PB2002-102751

ADOT

RHODES - ITMS TEMPE FIELD TEST PROJECT:

Implementation and Field Testing Of *RHODES*, A Real-Time Traffic Adaptive Control System

Final Report 447

Prepared by:
Pitu B. Mirchandani
David E. Lucas
ATLAS Research Center
Systems & Industrial Engineering Department
The University of Arizona
Tucson, Arizona 85721

September 2001

Prepared for:
Arizona Department of Transportation
206 S. 17th Avenue
Phoenix Arizona 85007
in cooperation with
U.S. Department of Transportation
Federal Highway Administration

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U.S. Department of Commerce
National Technical Information Service
Springfield, Virginia 22161

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Technical Report Documentation Page

1. Report No. FHWA-AZ01-447	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle RHODES-ITMS TEMPE FIELD TEST PROJECT: Implementation And Field Testing Of *RHODES*, A Real-Time Traffic Adaptive Control System		5. Report Date September 2001 6. Performing Organization Code
7. Author Pitu B. Mirchandani and David E. Lucas		8. Performing Organization Report No.
9. Performing Organization Name and Address: ATLAS Research Center Systems & Industrial Engineering Department The University of Arizona Tucson, Arizona 85721		10. Work Unit No. 11. Contract or Grant No. JPA 94-109 / SPR-PL-1(49)-447
12. Sponsoring Agency Name And Address: Arizona Department Of Transportation 206 S. 17th Avenue Phoenix, Arizona 85007		13.Type of Report & Period Covered Final Report 7/98-9/01 14. Sponsoring Agency Code

15. Supplementary Notes
Prepared in cooperation with the U.S. Department of Transportation, Federal Highway Administration

16. Abstract

RHODES is a traffic-adaptive signal control system that optimally controls the traffic that is observed in real time. The *RHODES-ITMS* Program is the application of the *RHODES* strategy for the two intersections of a freeway-arterial diamond interchange. This report addresses the latest phase of the *RHODES-ITMS* Program that resulted in a field-test in the City of Tempe, Arizona. In summary, this phase involved: (i) the integration of the *RHODES* logic within the signal controller, (ii) the validation of the *RHODES* logic using "hardware-in-the-loop" simulation, (iii) the integration of the *RHODES* algorithms within Tempe's traffic management system, (iv) the deployment of *RHODES* for the field test and (v) the data gathering and evaluation of traffic performance "with" and "without" the *RHODES* logic.

The objectives of this project were: (i) to see if a communication/computation infrastructure could be designed and implemented for second-by-second detector data collection and signal phase commands, (ii) to see if a traffic-adaptive signal control system could be implemented on an off-the-shelf Advanced Traffic Controller, (iii) to determine whether the RHODES strategy is viable in the field, and (iv) to evaluate the traffic performance of *RHODES*.

The answers for the first three objectives were positive: that is, the communication/computation infrastructure was designed and implemented, and *RHODES* control strategy was integrated within the infrastructure and proved to be viable. With regard to the fourth objective, *RHODES* was able to match the performance of the current well-tuned semi-actuated control being used by the City of Tempe.

The major contributions of the *RHODES-ITMS* Program can be categorized into the development and implementation (i) of new integrated hardware/software infrastructure that includes a new communication system, and (ii) of a traffic-adaptive signal control system. The infrastructure (i) integrates traffic-adaptive features within the 2070 Advanced Traffic Controllers, (ii) deploys, for the first time, a 2070 Controller within a TS2 cabinet, and (iii) implements a communication system for second-by-second decision making. The traffic-adaptive system has the following attributes and benefits: (i) it is second-by-second responsive, (ii) it has a hierarchical and distributed modular architecture that allows additional traffic control features, and (iii) it requires low maintenance of timing plans by traffic engineers. Last, but not least, the effort has extended the cutting edge in systems engineering methodology for the design of real-time decision-making systems and has expanded the workforce in traffic systems engineering by graduating several students through this research effort.

17. Key Words RHODES, Real-time Traffic Adaptive Signal Control, 2070 Advanced Traffic Controller, Interchange Traffic Control		18. Distribution Statement Document is available to the U.S. Public through the National Technical Information Service, Springfield, Virginia, 22161		23. Registrant's Seal
19. Security Classification Unclassified	20. Security Classification Unclassified	21. No. of Pages 97	22. Price	

METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

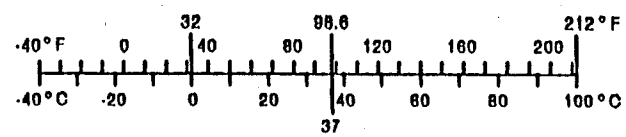
Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	2.54	centimeters	cm
ft	feet	0.3048	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	6.452	centimeters squared	cm^2
ft^2	square feet	0.0929	meters squared	m^2
yd^2	square yards	0.836	meters squared	m^2
mi^2	square miles	2.59	kilometers squared	km^2
ac	acres	0.395	hectares	ha
		MASS (weight)		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.0328	meters cubed	m^3
yd^3	cubic yards	0.765	meters cubed	m^3
Note: Volumes greater than 1000 L shall be shown in m^3.				
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
yd	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	millimeters squared	0.0016	square inches	in^2
m^2	meters squared	10.764	square feet	ft^2
yd^2	kilometers squared	0.39	square miles	mi^2
ha	hectares (10,000 m^2)	2.53	acres	ac
		MASS (weight)		
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams (1000 kg)	1.103	short tons	T
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	meters cubed	35.315	cubic feet	ft^3
m^3	meters cubed	1.308	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F

These factors conform to the requirement of FHWA Order 5190.1A

*SI is the symbol for the International System of Measurements



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LIST OF ACRONYMS

ABOR	Arizona Board of Regents
ADOT	Arizona Department of Transportation
ADT	Average Daily Traffic
ATLAS	Advanced Transportation, Logistics, Algorithms and Systems
ATMS	Advanced Traffic Management System
ATRC	Arizona Transportation Research Center
AVL	Automatic Vehicle Location
BIU	Bus Interface Unit
CAPRI	Categorized Arrival-based Phase Re-optimization at Intersection/Interchange
CID	Controller Interface Device
CORSIM	Corridor Simulator
DLL	Dynamic Link Library
DP	Dynamic Programming
FHWA	Federal Highway Administration
LCD	Liquid Crystal Display
MAG	Maricopa Association of Governments
MIPS	Millions of Instructions Per Second
MMU	Malfunction Management Unit
MOE	Measure of Effectiveness
MTCS	Metropolitan Traffic Control System
MVP	Machine Vision Processor
NEMA	National Electrical Manufacturers Association
PAG	Pima Association of Governments
PC	Personal Computer
RHODES-ITMS	Real-time Hierarchical Optimized Distributed Effective System – Integrated Traffic Management System
RTMS	Remote Traffic Microwave Sensor
SCATS	Sydney Coordinated Adaptive Traffic System
SCOOT	Split, Cycle, Offset Optimization Technique
SDLC	Synchronous Data Link Control
SDRAM	Synchronous Dynamic Random Access Memory
TAC	Technical Advisory Committee
TOC	Traffic Operations Center
TOD	Time of Day
TRANSYT	Traffic Network Study Tool
UTCS	Urban Traffic Control System
VME	Versa Module Eurocard

PREFACE

This report documents the work performed on the *RHODES-ITMS Tempe Field Test Project.* The Arizona Department of Transportation (ADOT) funded this research effort. Essentially, the scope of this project was to implement in the field a method to optimally control, based on traffic observed in real time, the traffic signal operations of the two intersections of a freeway-arterial diamond interchange. The development of the architecture, algorithms, and simulation-based analysis was addressed in an earlier phase of the RHODES-ITMS Program [Head and Mirchandani, 1997]. This report addresses the latest phase of the program that resulted in the field-testing of RHODES-ITMS in Tempe, Arizona. In summary, this phase involved:

- the integration of the RHODES logic within the controller,
- the validation of the RHODES logic using "hardware-in-the-loop" simulation,
- the integration of the RHODES algorithms within Tempe's traffic management system,
- the dèployment of RHODES for the field test, and
- the data gathering and evaluation of traffic performance "with" and "without" the RHODES logic.

The major objectives of this project were:

1. to see if a communication/computation infrastructure could be designed and implemented for second-by-second detector data collection and signal phase commands,
2. to see if a traffic-adaptive signal control system can be implemented on an off-the-shelf advanced traffic controller using either the existing operating system or an external board that communicates with the operating system,
3. to see if RHODES real-time control strategy is viable in the field with the above communication/computation infrastructure plus whatever other existing traffic system hardware/software, for example the traffic control cabinets, various types of detector systems, and existing traffic management system, and,
4. to evaluate the traffic performance of the new traffic-adaptive strategy referred to as RHODES.

The answers for the first three objectives were positive: that is, the communication/computation infrastructure was designed and implemented, and RHODES control strategy was integrated within the infrastructure and proved to be viable. With regard to the fourth objective, RHODES was able to match the performance of the current well-tuned semi-actuated control being used by the City of Tempe. Although the main focus of the project was to implement RHODES and measure the resultant traffic performance, the contributions of the project were of much greater dimension and extent. The major contributions were:

- **Second-by-Second Traffic Responsive**. This was the first implementation of a traffic adaptive control system that measures traffic variables every second and computes phase durations to be implemented for the next few minutes.

- **Hierarchical and Distributed Modular Architecture**. The RHODES architecture that was implemented is both hierarchical to account for the natural time constants of obtained traffic measures, and distributed to exploit the spatial aspects of traffic activities and local processing of these measurements. Also, this architecture allows for straightforward modular expansion that can include several other traffic control functions such as transit priority and railway grade crossing preemption.

- **Integration of Adaptive Features in the 2070 Controller**. This is the first time that a traffic control system was implemented that includes a second-generation UTCS with an adaptive feature which can be turned ON or OFF by a traffic engineer.

- **Implementation of a 2070 within a TS2 Cabinet**. This was the first time a 2070 Controller was implemented in a TS2 cabinet.

- **Implementation of a communication system for second-by-second decision making**. A new engineering design was implemented where data from upstream detectors to a central traffic control system, and then to a traffic controller at the interchange, was communicated with latency of a less

than a second. Also, the subsequent optimal setting of signals was communicated with the latency of less than a second.

- **Implementation of a system that requires low maintenance by traffic engineers**. A system such as RHODES does not require continuous manual refinement of timing plans to maintain its performance level, thereby freeing transportation staff for other tasks.

- **Workforce expansion**. Over the course of the project several graduate students from the University of Arizona with significant background and experience in traffic and systems engineering have gone into the workforce, thereby considerably expanding the workforce in traffic systems engineering.

- **Real-time decision-making and optimization**. This project also extended the cutting edge in systems engineering by (i) developing a system design framework for real-time decision systems and (ii) the subsequent implementation and deployment of a system that uses a client-server framework for automated real-time optimization

This report was written primarily by the principal investigator, **Pitu B. Mirchandani**, and by co-investigator, **David E. Lucas,** both of the ATLAS Research Center, Systems and Industrial Engineering Department at the University of Arizona. Also, several other individuals have contributed towards the writing and/or field implementation and data gathering. In particular, the efforts of the following individuals are acknowledged:

Douglas Crawford	Siemens Gardner Transportation System Inc., Tucson, AZ
Jim Decker	Transportation Department, City of Tempe, AZ
K. Larry Head	Siemens Gardner Transportation System Inc., Tucson, AZ
Ken M. Howell	TASK Engineering Company, Inc.; Phoenix, AZ

In addition, the principal investigators wish to acknowledge their appreciation to the Project's **Technical Advisory Committee** (TAC) whose continual active participation, technical input and support resulted in the *RHODES-ITMS* results being even more relevant to traffic engineering and control. The following individuals served on the TAC at various times:

Jim Decker	Traffic Operations, City of Tempe
Ron Amaya	Traffic Operations, City of Peoria (previously City of Tempe)
Sarath Joshua	Maricopa Association of Governments (previously at ATRC, ADOT)
Alan Hansen	Federal Highway Administration
Tom Fowler	Federal Highway Administration
Tim Wolfe	ADOT Technology Group
Dan Powell	ADOT District 1
Tom Parlante	ADOT Traffic Engineering
Glenn Jonas	ADOT Freeway Management
Manny Agah	ADOT Freeway Management
Jerry Pfiefer	ADOT Freeway Management
Phil Carter	ADOT Freeway Management
Jim Shea	ADOT Freeway Management
Pierre Pretorius	Maricopa County Transportation and Development Agency
Don Wiltshire	Maricopa County Transportation and Development Agency
Dave Wolfson	Maricopa County Transportation and Development Agency
Ben McCawley	Maricopa County Transportation and Development Agency
Scott Nodes	Traffic Operations, City of Peoria (previously City of Phoenix)
Steve Owen	RHODES-ITMS Project Manager, ATRC, ADOT

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views of the Arizona Department of Transportation, or the Federal Highway Administration. This report does not constitute a standard, specification or regulation.

1. INTRODUCTION AND PROJECT BACKGROUND

1.1 Project Scope and Objectives

Over the last ten years, a research team at the University of Arizona (UA) has been developing a real-time traffic adaptive system referred to as RHODES (Real-time Hierarchical Optimizing Distributed Effective System) that is based on second-by-second real-time vehicle detection and phase setting. During the period of system development, Arizona Department of Transportation (ADOT) and Federal Highway Administration (FHWA) have provided research funding to assist in the exploration of RHODES concepts, the development of its algorithms, and the design and prototype development of the software system. The previous phase of ADOT support referred to as "The RHODES-Integrated Traffic Management System (ITMS) Project" addressed the design and development of a real-time traffic adaptive control system for Freeway-Arterial Diamond Interchanges using the concepts underlying the RHODES traffic-adaptive signal control system. This document reports the results of the next phase of ADOT on "Implementation and Field testing of RHODES-ITMS" at a specific diamond interchange in Tempe, Arizona.

The traffic "controls" at a diamond interchange are the two sets of closely spaced traffic signals located at the arterial, on both sides of the freeway, and the ramp meters at the on-ramps to the freeway. To efficiently manage all the traffic at the interchange, the control system must do both, in real time, set the phase durations of the intersection traffic signals and control the ramp-metering rates, taking into account local traffic objectives as well as network-wide objectives. However, the scope of RHODES-ITMS Project was to develop a method to optimize only the interchange traffic signal operations, for only the traffic that passes through the two intersections of the interchange, either entering or exiting the freeway or progressing along the arterial, <u>with ramp-metering rates given externally</u>. Nevertheless, it is necessary to have information about the queues at the on-ramps in order to effectively manage all the vehicles that use the arterials, the frontage roads parallel to the freeway (if they exist) and the ramps at the interchange.

There are two reasons for not adjusting the ramp-metering rates locally: (1) current practice is that the state traffic agency (e.g., ADOT in Arizona) sets these rates directly, with consideration of region-wide freeway flow management objectives, and (2) ideally, ramp-metering rates should consider first area-wide traffic management objectives and then, only secondarily, consider the local flows at the interchange. (In fact, in a complementary project "RHODES-ITMS Ramp Metering Field Test" [Ciarallo and Mirchandani, 1998], ADOT is exploring methods to adaptively set ramp metering rates in real time.)

The development of the RHODES-ITMS architecture, algorithms, and simulation-based analysis was addressed in an earlier phase of the project [Head and Mirchandani, 1997]. This report addresses the latest

phase of the project that resulted in the field-testing of RHODES-ITMS in Tempe, Arizona. In summary, this phase involved:

1. the integration of the RHODES logic within the controller,
2. the validation of the RHODES logic using "hardware-in-the-loop" simulation,
3. the integration of the RHODES algorithms within Tempe's traffic management system,
4. the deployment of RHODES for the field test, and
5. the data gathering and evaluation of traffic performance "with" and "without" the RHODES logic.

These were all accomplished as planned, except that the implemented RHODES system was a version that did not include the consideration of queues at the on-ramps because the component to get vehicle detections and the associated communication subsystem to send these detections to the RHODES controller was not available to the research team during the field test.

The major objectives of this phase were:

1. to see if a communication/computation infrastructure can be designed and implemented for second-by-second detector data collection and signal phase commands,
2. to see if a traffic-adaptive signal control system can be implemented on an off-the-shelf advanced traffic controller using either the existing operating system or an external board that communicates with the operating system,
3. to see if RHODES real-time control strategy is viable in the field that has the above communication/computation infrastructure plus whatever other existing traffic system hardware/software, for example the traffic control cabinets, various types of detector systems, and existing traffic management system, and,
4. to evaluate the traffic performance of the new traffic-adaptive strategy referred to as RHODES.

The above objectives seek new research results and boundaries in traffic management systems and, if successful, the project will contribute significantly to traffic engineering and science.

1.2 Background and History of the Project

In June 1991, the Arizona Department of Transportation, working closely with the City of Tucson and the Pima Association of Governments (PAG), supported the initial R&D efforts on the development of the RHODES surface street traffic control system within the Department of Systems and Industrial Engineering at the University of Arizona [Mirchandani and Head, 1994; Head and Mirchandani, 1994].

