 10 primary routes. The four selected routes were a mix of well and poorly progressed routes, but they were considered representative of the overall system performance. For example, Routes 1 and 2 had good quality progression, where the number of stops was minimal and the travel time was short. However, Routes 3 and 4 involved some stops and delays. Based on results shown in the above figures, it can be seen that a significant reduction in travel time was achieved on Routes 1, 2 and 4 with the new signal timing. The travel time reductions were approximately 70%, 25% and 55% for the three routes during the AM and the PM peak periods. However, no significant change in travel time was found for Route 3, which was one of the minor movements inside the network not prioritized for progression. Although an 8% travel time reduction was found for the AM peak on Route 3, a 16% increase in travel time was noticed during the PM peak. Another interesting fact was that, for most of the cases, the fully actuated operation without coordination actually improved the travel time in these routes over the before case when the previous coordination plans were running.

Figure 21 shows the average number of stops for the four selected routes. It can be seen that the new timing resulted in significant reductions in the number of stops over the previous coordinated timing plans. The reductions were about 60% and 40% for the AM peak and the PM peak, respectively. It is also interesting to see that the actuated operation without coordination had the highest number of stops compared to other coordinated operations. Using fixed time coordination plans resulted in less stops compared to the ones where no maximum recalls were used.

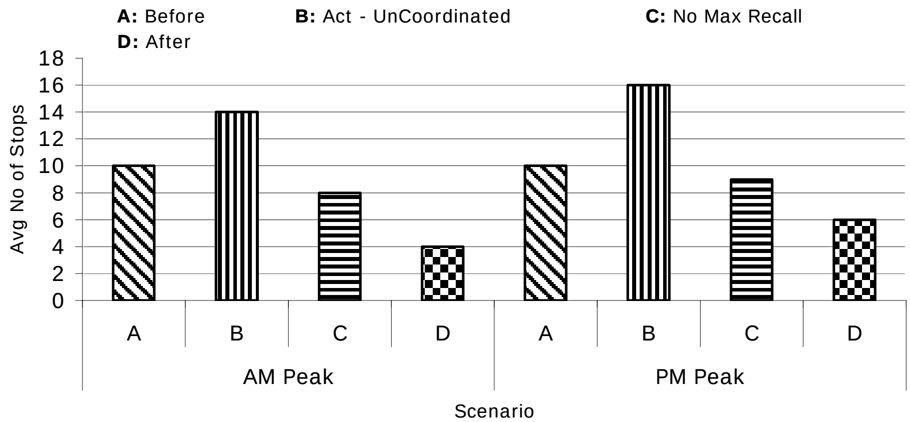



Figure 21 Average Number of Stops – All Routes (AM and PM Peak)

Figure 22 illustrates the travel times and stops experienced on Route 2 under the four operational cases. Route 2 serves one of the heaviest movements (see Figure 4, Figure 5, Figure 6) coming from the westbound I-80 off-ramp and heading south on Sierra Street towards downtown Reno. The figure depicts where the vehicle stopped, how long it stopped and the total time it needed to complete the route. As can be clearly seen from the figure, the "After" timing outperformed all other timing plans. For example, under the "After" timing, the vehicle completed the travel time run in 37 seconds without any stops in the middle. The "Before" coordinated timing resulted in one stop at Virginia Street and a total travel time of 53 seconds. In this case, the coordinated new timing without maximum recalls resulted in the worst experience with two stops and a 93 second total travel time.

The results from both the simulation analysis and field travel time runs showed significant reductions in vehicle stops and travel time. The timing strategies can normally result in a 40% to 60% reduction in stops and 25% to 55% reduction in travel times. The advanced strategies can be adopted in other locations possessing similar traffic flow, directional movements and geometric characteristics. It would be in the best interest of the motoring public that the City of Reno maintains the advanced timing strategies developed, implemented and evaluated in this research.

