Final Report

October 2018

DEVELOPING AND TESTING PROACTIVE SIGNAL CONTROL STRATEGIES FOR ARTERIAL-FREeway DIAMOND INTERCHANGES (TASK G)

SOLARIS Consortium, Tier 1 University Transportation Center
Center for Advanced Transportation Education and Research
Department of Civil and Environmental Engineering
University of Nevada, Reno, NV 89557

Viswanath Potluri, PhD student
Pitu Mirchandani (PI), Sc.D.
School of Computing, Informatics, and Decision Systems Engineering
Arizona State University
Tempe, AZ 85287
DISCLAIMER:

The contents of this report reflect the views of the authors, who are responsible for the facts and accuracy of the information presented herein. This document is disseminated under the sponsorship of the U.S. Department of Transportation’s University Transportation Centers Program, in the interest of information exchange. The U.S. Government assumes no liability for the contents or use thereof.
EXECUTIVE SUMMARY

The enormous increase of road traffic has led to the inefficient utilization of supply, that is, link capacities and traffic signals. Thus arises the need for effective congestion management and has motivated traffic researchers to study various traffic signal control strategies, such as optimal fixed timing, reactive, and proactive signal controls. In this project, a novel traffic control approach called MIDAS was studied here, which proactively manages traffic demand at arterials and diamond interchanges. Unlike existing proactive traffic control solutions, MIDAS is a cycle free solution which allows flexible phase sequencing.

Efficient traffic movement at any closely spaced intersections like Diamond interchange is often a major challenge to traffic engineers’ due to complicated traffic movements and heavy demand fluctuations. This report presents a dynamic programming (DP) based real-time proactive traffic control algorithm that considers the vast number of possible durations for each of these paired phases (meta-phases), in a computationally efficient manner, and selects the durations that optimize jurisdiction’s objective function such as delays, stops, or queues, etc. Like RHODES [8], MIDAS uses forward recursion Dynamic Programming (DP) over a finite-time horizon that rolls forward and, then uses a backward recursion to retrieve the optimal phase sequence and duration of phases, but has efficient data structures and responds well to regular as well as intermittent traffic smoothly without any “transition” issues. MIDAS also uses Lagrangian measurement data, like GPS data from smart phones, to estimate real-time link travel times, turning movements, etc. For every time horizon, MIDAS predicts future arrivals, and predicts queues at the interchanges. Subsequently, it uses the DP algorithm to compute the phase durations for the time horizon. These durations are changed if necessary when new predictions are available.
This report includes an experimental study that shows MIDAS outperforming optimal fixed timing (OFTC) signal control and RHODES control. A diamond interchange (I-17/19\textsuperscript{th} Ave., Phoenix, AZ) was simulated on VISSIM micro-simulation platform, where MIDAS, RHODES, and OFTC strategies were evaluated for various traffic loads.

\textit{Keywords}: Microscopic Simulation Modeling, VISSIM, Proactive Traffic Control, Adaptive Control, MIDAS Traffic Control, RHODES Traffic Control
1. INTRODUCTION AND BACKGROUND

Most adaptive traffic control strategies, whether for a single intersection or for an arterial, treat each intersection signal group as the smallest control element and adaptively decide on the durations of the phase at the intersection, whether directly in cycle free schemes or indirectly through splits and cycle times in cycle-based schemes. This is appropriate for majority of traffic signals in the USA, but there is a significant fraction of paired signals at diamond interchanges (see Figure 1).

![Figure 1: Paired intersections at an interchange](image)

Effectively, there are four traffic signals at each on the intersections A and B at the interchange, and the “phases” at each of the intersections need to be synchronized to handle EW straight through traffic on the arterial, off-ramp traffic streams from the north and from the south, and turning traffic streams from the west and from the east going to the north and south on-ramps. High EW traffic would need more straight through durations at A and B to decrease average delays, while high off-ramp traffic would require more time for the left-turners from the off ramps at A and B. Current approaches to handle traffic at interchanges is to go through a fixed set of sequence of phases and their durations for each of the two signal groups, with actuations to allow for overlaps and force-offs.
It is surprising that very little research and development has been focused on proactive control of diamond interchanges. Several signal timing strategies have been developed for diamond interchanges, but none proactively responding to ongoing demand fluctuations. One of the early works on the optimization of signalized diamond interchanges was conducted by Messer and his colleagues and students who were instrumental in developing PASSER signal optimization which was then extended to PASSER III for diamond interchanges, which determines off-line the fixed signal plan, among a restricted number of alternatives, based on assumed traffic demand. Fixed signal plan is not responsive to real time traffic demand [1, 2].