In December 1993, ADOT (from SP&R funds) and Maricopa Association of Governments (MAG) jointly funded the project entitled "Real-Time Traffic Adaptive Control for Integrated Traffic Management of the I-17 Corridor" and referred to as the "RHODES-ITMS Project" for short. The scope of the project was to

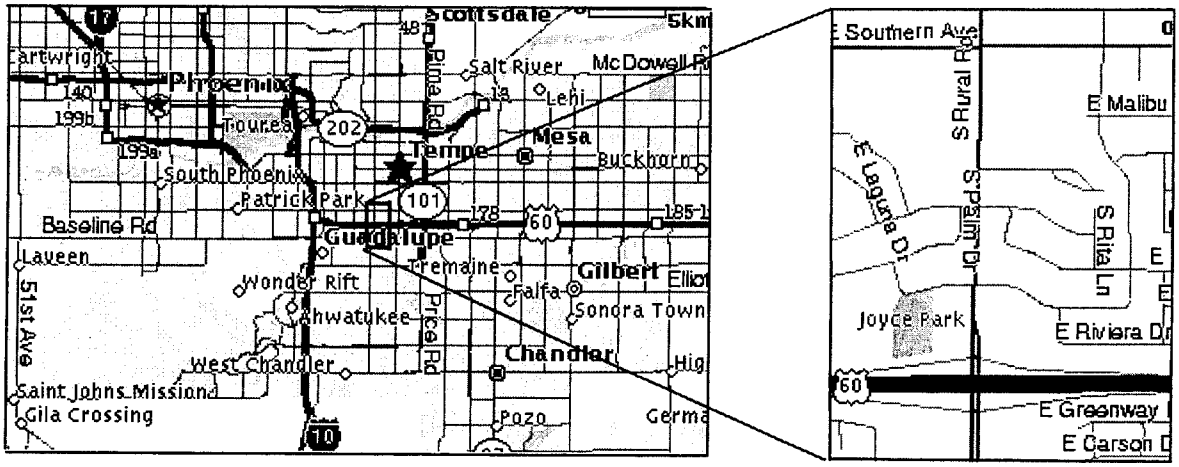
develop an improved traffic control strategy for a freeway-arterial diamond interchange using RHODES concepts, for a possible field testing at a site on Interstate 17 in Maricopa County. The activities and the findings of that project are documented in the final report [Head and Mirchandani, 1997].

In June 1994, FHWA initiated a project with the RHODES Team (with JHK & Associates as subcontractors) to develop a working prototype of the RHODES strategy, implementing only the last two levels of the hierarchy - intersection and network flow control, which was to be laboratory tested by a third party contractor. Since the RHODES system requires some innovative communication approaches and on-line algorithmic computations, FHWA awarded a follow-up contract entitled "*An Open Systems Communication/Control Architecture for Real-Time Traffic Adaptive Signal Control*" **in September 1997**, which included the implementation of RHODES on an arterial corridor in Tucson.

In July 1998, based on the results from the RHODES-ITMS Project, and due to the special requirements for communication and on-line computations needed for RHODES, ADOT initiated another project to field test the RHODES-ITMS system developed in the 1993-97 project. This project was referred to as the "*RHODES-ITMS Tempe Field Test Project*" and this document is the final report for that project. The freeway-arterial diamond interchange at US60 and Rural Road, in the City of Tempe, was selected over a site on I-17 because of several factors including:

- This interchange has functioning ramp meters,
- This interchange was highly detectorized, needing only a few more detectors for RHODES,
- Because of another major ITS Project (*AzTech*) that included Rural Road, second-by-second detection from upstream intersections was implementable,
- Tempe's Transportation Department staff assured the research team that the Computran system that operates Tempe's traffic signals was flexible enough for it to be modified so that data from upstream detectors could be communicated to the RHODES algorithms, and
- Above all, Mr. Jim Decker and other staff in Tempe's Transportation Department were champions for the RHODES-ITMS field test project and had volunteered to be dedicated partners in this endeavor.

The Rural Road test site is one of the busiest diamond interchanges in the Phoenix metropolitan area (see Figure 1). It carries 51,000 average daily traffic (ADT) north of U.S. 60, and 56,000 ADT south of U.S. 60, according to the City of Tempe Traffic Counts Map.



Scale: 5 km

Scale 900 ft

Figure 1 - Map of Site (Source: www.mapquest.com, July 28,2001)

Rural Road has three lanes in each direction at this location. Each ramp terminal is signalized, and a single controller operates both signals. The controller normally runs a time-based semi-actuated and coordinated signal control plan.

Each off ramp has separate right and left turn lanes and middle shared left-right turn lane. There are dual left turn lanes on Rural Road between the ramp terminals, which can store queues of about 16 vehicles. Left turn lane storage capacity extends to the north and south along Rural Road, far enough that left turn bay overflow conditions were not observed during the test.

Upstream signals in the north are on the intersection of Rural and Southern Avenue and in the south at Rural and a minor street serving the Embassy Suites Hotel. The Southern Avenue signal is located about one-half mile north (about 30-40 seconds at free-flow speed). The Embassy Suites signal is located about 600 feet south (about 8-10 seconds south) of the eastbound on-ramp. The on-ramps are metered during AM and PM peak hour conditions. Separate controllers under ADOT jurisdiction control the ramp meters.

Tempe's current approach to control the traffic on the arterial of the interchange is a time-of-day semi-actuated approach, where loop detectors recognize traffic on specific lanes and/or movements and based on some pre-defined logic provide specified phases, phase extensions, force-offs and gap-outs to allow for the movement of the detected traffic. The nominal offsets, splits, and cycle time parameters are included in time-of-day traffic plans that are pre-determined and loaded on the interchange controllers. The major deficiency of such a strategy is that there is no way for the controller to respond to actual arrivals - by varying phase durations and/or using more appropriate cycle times and phase sequencing - even though

detectors at upstream intersections and at the off-ramps may have identified unusual traffic conditions (either unusually large volumes or very small volumes, due to, for example, events and incidents). Also, unusually large queues detected at the on-ramps are not considered in phase durations; vehicles may be directed on to the queued on-ramps, which results in no apparent effect on their delays but instead induces queue spillbacks and possibly increases delays for other traffic. Furthermore, queue spillback into the freeway from the off-ramps can also occur at this diamond interchange but current detections do not allow RHODES to observe this.

The previous studies of RHODES-ITMS had indicated, through simulation, that the RHODES strategy had the potential to improve traffic performance at an interchange [Head and Mirchandani, 1997]. However, since the RHODES system requires considerable on-line data gathering, data handling, communication networking and on-line algorithmic computations, implementing such a system poses many challenges. Therefore, besides the major goal of developing and field testing a new traffic-adaptive method to optimize the interchange traffic signal operations, the other goals of the project were to investigate whether the interchange control/communication/detection systems can be configured to send data/commands at once-per-second frequencies, and to configure the new 2070 Controller to set phase durations instead of the traditional cycles/splits/offsets timing parameters. Success for the latter two goals will allow testing for other phase-optimizing approaches besides the RHODES approach tested in this project.

Thus, in summary, the objectives of the RHODES-ITMS Tempe Field Test Project were to (1) integrate control/communication/detection systems to send data/commands at once-per-second frequencies, (2) configure the new 2070 Controller to set phase durations, (3) investigate if the RHODES-type strategy works in the field, and (4) determine if the RHODES-ITMS system improves traffic performance.

Figure 2 gives a schematic diagram of the field test site. Only the interchange traffic signals, for the traffic that passes through the two intersections of the interchange including traffic on off-ramps and on-ramps (and not the freeway traffic going under the interchange) were under real-time adaptive control using the RHODES-ITMS System.

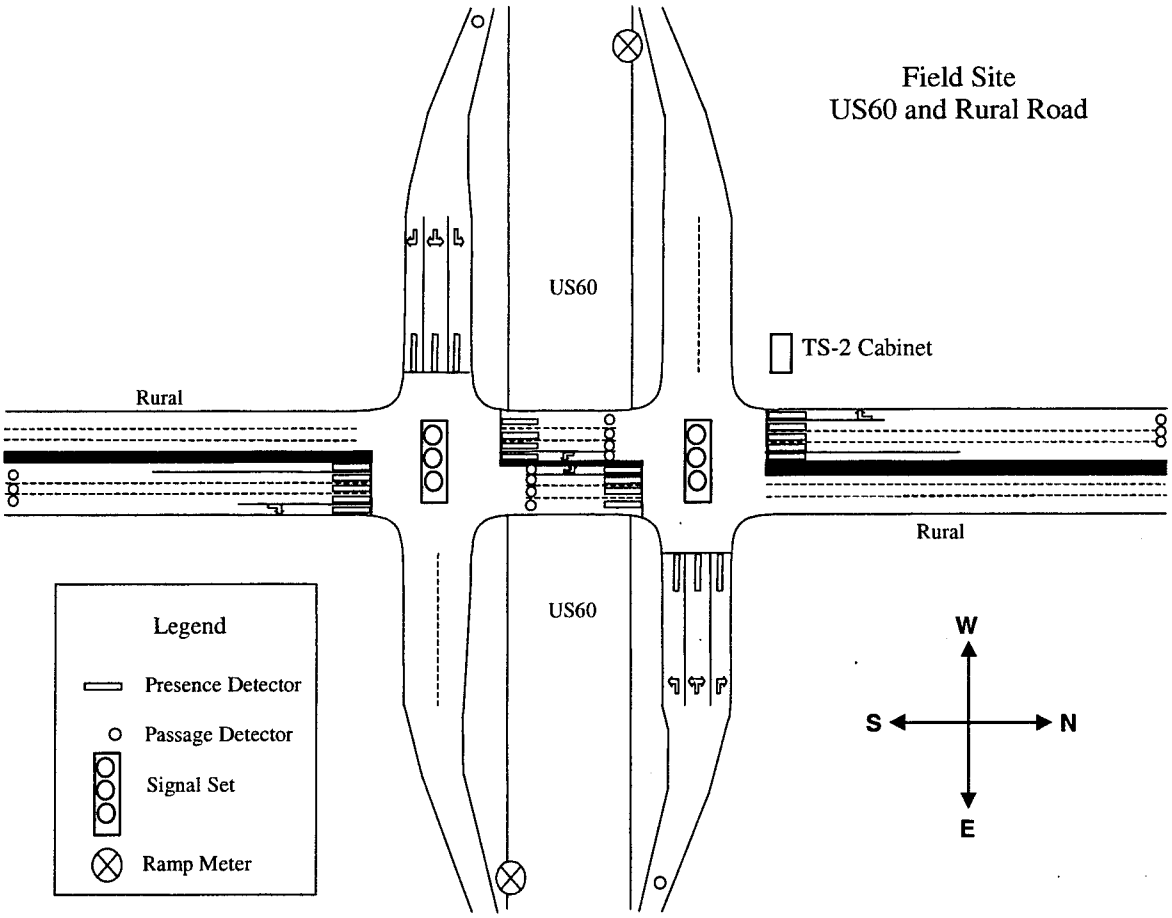


Figure 2 - The interchange: control area and detectors utilized

1.3 Project Tasks

The RHODES-ITMS Tempe Field Test Project consisted of the following tasks:

Task A: Simulation Modeling and Analysis

Task B: Integration of RHODES within 2070 Controller

Task C: Hardware-in-the-loop Simulation

Task D: Integration of RHODES/2070 Controller/TS2 Cabinet

Task E: Integration of RHODES/2070 Controller/TS2 Cabinet/TOC Systems

Task F: Laboratory Testing

Task G: Field data gathering for RHODES Parameters

Task H: Field Implementation

Task I: Field Bench Testing

Task J: Field Testing: Field Data Collection and Evaluation

Task K: Organizing TAC Meetings and Demonstrations

Task L: Draft and Final Reports

Below we briefly describe these tasks. Some of these tasks, and the design and analysis as a result of these tasks, are further elaborated in later subsections.

Task A consisted of developing a CORSIM simulation model of the Tempe (Rural Road and U.S. 60) Interchange:

1. for assuring that the RHODES Team had all the physical and traffic information for the interchange (much of this is also needed for the RHODES algorithms),
2. to get an idea of the traffic performance under current operations, and
3. to get an idea of anticipated performance under RHODES control.

In the first phase of the RHODES-ITMS Project a simulation model of the Indian School Road and I-17 Interchange was developed. Some of the lessons learned were beneficial for developing a model for the Tempe Interchange. Anderson [1997] gives details of the simulation model in a Master-of-Science Report.

Task B focused on the integration of the RHODES code on the 2070 Controller that was to be implemented at the Interchange. For this purpose a field-hardened processor was purchased from Mikro Elektronik Gmbh (MEN) in Nürnberg, Germany. Hereafter referred to as a "MEN Card", this unit contains a 50 Mhz Motorola 68060 processor with 32 MB of SDRAM for storage and processing of the RHODES data and algorithms and is enclosed within the VME chassis of the 2070. In this configuration, RHODES receives and transmits information from/to the 2070's processor (in this case, a Motorola 68360) via the 2070's internal VME bus. Running under the OS-9 operating system, the *NextPhase* controller software, developed by Gardner Transportation Systems (GTS, now a business unit of Siemens Energy and Automation, Inc.), was used to control the diamond interchange in accordance with Tempe's existing traffic control plans. Thus, Task B entailed the integration of the RHODES algorithms (residing on the MEN Card) with the *NextPhase* software within the 2070 Controller.

Task C was to integrate the CORSIM model of the Tempe Interchange with the 2070 Controller programmed with the RHODES logic. In other words, the CORSIM model simulated detector and signal status data, which were then input to the 2070 via a Controller Interface Device (CID). This was to assure that messages that emulated the field were passed to the controller, which in turn provided the phase duration messages (from RHODES) to run the simulation.

The signal cabinet that Tempe uses at the Interchange is a NEMA TS2 type. The proposed configuration called for the integration of the 2070 Controller within this cabinet. Since RHODES requires local signal and detector information as well as the same from upstream intersections, the integration also required that this information (from loops, video detectors, signals, etc.) be properly channeled to the RHODES processor. **Task D** was the effort to do this integration.

The current traffic management system at the Tempe Traffic Operations Center (TOC) is the one developed by Computran Inc. Thus the natural follow-on to Task D is to interface the field 2070 with the Computran System, making sure that the upstream detector and signal data is actually received by the 2070, through the Computran System, with negligible delays (for real-time traffic control purposes) and with appropriate reliability. **Task E** focused on this interfacing.

Three venues for laboratory testing were (1) the RHODES Laboratory at the University of Arizona (UA), (2) the testing laboratory at GTS, and (3) the Tempe TOC. In **Task F**, we tested the interfaces between RHODES on the MEN Card and *NextPhase* on the 2070 CPU using a TS2 suitcase tester in the UA laboratory. The interface between the 2070 (including NextPhase and RHODES) and TS2 was tested in the GTS laboratory, and the complete integration between Computran and 2070/NextPhase/RHODES was tested in the Tempe TOC.

In order to run RHODES at a particular intersection, fixed parameters such as number of lanes, permitted and protected turn movements, and distances from upstream detectors need to be hard coded within RHODES. Traffic parameters such as turn ratios, travel times or speeds, and queue discharge rates needed to be measured and input for associated parameter values within RHODES. **Task G** was to gather this data for the particular field site and input it in RHODES.

Task H, Field Implementation, entailed (1) having the site-specific RHODES version on the MEN Card, (2) having *NextPhase*/2070 run the interchange under the standard timing plans that Tempe uses, (3) making sure that the communication system between the upstream detectors and the field 2070 (through the Computran System) was functioning, (4) fine-tuning some of the RHODES prediction parameters so that queue estimates at the stop-bars were approximately correct, and (5) ensuring that RHODES was properly called and functioning when "adaptive control" is requested through *NextPhase.*

Once the research team felt that the hardware and software were all functioning, RHODES was run in the field for several hours. The controller was observed to see if everything was properly functioning, and to check the response when something unexpected occurred, such as, for example, when the signals are being preempted by an emergency vehicle, or when there is a power shut down. This was done in **Task I**, referred to as Field Bench Testing.

Only after the research team had run RHODES for several hours on different days during Field Bench Testing, was the system run for field test data collection and evaluation by a third-party evaluator (TASK Engineering, Inc.) under **Task J**.

Due to the long duration of the project, and several natural milestones, there were many Technical Advisory Committee meetings and demonstrations of RHODES running in (1) a hardware-in-the-loop simulation, (2) the Tempe TOC, and (3) in the field, at the interchange. The effort on this is grouped as **Task K**. Finally, **Task L** is the documentation of the project through which this final report was prepared.

1.4 Project Oversight

A Technical Advisory Committee (TAC) comprised of representatives from key agencies provided project oversight. The project was administered by the Arizona Transportation Research Center (ATRC) of ADOT. The following individuals served on the TAC at various times:

Jim Decker	Traffic Operations, City of Tempe
Ron Amaya	Traffic Operations, City of Peoria (previously City of Tempe)
Sarath Joshua	Maricopa Association of Governments (previously at ATRC, ADOT)
Alan Hansen	Federal Highway Administration
Tom Fowler	Federal Highway Administration
Tim Wolfe	ADOT Technology Group
Dan Powell	ADOT District 1
Tom Parlante	ADOT Traffic Engineering
Glenn Jonas	ADOT Freeway Management
Manny Agah	ADOT Freeway Management
Jerry Pfiefer	ADOT Freeway Management
Phil Carter	ADOT Freeway Management
Jim Shea	ADOT Freeway Management
Pierre Pretorius	Maricopa County Transportation and Development Agency
Don Wiltshire	Maricopa County Transportation and Development Agency
Dave Wolfson	Maricopa County Transportation and Development Agency
Ben McCawley	Maricopa County Transportation and Development Agency
Scott Nodes	Traffic Operations, City of Peoria (previously City of Phoenix)
Steve Owen	RHODES-ITMS Project Manager, ATRC, ADOT.

