

**APPLICATION OF DIAMOND INTERCHANGE  
CONTROL STRATEGIES AT CLOSELY-SPACED INTERSECTIONS**

Zong Tian, Ph.D., P.E. (Corresponding Author)  
Assistant Professor  
Department of Civil & Environmental Engineering  
University of Nevada Reno  
Reno, NV 89557  
(775) 784-1232  
[zongt@unr.edu](mailto:zongt@unr.edu)

Tom Urbanik, Ph.D., P.E.  
Professor  
Department of Civil and Environmental Engineering  
The University of Tennessee  
Knoxville, TN 37996  
865-974-7709  
[turbanik@utk.edu](mailto:turbanik@utk.edu)

Reed Gibby, Ph.D., P.E.  
Research Coordinator  
Nevada Department of Transportation  
1263 S. Stewart Street  
Carson City, NV 89712

Total Text: 4080  
Total Figures: 8  
Total Tables: 1  
Total Words: 6330

Submitted for Presentation and Publication at the 86th Annual Meeting of the  
Transportation Research Board

November 10, 2006

## ABSTRACT

Signalized diamond interchanges are one of the most common interchange types in U.S. urban areas. Special signal control strategies have been developed in the past for diamond interchanges to address the unique traffic flow and geometric characteristics such as tight spacing and one-way cross streets. This paper documents the application of diamond interchange signal control strategies on a site consisting of six closely-spaced intersections in Reno, Nevada. These intersections represent or closely resemble a standard diamond interchange. Advanced control strategies are derived based on diamond interchange signal control schemes. Simulation results of the timing strategies indicate significant reductions of the number of stops; however, no significant change is found for the overall travel time and delays for the study site. Because the proposed control strategies emphasize maximum progression between closely spaced paired signals, the external approaches normally experience increased delays and stops. The proposed control is considered more efficient than the existing control due to significant reduction of stops and much improved driving experience and driver's expectations. Public reaction to the new timings has been positive. Similar applications could be easily adopted at other locations of similar site characteristics. The proposed control enhances the knowledge of traffic signal control and coordination for closely spaced intersections.

**Keywords:** Diamond interchange, signal control, coordination, traffic progression, closely-spaced signals

## INTRODUCTION

In January 2006, the University of Nevada Reno initiated a research project with funding from the Nevada Department of Transportation. The research project was to investigate the current operations at many signalized diamond interchanges in Nevada's urban areas. Similar to other states in the U.S., signalized diamond interchange is the most common interchange type in Nevada's urban areas (1). For example, in the Reno-Sparks Urbanized area in northern Nevada, signalized diamond interchanges account for approximately 60% of all the interchanges. Due to the lack of knowledge of diamond interchange signal control strategies, most of the diamond interchanges in Nevada are probably not operating under the most efficient controls. Using two separate controllers was common for controlling most standard tight urban diamond interchanges (spacing less than 400 ft). Although coordination plans are implemented for the signals, the most efficient diamond phasing schemes are not always used, which often lead to excessive stops, queuing and delay within an interchange. The primary objective of this paper is to demonstrate, through a case study, how diamond interchange traffic signal phasing strategies could be applied to improve traffic operations at closely-spaced intersections that either form standard

diamond interchanges and most importantly be extended to locations that closely resemble diamond interchanges.

The remainder of the paper is organized as follows. First, some background information is provided regarding diamond interchange signal phasing and operations. A case study, using a traffic network located in Reno, Nevada, demonstrates how the existing signal control could be improved by applying advanced diamond interchange signal timing strategies. Finally, a summary and conclusions section is given.

## BACKGROUND

Diamond interchanges are important locations for both freeways and urban streets due to their unique traffic flow patterns and geometric characteristics. A standard diamond interchange consists of two signals, with typical spacing ranging between 200 ft and 1000 ft, and tight-urban diamond interchanges (spacing less than 400 ft) are very common. Figure 1 illustrates an example diamond interchange layout.