In their comprehensive works, Tian and colleagues [3, 4, 5, 6] considered both the traffic signals and the ramp meters at the interchange and developed schemes to integrate their operations for given traffic streams. However, they did not address predicted or measured fluctuating demands in the approaching streams to proactively manage the integrated system.

Messer and Chang [7] were perhaps the first to study actuated control at the interchanges. They showed that there was some improvement in traffic performance. Few years later, Mirchandani and his research collaborators were among the first to address adaptive control of a diamond interchange using the dynamic programming (DP) based RHODES strategy [8-10] and actually conducted a field test that showed significant traffic performance improvements compared to well-timed pair of signals at the interchange. In that system each signal pair was treated independently in the logic although the execution of the result of the algorithm the signals were coupled because of the control configuration at the interchange. Limited prediction was available from upstream arterial intersections.
while predictions from the off-ramps was based on assumed off-ramp demand. Still the proof of concept was successful. Still later Fang and Elefteriadou [11] reported a DP-approach to adaptively control an interchange; however, their underlying model for the DP was less efficient and their approach to solving it was ad-hoc. Their model was also not field tested.

This project is to study a proactive traffic control scheme for diamond interchanges based on the recently developed MIDAS framework (a RHODES-type DP with better demand predictions) [12, 25]. Here each potential interchange phase in the DP logic is actually possible paired phases at the individual interchange. Mirchandani has been the principal architect of the well-received RHODES real-time traffic adaptive system [8-10,13-20], and the state-of-the-art MILOS ramp-metering system [21-24] and is currently leading a team to develop this integrative concept MIDAS based on streaming data from 4G telephony data from mobile travelers and connected vehicles. Recent reviews of adaptive signal control and adaptive ramp metering are given by Stevanovic [26] and Papageorgiou [27], respectively.

In this study, the MIDAS algorithm is tested on a VISSIM-based simulation platform. The traffic performance for the following two cases are considered:

(1) Optimal fixed timings for a several levels of traffic volumes.

(2) Proactive timing using data from observed traffic.

A VISSIM-based simulation model was developed for an actual interchange. VISSIM [28] has been used in studying this new novel strategy. VISSIM has been used for traffic adaptive signal control before [29, 30]. Data for that interchange was obtained from the Arizona Department of Transportation.
2. DIAMOND INTERCHANGE

A Diamond Interchange consists of two closely spaced intersections with complicated phase movements. Diamond interchanges are equipped with four traffic lights, at each of the intersection and the phases at each of the intersection should be synchronized to accommodate heavy traffic movements on off ramps and arterial streets. A typical diamond interchange is shown in Figure 1, with 8 possible traffic movements that accommodate on-ramp, off-ramp and arterial street traffic.

![Diamond Interchange Diagram](image)

Figure 1 Diamond Interchange

Some examples of a very large number of resulting phases are shown in Figure 2.
2.1 Signal Phasing in Diamond Interchange

Several combinations of the phases, denoted by Φ’s, are referred to as Lag-Lag, Lead-Lag, etc. are listed below and illustrated in Figures 3-6.

3Φ LAG-LAG (see Figure 3)

This pattern serves heavy through traffic on the crossroads but will not service heavy ramp traffic volumes or heavy cross road left turn volumes, as these movements are restricted by internal storage capacity. It is good for two-way progression on the crossroads when the interchange falls on the \( \frac{1}{2} \) mile grid in a zero-offset plan. Also, a good pattern for lower cycle lengths.

4Φ LEAD/LAG – LAG (see Figure 4)

This pattern serves heavy through traffic on the cross road and heavy ramp traffic (on both ramps) but will not service heavy crossroad left turn volumes. Again, the
crossroad left turn volumes are restricted to the internal storage capacity. This pattern also favors two-way progression under the conditions listed above.

**4Φ LEAD/LAG** (see Figure 5)

This pattern serves heavy through traffic, heavy ramp traffic (on both ramps) and a heavy crossroad left turn demand in one direction. The left turn in the opposite direction must, again, store on the inside. This pattern also has the potential for good two-way progression for conditions previously described, but the inside 02 left movement will reduce the bandwidth for the opposing through movement.

**3Φ WITH "OVERLAPS"** (see Figure 6)

This pattern is very similar to the 30 lag-lag pattern, with the added ability to service one heavy ramp movement and one heavy crossroad left turn movement at any given time.

The pattern also has the ability to change which ramp or crossroad left turn movement is favored based on time of day programming.