2. RHODES TRAFFIC SYSTEM: TECHNICAL BACKGROUND

2.1 RHODES System Architecture

RHODES-ITMS uses the concepts underlying the RHODES traffic-adaptive signal control system [Head, Mirchandani and Sheppard, 1992]. The current approaches to control the traffic on the arterial of the interchange are (1) fixed time, perhaps based on time-of-day traffic conditions, and (2) actuated (or semi-actuated) where loop detectors detect traffic on specific lanes and/or movements and based on some pre-defined logic to provide specified phases, phase extensions, force-offs and gap-outs to allow for the movement of the detected traffic. The major deficiency for such types of strategies is that there is no way for the control system to tradeoff or optimize signal settings to respond to anticipated arrival volumes - by varying phase durations and/or using more appropriate cycle times and phase sequencing - even though detectors at the off-ramps and upstream intersections may have identified unusual traffic conditions (either unusually large volumes or very small volumes, due to, for example, events and incidents). Also, unusually large queues detected at the on-ramps are not considered in phase durations; vehicles may be directed on to the queued on-ramps, which results in no apparent effect on their delays but instead induces queue spillbacks into the intersections and possibly increases delays for other traffic. The RHODES concept and architecture (Figure 3) responds to this deficiency.

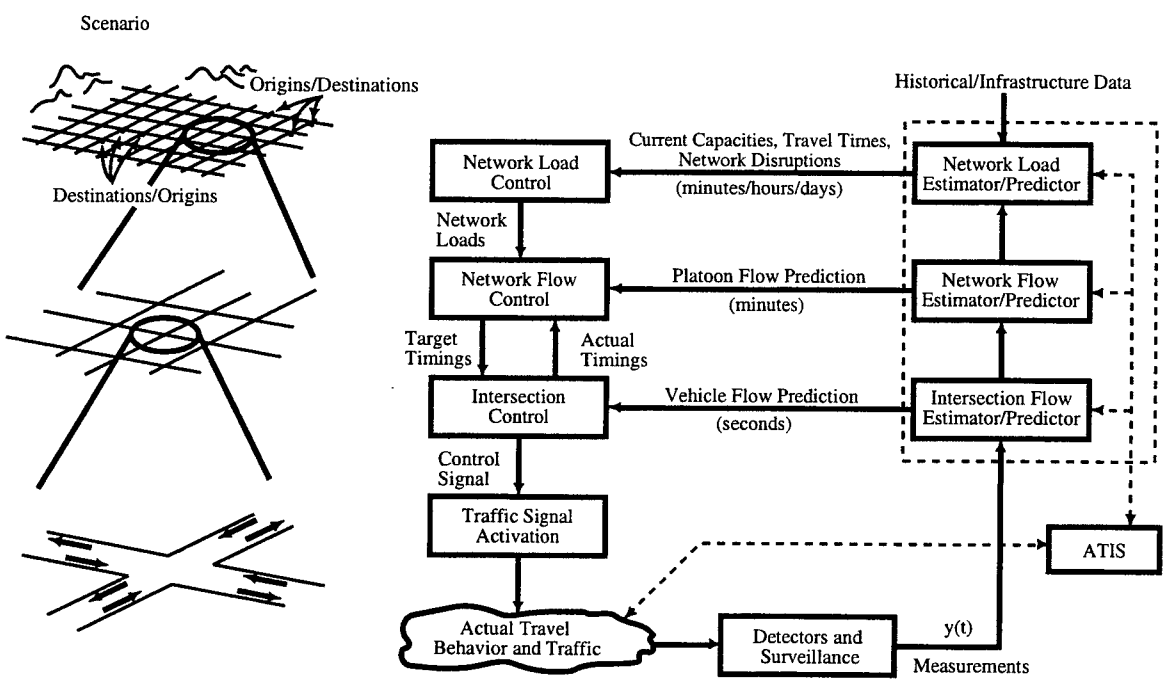


Figure 3 - The RHODES Architecture

To briefly review the RHODES concept, the RHODES architecture for surface streets is depicted in Figure 3. At the highest level of RHODES is the *"dynamic network loading"* model that captures the slow-varying characteristics of traffic. These characteristics pertain to the network geometry (available routes including road closures, construction, etc.) and the typical route selection of travelers. Based on the slow-varying characteristics of the network traffic loads, estimates of the load on each particular link, in terms of vehicles per hour, can be calculated. The load estimates then allow RHODES to allocate "green time" for each different demand pattern and each phase (North-South through movement, North-South left turn, East-West left turn, and so on). These decisions are made at the middle level of the hierarchy, referred to as *"network flow control"*. Traffic flow characteristics at this level are measured in terms of platoons of vehicles and their speeds. Given the approximate green times, the *"intersection control"* at the third level selects the appropriate phase change epochs based on observed and predicted arrivals of individual vehicles at each intersection. The RHODES architecture and its software implementation are modular; it allows the accommodation of new modeling methodologies and new technologies as they are developed.

There are three aspects of the RHODES philosophy that make it a viable and effective system to adaptively control traffic signals. First, it recognizes that recent technological advances in communication, control, and computation (a) make it possible to move data quickly from the street to the computing processors (even now most current systems have communication capabilities that are not utilized to their potential), (b) make processing of this data to algorithmically select optimal signal timings fast, and (c) allow the flexibility to implement, through modern controllers, a wide-variety of control strategies. Second, RHODES recognizes that there are natural stochastic variations in the traffic flow and therefore one must expect the data to stochastically vary (simply smoothing the data and working with average values does not make the actual traffic that the system sees smooth and average, as assumed by other real-time traffic control schemes). And third, RHODES proactively responds to these variations by explicitly predicting individual vehicle arrivals, platoon arrivals and traffic flow rates, for the three corresponding levels of hierarchies described above.

The implemented RHODES-ITMS algorithms relate only to the third level - here referred to as *intersection/interchange control* (recall that the diamond interchange includes intersections on both sides of the freeway). Basically, the developed RHODES-ITMS system predicts arrivals and queues of individual vehicles at the arterial approaches on both sides of the freeway, as well as arrivals from the off-ramps, and the departures and queues at the on-ramps; and based on these predictions and a given criterion of performance determines the optimal phasing of the signals at the two intersections. The prediction and the optimization algorithms for this purpose are briefly reviewed in Sections 2.3 and 2.4.

To test real-time algorithms (RHODES or any other), we developed a CORSIM-based simulation model (CORSIM is a software package, developed by FHWA, for modeling and simulating traffic on a network.) This was used as a platform to implement and test RHODES-ITMS. Issues related to the simulation modeling and the simulation-based testing of the algorithms are discussed in the next section. Results of the RHODES simulations are discussed in Section 2.5.

2. 2 Simulation Modeling for Testing Real-Time Algorithms

It is clear that any type of traffic control algorithm needs to be tested in the "laboratory" before it is implemented and evaluated in the field. The most appropriate method to do this "laboratory" testing is to (1) have a realistic simulation model of traffic flow at an interchange, (2) emulate the (loop) detection of the traffic flow, and (3) observe the resulting changes that would come about if the algorithm was implemented in place of the current control system. The functional requirements for simulation models for development, testing and evaluation of real-time traffic-adaptive signal control logic in this setting include:

- the ability to realistically simulate arriving/departing vehicular traffic at an interchange;
- the ability to generate dynamic traffic conditions, including recurrent and non-recurrent congestion such as incidents and special events;
- the ability to obtain surveillance/detector output at required frequencies;
- the ability to implement decisions (e.g., from RHODES) to control traffic signals in real-time; and
- the ability to compute various measures of effectiveness based on traffic characteristics (including those that are not necessarily observable, such as queue lengths).

The ability to represent dynamic recurrent and non-recurrent congestion, as well as other non-congested traffic conditions, is needed for measuring the algorithm's capability to respond to real-time traffic conditions.

Simulation models used for testing must provide the same surveillance and detection information as that available in the field. The frequency of surveillance and detector system output and the frequency of the signal control input dictate the minimal resolution, and hence the responsiveness, of the signal control logic. Also, the simulation model must be able to represent data-input and control-output rates that will be achievable when the control logic is implemented for field-testing.

It may be desirable for the signal control algorithms to optimize different measures of performance, based on traffic conditions or dictated by the operating jurisdictions. Therefore, it is essential that the simulation

model provide a wide variety of measures of effectiveness (MOE) to evaluate the real-time traffic adaptive signal control algorithms.

The simulation model requirements from a development and testing perspective differ from the requirements for performance evaluation. Clearly, the most important requirement of a simulation model is that it accurately represents the dynamics of traffic flow and its response to dynamic signal control. This requirement dictates that the simulation model chosen for development and testing not be based on a macroscopic flow model that assumes constant cycle length and deterministic traffic flow characteristics. Rather, the model should include microscopic flow characteristics, such as car following, and include an ability to simulate real-time traffic controls (not necessarily having constant cycle lengths) and attendant vehicle response to actual traffic signals.

During the development and testing phase it is essential to have access to both traffic and signal control variables so that detailed behavior can be studied. One may distinguish between traffic simulation information/data that is needed for validation and testing and that information/data which is available as traffic surveillance/detection data for the signal control algorithms. For example, for the purpose of testing a traffic model used in an optimization routine, it may be desirable to compare the traffic model's state-of-the-traffic measures, such as queue length, to the corresponding measures in the simulation model. This form of testing requires that the traffic simulation model provide accurate measurements of queue lengths despite the fact that the existing traffic surveillance technology may not provide this information.

Another important consideration is the frequency at which required testing data is available. For example, the average queue length for a simulation period is insufficient for testing a routine that estimates real-time queue lengths. This information must be available as frequently as possible, at least as frequently as queue estimates are generated.

The interchange and the neighboring area simulated consisted of the freeway (US 60), a cross arterial (which makes this a diamond interchange), six signalized intersections (two on one side and four on the other side of the freeway), and pairs of off-ramps and on-ramps (see Figure 4). The fact that the two signals right next to the freeway are rather closely spaced (375 feet apart) poses a significant traffic control challenge to keep the traffic moving, as well as to prevent excessive queue spillbacks. Fixed-time and actuated signal control strategies (internal to CORSIM) were implemented and animations were observed to confirm if the traffic was indeed moving appropriately. Having fine-tuned the actuated timing parameters within the simulation model so that traffic performance was as good as can be expected, RHODES-ITMS was interfaced with the simulation model and evaluated (results are given in Section 2.5). Figure 5 shows

the various phases, and their corresponding minimum and maximum green times, which were used in simulating the current actuated signal control.

US60 & Rural Road Network

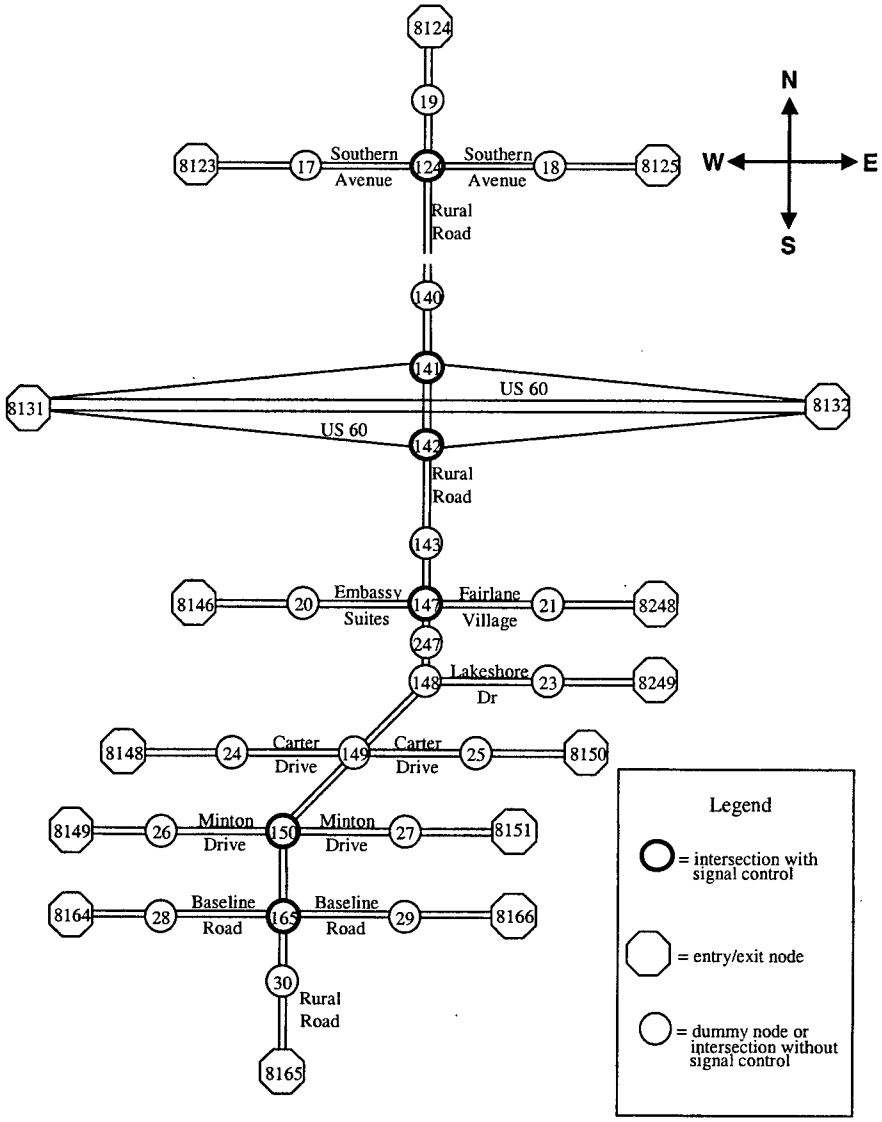


Figure 4 - CORSIM Simulation Model

An essential element of external real-time signal control logic is the traffic surveillance system. In the experiments performed by the research team, the internal surveillance detector logic of CORSIM was used for the placement and processing of detector events, while external logic was used for processing this detector data. This approach allows the estimation of any necessary traffic parameter(s), in addition to the standard count and occupancy values.

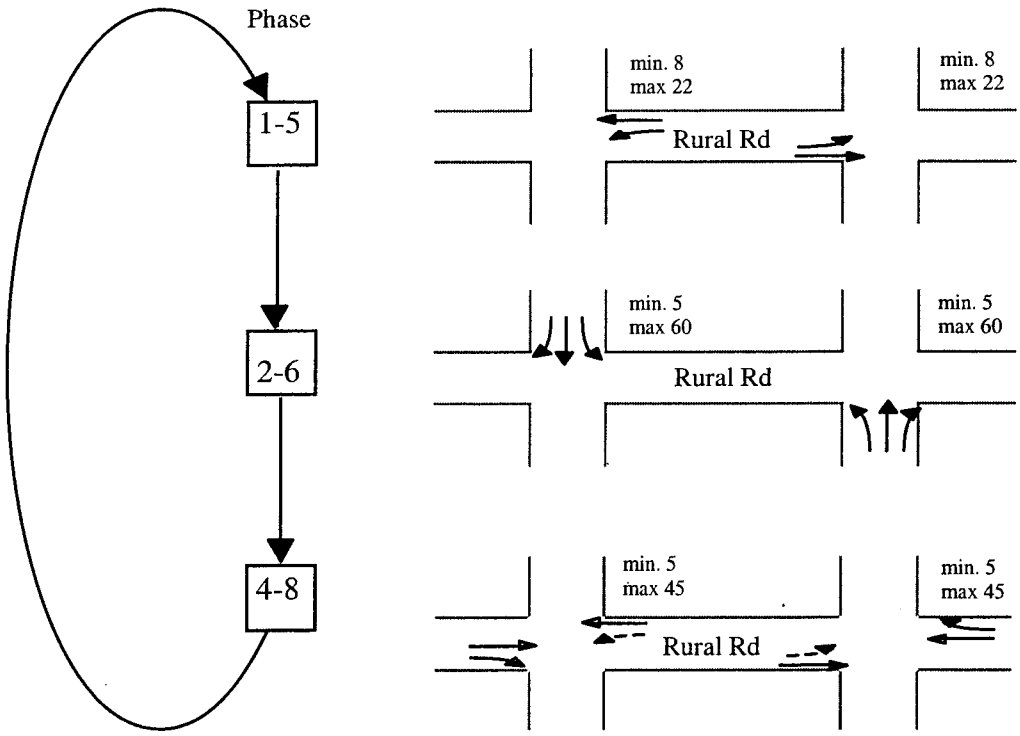


Figure 5 - Actuated signal phasing with minimums and maximum green times (in seconds)

2.3. Prediction Algorithms in RHODES-ITMS

This section will only review prediction algorithm in RHODES-ITMS; more details are available in an earlier report [Head and Mirchandani, 1997]

For proactive traffic control, it is important to predict vehicle arrivals, turning ratios and queues at an intersection, in order to compute phase timings that optimize a given measure of effectiveness (e.g. average delay). To emphasize this importance, consider the intersection shown in Figure 6. This intersection has four approaches. Associated with each approach are several possible traffic movements: left turn, right turn and a through movement. For the purpose of signal timing, the right turn and through movements are generally considered as a single movement. Any non-conflicting combination of movements that can share the intersection at any one time can be assigned a signal phase that allows those movements protected use of the intersection. The traffic demand for a phase is determined by the approach volume (measured using a group of loop detectors on the approach to each intersection and in the left-turn pockets) and the turning ratios associated with vehicle routes.