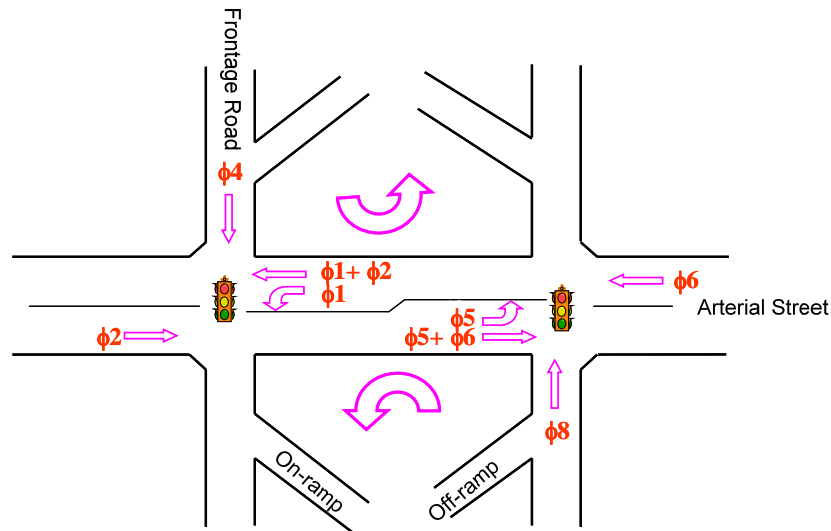


Figure 1 Typical diamond interchange

Diamond interchanges possess unique traffic flow patterns, and managing their operations can be challenging due to the unique traffic flow when tight spacing exists. As shown in Figure 1, the left-turn traffic on the arterial street interlocks each other and cannot make simultaneous left-turns as at traditional signalized intersections. The cross streets are essentially one-way streets, freeway on/off-ramps, and sometimes the ramps merge with one-way frontage roads. Often there are frontage road intersections in close proximity to the ramp intersections. A standard 8-phase NEMA controller is sufficient to control both signals at a diamond interchange, as indicated by the phase designations in Figure 1. However,

greater flexibility of control can be obtained using controllers with 16-phase capability. It is not, however, necessary to have output channels for the additional phases (2).

Over the years, researchers and traffic engineers have been developing special signal timing strategies to manage diamond interchange operations (3, 4, 5). Advanced signal phasing strategies have been focused on using one signal controller to control both signals at a diamond interchange (6, 7, 8). However, many jurisdictions may not be well aware of such strategies, or are hesitated to implement them. Due to some maintenance related issues and concerns over wiring and view obstruction, diamond interchanges may need to be designed with the conventional two-controller operation when the distance between the two signals is large (e.g., larger than 800 ft). Experienced traffic engineers who are well aware of these special diamond control strategies may try to mimic a single controller operation. In such a case, pre-timed operation is usually required to achieve the expected progression. On the other hand, some traffic engineers may just treat the diamond interchange as if they were two regular traffic signals. Although some traffic signal coordination plans are usually attempted to achieve progression at the interchange, such signal coordination plans generally do not take into consideration the unique traffic flow characteristics at diamond interchanges, thus traditional separate intersection signal timing plans (i.e., three phase control described later) may not be optimal (9).

Various signal phasing schemes have been developed specifically for diamond interchange operations, which can be classified into two broad categories: three-phase and four-phase (10). These phasing schemes are generally developed based on a one-controller concept (11, 12). Three-phase strategies can be implemented in various forms, including basic three-phase and three-phase with different lead/lag sequences (9). Basic three-phase operation requires the two cross roads phases starting and terminating at the same time, which is suitable when the two ramps have equal traffic demands and sufficient queue storage is available between the two intersections. When the cross roads do not have equal demands, three-phase with lead/lag is then preferred. Three-phase favors progression for the arterial through movements, but the cross roads and arterial left-turn traffic normally stops, where sufficient queue storage spaces must be provided to avoid queue spillback at the interchange. Four-phase with overlap (also called TTI-4-phase) is commonly seen when the spacing is short and queue spillback would be a major concern if operated with three-phase. Because four-phase operation is essentially a split phasing scheme, it is not as efficient as three-phase operations from a capacity's point of view. However, when timed appropriately, the TTI-4-phase can eliminate majority of the vehicle stops and queues on the arterial between the two cross streets; thereby better meeting driver expectations. The use of two overlap phases (note the usage of the term overlap is a legacy term which is more appropriately called a transition interval) also supplements the efficiency loss by serving the cross street phases and the arterial phase simultaneously (13).

When using one traffic signal controller to control a diamond interchange, special programming of the traffic signal controller settings is necessary. deCamp (6) detailed how various diamond interchange phasing schemes can be implemented using the standard 8-phase NEMA controllers. Some controller manufactures have also built-in certain phasing schemes within the controllers, so that they are ready to use with little programming efforts (*14, 15, 16*). Examples of such manufacturers include Eagle and Naztec, which have built-in phasing schemes for the basic three-phase and TTI-4-phase operations. These controllers provide capabilities of up to 16 separate signal phases and 4 programmable rings. For TTI-4-phase, the overlap phases are designated as  $\phi_{12}$  and  $\phi_{16}$ , with  $\phi_{12}$  following  $\phi_4$  and  $\phi_{16}$  following  $\phi_8$ .

Diamond interchange phasing can be applied to any two signalized intersections possessing diamond interchange traffic flow characteristics. For example, a split intersection has exactly the same features of a diamond interchange, thus can be controlled by standard diamond phasing schemes (*17*). Many closely spaced intersections may not have the exact features of a diamond interchange; however, diamond control concepts may be applied to provide improved traffic operations at such locations. The literature search found a very limited number of documents to address these special applications. As one of the major objectives of this research, the application of advanced diamond interchange signal control strategies is demonstrated in the case study presented below.

## CASE STUDY

### Site Description

The study site includes six closely spaced signalized intersections on the south side of the University of Nevada Reno (UNR) campus (See **Figure 2**). **Figure 2** also includes the P.M. peak hour traffic volumes, the intersection geometry, and the intersection level-of-service. Six individual signal controllers are used to control the six signalized intersections (see Figure 4 for the existing signal control and phasing). Although the traffic signals are coordinated with time-of-day plans, significant queuing and stops are often experienced due to the lack of consideration of the unique traffic flow patterns within the network. Because all the intersections have sufficient capacities, the lack of traffic progression is clearly noticeable by the drivers, thus complaints are often received from the public.