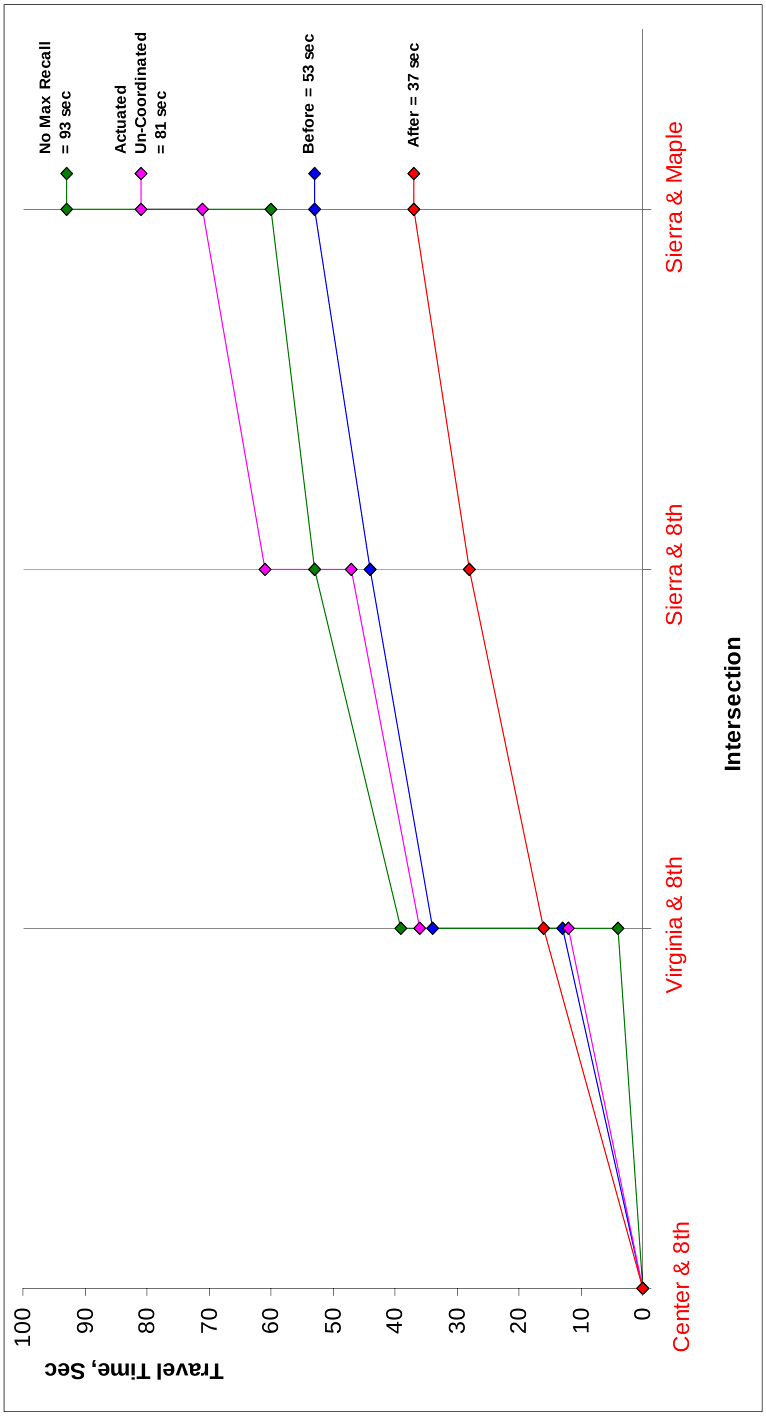



Figure 22 Travel Time of Route 2 – AM Peak – Single Run – All Timing plans tested

### *Case Study 2: US 395/Moana Lane Interchange*

#### Site Description and Existing Signal Timing Plan

The study site was the US 395/Moana Lane interchange, a tight urban diamond interchange located in Reno, Nevada. Figure 23 shows the interchange with the existing lane configuration and traffic volumes during the PM peak hour. The two intersections forming the interchange were 400 ft apart and were controlled by two controllers running a 130-second cycle length during the PM peak period. The case study was specific to the PM peak period.


Figure 23 Existing traffic demands and lane configurations at the US 395/Moana Lane Interchange

Although the signals were coordinated with recently-updated time-of-day plans, significant queuing and stops were observed for some traffic movements at the interchange. There is a major right-turn movement at the US 395 southbound off-ramp approach. Two exclusive right-turn lanes are provided to serve this major movement. As a result, the right-turn movement is not allowed to make right-turn-on-red.

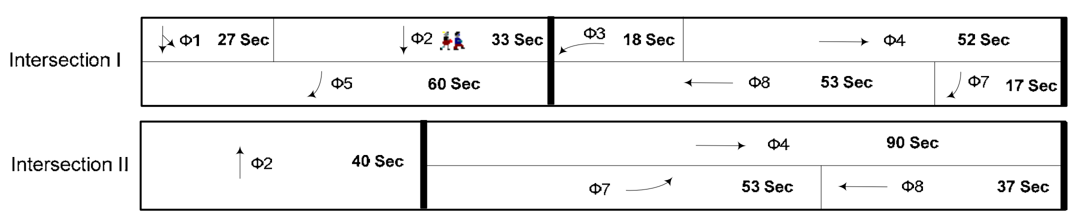


**Figure 24**Figure 24 shows the before case phase and ring diagram for the two intersections (I & II) forming the interchange. As can be seen from the figure, two separate phases were used for the heavy right turn movement at intersection I (Φ5 & Φ7). The right-turn phase was overlapping with three other phases: the adjacent through and left-turn movement phase (Φ1), the pedestrian phase (Φ2), and part of the eastbound movement phase (Φ4). Φ2 was a dedicated pedestrian phase for the east side crosswalk. This phase was activated with a pedestrian push button.

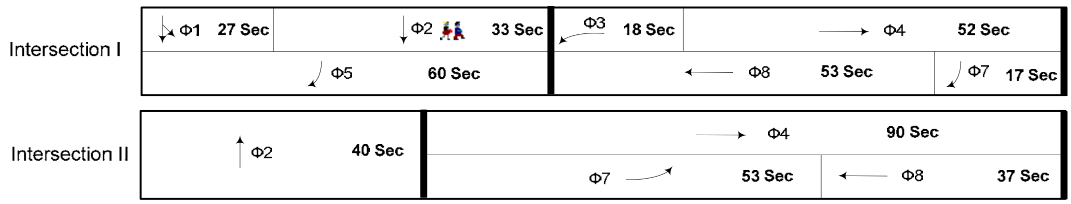



Figure 24 Before case phase and ring diagram – Two controllers

The before PM peak signal timing plan favored the heavy right turn movement and dedicated almost 60% of the cycle length to serve that movement. Based on field observations during the PM peak period, it was found that the offset between the two intersections was set up in such a way that the westbound through movement (Φ8) progressed with a very short pause at intersection I. The northbound off-ramp left-turn movement (Φ2) at intersection II followed the westbound through movement (Φ8) and completely progressed through intersection I. The southbound off-ramp left turn movement (Φ1) at intersection I also progressed completely through intersection II without having to stop. On the contrary, the heavy eastbound through movement (Φ4) at intersection I encountered a long stop time. Once that movement started to move from intersection I, the northbound off-ramp movement (Φ2) at intersection II started. This could result in a stop time of 40 seconds if the southbound off-ramp (Φ2) extended to its maximum split. This long stop time could result in extensive queue spillbacks in the two eastbound left turn lanes at intersection II. As a result, intersection I could be completely blocked, or the green time for the eastbound movement (Φ2) could be underutilized because of the queue spillbacks.