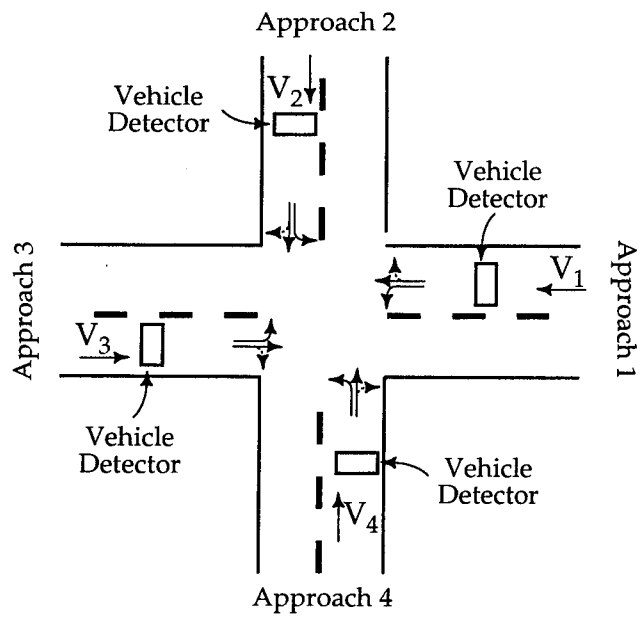


Figure 6 - Basic traffic intersection showing approaches, approach volumes, movements and vehicle detectors.

Now consider the signal-timing problem given two possible perfect predictions of arrivals during the planning horizon as depicted in Figure 7. Each arrival pattern represents the number of vehicles to arrive at an intersection in fixed time intervals. Both arrival patterns are identical until time t_0 when the signal control has to decide whether to serve this approach or to serve another approach. In the top case, the demand occurs immediately following t_0, whereas in the bottom case there is little demand immediately following t_0 and greater demand in the future. In each case the total number of vehicle arrivals are equal.

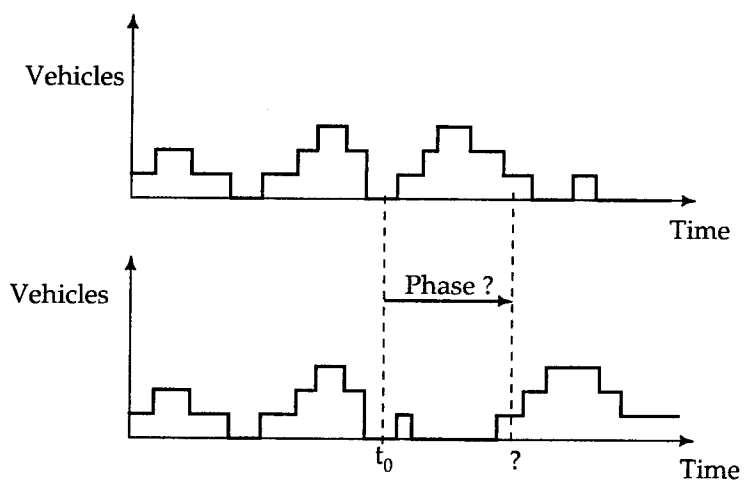


Figure 7 - Graphical depiction of the effect of future arrivals on scheduling phase sequences and durations.

However, the optimal signal timings could be significantly different. It is essential to know the temporal arrival distribution to build truly real-time traffic-adaptive signal control logic.

Three issues are important to predicting traffic flow: (1) the length of the time horizon, (2) the number of prediction points per time horizon (called the prediction frequency) and (3) the number and location of information sources. The prediction time horizon provides the real-time traffic-adaptive signal timing control logic with the ability to plan future signal timing decisions. If the prediction horizon is short, perhaps several seconds, then the signal timing decisions are restricted. For example, if the predictions are made over a 10-second horizon, the signal timing logic can only make timing decision that extend or shorten the current phase. On the other hand, if the predictions are made over a longer horizon, the signal timing decisions can include decisions on phase termination times and phase sequencing. For example, if the prediction horizon is 30-40 seconds, then the signal timing logic might schedule the next two phases and their durations based on the predicted demand instead of following a fixed phase sequence.

The prediction frequency provides information about the distribution of vehicle arrivals over time. If the predictions are made at a frequency of only one prediction for the decision time horizon, then the signal timing logic must assume that the vehicles are distributed uniformly over that time. If the predictions are made more frequently, say every second over the prediction horizon, then the signal timing logic will have a more accurate representation of the distribution of vehicle arrivals over time.

The number and location of information sources determine the ability of any prediction algorithm to predict future conditions based on current conditions at other spatial points. For example, if a detector is located, say, 10 seconds upstream of the desired prediction point, then prediction will be easier but only for a 10-second horizon. The further away the location of other information sources, the longer the potential prediction horizon. But, the temporal information may become more distorted (e.g. due to platoon dispersion) and thus less valuable for prediction. In addition, the further away the information sources are located, the greater are the effects of exogenous factors, such as traffic signals and traffic sources/sinks, on prediction. Clearly, a system with many well-placed detectors will provide the best information for prediction.

The PREDICT algorithm [Head, 1995] in RHODES-ITMS uses the output of the detectors on the approach of each upstream intersection, together with information on the traffic state and planned phase timings for the upstream signals, to predict future arrivals at the intersection/interchange under RHODES control. This approach allows a longer prediction time horizon since the travel distance to the intersection is longer and the delays at the upstream signal are considered. A benefit of this approach is that it includes the effects of the upstream traffic signals in the intersection/interchange control optimization problem.

To understand how this approach works consider the scenario shown in Figure 8. It is desired to predict the flow approaching intersection A at detector d_A. Making the prediction for the point d_A is important because it is a point on link AB where the actual flow can be measured, hence the quality of the prediction can be assessed in real-time.

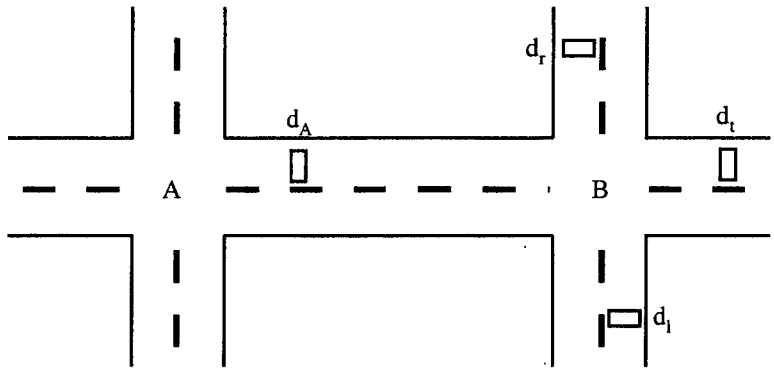


Figure 8 - Prediction scenario based on detectors on the approaches to the upstream intersection (B)

Traffic contributing to the flow at d_A originates from the approaches to intersection B and can be measured at detectors d_l, d_t and d_r representing the flows that will turn left, pass through and turn right, respectively, onto link AB. It is possible to have other traffic that originates at sources between intersections A and B, but this can be considered as immeasurable "noise". Also, it is possible that vehicles passing over d_l, d_t, and d_r will terminate their trip before arriving at d_A. This can also be considered as "noise" in the prediction.

When a vehicle passes a detection point, say d_i where $i \in \{l,t,r\}$, several factors affect when it will arrive at d_A including (1) the travel time from d_i to the stop bar at intersection B, (2) the delay due to an existing queue at B, (3) the delay due to the traffic signal at B, and (4) the travel time between B and d_A.

Figures 9 (a)-(d) depict the delay associated with each of these factors. In Figure 9(a) the vehicle arrives at detector d_i and passes freely to detector d_A. In Figure 9(b) the vehicle arrives at detector d_i and is delayed by the signal at intersection B. Hence the travel time from d_i to d_A must account for the travel time from d_i to the stop bar, the delay due to the signal and the travel time from the stop bar to d_A. In Figure 9(c) the arrival at d_i encounters delay for the signal as well as a standing queue, and has to travel from d_i to the stop bar at B, and from the stop bar to d_A. Figure 9(d) depicts the case when the arrival at d_i occurs after the signal has begun serving the desired phase, but a standing queue is present. This case is

similar to the above, except that the delay due to the standing queue must be adjusted based on the amount of time that has elapsed between the onset of the signal and the arrival of the vehicle at d_i and the travel time to the back of the queue.

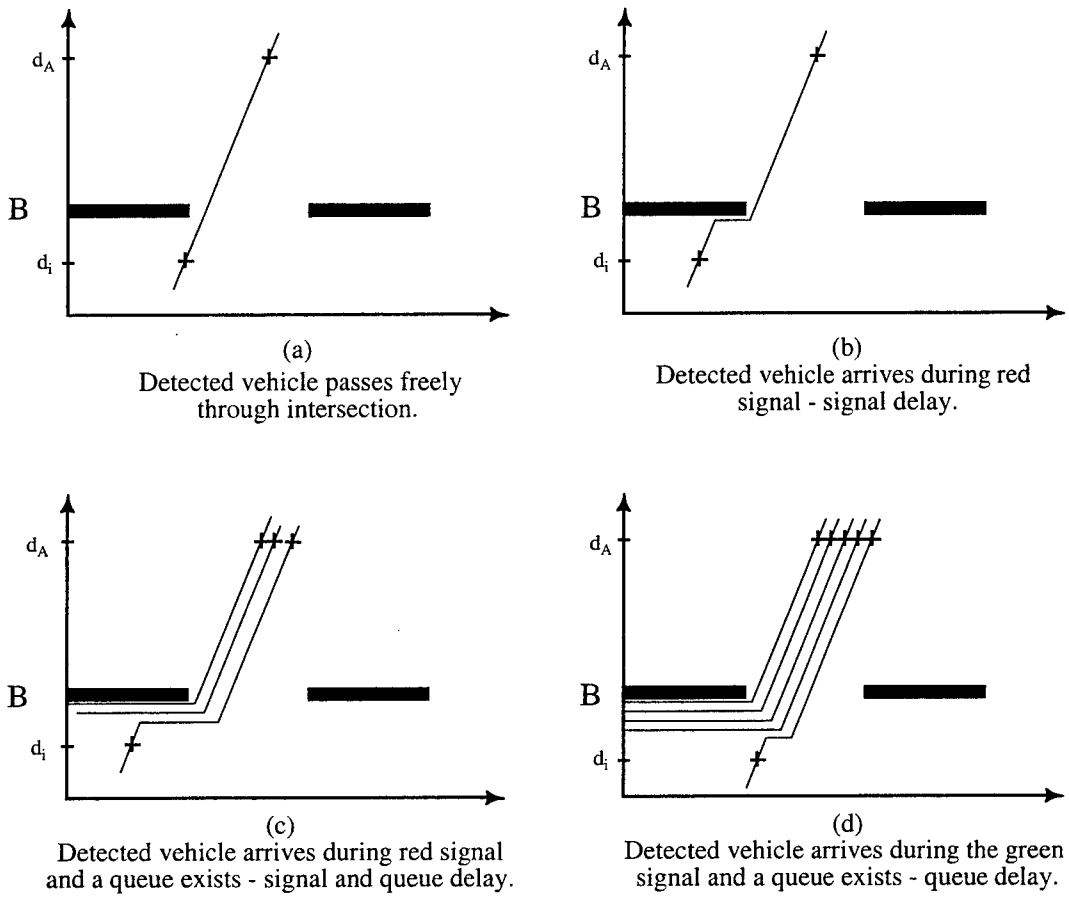


Figure 9 - Delays associated with the prediction of arrivals at the detector d_A

Once the arrival time at d_A is predicted, the PREDICT model adds a fraction to the current estimate of the expected number of arrivals at that time. For example, if 15% of the vehicles that pass over d_i continue on to d_A, then for each actuation of d_i, 0.15 is added to the current estimate of the expected number of arrivals at the predicted arrival time t_a.

Note that to use the PREDICT model, several parameters (given in bold) need to be provided: (1) travel times on links (detector to detector) which depends on the **link free-flow speed** and current traffic volumes, (2) **queue discharge rates** which also depends on volumes (as well as on queue spillbacks and opposing- and cross-traffic volumes), and (3) **turning ratios**.

Link free-flow speed can be estimated from historical data and capacity analysis. Link free-flow speeds are needed even in traditional off-line models to optimize fixed phase timings (cycle times, offsets, splits) so to obtain these should pose no major problem. Appendix 1 gives the travel times (instead of the speeds) used for the field site.

Through-traffic **queue discharge rates** are affected by downstream through-traffic volumes, which can be easily measured. Likewise, left-turn queue discharge rates depend on opposing traffic volumes, and right-turn queue discharge rates depend on cross-traffic in that direction. These three discharge rates may be initially given from calculated default functions (functions of traffic volumes), and then can be adjusted based on how well they predict remaining queues at the stop-bar presence detectors. For example, if the left-turn queue estimate tends to be non-zero when in fact it is zero then the left-turn discharge rate can be adjusted upwards. An approach to adjust discharge rates is given in Mirchandani and Head [2001]; in the field test, however, we used default values and did not adaptively change discharge rates. Appendix 1 gives queue discharge rates used for the field site.

The PREDICT model, as well as the interchange control algorithms (referred to as CAPRI later), requires that **turn ratios** are known. An assumption for RHODES (as well as current off-line methods to set signal timings) is that some estimates for turn ratios at the intersection are given. Even the CORSIM model needs this information. However, from real-time traffic control perspective, these ratios are not deterministic; they change stochastically over time. For example, suppose P_{WN} is the ratio that a vehicle arriving from the West to some intersection will turn left (North), then it is clear that P_{WN} will depend on the time of the day, the volume of traffic, and the particular mix of the origins/destinations in the group of arrivals being modeled. In other words, P_{WN} is described by a random process.

Our assumptions for P_{WN} are (1) a prior estimate is available whose uncertainty is modeled with a Normal distribution with known mean and variance; (2) at any given time, we have measured the percentage of vehicles that have turned left in the last, say, three phase durations, as well as percentages that turned right and driven straight through the intersection; and (3) we know the error distributions for these measurements. An approach to adjust turn ratios is given in Mirchandani, Nobe and Wu [2001]; in the field test, however, we used measured values for three time-of day periods and did not adaptively change turn ratios. Appendix 1 gives these turn ratios for the field site.

It is important to note that the PREDICT model is based on processing arrival data as it becomes available. At any point in time the predicted arrival flow pattern at d_A accounts for vehicles that have already passed the detectors d_l, d_t and d_r. The benefit of this vehicle-additive process of the predictor is that it constantly provides, for a given prediction horizon, (1) nearly complete information of anticipated vehicle

arrivals in the very near future (of those vehicles that have already passed the upstream intersections) and (2) partial information of anticipated vehicles in remaining part of the prediction time horizon (of those vehicles that have not passed the upstream intersections, since some new vehicles may still arrive that will effect the delays in the prediction time horizon). Results of an evaluation study of the PREDICT algorithm for arrivals at an intersection have been reported by Head [1995].

Interchange Predictions

Unlike the case of predictions of vehicle arrivals and queues at an intersection, in the case of the interchange we need to get detector data from additional sources such as off-ramps and on-ramps detectors, and predict arrivals/queues at two intersections and two on-ramps.

Referring to Figure 2, in the interchange scenario the prediction method takes (1) input from passage detectors (one for each lane) just after (on the far-side of) the upstream arterial intersection locations, from passage detectors at the two signals of the interchange locations, and from passage detectors at off-ramps for predicting arrivals, and (2) input from presence detectors (one for each lane) at the two interchange signals, from presence detectors at off-ramps, and from presence detectors at on-ramps for predicting queues; the method outputs prediction of arrivals/queues at interchange signals and at on-ramps. It is important to note that the predictions require the state of the signals at all times and the ramp metering rates. As we indicated earlier, the scope of this effort does not allow our RHODES-ITMS algorithm to set ramp metering rates; the algorithm assumes that these rates are set externally to the interchange control. These rates need to be provided to PREDICT for estimating on-ramp queues in real-time.

The prediction equations for the interchange are similar to those for PREDICT for an intersection but there are more cases to consider. For example arrivals on the far side of bridge, from the North, depend on the arrivals from the upstream signal at Southern, from left-turners at the off-ramps from the East, and on the corresponding phase durations at the North-side signal at the interchange. Similarly, queues at on-ramp to the West depend on arrival streams from that location on the bridge, the arrival streams from Southern, the signal timings at intersection at the North-side signal, and the ramp metering rate at the on-ramp.

2.4. Optimization Algorithms in RHODES-ITMS

Existing control strategies are based on a signal timing plan defined in terms of operating parameters for traditional signal control, namely *cycle time, splits*, and *offsets*. These parameters are generally developed based on traffic studies and standard procedures, such as the Highway Capacity Manual [Transportation Research Board, 1998], or signal timing software such as TRANSYT [Robertson, 1969; Wallace et al.,

1998] and PASSER [Chang and Messer, 1991]. The traffic studies result in estimates of traffic conditions, link volumes and turning percentages, for specified time periods. Signal timing parameters are developed for each of these time periods and, typically, implemented on a time-of-day basis considering only average or typical traffic conditions. In many cases, even the use of standard procedures for the development of signal timing plans is abandoned and traffic engineers operate in a judgment-based fashion with moderate levels of success. None of these approaches is truly traffic-adaptive or even attempt to actually minimize some measure of real-time traffic performance such as average vehicle-delay.