**4Φ WITH "OVERLAPS" (TTI) PHASING:**

This pattern serves heavy traffic on all four external approaches including the x-road left turn movements. This is accomplished by operating in what is essentially a split phasing type of operation. Therefore, the pattern also has some of the shortcomings generally associated with split phasing (or servicing one approach at a time). Some added efficiency can be achieved through the early release of the far side through movements.
Figure 3  3-Φ Operation LAG – LAG
Figure 4  4-Φ Diamond Lead/ Lag - Lag
Figure 5. 3-Ω with overlaps
Figure 6. 4-Ф with overlaps
3. TRAFFIC CONTROL STRATEGIES

In this project, researchers evaluated the performance of MIDAS signal control with other existing signal control strategies. One of the strategies is an adaptive signal control algorithm called RHODES [e.g., 8-10], which is considered to be among first adaptive traffic control implemented and successfully field tested.

3.1 Optimal Fixed Time Signal Control

To evaluate the performance of any proactive traffic control algorithm, it is advised to compare the metrics one is trying to minimize, against an optimal fixed time signal setting. In this paper, we studied optimal fixed time signal control strategy by simulating different traffic loads in VISSIM. VISSIM performs green time optimization of stage-based fixed time controllers by repeatedly calculating simulations of the entire network. The simulations are continued as long as changes in green times of the stages leading to an increase in the flow (volume) or to a reduction in the average vehicle delay.

To obtain “Optimal Fixed Time Signal”, VISSIM determines the average delay of all vehicles that have passed through the nodes on the lanes with signal heads of the signal group, using an automatically created node evaluation for each signal group over the entire simulation run.

- For optimizing, the signal group in which the vehicles have the highest delay is determined for each stage.
- The stage with the lowest maximum average delay is selected as the best stage.
- The stage with the highest maximum average delay is selected as the worst stage.
- A second of green time is deducted from the best stage.
- A second of green time is added to the worst stage.
- If a second can no longer be deducted from the best stage, the second-best stage is used. If this can no longer be shortened, the next worst stage is always taken iteratively. If no other stage can be shortened, the optimization is terminated.
- A signal program is better than another if one of the following criteria is met:
If the flow formed by the total number of vehicles driven through the node during the simulation run has increased significantly by at least 25 vehicles or by 10% if this is less.

If the flow has not significantly decreased by 25 vehicles or by 10% and the average delay across all vehicles has decreased.

- If a signal program is better than the best rated, it replaces this as the best. The optimization is continued with the next step.
- The optimization is terminated if one of the following criteria is met:
  - Once the signal program does not improve within 10 simulation runs.
  - Once the flow decreases by more than 25% compared to the best signal program.
  - Once the average delay increases by more than 25%.

3.2 MIDAS Control

In any proactive traffic control system, the signal control algorithm is the key component in determining the optimal phase sequence and phase durations, by minimizing some user defined traffic performance measure, such as minimizing total delays, stops or queues at the intersections. Many researchers have worked towards developing an adaptive traffic control system in the past, of which RHODES [8-10, 12-20, 22-24] is a better performing real time adaptive traffic control system and also has been field tested. But like any other existing adaptive traffic control systems, RHODES uses data from fixed loop detectors for prediction and estimation. On the other hand, MIDAS traffic control installed at each intersection uses Lagrangian data from PICT devices from all the approaches, combined with traffic estimation methods [25] to predict approaching vehicles’ individual arrival times, platoon movements, lane-based traffic, and to estimate turning ratios at the intersection. As these variables get updated dynamically for a user defined time horizon, MIDAS traffic control algorithm feeds on the updated predictions to estimate the queues in each lane on all approaches of each intersection, at each decision epoch with corresponding time horizons.
Similar to RHODES, MIDAS control algorithm predicts approaching traffic and estimates queues at the intersection based on the estimated or user defined queue discharge rates. Unlike making predictions using fixed upstream loop detectors in case of RHODES, MIDAS utilizes GPS (global positioning system) data from vehicles which are considered as a Lagrangian measurement. With GPS data MIDAS knows the O-D paths of the approaching traffic, which means MIDAS knows exact turning movement of the individual vehicle at the intersection. Also, GPS data helps in estimating travel times on link, so that MIDAS can predict the arrival time, \( T_n \), of each individual vehicle \( n \), at the back of the queue, \( Q(T_n) \).

\[
Q(T_n) = Q(T_{n-1}) + A(T_n, T_{n-1}) - D(T_n, T_{n-1}) \tag{1}
\]