It is worth mentioning that the before timing plan also treated the pedestrian movement (Φ2) at intersection I as a lagging movement to the southbound left turn movement

(Φ1). As a consequence, if a pedestrian pushed the button initiating a call for Φ2 after Φ1 had already extended beyond 27 seconds, the pedestrian phase would start and continue for its complete split of 33 seconds. This automatically resulted in the two signals going out of coordination, imposing extra queues and stop times for all other movements. It would normally take three to four complete cycles before the two signals would come back to coordination.

**After Signal Timing Development**

The after signal timing plan was mainly derived from the standard TTI-4 phase scheme with some special modifications to fit the unique traffic flow and geometry characteristics of the Moana Lane interchange.

TTI-4 phase is commonly applied when the spacing between the two signals is short and queue spillback would be a major concern if operated otherwise. TTI-4 phase scheme is essentially a split phasing scheme. TTI-4 phase can be implemented using one signal controller as shown in Figure 25 and Figure 26.

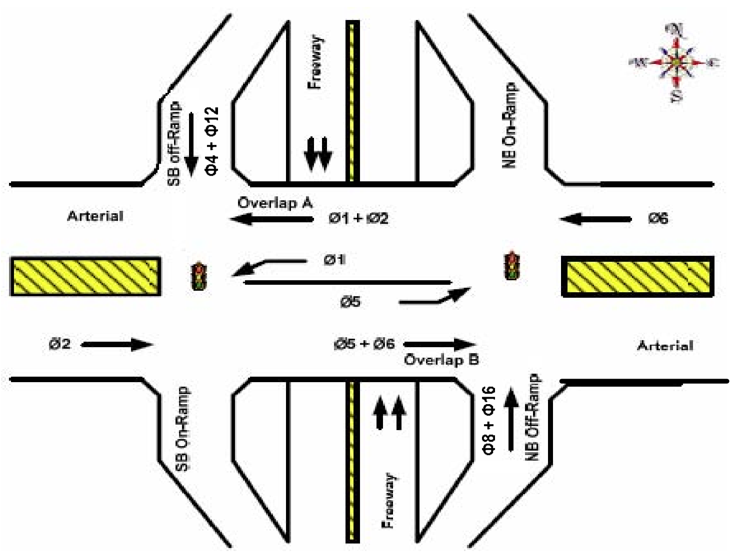



Figure 25 Standard Diamond Interchange Operated with TTI-4 Phases Scheme

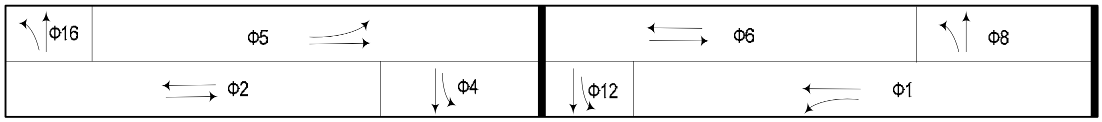



Figure 26 Standard TTI-4 phase scheme ring and phase diagram - One controller

Although TTI-4 phase can normally eliminate vehicle stops and queues between the two signals, it is not as efficient as other three-phase operations from the capacity view point. However, it is a preferred phasing scheme because it better meets driver's expectation by progressing through the two signals without having to stop. The use of two overlap phases (Φ12 and Φ16) also supplements the efficiency loss by serving the off-ramp phases and the arterial phases simultaneously for duration close to the travel times between the two intersections.

For the US 395/Moana Lane interchange, a modified TTI-4 phasing scheme was proposed.  This scheme attempts to at better serve the heavy off-ramp right-turn movement while still maintaining good progression for the other movements.

Under the standard TTI-4 phasing scheme, the eastbound through movement (Ø6) cannot run simultaneously with the southbound right-turn movement (Ø8 and Ø16). In fact, both movements do have conflict and can be possibly run simultaneously by using an overlap phase. It can be seen from Figure 26 that while the eastbound movement (Ø2) is on, no other movements will be served after the last vehicle coming from the northbound off-ramp (overlap Ø16) at intersection II passes intersection I. This is due to the fact that when Ø2 traffic at intersection I arrive at intersection II, the internal eastbound left turn Ø5 will be on at intersection II, and consequently no other movements will be progressed from intersection II to intersection I. Under such a condition, the remaining duration of overlap A at intersection I (see Figure 25) will be totally unused.

The proposed modified TTI-4 phase scheme aims at terminating the arterial through movement (overlap A) at intersection I after the last vehicle coming from the northbound off-ramp (Ø16) passes intersection I. A new overlap Ø10 will start, so that the new overlap phase allows the arterial eastbound through movement to progress through while simultaneously serving the heavy off-ramp right-turn movement. The duration of that new overlap phase can be calculated by simply reducing the eastbound through Ø2 split at intersection I to be equal to twice the travel time between the intersections—this is the time required for the first vehicle of Φ2 to reach intersection II in addition to the time required for the last vehicle coming from the northbound off-ramp (Ø16) at intersection II to pass intersection I. The remaining time from the original Ø2 is then dedicated to the now overlap Ø10 (see Figure 27). It should be noted, however, that such an approach is feasible only if the remaining time in Φ2 is a reasonable duration (i.e., no less than 15 seconds).

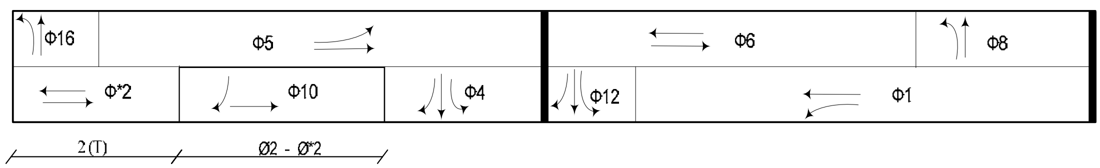



Figure 27 Modified TTI-4 phase ring and phasing structure - one controller

## After Case Signal Timing and Implementation

Because the City of Reno did not plan to modify the existing signal control infrastructure, the after case signal timing was developed utilizing the existing two signal controller operation.  However, similar to case study 1, the phasing scheme was developed to mimic a one-controller operation. The existing cycle length and phase numbering was maintained. The new proposed signal timing is illustrated in Figure 28.