Currently available traffic responsive systems such as SCOOT [Hunt et al., 1981] and SCATS [Luk, 1984; Sims, 1988] attempt to address the problem of responding to actual traffic conditions by switching these parametric signal timing plans based on average wide-area traffic conditions observed in the last several minutes rather than time of day. This requires that signal-timing parameters be developed for a variety of possible traffic conditions. Nevertheless, implicit in the usage of parametric timing plans is the assumption that for the next several minutes, or even hours, the traffic in the network can be well characterized by the observed average flows and parameters. No account is taken of the fact that the second-by-second and minute-by-minute variability of traffic are significant and plans based on averages produce unnecessary delays for some traffic movements when the traffic on conflicting movements is absent, or very small, during some periods.

The RHODES approach is to predict both the short-term and the medium term fluctuations of the traffic (in terms of individual vehicle arrivals and platoon movements respectively), and explicitly set phases that maximize a given traffic performance measure. Note that RHODES does not set timing plans in terms of cycle times, splits and offsets, but rather in terms of **phase durations** for any given phase sequence. (RHODES does not necessarily require a pre-specified phase sequence, but since many traffic engineers prefer a pre-specified sequence, RHODES has been developed to allow the traffic engineer to specify a desired sequence.) In other words, in the RHODES control strategy, the emphasis shifts from changing timing parameters in reacting to traffic conditions just observed to proactively setting phase durations for predicted traffic conditions.

To adaptively control an intersection in a surface street network, Sen and Head [1997] developed a dynamic-programming (DP) based model where each "stage" corresponds to a time interval (in our case, this is usually a second) and each stage corresponds to the phase in a given "phase order". The possible decision at each stage is to either remain in the current phase or switch to the next phase in the phase order. The solution of the DP gives a set of switching points. For this research effort, this model was generalized for the freeway-arterial diamond interchange. The total and average vehicle delays at the interchange are greatly reduced by explicitly considering these delays in selecting the controllers' phase durations as done

in the RHODES real-time interchange control scheme. (Traditionally, the tightly coupled operation of the two intersections comprising the interchange has been addressed by using a specialized phasing strategy with pre-defined time-of-day timing plans.) We refer to the intersection/interchange module of RHODES as CAPRI, referring to "Categorized Arrival-based Phase Reoptimization at Intersection/interchange", since in the general algorithm arrivals streams are categorized into classes (straight-through buses, left-turn cars, fire engines, etc.).

Figure 10 depicts the states of the dynamic programming (DP) formulation. A rolling horizon approach is used to allow the optimization to take advantage of the most recent predictions and observations. An optimization is started at some time t_0 and considers a time horizon of T seconds, say 45-60 seconds. A **phase order** is provided to CAPRI so that at each stage decision corresponds to a phase. The result of the DP optimization provides the time (x_j time units) that must be allocated to each phase j in the phase order. If the traffic engineer does not restrict the phases to be in a particular sequence, then this flexibility allows for variable phase sequencing through phase skipping (by effectively allocating zero time for the corresponding stage).

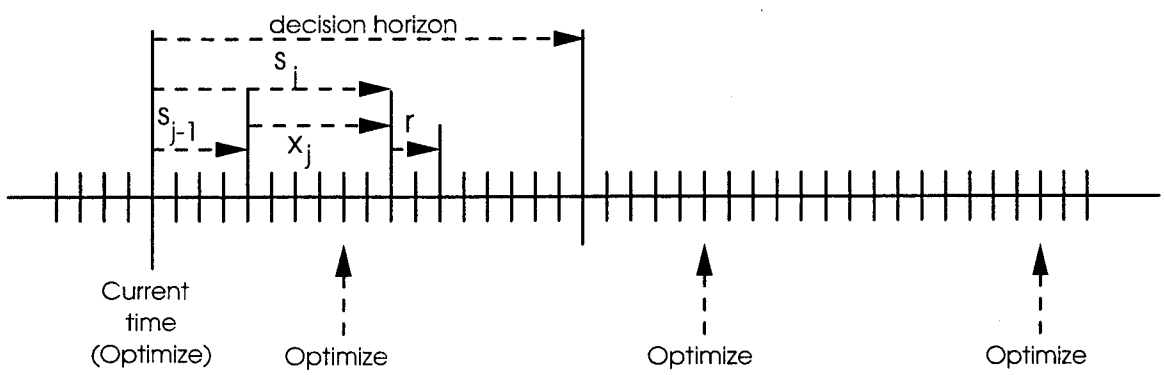


Figure 10 - Implementation of single-variable rolling horizon approach

Each decision x_j has an associated value based on a performance measure such as stops or delay. This value is determined by using the predicted vehicle arrivals, the current and prior decisions, and an imbedded traffic flow model that accounts for estimated queues, startup lost time, queue discharge and arrivals, as well as other traffic dynamics that relate the decision to the performance measure.

The decision for the first phase is implemented as the desired signal control. Just prior to the end of this first phase, the optimization problem is solved again in a rolling horizon approach. The sequence of phases in the second optimization begins with the current phase, which allow for the phase to be terminated early or extended based on the re-evaluation with more recent observations and predictions.

Since phasing sequence and timing decisions are applicable only for a short time-horizon, the problem is formulated such that the optimization horizon T is long enough to account for sufficient propagation of traffic flow to get good predicted performance measures, but "short enough" to allow for computations in real time. Furthermore, CAPRI implements timing decisions only for the first few seconds of the optimization horizon T, as depicted in Figure 10 (the variables on the figure will be described shortly). As predicted vehicle arrival information is updated with additional detector actuations, the algorithm runs again to re-optimizes the phase timings and sequence for the un-implemented portion of the previous optimization horizon, and propagates the optimization an additional t time units into the future. In this way, CAPRI produces a rolling-horizon optimization that can extend the timing of phases previously scheduled given new updated vehicle arrival information.

RHODES-ITMS proceeds as follows at any iteration: (1) collect current detector actuations at the interchange and adjacent intersections and update the detector database, (2) use the PREDICT model to propagate those detector actuations into the future and update flow predictions, (3) assess various phase timing/switching decisions with the CAPRI rolling-horizon dynamic programming algorithm.

CAPRI's DP framework allows one to take into account any operating and jurisdictional constraint imposed by the traffic engineer. For example, if it is required that a phase sequence is specified and phases cannot be skipped, then the phase order will correspond to the given phase sequence and a non-zero minimum green time threshold will be imposed on all the phases in the phase order. Or, if it is allowed that non-conflicting movements of two consecutive phases "overlap" instead of requiring explicit clearance phase, then this is also possible in the DP framework. Or, if a pedestrian clearance is required, the corresponding minimum green time can be set equal to the pedestrian clearance interval

Suppose any phase sequence is allowed, but a minimum green time of $g(\Phi_j)$ is required if phase Φ_j is used. Then, given the value for the state variable s_j, the control variable x_j (for the jth stage and the corresponding phase in the given phase order) can assume values from the following feasible discrete set:

$$X_j(s_j) = \begin{cases} 0 & \text{if} \quad s_j - r < g, \\ 0, g, g+1, \ldots, s_j - r & \text{otherwise.} \end{cases}$$

where r is the required clearance interval.

We use the following relationship between the stages of the DP (see Figure 10) if a clearance interval of length $r(\Phi_i|\Phi_k)$ is required between phases:

$$s_{j-1} = s_j - h_j(x_j)$$

where

$$h_j(x_j) = \begin{cases} 0 & if \quad x_j = 0, \\ x_j + r(p(j)/p(j-1)) & otherwise. \end{cases}$$

On the other hand, if some phases are allowed to overlap, then depending on $p(j)$, the current non-zero duration phase decision and $p(j-k)$, the last non-zero duration phase decision (say, at time $j-k$), clearance interval $r(p(j)/p(j-k))$ may be set to zero.

An important assumption for DP is that the objective function of the optimization should be additive, namely

$$v_j(s_j) = f_1(s_1, x_1) + f_2(s_2, x_2) + \ldots + f_j(s_j, x_j)$$

which is true for many types of performance functions. For the standard traffic performance measures, total delays and stops, this measure is approximately additive. In the simulation experiments reported in this paper we used delays (a linear combination of accumulated delays of currently queued vehicles plus expected delays of predicted arrivals) as our performance criteria that we tried to minimize with our traffic controls.

The forward DP recursion is performed to evaluate possible phase sequences, timings and the associated performance measures at each recursive step. To initialize, $v_0(s_0)$ is set to zero. Using the recursion

$$v_j(s_j) = Min_{xj} \{f_j(s_j, x_j) + v_{j-1}(s_{j-1}) \mid x_j \text{ in } X_j(s_j)\}$$

the DP starts with j=1 and proceeds recursively for j=2,3,... until $v_j(T)$ does not change for a whole cycle in the phase order. However, in the current implementation of the algorithm, for computational efficiency, we simply terminated the DP after a fixed number (M) of phases were determined. The resulting errors from the optimal solution were small. At each stage in the forward recursion, the method computes the optimal value of $v_j(s_j)$, and stores the optimal $x_j(s_j)$ and the corresponding phase $p(j)$, for all possible values of s_j:

The optimal phase sequence and timings are retrieved in a backward pass, beginning at the end of the time horizon and progressing towards the beginning. Since M denotes the last stage for which the value function $v_j(s_j)$ has been computed, we simply perform the following backward recursion starting with $j = M-1$, and ending with $j = 1$.

The set of phases that must be considered by CAPRI and the corresponding phase order to be used in the algorithm is a *design element* that must be provided by the traffic engineer in the implementation of CAPRI. In our current implementation of CAPRI we used three Phases 1-5, 2-6, 4-8 as the phase order, and the corresponding minimum and maximum green times shown in Figure 5.

Computation of Performance Function

If one does not consider the queues at the ramps, then the essential differences between the application of CAPRI for an intersection and an interchange are:

1. the phases and the phase order are different,
2. additional constraints for clearing the queued vehicles on the arterial segment between the two intersections of the interchange may be imposed, and
3. predictions of arrivals and queues for more locations are needed.

Here the performance functions based on delays are essentially the same. In the computation of the delay-based performance measure, every second a vehicle is delayed at the intersections being controlled contributes an additional one vehicle-second to the overall objective function value. Equivalently, one-second delay of V_T, a vehicle going straight through on the arterial, is equal to one-second delay of a vehicle V_L waiting to make a left turn on to the on-ramp.

However, when one considers the queues at the on-ramps that may result in an additional delay for V_L, then the last statement is not necessarily correct. For example, if one knows that it will take 10 seconds for vehicle V_L to reach the ramp-meter but the current queue q(t) at the ramp meter is large so that the vehicle will have to wait an additional 3 seconds at the on-ramp anyway, then there is <u>no</u> decrease in the total delay of vehicle V_L through the interchange if it is held back another 3 seconds at the intersection traffic signal. In the meantime, other vehicles like V_T may be able to get through the interchange without incurring a traffic signal delay.

On the other hand, if there is no queue, or a small queue, at the ramp meter then one-second delay of V_L does in fact contribute 1 vehicle-second to the overall objective function value. Thus, depending on the size of queue, if it exists, at the on-ramp, as well as on the turning ratio for getting on to the ramp, a one-second delay of vehicle V_L may have to be "discounted" using a multiplicative factor ρ, $0 \leq \rho \leq 1$. Details of this discounting approach are given in the earlier RHODES-ITMS Project report [Head and Mirchandani, 1997].

2.5. Simulation Results for the Tempe Interchange

Integration of CORSIM, PREDICT and CAPRI

As described earlier, CORSIM was used for laboratory testing the real-time traffic control algorithms for the freeway-arterial diamond interchange. Current system timing strategies, and associated timing parameters were obtained from the City of Tempe. Physical characteristics of the interchange were observed and required measurements such as distances from the intersections to the ramp-meters, the lengths of left-turn bays, distances between the detectors and stop bar, etc., were obtained either from detailed drawings of the interchange or through actual measurements. Although the simulation model was not validated - to see if it exactly represented the Rural/ US 60 interchange, the research team felt that it was sufficiently realistic for laboratory testing of the algorithms.

Briefly, the simulation procedure for the integrated set-up worked as follows:

1. Check if specified simulation end time has been reached. If yes, STOP.
2. Otherwise, simulate the traffic dynamics for one second (by execution of CORSIM)
3. Collect specified measures of effectiveness
4. Collect detector outputs and the signal states in the last second
5. Update predicted arrivals and queues (using PREDICT)
6. Check if CAPRI needs to be executed for the given predictions. If no, then go to Step 1.
7. Otherwise, run CAPRI for the specified rolling horizon. Schedule time for next CAPRI execution
8. Implement recommended phase decisions, and go to Step 1.

Simulation Results

Two scenarios were considered in the simulation testing. The first scenario consisted of semi-actuated (or coordinated actuated) control using signal phasing currently adopted by Tempe. This was for comparison purposes. The second scenario used an implementation of the RHODES algorithms.

Five loading factors were considered, all of them having relatively high transient loads to allow for some queue build-ups at the ramps, in order to test the effectiveness of the RHODES algorithms. Figure 11 gives a sample profile of traffic volumes input in one direction of the main arterial of the interchange (the other direction had a similar profile). With this arrival pattern, during the peaks the interchange is oversaturated (with large queues at the intersections and the ramps) and during the intervening lulls the congestion clears out. Observe that in the 240 minutes of simulation time, there are four peaks with oversaturated conditions

-- somewhat unrealistic as normal traffic conditions. However, since it is anticipated that a signal system that is truly traffic-responsive will be most beneficial in highly varying traffic conditions this profile was used to emphasize the potential benefits of a traffic-adaptive system.

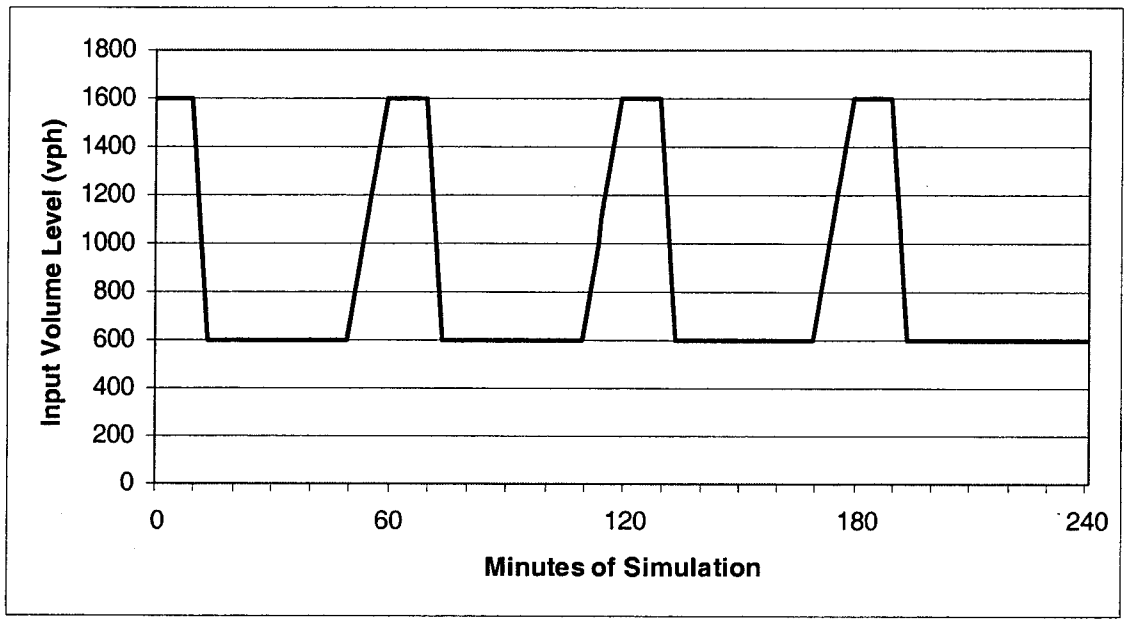
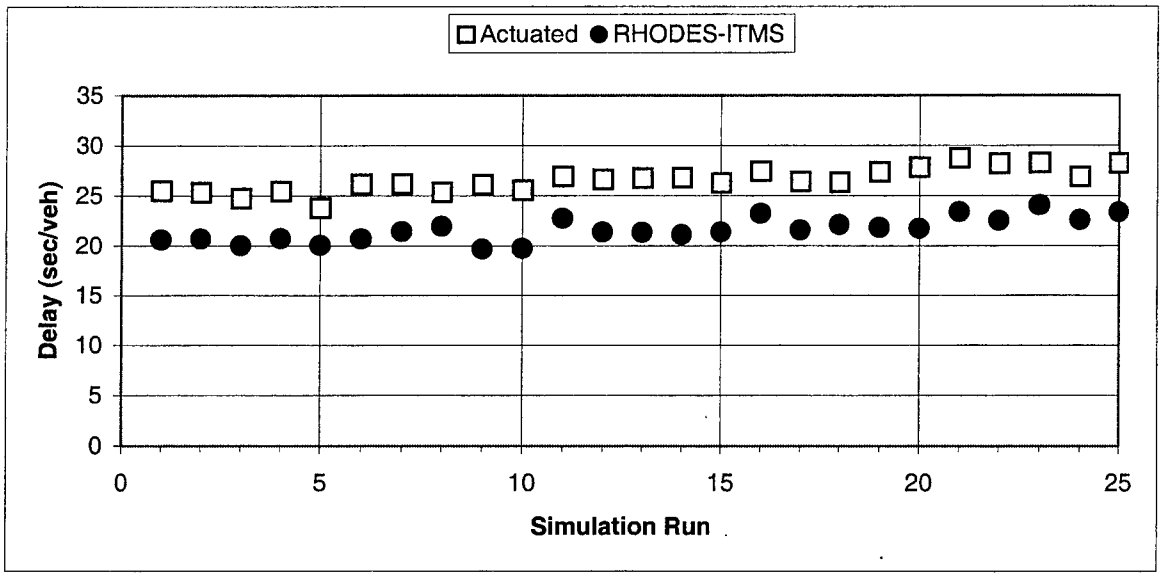