Both 8<sup>th</sup> Street and Maple Street are one-way streets, and include I-80 freeway on/off-ramps at the ends of both streets. The approximate distance between 8<sup>th</sup> Street and Maple Street is 300 ft. Virginia Street is a two-way arterial, serving major traffic flows for the UNR campus and downtown Reno. As illustrated on Figure 2, the two signals on Virginia Street form a standard tight diamond interchange. Center Street and Sierra Street are partial one-way/two-way arterial streets, mainly serving downtown Reno traffic exiting and entering I-80 freeway. The signals on both streets do not form standard diamond interchanges due to

either absence of or restrictions on certain traffic movements. For example, the traffic signals on Sierra Street do not have the internal northbound left-turn movement at 8<sup>th</sup> Street and the northbound through movement at Maple Street. The signals on Center Street do not have the southbound through movement at Maple Street, and split phasing is used for the north/south directions at both signals. No left-turn traffic is allowed for the westbound approach at Center Street/8<sup>th</sup> Street intersection. Despite such differences, these signals do have traffic flow patterns and signal spacing that resemble closely to tight diamond interchanges. We later refer the two signals on each of the three arterial streets as *paired* signals, where a single controller will be proposed to control each paired signal.

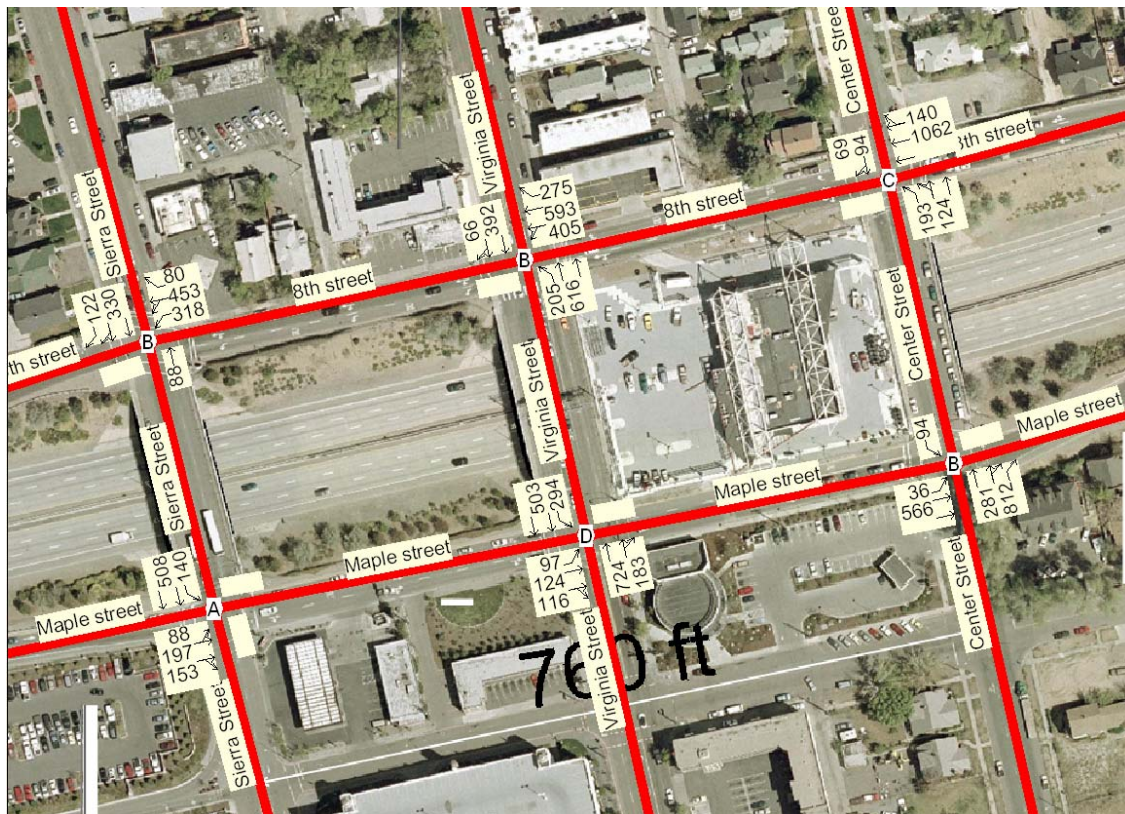


Figure 2 Intersection Geometry and Existing PM Peak Hour Traffic Demands

*\*Note: Letters at each intersection denote level-of-service*

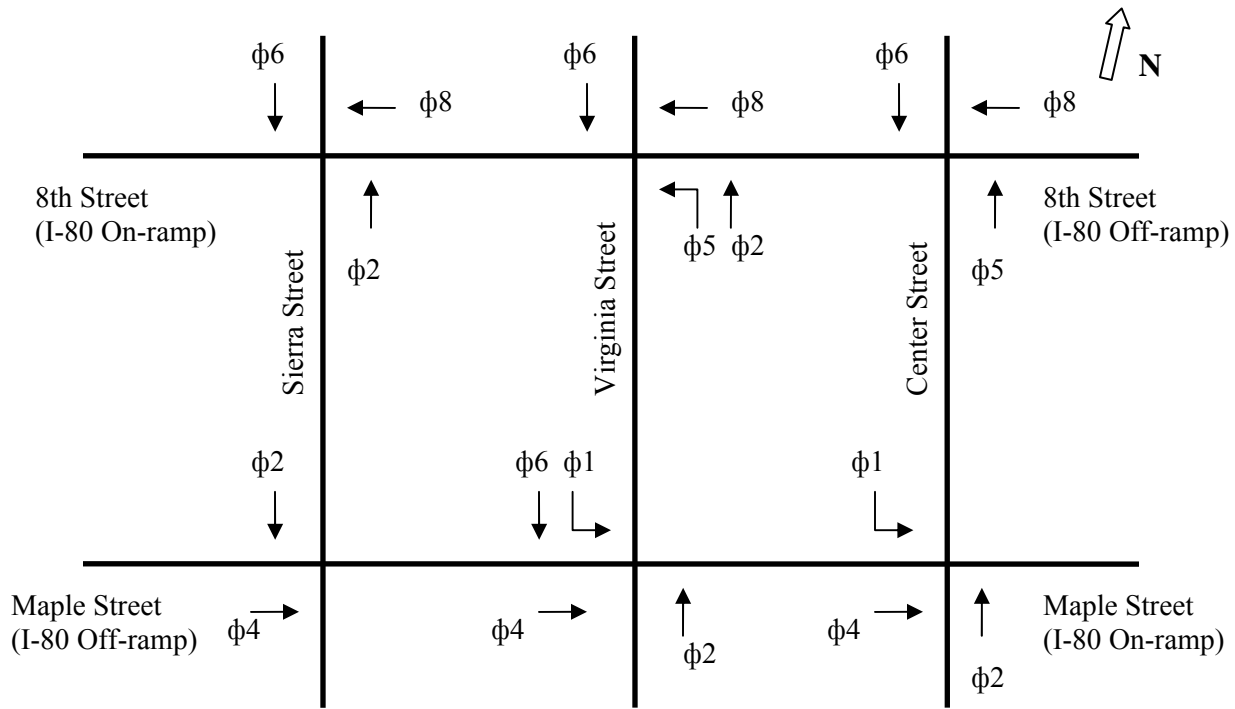
Traffic demands on **Figure 2** indicate that the major traffic flow movements at the study site include I-80 westbound off-ramp (i.e., the westbound approach at Center Street/8<sup>th</sup> Street) to south Virginia (majority of the 405 vph traffic), and to south Sierra (318 vph), southbound on Virginia Street to I-80 eastbound (294 vph). The existing timing plan focuses on progression of traffic along 8<sup>th</sup> street; however, the lack of efficient phasing and coordination often results in significant stops and queues between the paired traffic signals on the three arterial streets.

## Proposed Control

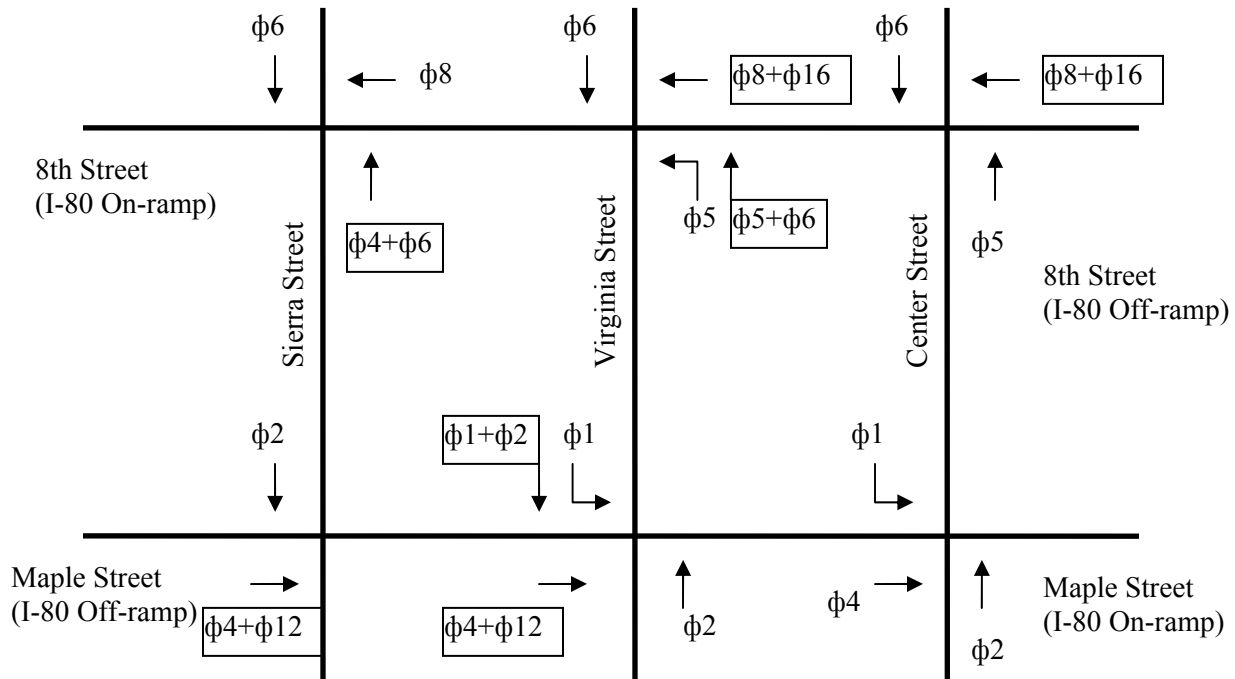
Our proposed control calls for using three controllers to control the six intersections: one for the paired signals on Virginia Street using the standard TTI-4-phase scheme; one for the signals on Center Street and one for the signals on Sierra Street. The signal control schemes for Center Street and Sierra Street are derived based on diamond interchange control schemes. **Figure 3** shows the proposed signal phases and Figure 4 shows the proposed phase and ring structures of the three signal controllers.