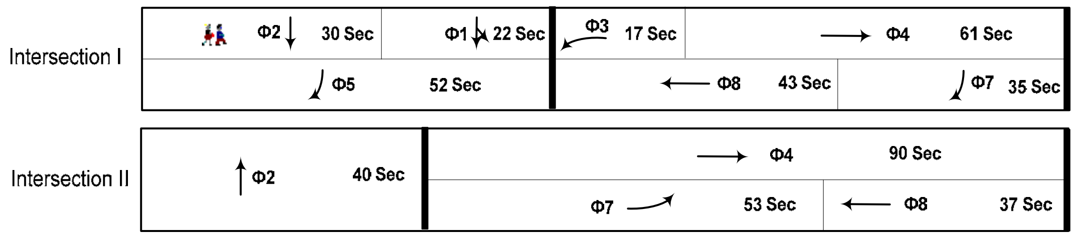



Figure 28 After case phase and ring diagram – two controllers (PM Peak)

There were two further major modifications to the modified TTI-4 phase scheme. The first modification was to set up the pedestrian phase (Ø2) at intersection I as a leading phase to the southbound left-turn (Ø1). This modification guarantees that the two signals will remain in coordination when the pedestrian phase is activated. If a pedestrian pushes the button initiating a call for Ø2 while Ø1 is running, the call will be served in the next cycle. Ø1 does receive a shorter split whenever the pedestrian phase is activated, but disruption to the normal operations is minimal due to low pedestrian volumes.

The second modification was to permit a short stop for the westbound through movement (Ø8 of intersection II) at intersection I. Since this movement had a low volume and can be stored adequately between the two intersections, it would not cause any significant queue spillbacks. This modification was achieved by increasing the overlap between the westbound through (Ø8) at intersection II and the southbound off-ramp (Ø1) at intersection I to be significantly higher than the travel time between the two intersections. Such a modification allocated more green time to the heavy southbound off-ramp (Ø1), which resulted in improvements to the overall interchange operations. Both off-ramp phases were set as actuated phases and thus could gap out once the vehicles had been served, allowing extra time to serve the arterial movements.

### Simulation Results

The before and after signal control and timing plans were evaluated using the *SimTraffic* simulation model. The performance measures used for the evaluation included the average vehicle delay and the system-level stops. Again, ten simulation runs were conducted for each scenario, with each run lasing 15 minutes with a 5-miniute warm-up time.

Figure 29 shows the before and after average delay per vehicle and Figure 30 shows the before and after system-level stops. Both figures include the average results from the ten simulation runs. The figures also include the 95% confidence intervals for identification of statistically significant differences.

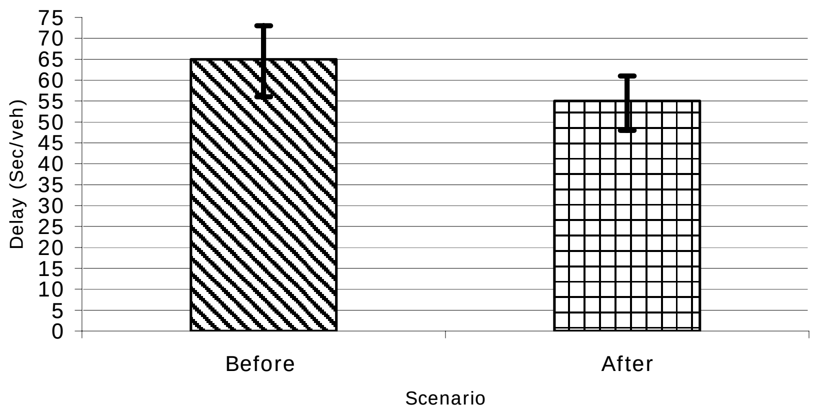



Figure 29 Before and after average delay results

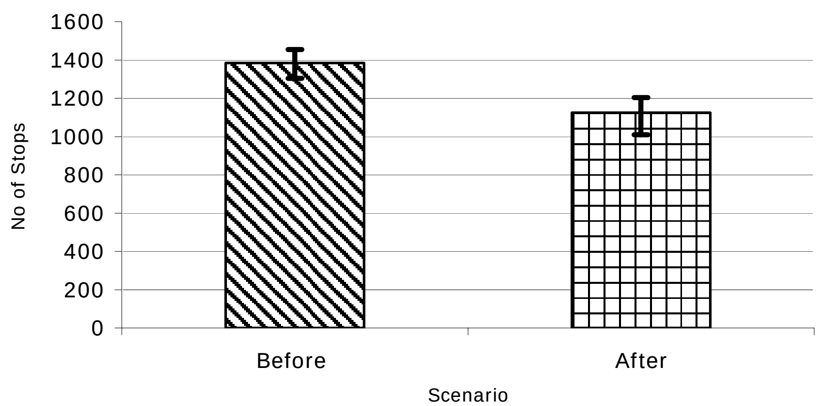



Figure 30 Before and after system-level number of stops

Figure 29 shows that the average delay was reduced by approximately 15% (from 65 sec/veh to 55 sec/veh) with the proposed signal timing plan. However, this reduction was found to be statistically insignificant (indicated by the overlapping confidence intervals). Figure 30 shows that system-level stops were indeed statistically different. An average reduction of approximately 19% was achieved with the proposed signal timing plan. It can be concluded from this result that the proposed signal control strategy would result in significant reductions in the number of stops, which is a considerable improvement over the existing control.