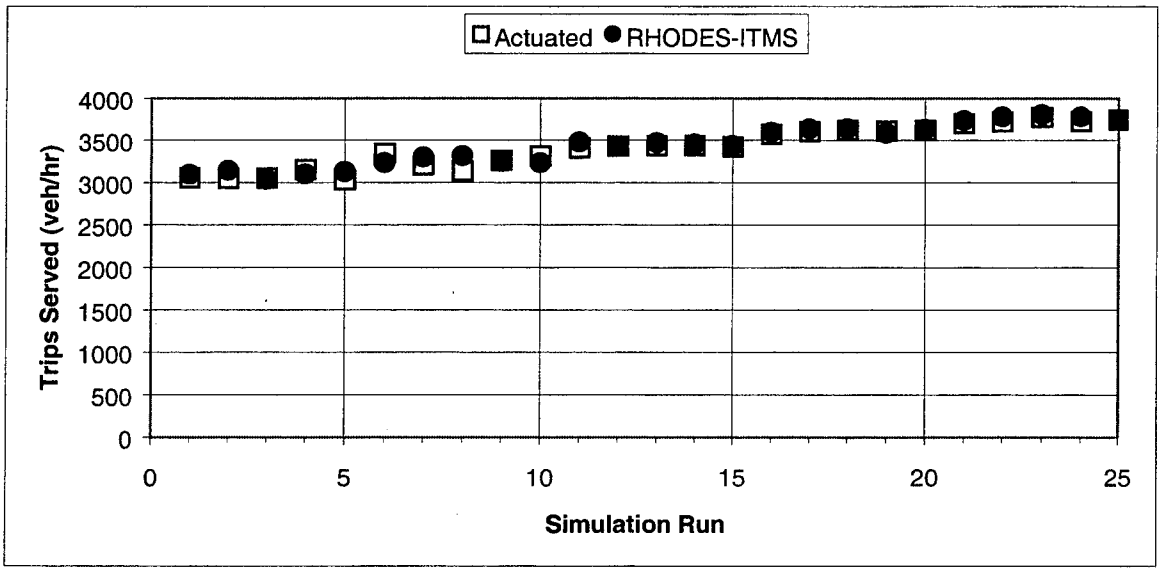
Figure 11 - Sample traffic volume profile for vehicles entering the interchange

For each of the loads, five runs were conducted for the "actuated" scenario and five for the "RHODES-ITMS" scenario. The lowest load averaged approximately 3100 vehicle-trips per hour through the interchange. In the next four levels, approximately 3250, 3450, 3600 and 3750 vehicle trips per hour were loaded, respectively. Figure 12(a) shows total delay (in seconds per vehicle) of the vehicles through the interchange; and 12(b) the total number of vehicles trips on the links of the interchange, for each of the 25 runs for the two control scenarios.

Observe first, from Figure 12(b), that the number of trips through the interchange was mostly the same for actuated and RHODES-ITMS scenarios. This should be expected since in steady state the number entering must equal to the number exiting for otherwise the queues would grow indefinitely and oversaturation would take place. Now observe, from Figure 12(a) that the total vehicle delay for RHODES-ITMS was always lower than for the actuated scenario. RHODES-ITMS reduced average delays by 18.3%, 20.1%, 19.2%, 18.5%, and 17.5% for load levels 1 to 5, respectively. (See Table 1).



(a)



(b)

Figure 12 - (a) Total vehicle delay and (b) vehicle trips served using actuated control and RHODES-ITMS control strategies

Table 1 - Means and variances for vehicle delays (in seconds)

		Level 1	Level 2	Level 3	Level 4	Level 5
Actuated						
	Mean	24.98	25.89	26.70	27.10	28.10
	Standard Deviation	0.73	0.39	0.26	0.68	0.69
RHODES						
	Mean	20.41	20.69	21.58	22.09	23.19
	Standard Deviation	0.35	1.01	0.65	0.66	0.64
	Differential	4.57	5.20	5.12	5.01	4.91
	(as % of Actuated)	18.3	20.1	19.2	18.5	17.5

To account for the delay based on throughput, one can plot delay per vehicle (in seconds) versus trips per hour, by dividing the total delay (in vehicle seconds) by the number of vehicles trips completed during the simulation period. Figure 13 gives such a plot.

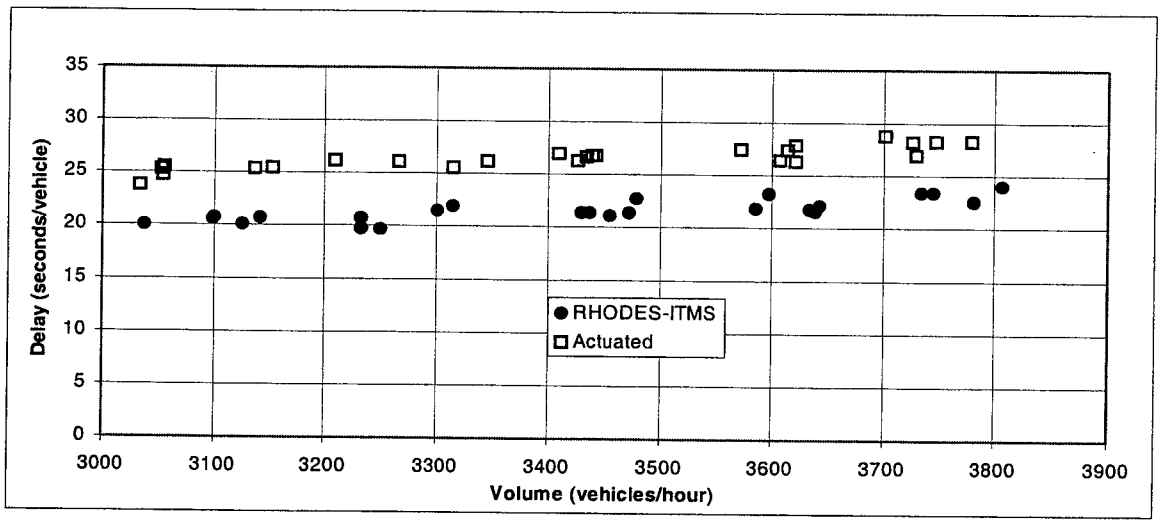


Figure 13 - Average vehicle delay versus throughput (vehicle trips per hour) using actuated control and RHODES-ITMS control strategies

From Table 1 and Figure 13 we see that, in the low load case, RHODES-ITMS results in vehicle delays of 20.4 seconds versus the 25 seconds for the actuated case - a 18.3 % improvement. For the next level the respective numbers are 20.7 seconds for RHODES-ITMS and 25.9 seconds for the actuated case (a 20.1 % improvement); for the third level they are 21.6 seconds for RHODES-ITMS versus 26.7 seconds for the actuated case (a 19.2% improvement) and for the fourth level they are 22.1 seconds for RHODES-ITMS versus 27.1 seconds for the actuated case (a 18.5% improvement). For the highest level the averages are 23.2 seconds for RHODES-ITMS versus 28.1 seconds for the actuated case (a 17.5% improvement).

IMPLEMENTATION OF RHODES WITHIN 2070 CONTROLLER

3.1 Integration of RHODES within 2070

Having demonstrated the potential effectiveness of the RHODES algorithms through the use of simulation, the next objective was the migration of RHODES onto an actual traffic controller. Our first step, therefore, was to identify an appropriate hardware platform on which RHODES could operate. Most modern traffic controllers, such as the Econolite ASC/2-2000 or the Eagle EPAC 300, are specialized units that reliably provide basic signal control functionality in the harsh, uncontrolled environment of a traffic cabinet. Unfortunately, these controllers cannot be expanded to support additional features that may become available, such as the RHODES adaptive signal control system. Recently, however, a controller was developed by the California Department of Transportation, the City of Los Angeles, and other agencies to meet this deficiency.

The Model 2070 Advanced Traffic Controller (see Figure 14) was designed to meet the current and future needs of the nation's intelligent transportation systems. Incorporating the industry-standard Versa Module Eurocard (VME) computer platform, the 2070 can accommodate a variety of off-the-shelf modular (plug-in) components to provide a wide range of functionality (see Figure 15). This modular architecture, together with a powerful 32-bit microprocessor and a wide choice of input/output options, made the 2070 the perfect hardware platform upon which to implement the RHODES adaptive signal control system. However, various implementation issues needed to be resolved before RHODES could be successfully migrated onto the 2070 platform.

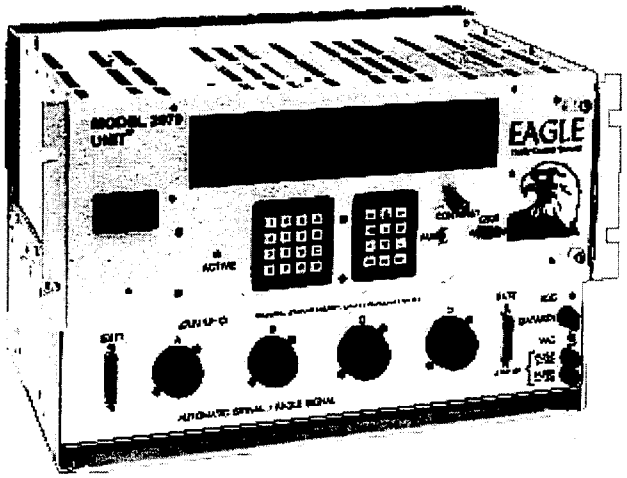


Figure 14 - Eagle 2070N Advanced Traffic Controller

(The "N" designation means that this has standard NEMA connectors on the base)

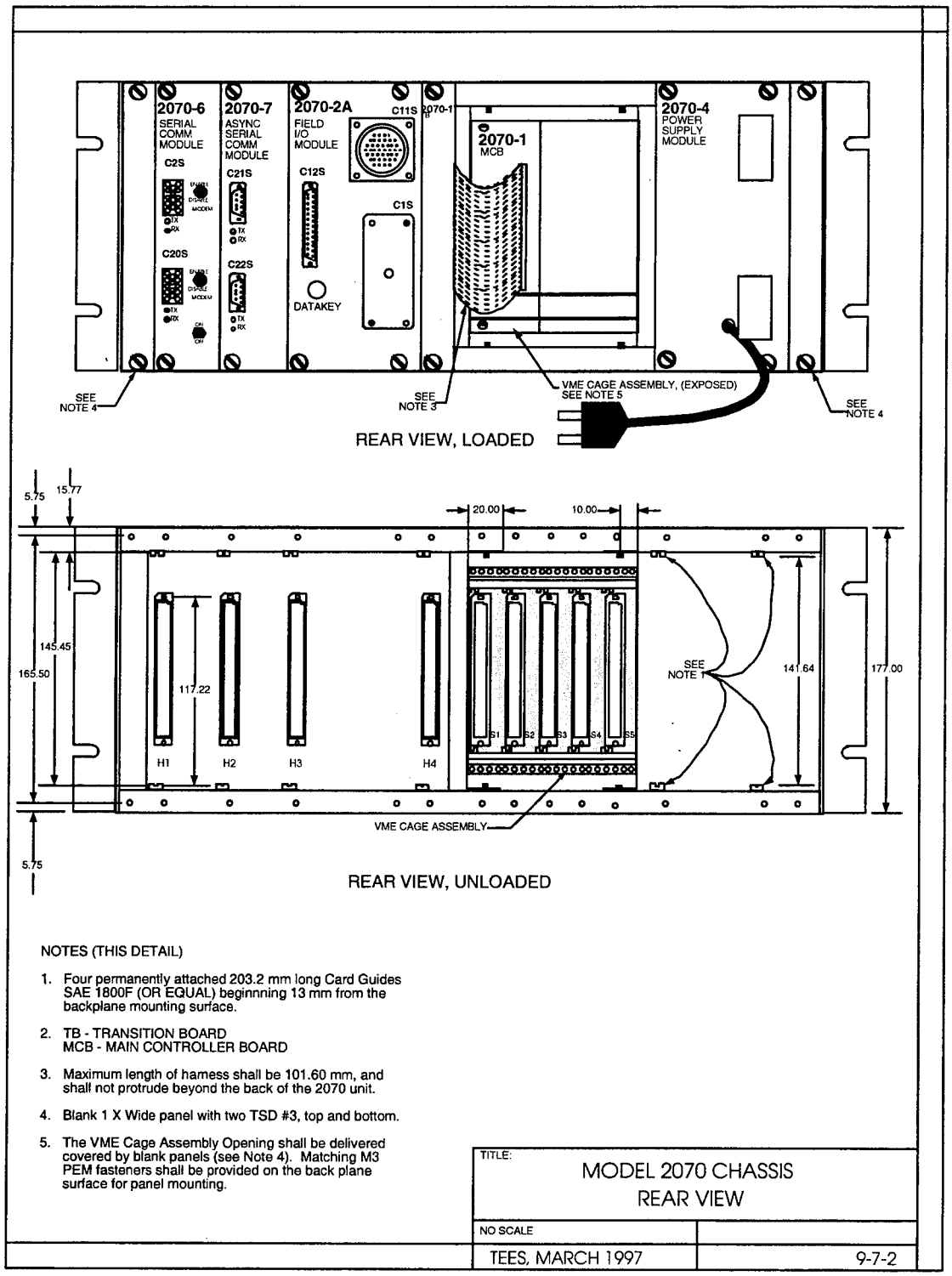


Figure 15 - Rear view of the 2070 showing the VME Chassis [Miller, 1996]

The research team's first issue concerned the processing and memory requirements of RHODES. Up to this point in its development, RHODES had existed as a *Dynamic Link Library* (DLL) software module containing the various control functions comprising the RHODES algorithms. Using the TSIS simulation environment and the CORSIM traffic simulator, a selected intersection would be placed under RHODES control by making a procedure call to the appropriate RHODES routines, once each second, to update the status of the traffic signal according to the phase durations produced by RHODES. All communication between RHODES and CORSIM was handled through a shared-memory environment that allowed each program to communicate indirectly with the other in order to exchange information on detector actuations and signal status indications. In addition, as the software was run within a personal computer (PC) environment with a large amount of RAM and disk space available, memory typically was not an issue. In addition, processing power merely affected how long it would take a given simulation to complete in real-world time, since the same basic computations would be completed, regardless of the speed of the PC's processor. Each time CORSIM placed a call to RHODES, requesting an update to the current signal status, the CORSIM simulation would be paused until the RHODES procedure returned its results. Thus, regardless of how much time had elapsed in the real world while RHODES performed its computations, only one second would have elapsed during this time in the simulation world. However, when running in a real-world environment within a 2070, RHODES would have a finite computational time budget and a memory budget to work with in order to produce timely and usable results.

As a result, the first task was to identify a processing environment that would allow RHODES to complete its computations within the desired time budget without exceeding the available memory. While the 2070's Motorola 68360 processor was indeed more powerful than those used in previous controllers, after examining RHODES' requirements in its current environment, it was determined that the 68360 would be insufficient to meet the computational load of the RHODES algorithms on top of the controller's current traffic control processing functions. For this reason, a modular processor that would fit in an available VME slot within the 2070 was considered for housing the RHODES software.

The research team first looked at Matrix Corporation's PENTX card, which consisted of a Pentium 133 MHz processor on a VME board, designed to provide full PC functionality for rugged, embedded applications. While the PENTX card provided a suitable platform for the RHODES algorithms within the 2070, and was successfully implemented as such, issues arose regarding its selection. For one, since the PENTX card was intended to provide the functionality of a full-fledged PC, all of the necessary peripherals needed to actually develop the application and make any modifications to it required that an external monitor, mouse, keyboard, hard disk and floppy drive be made available (usually in a standard mini-tower PC case), all of which were then to be connected to the PENTX card via external cables. While a potential benefit was the PENTX card's use of the Windows™ NT operating system, as it required less work to port

the source code, NT is not a real-time OS and includes much more functionality than is required for our purposes. These issues, in conjunction with concerns over the ability of the PENTX board to provide sufficient processing capability to satisfy the real-time operating requirement, led the research team to abandon the development on the PENTEX and consider other processing platforms.

As a result, a field-hardened processor manufactured by Mikro Elektronik Gmbh (MEN) in Nürnberg, Germany (see Figure 16) was selected for RHODES processing. Containing a Motorola 68060 processor running at 25 MHz (4.5 MIPS) with 32MB of SDRAM and 4MB of flash memory, this MEN card would also be capable of providing an operating platform for RHODES, but without the need for any external peripherals to provide access during development and/or operation. In addition, the MEN card used the same OS-9 real-time operating system as the 2070's 68360 processor. Use of the same operating system not only simplifies the interface between RHODES and the controller software, but also facilitates the eventual migration of the entire RHODES system onto the primary controller processor as future advances increase its computational power.