Similar to the overlap phases used in standard diamond interchanges, overlap phases are also used for the signals on Center Street ( $\phi 16$ ) and Sierra Street ( $\phi 12$ ). These two overlap phases are approximately the travel times between the two signals, which provide added efficiency while allowing vehicles to progress through without having to stop. With the proposed traffic signal control and phasing, vehicle stops and queues would be significantly reduced between the two signals on Virginia Street, except for a very few occasionally observed U-turn traffic (i.e., westbound on 8<sup>th</sup> Street going south on Virginia and then going eastbound on Maple). These U-turns are very minor, most of which are drivers who miss the turns. Most of the vehicle stops are also eliminated between the signals on Sierra Street. Occasional vehicle stops and queues may occur for those arriving during the latter portion of phase 8 (i.e., the westbound movement at 8<sup>th</sup> Street). On Center Street, vehicles coming from west on Maple and going north on Center would stop, but the effect would be minor due to low traffic demands (36 vph for the P.M. peak). Vehicles may also experience stops if they arrive during the latter portion of the signal phase for the northbound traffic.

As the six traffic signals within the study network are controlled by three signal controllers, the timing strategy focuses on providing the maximum progression for the major traffic movements. Once the offsets are determined to progress the major movements, progression for the other non-major movements are determined. For example, the offsets are determined in a way that they favor traffic progression along 8<sup>th</sup> Street, because it involves two major traffic movements within the network: westbound on 8<sup>th</sup> to southbound on Virginia, and westbound on 8<sup>th</sup> to southbound on Sierra. Once the offsets are set to progress such movements, progression for the other movements could not be further adjusted, whether the progression is good or not.



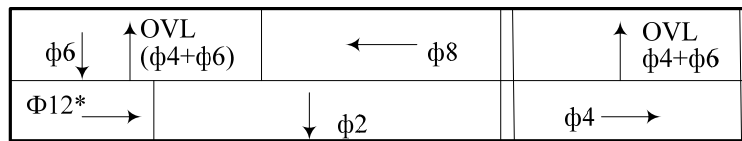
(a) Existing control and phasing



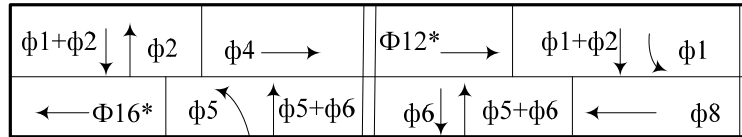
(b) Proposed control and phasing

- Notes: 1. Existing control uses 6 controllers; Proposed control uses 3 controllers.  
 2. Phasing changes are highlighted in part (b)

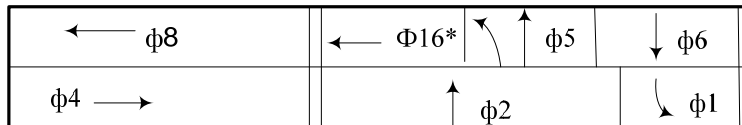
Figure 3 Existing and Proposed Signal Control and Phasing Scheme



(a) Phase and ring diagram for intersections on Sierra Street



(b) Phase and ring diagram for intersections on Virginia Street



(c) Phase and ring diagram for intersections on Center Street

*\*Note: These are overlap phases which approximately equal to the travel times between the intersections*

Figure 4 Proposed phase and ring structure

The same 90-sec cycle length is used to develop the new coordination plan with the proposed signal control. There are three particular reasons to use a 90-sec cycle. 1) A 90-sec cycle is found to be adequate in order to accommodate pedestrian crossing times at various locations in the network. 2) Using a 90-sec cycle is consistent with the existing cycle length, which would produce compatible performance measures for comparison purposes. 3) Finally, a 90-sec cycle is also found to provide optimal progression for the three major traffic movements as indicated in the time-space diagrams on Figure 5. The time-space diagram in the upper part of Figure 5 shows that a perfect progression is achieved along 8<sup>th</sup> 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 could also progress through the next signals without stop due to the proposed special phasing and one-controller operation. The time-space diagram in the lower part of Figure 5 shows that the major movement coming from north on Virginia Street and going east to I-80 could progress through the entire network without stop. It is likely that other traffic movements may not be well progressed, which is not unusual in the practice of signal timing and coordination.