The two major movements at the interchange are the southbound off-ramp right-turn movement and the eastbound through movement at intersection I. It is crucial to the interchange operations that queues not spillback to the US 395 freeway or the nearby intersections on Moana Lane. Figure 31 shows that both of these major movements would achieve average delay reductions of more than 25%.

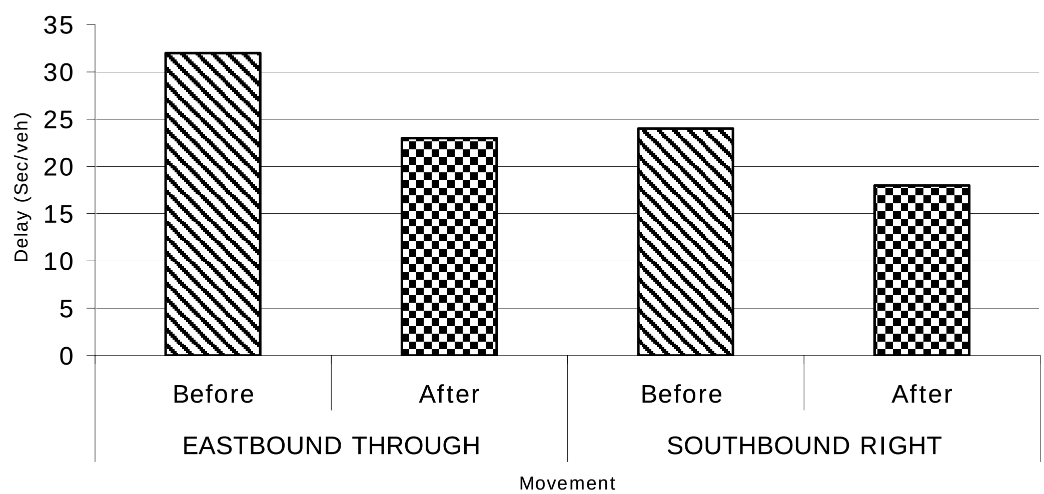



Figure 31 Major movement delays at intersection I

**Field Implementation and Evaluation**

After the simulation study indicated significant improvements at the interchange with the proposed signal timing plan, the next step was to implement and test the timing in the field. As discussed earlier, the City of Reno did not have immediate plans to modify the signal controller infrastructure; therefore, the timing was implemented using the existing two-controller structure. The phase and ring diagram shown in Figure 28 was used as the basis for the implementation. All phases were set to maximum recall, except for the off-ramp phases and the pedestrian phase. The off-ramp phases were set to minimum recalls to allow them to gap out, thus allocating the unused green time to serve the arterial movements. The pedestrian phase was set as actuated without recall, permitting the phase to occur only when a pedestrian pushes the button; when there is no pedestrian call, the time of that phase will be completely dedicated to serve the southbound off-ramp turn movements. The offsets between the two intersections were then set accordingly to ensure that the operation resembled the proposed timing (Figure 28). This was necessary due to the usage of two controllers and the specific requirements of the proposed phasing scheme.

During the field implementation process, it was noticed that the westbound left-turn movement (Ø3) at intersection I had a very low demand. Instead of using the max recall on this phase, a minimum recall was used in order to allow the phase to gap-out. This resulted in releasing the eastbound through movement (Ø4) earlier, providing more capacity for that movement but imposing an extra stop at the downstream signal. This was found to be beneficial to the eastbound through movement at intersection I during the peak hour, preventing queues from backing up to the upstream signal on Moana Lane. The extra stop time was usually short, however, especially when the northbound off-ramp phase gapped out earlier.

Because no before-case field travel time and delay data were collected, no after-case field data collection was conducted besides the evaluations using simulation.

## SUMMARY, FINDINGS, AND RECOMMENDATIONS

This research project involved several major research tasks, including: (1) a comprehensive literature review and a nationwide agency survey; (2) development of strategies and techniques for operating diamond interchanges; and (3) case studies to implement and evaluate the effectiveness of the strategies in the Reno-Sparks area. The nationwide agency survey included a list of questions posted on the internet regarding strategies and techniques for managing diamond interchange operations. The survey received a total of 24 responses, representing both the public and private sectors in 13 states. Two case studies were conducted in the Reno-Sparks area, where innovative diamond interchange signal control strategies were implemented and evaluated. One case involved a set of closely-spaced signals where signal control schemes were derived based on similar principles of diamond interchange operations. The other case involved a diamond interchange with a heavy right-turn movement at the off-ramp approach, where a modified TTI-4 phasing scheme was derived and implemented. Both case studies showed reductions in travel times and stops with the proposed diamond signal control strategies.

The research resulted in the following major findings and recommendations:

*Findings*

- Based on the agency survey, most agencies prefer using one controller to operate a diamond interchange, although most diamond interchanges in Nevada are operated with two controllers and no specific diamond phasing strategies are considered.

- Most agencies do not have specific guidelines on whether one controller or two controllers should be used for a diamond interchange. It seems that there is a continued debate on the advantages and disadvantages of either choice.

- It is apparent that the specific signal timing strategies for operating diamond interchanges are still not widely known to many traffic engineers. This is reflected by the lack of efficient operations at most of Nevada’s urban diamond interchanges.

- TTI-4 phase (standard or with some modification) proved to be most efficient in reducing the number of stops at an interchange, although it may result in longer delays when the traffic demands are high. However, using longer overlap phases can gain some efficiency with the tradeoff of some additional stops.

- As demonstrated in one of the case studies, innovative signal control strategies can be developed based on the diamond interchange signal control principles for controlling closely-spaced pared signals. Such strategies are generally specific to the traffic flow and geometric characteristics at a site.

*Recommendations*

- Diamond interchange signal control strategies should be further implemented and evaluated at most urban diamond interchanges in Nevada to improve their operations and safety.

- Further research is needed to address the issues related to using one controller versus two controllers for operating a diamond interchange. The research should address both efficiency and maintenance issues.