With the operating environment now completely determined, it was now necessary to migrate RHODES from Windows™ NT to OS-9. In addition, a means for communicating between RHODES and the controller software had to be developed. Whereas before RHODES communicated more or less directly with its environment via a segment of shared memory, in this environment a new communications method had to be created. In this endeavor, the UA research team worked with Gardner Transportation Systems (now a business unit of Siemens Energy and Automation, Inc.) to design an interface between RHODES and ***NextPhase***, Gardner's traffic control software for the 2070.

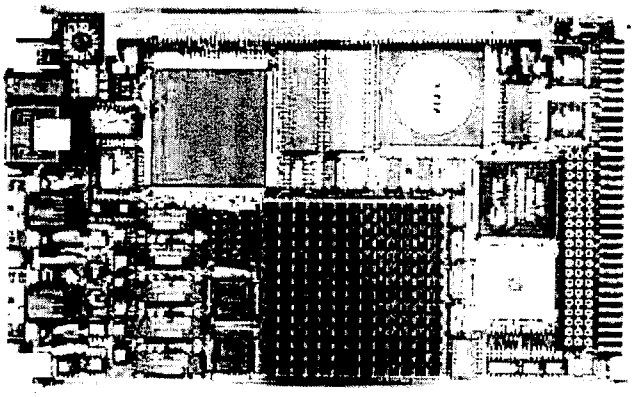


Figure 16 - MEN Card

As the traffic control software residing on the 2070, *NextPhase* would receive all controller inputs from the cabinet, such as pedestrian calls, detector actuations and signal states, and would provide all controller outputs, namely the current signal decisions. RHODES, residing on the 68060 processor on the MEN card, would receive its input from *NextPhase* and send its output to *NextPhase,* with RHODES having no direct connection to the traffic cabinet; *NextPhase* would be the intermediary between RHODES and the traffic cabinet. In field operation, *NextPhase* would implement signal changes according to either its own internal logic or, when RHODES is operating, according to the optimized signal phase settings received from RHODES (see schematic in Figure 17). In this configuration, phase settings received from RHODES would be subject to any constraints in place in *NextPhase,* such as minimum green times and pedestrian clearance intervals. In addition, the NEMA TS2 cabinet specification includes a Malfunction Management Unit (MMU) that continuously monitors the signal indications received from the controller to ensure that no conflicting movements (e.g., intersecting green phases) are permitted. Therefore, in this configuration, no explicit conflict resolution logic is required within RHODES as the supporting hardware environment already provides it.

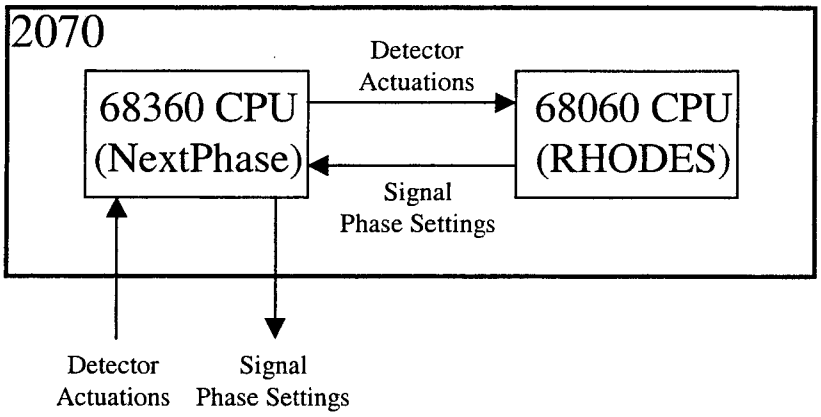


Figure 17 - Data transfer within the 2070

Using the concept of a *pipe*, which is a software construct that provides buffering/queueing of messages, several communications channels between the RHODES process (residing on the MEN card) and the *NextPhase* software (residing on the 2070's 68360 processor) were created. This was done using a shared area of memory on the MEN card for storage of the actual messages and communicated over the internal VME bus.

The data passed between RHODES and *NextPhase* were organized into four distinct messages (see Figure 18). The first is the **ModeMsg**, to be passed from *NextPhase* to RHODES once per second. This message contains both the current "traffic plan number" and the "mode" in which RHODES should be currently

operating. The "traffic plan number" allows RHODES to load time-of-day (TOD) specific information as needed, for example, different min/max green values to match those of the changing TOD plans within *NextPhase*. The "mode" reflects the method of RHODES operation, according to the current *NextPhase* setting, which is user determined. RHODES operates in three different modes, OFFLINE, STANDBY or ONLINE, indicating that RHODES is either not in operation; running in the background and passively collecting data; or is in control of the intersection signals, respectively.

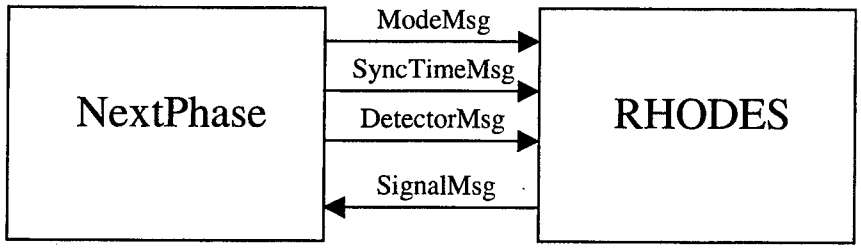


Figure 18 - Messages exchanged between *NextPhase* and RHODES each second

The second message is the **SyncTimeMsg**, passed from *NextPhase* to RHODES once per second for the purpose of ensuring that the operating system clocks on both processors are in synch -- by modifying the clock on the MEN card, if necessary, to match that of the 2070's 68360 processor.

The third, **DetectorMsg**, contains the values of all (up to 64) local detectors (i.e., those connected to the cabinet in which the 2070 resides) as well as the current signal status. This information is critical in order for RHODES to maintain an accurate picture of the intersection over which it has control. Upon receiving this data, RHODES updates its internal databases to reflect the changes since the last update. When running in ONLINE mode (i.e., RHODES is in control of the intersection's traffic signals) RHODES reruns, when necessary, its optimization routine, CAPRI, to determine the optimal signal phasing to implement. This information, in the form of forceoffs and holds, is communicated back to *NextPhase* via the **SignalMsg** returned by RHODES. Upon receipt of this message, *NextPhase* attempts to implement the signal phasing requested by RHODES. Note that it is possible that RHODES will not have its requested signal phasing put into effect by *NextPhase*, if for doing so conflicts, for instance, with timing parameters such as min/max greens. While this should not occur if care is taken when configuring RHODES so that all such parameters are in agreement, it is important to note that *NextPhase*, and hence the 2070, has the "final say" on what signal phasing is allowed. In addition, for emergency vehicle preemption, in which a specific phase is requested for the expedient passage of an emergency vehicle through the intersection, the control was configured so that *NextPhase* assumes control of the intersection for the duration of the preemption, effectively ignoring any signal phasing requests received from RHODES. It is in light of this

possibility that, as part of the **DetectorMsg**, RHODES receives information regarding the current signal phasing, so that it may determine if its last request was honored or not and can update its data accordingly.

At this point in the project, the communication system between the two processes was finalized. The system allowed RHODES to receive data from the intersection and return optimized signal phasing requests, in real-time. During laboratory testing, the research team experimented with varying latencies for the different message types to investigate which were feasible given the load placed on each processor by its various tasks. It was found that the RHODES' optimization algorithm, CAPRI, required less than a second of processing time to complete its computations, under all but the most congested traffic conditions, with the database update requiring minimal additional processing time.

3.2 Testing RHODES/2070 with Hardware-in-the-Loop Simulation

With RHODES implemented on the MEN card within the 2070 controller, the next step was to verify the data path between RHODES and the hardware in a realistic environment, which essentially consisted of two subtasks. First, it was necesary to verify communications between the real world and the 2070, then between the 2070 and RHODES. The Controller Interface Device (CID), developed by Bullock [1997] was utilized for this purpose. Using a CID, a TS1 cabinet environment was simulated with a CORSIM simulation model generating detections and receiving signal phasing from a 2070. As shown in Figure 19, the CID is connected to a 2070N using the standard NEMA - A, B, C connectors. The CID, in turn, is connected, via a serial cable, to a PC running a CORSIM simulation. (Although the 2070 would be installed within a TS2 cabinet at the Tempe interchange, a TS1 environment was used instead because a CID using the NEMA TS2's SDLC connection is not available currently.)

Figure 19 - TS1 Controller Interface Device

In this configuration, an intersection within the simulation is flagged for external control via the CID interface, much as was done during the earlier software-only simulations. Then, as vehicles within the simulation traverse the detectors located on the approaches to this intersection, actuations are sent over the NEMA - A, B, C connectors to the 2070, just as they would be in a real TS1 traffic cabinet environment. *NextPhase* then encapsulates this detector data within a **DetectorMsg** and passes it to RHODES via the internal VME bus. Upon receipt of this message, RHODES re-computes its optimized signal phasing considering any new detector data it may have received and issues a request for a specific signal phase via a set of holds and forceoffs. The signal phase request is encapsulated within the **SignalMsg** for transmission to *NextPhase*. *NextPhase* then implements the desired signal request, always ensuring, of course, that no timing constraints are violated. This results in the signal to either remain in the same phase or to begin transitioning to a different one. To communicate this information to the cabinet load switches, *NextPhase* sends this request out via the NEMA - A, B, C connectors connected to the CID. Upon receipt of the signal phasing request, the CID passes it on to the CORSIM simulation model via the serial interface connecting the CID and the PC. Accordingly, CORSIM then updates the status of the externally controlled intersection signals.

This entire cycle, from CORSIM to CID to 2070 to *NextPhase* to RHODES and back again, is repeated every second, and, ***most importantly***, is performed in real-time! Unlike software-only simulation, hardware-in-the-loop simulation, because it incorporates actual traffic control hardware, operates in real time. As a result, hardware-in-the-loop simulation afforded the research team the first opportunity to evaluate how RHODES would operate in a real-world environment.

Using the CORSIM (software-only) simulation of the U.S. 60 & Rural Road interchange that was used to provide the results in section 2.5, several extended tests of RHODES within the hardware-in-the-loop simulation environment were performed. These tests confirmed that all data received at the hardware interface properly reflected the data that was being received/transmitted by *NextPhase* and hence, RHODES. Most importantly, it was verified that, under realistic loading conditions, RHODES would be able to complete its required data transfer and processing within the available time budget, ensuring that it operates successfully in real-time. With the hardware-in-the-loop simulation completed, the research team was now ready to implement a RHODES-enabled 2070 within a TS2 cabinet to reflect the environment at the field test location.

4. IMPLEMENTATION OF RHODES IN THE FIELD

4.1 Integration of RHODES/2070 Controller/TS2 Cabinet

Surprisingly enough, though the 2070 is an Advanced Traffic Controller, it was not designed to be placed within a TS2 Type 2 cabinet. As a result, one of the first problems experienced in the field implementation was installing a 2070 in a TS2 cabinet. To do this, several different hardware-related issues had to be resolved.

In a TS2 cabinet, the unwieldy point-to-point wiring of the TS1 cabinet has been replaced by a backplane comprising a high-speed Synchronous Data Link Control (SDLC) serial data bus interconnecting all of the cabinet equipment. SDLC is a standard communication protocol and its use helps to ensure compatibility between hardware manufacturers as well as makes communication between components simpler, allowing components to be added in a modular fashion. In a TS2 cabinet, a Bus Interface Unit (BIU) is used to provide a communication interface between the controller and groups of detectors and load switches. In the typical configuration, detectors are arranged in "racks" of up to 16 detector cards each, with load switches arranged in "racks" of up to 8 each. A BIU in each rack handles communication between the rack components and the rest of the cabinet over the SDLC bus. Hence, for the 2070 to operate the cabinet, it must be able to communicate properly with each BIU in order to communicate with its associated elements.

When testing the 2070 within a TS2 cabinet, the research team found that there were problems with the communication via the BIU. The problem was traced to the C12 capacitor on the BIU, which was not capable of holding the RS485 signal up long enough for the 2070 to read the entire message. After notifying Econolite (the manufacturer of the BIUs used in the Tempe cabinet) of the problem, 'modified' BIUs which contained a different capacitor were received. In addition, as the Autoscope units incorporate the BIU functionality, these also were sent back for modification, so that the 2070 would be able to communicate with them to receive the associated detections.

After resolving the BIU problem, an incompatibility between the Econolite ASC2-2100 controller and the Eagle 2070 was discovered in the next attempt to place a 2070 within a TS2 cabinet. The Econolite controller, via its A connector, provides an input to the cabinet's fault monitor which indicates whether the controller is active or not, signaling the possible presence of a fault. Unfortunately, the 2070 does not provide this functionality. So, the initial, temporary, stopgap solution was to ground the fault monitor input on the cabinet's backplane with a jumper in order for the 2070 to operate in the cabinet. The final solution to this problem was to utilize the fault monitor output of the NEMA A connector of the 2070-8 base unit and set this value from within the *NextPhase* software to mirror the functionality of the Econolite

controller. It is for this reason, as well as another to be explained below, that the 2070-8 NEMA base was utilized as part of the 2070 implementation.

Yet, there was one more hardware issue to resolve. As mentioned earlier, the 2070 was not intended for use in a TS2 Type 2 cabinet. The 2070 Field Input/Output module comes in two versions. The 2070-2 is supplied with the basic 2070 controller and has both C1S and C11S 170-style connectors while the 2070-2A is supplied with the 2070N controller and has no inputs other than the connector from the 2070-8 NEMA base unit. As neither of these modules supplied the input/output needs alone, an alternative means of making an SDLC connection was necessary. To do this, one of the external serial ports (EXT1) on the front of the 2070-8 NEMA base unit was utilized as a SDLC port. Using this port required an adapter between the standard 15-pin sub D connector and the 25-pin sub D connector on the front of the 2070, but required no further hardware modification. Together with the need to utilize the fault monitor pin of the NEMA A connector, the usage of the EXT1 serial port required that the 2070 be used in its NEMA configuration, with the 2070-8 base unit and the 2070-2A FIO module.

At this point in the project, all hardware-related issues affecting the ability of the 2070 to operate within the Tempe TS2 cabinet had been resolved, and the research team focused on providing the input to RHODES. In order for RHODES to receive detector data from the many detectors located around the interchange (see Figure 20), detector inputs needed to be mapped between the various elements that would handle them. While some detector actuations would be received from more traditional inductive loops, the vast majority were 'virtual' actuations received from the two Autoscope Machine Vision Processors (MVP) located within the cabinet. For the Tempe interchange configuration, 8 Autoscope cameras were used, necessitating the use of two MVPs, as each can only handle up to four cameras. As mentioned earlier, the Autoscope MVP incorporates the BIU functionality, so Autoscope actuations are passed over the SDLC data bus in the same manner as other actuations. However, as the input from each individual detector is partially identified by its associated BIU, a mapping was needed between each of the detector inputs RHODES expected to see and where these data sources existed in the cabinet. Using this mapping, *NextPhase* could be configured properly to ensure that the data received by RHODES reflected its view of which detector would be associated with the data. Table 2 shows the mapping between the various passage and presence detectors placed along the six approaches of the interchange, as labeled in Figure 20. Note that detectors 91-93 and 97-99 are listed as 'Peer' detectors and are shown coming into the 2070 directly, rather than via a BIU as the others do. The purpose of these detectors and how their data were sent to RHODES will be described in the next section. Otherwise, they were treated as any other detector input in terms of how RHODES processed this detector data.