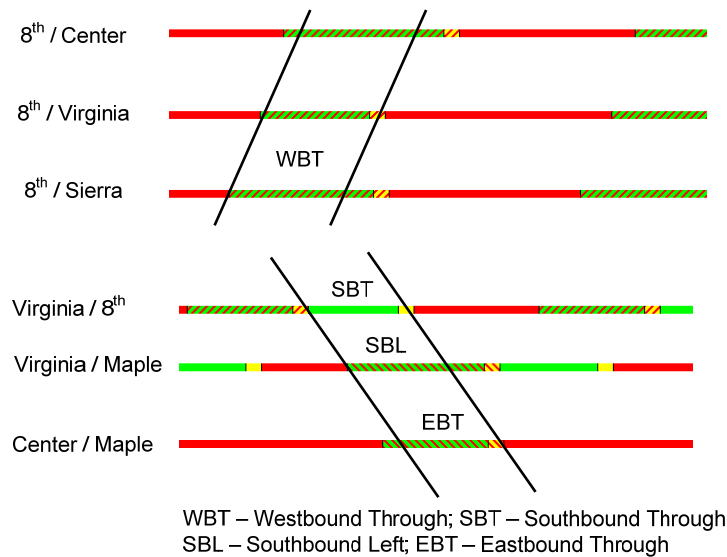


Figure 5 Time-space diagrams for major traffic movements

## Study Results

The proposed traffic signal phasing and timing is evaluated against the existing traffic signal scheme. The evaluation is conducted using *SimTraffic* (18) simulation model. The reason of choosing *SimTraffic* is due to the integrated *Synchro/SimTraffic* software where the signal timing plans developed in *Synchro* can be easily evaluated using *SimTraffic* microscopic simulation. Three traffic control scenarios are evaluated: 1) existing control with optimized offsets and splits; 2) existing control with optimized offsets, splits and phasing sequence; and 3) the proposed control scheme. The first scenario includes using six individual controllers for each of the signals. To achieve the best performance and make compatible comparison with the other scenarios, the signal timing is optimized using *Synchro* for the offsets and splits; however, no phasing sequence change is allowed from the existing control while performing the optimization. The second scenario is similar to the first scenario, except for also allowing optimization of the phasing sequence by *Synchro*. It is found that *Synchro* results in a phasing sequence that has lagging left-turns for the signals on Virginia Street. *Synchro* tends to select lagging left-turns due to its major optimization objective of minimizing delays. Lagging left-turn phasing usually results in lower delay at diamond interchanges, especially when the left-turn has protected/permissive operation. Left-turn phase may not be needed when the left-turn traffic is light, and can make the turns during the permitted phase. Lagging left-turn also allows for clearing the left-turn queues within the same cycle. All these factors could contribute to lower vehicle delays. The third scenario is the proposed control using three signal controllers.

Two performance measures are compared for the three scenarios: the system-level travel time and the system-level stops. The reason of selecting travel time as a performance measure is that travel time is