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# APPENDIX

## APPENDIX I: SURVEY QUESTIONS

### <u>Question (1)</u>

**Do you have particular concerns about safety and operations at diamond interchanges (e.g., crashes, queues, delays)?**

1. We have lots of diamond interchanges in Texas. There are certain operational strategies that should be applied depending on the design geometry, more specifically the distance separating the two sides. When it is under 250 ft, you should operate it as a 4-phase diamond and when the distance between the two sides is >=300 feet you could consider other operational strategies, but you need to be cognizant of the potential safety issues. One rule of thumb that I have is that you can start operating a diamond in one of the 3 phase patterns and if necessary you could convert to 4-phase operation, but I would typically say that I would be very reluctant to change a 4-phase operation to a 3-phase operation due to driver expectancies. That is just my personal opinion.

2. I do not have concerns about diamond interchanges in general although each location can have site specific issues.

3. Queue interactions

4. I am currently developing test procedures to test Texas 4 Phase operation and have uncovered a condition in which a car may be trapped.

5. Queue management at tight diamonds is always an issue as is progressing heavy turns movements from the ramp through the other side of the diamond.

6. We have some with sight distance restrictions for right-turners and have No Right Turn on Red signs. This causes much delay.

7. Yes, insufficient queue space leads to the other two.

8. Current concerns are in high traffic areas where exit ramps have rural designs with "free rights" and there is an immediate downstream left turn attraction to create a weaving problem. Mn/DOT has converted some of these to double right turn lanes with signal control. Sometimes on a separate phase from the exit ramp lefts.

9. No.

10. Section head. Drivers would get a green at the west frontage road, and it would turn green as they arrived at the east frontage road. In most places in Texas, this operation means that the diamond is the standard four-phase TTI operation, which includes a leading protected left turn. But the left turn in our case lagged. This violation of driver expectancy was causing about 20 accidents a year. We changed the operation to conventional TTI phasing and the accident problem ceased. Thus, when drivers cross the interchange, they should either get a fully protected green (including the left turn), or it should be solidly and obviously red.

11. See 10

12. Yes, queues on ramps and between signals can frequently cause safety concerns at diamond interchanges. Excessive delays are also a concern.

13. The typical rural diamond interchange is too often used in suburban/ semi- rural environments that develop after the roadway has been completed. Usually insufficient right of way was acquired to allow the interchange to be modified when it becomes necessary. Quite often the initial back to back left turn bays(if any were provided) when the initial construction was completed do not provide sufficient storage for the increased left turn demand and no provision was made to allow the roadway(especially on raised designs)to be expanded to parallel lanes when needed.

14. Not fun to change a diamond that has been running 4-phase for years to something different. Typically the tighter the diamond is, the more problematic this may become... People are creatures of habit and take time to learn. We take all precautions necessary (signing) when making these changeovers.

15. yes, excessive delay

16. 
    - Average accident rates are found higher than at/near common intersections.
    - Need better guidance for capacity/LOS calculation (other than HCM2000)

17. No, they generally work very well.

18. No more than any other traffic signal location

19. Yes, queues and delays

20. No.

21. Sometimes bridge structures do not allow enough left turn lane storage to accommodate the left turn demand onto the freeway on ramps.

22. safety and operation

23. No- only has 1 traditional diamond interchange.

24. They are what they are.

**<u>Question (2)</u>**

**Are you using one or two controllers for controlling a signalized diamond interchange?**

1. I have seen both used; in Texas they typically use one controller. And even with controllers that are supposed to be capable of handling all the specific diamond patterns there can be software issues that create undesired operations.

2. Mostly 2 controllers but several locations using 1 controller.

3. Both, depending on the spacing.

4. I am using a one controller configuration.

5. Two

6. Majority use one but a few have 2.

7. Typically 1

8. One

9. Generally two, but some of each. The loose guideline is if the travel time between signals for the through is less than 7 seconds, one controller should be considered. The signal main shops do not like this. They prefer separate cabinets.

10. Prefer one.

11. Never if I could help it.

12. Sometimes one, sometimes two depending on the distance between signals.

13. In a majority of cases only one controller is used. There are rare locations where the ramp locations are sufficiently separated that two controllers operating in coordination can be used successfully.

14. Most the diamond interchanges in the region are ran from a single controller...

15. 1

16. One

17. two

18. One Controller

19. two

20. Between the two sides, but most Nevada agencies use two. I think that increases the difficulty in providing reliable coordination between them and contributes to their operational problems.

21. We use both single and dual signal controller operations.

22. Both. We model the conditions and determine which arrangement gives us better results.

23. 2

24. One if closer than 800'.

**<u>Question (3)</u>**

**Are you using special signal timing and phasing to operate diamond interchanges?**

1. Sometimes, depends on what you call special.

2. Mostly typical diamond interchanges operation with alternating ramp phases (4 phases). When traffic patterns dictate then simultaneous ramp phases with lagging left turns are sometimes used (3 phase). Separate right turn phases for the off ramps are also sometimes used.

3. Depends on the spacing.

4. I am using the default timing on the Eagle Controller with some intervals extending to ensure that the states can be verified.

5. Phase sequence and timing is different at every diamond based on the particular traffic flow and geometry

6. Yes

7. Just standard phase overlaps

8. TTI 4 phase.

9. Tight diamonds get lead-lag. Generally the light left leads and the heavy lags. Wide diamonds are typically lag-lag.

10. TTI 4-phase

11. We typically used either three-phase operation or four-phase operation with overlaps (i.e., TTI phasing).

12. In some situations.

13. In some cases special timing and phasing were necessary; however, usually just the normal eight (8) phase quad left turns phasing was sufficient. In many cases only a six (6) phase sequence was necessary since no left turn phases were necessary on the off-ramps.