MIDAS signal control algorithm uses forward recursion Dynamic Programming (DP), to minimize the user defined performance measure over a finite-time horizon that rolls forward and, then uses a backward recursion to retrieve the optimal phase schedule. The signal control algorithm of MIDAS is similar to the ones to RHODES [10] but with an efficient data structure. MIDAS signal control algorithm determines the optimal signal phase sequence and duration of each phase in the sequence, by taking user defined set of phases (any number of phases) and time horizon as input parameters. Control algorithm runs DP at some time stamp ‘t’, with prescribed time horizon ‘T’ and, considering the tentatively estimated arrivals on all approaches of the intersection over the timeline ‘t+T’. The DP is formulated such that each “stage” of the DP is associated with a signal phase and a number of time units allocated to all past phases before the current stage is defined as stage variable. The DP solution consists of the phase sequence and time units allocated to each phase over the next ‘T’ time units. At every DP run, the sequence of phases begins
with the current phase that is green at the intersection, which allows for the phase to be terminated or extended based on the updated observations. Figure 7 illustrates the output of the DP Algorithm.

![Diagram](image)

(A) set of sample phases  
(B) DP solution example

**Figure. 7 Illustration of the DP Output**

### 3.2.1 Exponential Weighting:

One of the main challenges in setting optimal phase decisions for diamond interchange is to avoid spill backs due to limited inter storage capacity between closely spaced intersections. To address this challenge, MIDAS employs an exponential weighting system. MIDAS assigns a weight to the internal storage lane based on its current estimated queue length while calculating delays in DP. The weight of internal storage lane ‘L’ at any time ‘t’ is an exponential function of queue length of lane ‘L’ at a time ‘t’ as shown in equation (2) and illustrated in Figure 8.

\[ W(L, t) = e^{k \cdot Q_L^2(t)} , \text{k is a multiplication constant.} \]  

Where:

- \( W(L, t) \) = Weight of internal storage lane L at any time t.
- \( L \) = Internal storage lane L, between closely spaced intersections of diamond interchange.
- \( Q_L(t) \) = Queue length of internal storage lane L at time t.
Figure 8 Projection of estimated queue over Time Horizon
4. EVALUATION RESULTS

4.1 Simulation Network

To evaluate the efficiency of the MIDAS control algorithm, a freeway interchange (at i-17/19th AVE., Phoenix) has been simulated using VISSIM, a microscopic multi-modal traffic flow simulation platform, as shown in Figure 9. The simulated network layout was calibrated with the help of the Arizona Department of Transportation (ADOT).

![Figure 9 1-17/19th AVE network on VISSIM](image)

Since MIDAS control is designed to minimize any user defined objective/ metric, in this report MIDAS DP minimizes the sum of delays of traffic approaching the interchange from off ramps and arterial streets. MIDAS controls the simulated interchange in VISSIM, via its COM interface. Vehicle delay is measured as the additional time required to pass a signal-controlled intersection compared to a free through route or an intersection without any type of signal control. The performance of MIDAS signal control
has been evaluated by running multiple simulation runs with different traffic demands or network loads and each simulation run ends after 3600s. After the end of every simulation run, VISSIM reports simulation statistics and node evaluation results collected all through the run. For instance, a set of key performance results at the network and intersection level are shown in Tables 1 and 2.

- DelayAvg: Average of all vehicle delays due to the presence of signal controller in their path when compared to free flow, without any signal control.
- TotalDelay: Sum of all vehicle delays in the network, in seconds.
- StopsAvg: Average number of stops made by a vehicle at the interchange.
- AvgQLEN: Average queue length at any given movement at the stop line of the interchange.
- TotalTravelTimes: Sum of travel times of all vehicles in the network, in seconds.

**Table 1: Network Level Performance**

<table>
<thead>
<tr>
<th>Signal control</th>
<th>SimTime(s)</th>
<th>TrafficLoad</th>
<th>DelayAvg(s)</th>
<th>TotalDelay(s)</th>
<th>TotalTravelTime(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIDAS</td>
<td>3600</td>
<td>4900</td>
<td>13.25</td>
<td>66235.87</td>
<td>414791</td>
</tr>
<tr>
<td>RHODES</td>
<td>3600</td>
<td>4900</td>
<td>14.5</td>
<td>72472.17</td>
<td>421109</td>
</tr>
<tr>
<td>OFTC</td>
<td>3600</td>
<td>4900</td>
<td>32.05</td>
<td>160218.469</td>
<td>467528</td>
</tr>
</tbody>
</table>