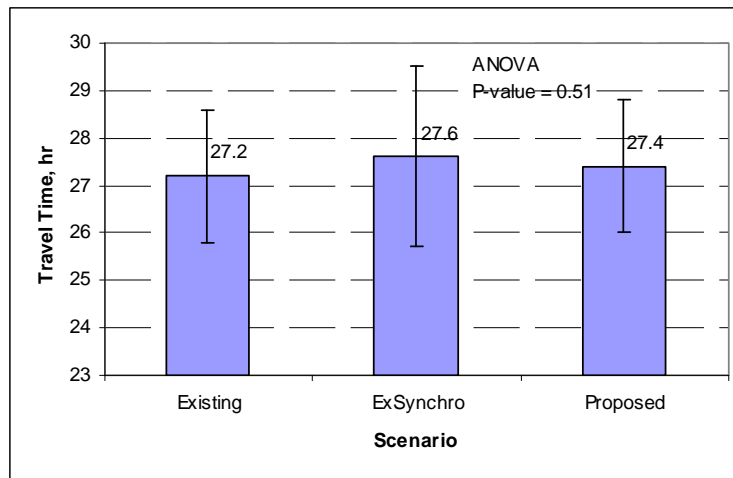


Figure 7 Comparison of system-level travel time

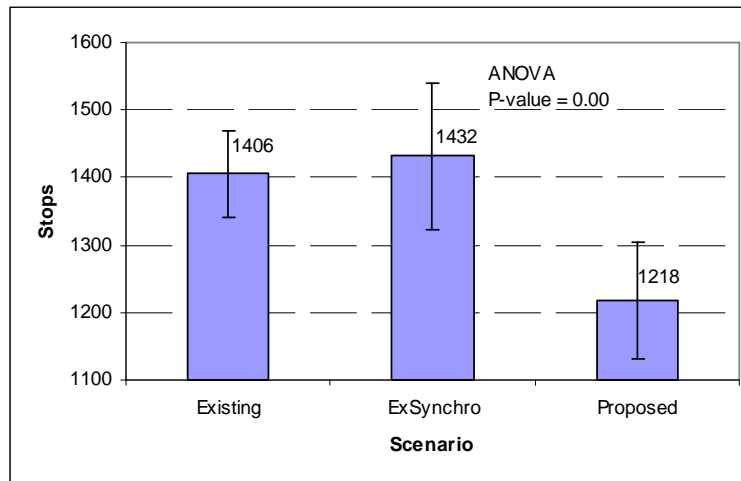


Figure 8 Comparison of system-level stops

Figure 7 shows that non-statistically different travel time results are found for the three scenarios as indicated by the p-value of 0.51. A p-value of greater than 0.05 from ANOVA indicates that there is no evidence that the results are statistically different from each other at the 5% significance level. However, Figure 8 indicates that at least two of the results are statistically different at the 5% significance level as indicated by the p-value of 0.000. Based on the 95% confidence intervals, it can be seen that the proposed signal control and timing results in significantly lower number of stops than the other scenarios. In both figures, it can also be noticed that the optimized solutions by *Synchro* (Scenario 2) results in slightly worse performance than using the existing phasing sequence. What can be concluded from this result is that the proposed signal control strategy would not result in significant reduction in travel time and delay, but could significantly improve the number of stops, which is considered a significant improvement over the existing control. As can be noticed in **Table 1**, significant reductions on travel time and stops are achieved within the paired signals on the three arterial streets. For example, vehicle stops are completely

eliminated between the two signals on Virginia Street, and on the northbound approach at Sierra Street/8<sup>th</sup> Street. The southbound approach at Sierra Street/Maple Street also reduces to 11 stops from 89 (with the existing control and offset optimization) and 129 (with the existing control and *Synchro* full optimization). The proposed control results in some increased travel times and stops on the external approaches of the paired intersections. Drivers would generally face some longer delays on the external approaches, but once depart from the signal, could generally traverse the system with minimal delays and stops. Nevertheless, the three major traffic movements could progress through the entire network without stops. Although not being a problem with the existing traffic demands, the queues on the freeway off-ramps (westbound on 8<sup>th</sup> and eastbound on Maple) should be monitored in the future to prevent potential queue spillback to the freeways.

Table 1 Details of travel times and stops for the study scenarios

Intersection	Approach	Travel Time, hr			Total Stops		
		Existing	ExSynchro	Proposed	Existing	ExSynchro	Proposed
Virginia/8th	NB	0.7	0.9	0.4	91	55	0
	SB	1.8	1.8	2.1	111	110	124
	WB	2.0	2.0	2.4	95	104	135
Virginia/Maple	NB	1.6	1.6	1.7	110	108	116
	SB	0.6	1.1	0.6	11	74	0
	EB	1.1	0.8	1.1	80	64	58
Center/8th	NB	0.8	0.8	0.8	43	34	32
	SB	0.2	0.2	0.3	22	22	22
	WB	2.8	2.8	2.8	187	187	176
Center/Maple	NB	2.6	2.6	2.5	176	180	167
	SB	0.1	0.1	0.1	4	3	3
	EB	1.5	1.7	1.3	98	111	93
Sierra/8th	NB	0.2	0.1	0.1	23	14	0
	SB	1.4	1.4	1.8	102	101	125
	WB	1.5	1.2	1.3	87	64	58
Sierra/Maple	SB	1.1	1.4	0.7	89	129	11
	EB	1.3	1.2	1.6	77	72	96

\*Note: Existing – optimized timing based on existing signal control and phasing;  
 ExSynchro – Synchro solution based on existing signal control and phasing sequence optimization;  
 Proposed – proposed signal control based on diamond interchange concepts

## Next Steps

The next phase of the project will focus on field implementation of the proposed control. City of Reno does not have immediate plans to modify the existing signal controller uses and re-wiring the cabinets to implement the proposed control strategies. Therefore, the first step is to implement a fixed-time coordination to test the proposed control strategies. This is necessary due to the current usage of multiple controllers and the specific requirements of the proposed phasing schemes. In fact, fixed-time coordination is considered adequate and is expected to provide similar performances, since the six signals

form a grid network which is similar to some downtown network, where fixed-time operation is generally preferred.

## **SUMMARY AND CONCLUSIONS**

The paper documents a study on applying advanced diamond interchange signal control strategies to control a signalized network that possesses similar traffic flow and geometric characteristics to diamond interchanges. A study site in Reno, Nevada is used to demonstrate the strategies. The study network consists of six closely-spaced signalized intersections along three arterial streets. Control strategies are proposed to use three signal controllers to control all the signals instead of the current six controllers.