14. Yes... We use the NextPhase software and have logic to run the desired operation fully actuated. The operations include 3-phase, 4-phase, Figure-6 / Figure-7, and a couple other variations... We have the capability of switching between the different operations (by time-of-day), and will switch lead / lag (for Figure-6/7), for progression purposes but we avoid switching in and out of 4-phase operation...

15. yes, but to work it has to be fixed-time

16. Texas 4 phase

17. Most operate lag-lag or lead-lead

18. Generally what we refer to is a 2 x 4 operation. Basically two intersections operating with 4 phases.

19. We are in the process of doing so now. We have recently developed software to help us model two controllers using the TTI phasing or sometimes called "4 phase plus overlap".

20. Yeah. Recently I've successfully recommended Texas-style TTI phasing to FAST system technicians for three or four diamonds around Las Vegas. Of course, it's required going to essentially pre-timed operation since they're locations using two controllers.

21. We have one intersection with a modified diamond interchange program designed to give preference to SB traffic. This location is at Interstate 5 and SR 539, in Bellingham, Washington.

22. They all may have different characteristics, outer roads, spacing, so there could be some "special" phasings.

23. Yes- lagging lefts w/ conditional recall (call on ramp calls mainline left) to keep progression window open.

24. The Texas Diamond standard software

**Question (4)**

**What kind of controller (manufacture and model) are you using at diamond interchanges?**

1. Local agencies use 170's, and special TxDOT Spec diamond controllers from Eagle & Naztec.

2. Model 170E or HC11 with Wapiti controller software both for 2 controller situations or 1 controller situations.

3. Wapiti with Type 170 controller in Portland, OR

4. I am currently validating the test procedures on Eagle Traffic Signal Controller EPAC 300. I am planning to test the procedures on a Naztec and Econolite controllers.

5. Eagle (Siemens) M42

6. Econolite ASC/2

7. Econolite

8. Eagle EPAC 300

9. Econolite, Traconex, Eagle - various models sometimes we use more than 8 phases and add overlaps as well.

10. Econolite, Eagle, Naztec

11. It did not matter.

12. 2070L (North Carolina state standard)

13. Naztec eight phase NEMA controllers.

14. Mainly 2070's with NextPhase software... There are also some Naztec 900's controllers or EPAC-300's running in "diamond mode" at some locations. These are primarily used by the other jurisdictions in the area...

15. Safetran 170

16. 170E

17. 170, 170E or HC11

18. Naztec 900 series currently.

19. Eagle Epac 300 and Econolite ASC2's.

20. Eagle 2070s running Siemens Nextphase, in the FAST system.

21. Econolite ASC 2 and Eagle 2070 (SEPAC software).

22. Missouri allows the use of several different controllers. We are primarily and NEMA state.

23. Safetran 170.

24. Eagle 2070 and earlier models.

**Question (5)**

**What are the issues (e.g., obstruction of view) you have when using one controller to control a diamond interchange? How did you resolve them?**

1. No issues.

2. The ones that are 1 controller are not resolved as far as obstruction of view although there is a method for resolving this by having 2 controllers mimic 1.

3. One controller is selected when these isn't issues aren't of concern.

4. My environment is testing and therefore does not have any environmental issues.

5. NA
6. Unknown

7. Clear the short queue approaches resulting in inefficient timing

8. Too many inputs for one cabinet. And, we can not put the intersection into flash with two technicians.

9. The signal shops do not like all of the load switches and detectors in one cabinet. We have used two cabinets to split those items. Or we have reminded them that they get paid by the hour.

10. Not good over 800 feet between intersections.

11. We always made sure that the downstream signals were visible to motorists at the upstream signal. We also made sure we had enough ambient light so that the geometry of the interchange was plain to see.

12. Haven't had any issues

13. The present of support columns in the center median created the view obstruction that most often had to handle since it often prevented vehicles on the ramps from seeing approaching vehicles. This can usually be prevented by not using the center type support and often helps eliminate the future problems with left turns described above. A traffic signal is also a common method to solve the sight restriction issue.

14. With 4-phase operations I see no issues; however the operation can be very inefficient when the turning traffic is light (particularly from the frontage roads). With the other operations (LD-LG), particularly those with shared lanes in the middle, I do everything necessary to ensure the left-turn arrow is on by the time the arterial arrives at the other junction. This is all done in logic. True 3-phase operation seems unpopular in this region because all turning traffic must stop (including the arterial left-turns). I've had much better luck with the LD-LG operation when implemented under the right traffic scenarios...

15. none

16. Pretty efficient.

17. ODOT has replaced most of the single-controllers with dual controllers. Obstruction of view was one of the factors.
18. Don't have any major issues

19. We unfortunately use two controllers (I would prefer one). UDOT generally uses two because our signal maintenance crew prefers two for ease of maintenance (i.e. easier to see intersection; if one flashes, they both flash; simplicity in not having to use overlaps).

20. The most common complaint from technicians is that it's hard to watch traffic at the two separate intersections for putting the signals from flash back to colors after working a service call. I consider that far too minor a problem to justify the operational degradation using separate controllers involves, and could think of several mitigation measures.

21. There is an issue with not being able to adequately observe the intersection that is not adjacent to the traffic signal controller cabinet. We try to exercise extreme caution when working at these intersections. We do not have any special procedures in place while working at these intersections.

22. Space on the back panel. Controller functionality. Double cabinets, TS2 cabinets, newer controllers.

23. NA

24. We use the more efficient 3 phase mode until there is a problem with queuing or accidents, and then we will use the four phase mode.

**Question (6)**

**Do you have specific guidelines for signal timing at diamond interchanges (e.g., use of three phase vs. four phase)?**

1. Sort of.

2. This is dictated by a combination of analysis, judgment, and experience.

3. No.

4. No opinion

5. Three phase operation but may alter sequence by time of day

6. No, we use all types of phasing.

7. Not sure what the State does

8. Queue management is the primary concern. The operation depends on the volume and geometric configuration.

9. For single controller operation it is typically an 8 phase operation with lead-lag patterns for left turns to ramps and off ramp phases. Minnesota has few one way frontage road systems. Most diamonds are stand alone with little ramp to ramp throughs.