**Table 2: Intersection Level Performance**

<table>
<thead>
<tr>
<th>Signal Control</th>
<th>SimTime(s)</th>
<th>TrafficLoad</th>
<th>DelayAvg(s)</th>
<th>StopsAvg(s)</th>
<th>Total Stops(s)</th>
<th>Avg Queue</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIDAS</td>
<td>3600</td>
<td>4900</td>
<td>11.5</td>
<td>0.68</td>
<td>3337</td>
<td>2.47</td>
</tr>
<tr>
<td>RHODES</td>
<td>3600</td>
<td>4900</td>
<td>12.96</td>
<td>0.81</td>
<td>3964</td>
<td>2.75</td>
</tr>
<tr>
<td>OFTC</td>
<td>3600</td>
<td>4900</td>
<td>25.74</td>
<td>1.01</td>
<td>5902</td>
<td>18.23</td>
</tr>
</tbody>
</table>

In this simulation based evaluation, we consider *MIDAS* control with 100% market penetration, meaning that *MIDAS* control is fed with GPS data of every vehicle, approaching the interchange. With GPS data *MIDAS* estimates the turning movement of each vehicle at the interchange, along with link travel time of vehicle before joining the
queue at the interchange. In this study, link travel times are estimated by averaging the travel times observed in the last 5 minutes.

4.2 Average Delay

Average delay is a key performance metric used in traffic science to understand how good a traffic control model is when compared to other existing models. Since many diamond interchanges in the US implement pre-timed signal control with fixed phase sequences like 3-phase or 4-phase plans, it would be legitimate to compare the average delays in the network shown above, due to MIDAS control with optimal fixed time control. Figure 10 below compares MIDAS control traffic delays with RHODES and OFTC for different traffic loads, simulated in VISSIM using COM model. MIDAS control shows a significant reduction in total delays when compared to other two control strategies. RHODES has better delay times than OFTC, but it tends to catch up with OFTC at a faster rate when the traffic load increases.

![Figure 10: Comparison of Avg. Delays vs Traffic Load for different signal control policies](image-url)
4.3 Average Stops

Average number of stops is another important performance measure, that traffic engineers are interested in minimizing. It is the average number of times a vehicle had to stop due to the traffic congestion and intersection traffic signals in the network. Figure 11 compares average stops due to MIDAS control with other traffic control strategies by simulating different traffic loads using VISSIM and COM module. It is evident that MIDAS performs better when compared to RHODES and OFTC, whereas RHODES performed slightly better than OFTC.

![Figure 11: Comparison of Average Stops vs Traffic Load for different Control Systems](image)

**Figure 11** Comparison of Average Stops vs Traffic Load for different Controls Systems

4.4 Average Queue Lengths

Often traffic engineers try to come up with traffic policies to minimize the queues formed at the intersection due to traffic signals. Based on the VISSIM simulations for different traffic loads, a comparison of average queue lengths due to MIDAS, RHODES, and OFTC are shown in Figure 12. Again, MIDAS outperforms other two traffic strategies by a
significant difference. RHODES performed well at low traffic loads but queue lengths tend to increase at a high rate when the load increases.

Figure 12 Comparison of Average Queue Lengths vs Traffic Load for Different Signal Systems
5. CONCLUDING REMARKS

A novel traffic control approach called MIDAS was studied in this project and was evaluated on a VISSIM-based simulation platform. In this scenario, MIDAS proactively manages traffic demand at a diamond interchange.

MIDAS is a dynamic programming (DP) based real-time proactive traffic control algorithm that considers the vast number of possible durations for each of these paired phases (meta-phases), in a computationally efficient manner, and selects the durations that optimize jurisdictions objective function such as delays, stops, or queues, etc.

MIDAS uses Lagrangian measurement data, like GPS data from smart phones, to estimate, in real-time, link travel times, turning movements, etc. For every time horizon, MIDAS predicts future arrivals and queues at the interchange. Subsequently, it uses the DP algorithm to compute the phase durations for the time horizon. These durations are changed, if necessary, when new predictions are available.

Simulation based experimental study for a diamond interchange (I-17/19th Ave., Phoenix, AZ) on VISSIM micro-simulation platform shows MIDAS outperforming optimal fixed timing (OFTC) signal control and RHODES control for several performance metrics.

Acknowledgements

The authors acknowledge the assistance of Mr. Brent A. Cain, PE, Assistant Director, TSM&O, Arizona Department of Transportation, and Mr. Mark J. Poppe, PE, Maintenance Engineer, ITS & Electrical Operations Arizona Department of Transportation for helping the team with providing data for the VISSIM simulation model used for MIDAS evaluation.
REFERENCES