The proposed control strategies are evaluated using a micro-simulation model. The study results shows significant reductions on the number of stops; however, the system-level travel time and delay do not change significantly. This is mainly due to the fact that the proposed control significantly reduces the vehicle stops and delays within the paired signals along the three arterial streets. The consequence of the proposed control would likely incur increased delays and queues on some external approaches. However, the proposed control is considered more efficient due to significant reduction in vehicle stops, thus improving driver's perception and driving experience. Public reactions to the new timings have been positive. The traffic signal control concept introduced in this study could be easily adopted at other similar locations and would enhance the state-of-practice of traffic signal control and coordination, especially at closely-spaced intersections.

## **ACKNOWLEDGEMENT**

The work reported in this paper is part of a research project sponsored by the Nevada Department of Transportation under contract #P014-06-803.

The views expressed in this paper do not necessarily reflect those of the sponsor.

## **REFERENCES**

1. Garber, N.J., and M.D. Fontaine. "Guidelines for Preliminary Selection of the Optimum Interchange Type for a Specific Location", Report FHWA/VTRC 99-R15. Federal Highway Administration, Washington, D.C., 1999.
2. Sunkari, S.R. and Urbanik, T. "Signal Design Manual for Diamond Interchanges", Texas Transportation Institute, Report #1439-6, September 2000.
3. Messer, C.J. and Berry, D.J. "Effects of Design Alternatives on Quality of Service at Signalized Diamond Interchanges", Transportation Research Record 538, 1975, pp 20-31.

4. Messer, C.J., D.B. Fambro, and S.H. Richards. "Optimization of Pretimed Signalized Diamond Interchanges", *Transportation Research Record* 644, 1977, pp 78-84.
5. Kovvali, V.G., Messer, C.J., Chaudhary, N.A., and Chu, C-L. "Program for Optimizing Diamond Interchanges in Oversaturated Conditions", *Transportation Research Record* 1811, 2002, pp 166-176.
6. deCamp, G.B., "A Primer on Diamond Interchanges", *TexITE Newsletter*, Spring, 1993.
7. Engelbrecht, R.J. and Barnes, K.E. "Advanced Traffic Signal Control for Diamond Interchanges", *Transportation Research Record* 1856, 2003, pp 231-238
8. Nelson, E.J., Bullock, D. and Urbanik, T. "Implementing Actuated Control of Diamond Interchanges", *Journal of Transportation Engineering*, Volume: 126 Issue: 5, 2000, pp 390-395.
9. Irvine, Y. and Daniel B. Fambro. "Implementation Guidelines for Retiming Diamond Interchanges," *Texas Department of Transportation, Research Report* 1164-3, Austin, TX, December 1992, pp. 7-16.
10. Messer, C. J. and Myung-Soon Chang, "Traffic Operations of Basic Actuated Traffic Control Systems at Diamond Interchanges," *Texas State Department of Highways and Public Transportation, Research Report* 344-2F, Austin, TX, August 1985, pp. 7-21.
11. Tian, Z., Messer, C., Balke, K. and Urbanik, T. "Integration of Diamond Interchange and Ramp Metering Operations", *Transportation Research Record* 1925, 2005, pp 101-111.
12. Tian, Z., Messer, C. and Balke, K. "Modeling the Impact of Ramp Metering Queues on Diamond Interchange Operations", *Transportation Research Record* 1867, 2004, pp 172-182.
13. Woods, D.L. "Limitations of Phase Overlap Signalization for Two-level Diamond Interchanges", *Traffic Engineering, ITE*, 1969, Vol. 39, Issue 12, pp 38-41.
14. Engelbrecht, R.J., Venglar, S.P. and Tian, Z. "Research Report on Improving Diamond Interchange Operations Using Advanced Controller Features", *Report No: FHWA/TX-02/4158-1*, Texas Transportation Institute, College Station, Texas, 2001.
15. Koonce, P., Urbanik, T, and Bullock, D. "Evaluation of Diamond Interchange Signal Controller Settings by Using Hardware-in-the-loop Simulation", *Transportation Research Record* 1683, 1999, pp 59-66.
16. Nelson, E.J., Bullock, D. and Urbanik, T. "Implementing Actuated Control of Diamond Interchanges", *Journal of Transportation Engineering*, Volume 126, Issue 5, 2000, pp 390-395.
17. Bared, J.G. and Kaiser, E.I. "Benefits of Split Intersections", *Transportation Research Record* 1737, 2000, pp 34-41.
18. Husch, D. and Albeck, J. "SimTraffic 6 Traffic Simulation Software – User Guide", *Trafficware, Inc.*, Albany, California, 2003.
19. Tian, Z., Urbanik, T., Kacir, K., Vandehey, M., Long H. "Pedestrian Timing Treatment on Coordinated Signal Systems", *Proceedings of ICTTS'2000, ASCE*, Beijing, China, August 2000.
20. Tian, Z., Urbanik T., Engelbrecht, R., and Balke, K. "Variations on Capacity and Delay Estimates from Microscopic Simulation Models", *Transportation Research Record* 1802, 2002, pp. 23-31.