10. Depends on volumes.

11. My preference is to use three-phase at wider diamonds where there is sufficient left turn storage. When the storage is sufficient, three-phase allows shorter cycles, higher green-time percentages, and lower delay. When the left turns spilled out, however, we used four-phase with overlaps to prevent the problem.

Also, we timed the overlap in four-phase operation so that the downstream signal turned green just as the arterial traffic was halfway across the interchange.

12. No

13. It usually depended on the particular situation; however, the three (3) phase arrangement usually works the best only when two (2) separate controllers are being used.

14. We don't have many diamonds, but if we had new ones going in under my control, I would avoid using 4-Phase operation as much as possible, due to the fact that the frontage roads can't run together. 4-Phase is good for locations with high turning volumes and minimal storage, however if this doesn't exist, then I think the engineer would be better off using other operations that can move more traffic and teach the motorist to always be alert. This is best to be done from the day of the turn-on when you have their attention...

15. NA

16. No.

17. No specific guidelines.

18. We do not have any written guidelines. Timing and phasing is determined by the district traffic engineer.

19. We don't necessarily have specific guidelines; however, we are experimenting with the 4 phase plus overlap phasing. Our signal technician just recently programmed a simple ring structure to allow us to essentially get the same effect as the one controller running the TTI phasing, however, to do it with two controllers. If you are interested in the software, send me an Email and I will send it to you.

20. I recommend whatever appears most effective in each situation based on comparative field observation

21. We use phases 2 & 6 as mainline phases with associated left turns as phases 1 & 5. The ramps are usually coded as phases 3 and 4 for sequential operation. Typically overlap phases are assigned as OLA=2+3; OLB=6+4; OLC=3+5; and OLD=4+1

22. We have some "prepackaged" phasing schemes developed. Timing is developed based on volumes.

23. NA

24. See #6.

**Question (7)**

**What other special treatments or techniques have you implemented to improve diamond interchange operations?**

1. Design with plenty of lane capacity and enough distance between two sides to provide future operational flexibility.

2. It can be helpful to have right turn signalization for the off-ramps when there is heavy right turn movements as the right turn can go with one of the through movements.

3. NA

4. None.  If it up to me, I would additional logic to address impact of trap noted in question 1.

5. Lead/lag by time of day. Protected lefts in some cases (sometimes by time of day)

6. Unknown

7. Reconstruct them to SPUI

8. We've implement the super-duper neato software from Siemens called NextPhase.

9. We have on occasion run the frontage road and ramp intersections with a signal controller.
10. Dynamic lane control.

11. We always make sure that we keep the cycle length down. A four-phase overlap compensates for the effects of the phase-change lost time, so there is no need to increase cycle length to reduce the effects of lost time. We would only increase the cycle enough to provide equitable green times and adequate pedestrian clearance.

12. None

13. Many different approaches have been used in various locations depending on the problems that were encountered and how much money was available to solve the problem.

14. Double serving one or more of the arterial left-turns by time-of-day, depending on the traffic scenario and volumes present...

15. NA

16. The effect of u-turn movements on capacity and safety is being investigated

17. None.

18. Some extension Ramps to operate with through's because of heavy ramp traffic exiting Interstate.

19. The TTI phasing or 4-phase + overlap seem good and promising. For it to work effectively, we have found that we need to often place recalls on the left turns to keep them from gapping out prematurely

20. Here's one which I haven't gotten any roadway designers to give me the geometrics for, but routinely ask for when I think one of them is listening: Start the left turn pockets for traffic turning from the crossing arterial onto the freeway on-ramps on the outside approaches about 400 feet before the first signal, and line them up side-by-side between the two intersections, rather than back-to-back on or under the bridge as they do now. Doing that will improve the discharge capacity of the signals substantially.

21. NA

22. NEMA TS2 cabinets and controllers, overlaps, changed the design of the interchange, optically limited signal heads, controlling two closely spaced intersections as one.
23. NA

24. We will split the rings so each end operates as a separate signal, and then use the coordinator in the controller to re-link the two ends. Using this method, any sequence or operation is possible.

**Question (8)**

**Other comments;**

1. (2) The biggest problem with diamond interchanges is understanding which timing alternatives are available and under which conditions they are suitable. Also, using 1 controller operation can lock you into 1 type of timing.

2. (4) The procedures I am developing will be documented in NTCIP 8007 format. Scripts that fully automate the test will be developed in the Tool Command Language and will run under SimpleTester for NTCIP.

3. (8)NA

4. (9)We have road designers who would rather spend $3 million more to build a SPUI so they don't have to think about this.

5. (11)I was in the public sector in responsible charge of signal timing from 1981 through 1993. My comments reflect that experience. Since that time, I have acted as a consultant, though nothing I have seen as a consultant has suggested to me that my experience is either invalid or out-dated.

6. (14) Interested in seeing the results when you're done with this study!

7. (15) Would rather see diamond (especially tight diamond) interchanges replaced with SPUI or double roundabouts.

8. (16) Timely survey!

9. (17) I suspect that ODOT could improve efficiencies at diamond intersections. Staff available to do that work is spread rather thin, and may not be particularly well-trained in diamond timing.

10. (18) none

11. (19) We have recently developed software to assist us with the two controllers running the TTI phasing. The software shows both intersections and both rings for each intersection and the split and offsets needed to make it work.

12. (21) Sometimes pedestrian service becomes an issue. The use of pedestrian overlaps may be desirable.

# APPENDIX 2: CONTACT LIST OF PARTICIPATING EXPERTS AND THEIR RESPECTIVE ORGANIZATION

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