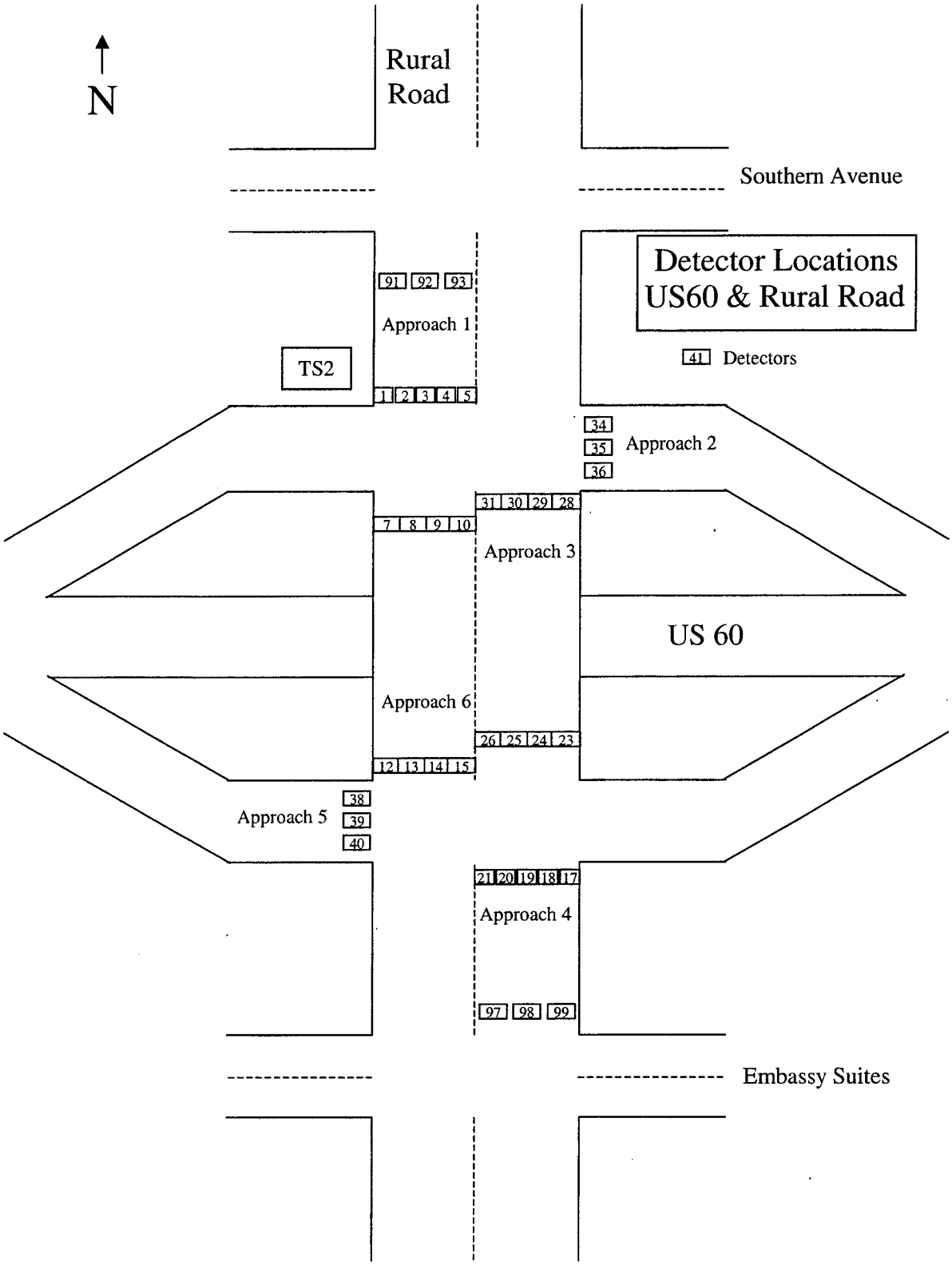


Figure 20 – Detector location diagram (not to scale)

Table 2 - Detector mapping between TS2/*NextPhase*/RHODES

Detector Type	Detector Location	Approach	Equipment Connection	TS2 Cabinet Connection	NextPhase	RHODES
Presence	Southbound Right Turn Pocket	1	AutoScope 2 - Switch 2 - LED 1	Rack 2 - Detector 1	Detector 1	Detector 1
Presence	Southbound Through Lane 1	1	AutoScope 2 - Switch 2 - LED 2	Rack 2 - Detector 2	Detector 2	Detector 2
Presence	Southbound Through Lane 2	1	AutoScope 2 - Switch 2 - LED 3	Rack 2 - Detector 3	Detector 3	Detector 3
Presence	Southbound Through Lane 3	1	AutoScope 2 - Switch 2 - LED 4	Rack 2 - Detector 4	Detector 4	Detector 4
Presence	Southbound Through Lane 4	1	AutoScope 2 - Switch 2 - LED 5	Rack 2 - Detector 5	Detector 5	Detector 5
			AutoScope 2 - Switch 2 - LED 6	Rack 2 - Detector 6	Detector 6	
Passage	Southbound Bridge Through Lane 1	6	AutoScope 2 - Switch 2 - LED 7	Rack 2 - Detector 7	Detector 7	Detector 7
Passage	Southbound Bridge Through Lane 2	6	AutoScope 2 - Switch 2 - LED 8	Rack 2 - Detector 8	Detector 8	Detector 8
Passage	Southbound Bridge Through Lane 3	6	AutoScope 2 - Switch 6 - LED 1	Rack 2 - Detector 9	Detector 9	Detector 9
Passage	Southbound Bridge Through Lane 4	6	AutoScope 2 - Switch 6 - LED 2	Rack 2 - Detector 10	Detector 10	Detector 10
			AutoScope 2 - Switch 6 - LED 3	Rack 2 - Detector 11	Detector 11	
Presence	Southbound Bridge Through Lane 1	6	AutoScope 2 - Switch 6 - LED 4	Rack 2 - Detector 12	Detector 12	Detector 12
Presence	Southbound Bridge Through Lane 2	6	AutoScope 2 - Switch 6 - LED 5	Rack 2 - Detector 13	Detector 13	Detector 13
Presence	Southbound Bridge Through Lane 3	6	AutoScope 2 - Switch 6 - LED 6	Rack 2 - Detector 14	Detector 14	Detector 14
Presence	Southbound Bridge Left Turn Pocket	6	AutoScope 2 - Switch 6 - LED 7	Rack 2 - Detector 15	Detector 15	Detector 15
Passage	Eastbound Offramp	5	AutoScope 2 - Switch 6 - LED 8	Rack 2 - Detector 16	Detector 16	Detector 16
Presence	Northbound Right Turn Pocket	4	AutoScope 1 - Switch 3 - LED 1	Rack 3 - Detector 1	Detector 17	Detector 17
Presence	Northbound Through Lane 1	4	AutoScope 1 - Switch 3 - LED 2	Rack 3 - Detector 2	Detector 18	Detector 18
Presence	Northbound Through Lane 2	4	AutoScope 1 - Switch 3 - LED 3	Rack 3 - Detector 3	Detector 19	Detector 19
Presence	Northbound Through Lane 3	4	AutoScope 1 - Switch 3 - LED 4	Rack 3 - Detector 4	Detector 20	Detector 20
Presence	Northbound Through Lane 4	4	AutoScope 1 - Switch 3 - LED 5	Rack 3 - Detector 5	Detector 21	Detector 21
			AutoScope 1 - Switch 3 - LED 6	Rack 3 - Detector 6	Detector 22	
Passage	Northbound Bridge Through Lane 1	3	AutoScope 1 - Switch 3 - LED 7	Rack 3 - Detector 7	Detector 23	Detector 23
Passage	Northbound Bridge Through Lane 2	3	AutoScope 1 - Switch 3 - LED 8	Rack 3 - Detector 8	Detector 24	Detector 24
Passage	Northbound Bridge Through Lane 3	3	AutoScope 1 - Switch 7 - LED 1	Rack 3 - Detector 9	Detector 25	Detector 25
Passage	Northbound Bridge Through Lane 4	3	AutoScope 1 - Switch 7 - LED 2	Rack 3 - Detector 10	Detector 26	Detector 26
			AutoScope 1 - Switch 7 - LED 3	Rack 3 - Detector 11	Detector 27	
Presence	Northbound Bridge Through Lane 1	3	AutoScope 1 - Switch 7 - LED 4	Rack 3 - Detector 12	Detector 28	Detector 28
Presence	Northbound Bridge Through Lane 2	3	AutoScope 1 - Switch 7 - LED 5	Rack 3 - Detector 13	Detector 29	Detector 29
Presence	Northbound Bridge Through Lane 3	3	AutoScope 1 - Switch 7 - LED 6	Rack 3 - Detector 14	Detector 30	Detector 30
Presence	Northbound Bridge Left Turn Pocket	3	AutoScope 1 - Switch 7 - LED 7	Rack 3 - Detector 15	Detector 31	Detector 31
Passage	Westbound Offramp	2	AutoScope 1 - Switch 7 - LED 8	Rack 3 - Detector 16	Detector 32	Detector 32
Presence	Northbound Bridge Left Turn Pocket		Local Loop - Direct Connect	Rack 1 - Detector 1	Detector 33	
Presence	Westbound Offramp Right Turn Pocket	2	Local Loop - Direct Connect	Rack 1 - Detector 2	Detector 34	Detector 34
Presence	Westbound Offramp Middle Lane	2	Local Loop - Direct Connect	Rack 1 - Detector 3	Detector 35	Detector 35
Presence	Westbound Offramp Left Turn Pocket	2	Local Loop - Direct Connect	Rack 1 - Detector 4	Detector 36	Detector 36
Presence	Southbound Bridge Left Turn Pocket		Local Loop - Direct Connect	Rack 1 - Detector 5	Detector 37	
Presence	Eastbound Offramp Left Turn Pocket	5	Local Loop - Direct Connect	Rack 1 - Detector 6	Detector 38	Detector 38
Presence	Eastbound Offramp Middle Lane	5	Local Loop - Direct Connect	Rack 1 - Detector 7	Detector 39	Detector 39
Presence	Eastbound Offramp Right Turn Pocket	5	Local Loop - Direct Connect	Rack 1 - Detector 8	Detector 40	Detector 40
Passage	Southbound Upstream Through Lane 1	1	2070 - Port 1	Peer 1 - Detector 1	Peer 1 - 1	Detector 91
Passage	Southbound Upstream Through Lane 2	1	2070 - Port 1	Peer 1 - Detector 2	Peer 1 - 2	Detector 92
Passage	Southbound Upstream Through Lane 3	1	2070 - Port 1	Peer 1 - Detector 3	Peer 1 - 3	Detector 93
Passage	Northbound Upstream Through Lane 3	4	2070 - Port 1	Peer 4 - Detector 4	Peer 4 - 4	Detector 97
Passage	Northbound Upstream Through Lane 2	4	2070 - Port 1	Peer 4 - Detector 5	Peer 4 - 5	Detector 98
Passage	Northbound Upstream Through Lane 1	4	2070 - Port 1	Peer 4 - Detector 6	Peer 4 - 6	Detector 99

4.2 Integration of RHODES within Tempe TOC

With the hardware issues more or less resolved, the research team was now at the point where the Econolite controller could be replaced with an Eagle 2070 and have it control the interchange using the *NextPhase* traffic control software to mimic the functionality of the Econolite. Furthermore, RHODES could now receive all local detector actuations, as well as the signal indications, run its optimization routines and issue signal requests to the cabinet hardware. However, RHODES was not quite ready to control the interchange. In addition to the local detector actuations from the interchange (detectors 1 through 40 on Figure 20), the implementation also called for upstream peer data from the intersections of Rural & Southern and Rural & Embassy Suites (detectors 91-93 and 97-99 on Figure 20). This data was required to provide RHODES with the ability to predict future vehicle arrivals at the north and southbound approaches to the interchange in order to determine an optimal signal phasing for the next several seconds (refer to the discussion in Section 2.3).

As the City of Tempe did not have any upstream passage detection capability on the north and southbound approaches to the interchange, it was decided to add this capability in the following way. First, the northbound-facing camera of the Autoscope system currently in place, but unused, at the intersection of Rural & Southern was turned 180 degrees and was pointed down at a steep angle, so that it could obtain "farside" (after the intersection) detections for the traffic that would be arriving from the north of the interchange. Next, the City of Tempe installed a Remote Traffic Microwave Sensor (RTMS) on the farside of the northbound approach of Rural & Embassy Suites to provide detection data for the traffic that would be arriving from the south of the interchange.

Once the detection equipment was in place, a way to communicate the detector actuations to RHODES was needed. To provide this capability, the RHODES research team requested that Computran Systems Corporation, through the City of Tempe, make a small modification to its Metropolitan Traffic Control System (MTCS), which Tempe uses to monitor all of its signalized intersections. Computran, through a subcontract with UA, added the ability to obtain second-by-second signal and detector data from a number of intersections surrounding the U.S. 60 & Rural interchange, including the two of interest, and communicating this data back to the MTCS at Tempe's Traffic Operations Center (TOC) where it could be accessed. Next, the specific data RHODES required from within this new data stream needed to be isolated and, subsequently, sent to RHODES, within the 2070 at the interchange. Towards this end, it was decided to create a software program that would read in the output from the MTCS modification, and filter out the specific data desired (i.e., detections from the two intersections of interest). This program would then repackage this data and transmit it to RHODES over a phone line between the TOC and the interchange, using an external modem at each end. Upon arrival at the interchange, *NextPhase* would read the data, via

an available serial port on the back of the 2070, where it would then be passed on to RHODES each second via an internal communications channel over the VME bus. This configuration is illustrated in Figure 21.

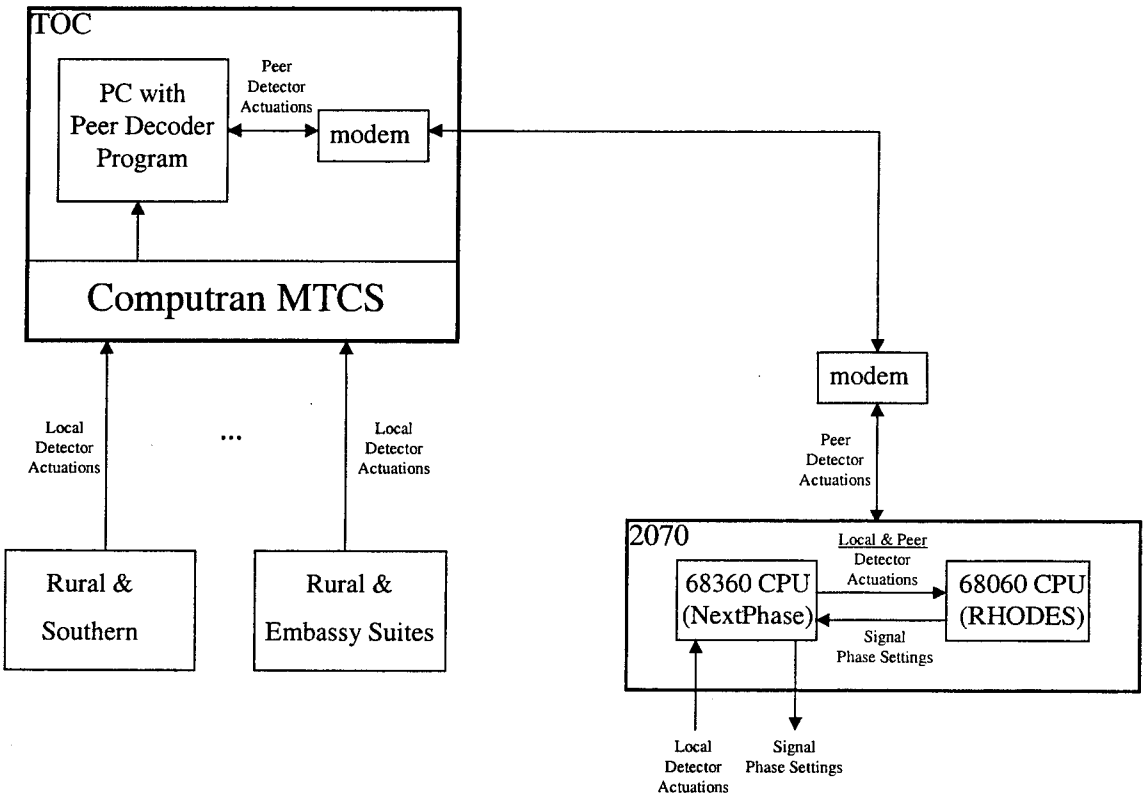


Figure 21 - Physical configuration of the Peer Communications Network

To provide this functionality, a personal computer (PC) was located within the computer room of the Tempe TOC in order to have direct access to the output from the Computran system via a serial connection. Using the Windows™ NT operating system, a service called *ITMSComm* was installed on the PC. This service is used by Gardner Transportation Systems (GTS) to provide communication between its Advanced Traffic Management System, *icons*™, which was also installed on the PC, and each intersection within its network (in this case, just U.S. 60 & Rural). Using this service allowed the use of the communication functionality already available between *NextPhase* and *ITMSComm*. The *Peer Decoder* program, developed by GTS, filtered out the desired data from the Computran System and sent it out using one of the PC's serial ports connected to an external modem, over a dedicated phone circuit between the TOC and the interchange cabinet. Upon arriving at the traffic cabinet, the data was received by *NextPhase* through an external modem that was connected to a serial port on the back of the 2070. *NextPhase*, in addition to its other tasks, monitors this serial port; upon receiving data on this link, it packages it up into a **DetectorMsg** for transmission to RHODES via the VME bus. To differentiate between the local **DetectorMsg** and the one containing peer data, an address field within the message was used to prevent confusion.

With this communications path in place, the research team made further use of it by having *NextPhase* send a RHODES **status message** back to the TOC each second (note the bi-directional arrows in Figure 21). This message travels the same path back to the PC located at the TOC, where it is displayed on the PC's monitor by the *Peer Decoder* program to provide real-time status information that is specific to RHODES. (The details of what is included in this RHODES status message will be discussed in the next section.) In addition, *NextPhase* sends its standard status message back to *ITMSComm* each second, which is then used to update the intersection's status within *icons*™, showing the current signal settings. An additional benefit of having an *icons*™ PC available in the TOC was the capability to remotely change the current traffic plan being used by *NextPhase* at the intersection. As RHODES was only operational when the current traffic plan ran in the "Adaptive" mode of *NextPhase*, this functionality effectively provided the ability to turn RHODES "ON" or "OFF" from the Tempe TOC. (This feature was not used during the field test, except to verify that RHODES worked during the experiment.)

With this communication configuration, RHODES now had the capability to receive upstream detector actuations critical for prediction of arrivals to the interchange. In addition, real-time monitoring of the control status was now possible. Because this peer data is critical to the effective operation of RHODES, the research team decided that the absence of this data, due to a communications failure, should also be detectable by RHODES so that in the event this data stream is lost, RHODES could automatically switch to "STANDBY" mode until upstream peer data is once again available. In order to do this, the arrival of data from each peer was tracked and, in the case where no data was received from a peer for a period of 10 seconds, the status of that peer would be indicated as FAULT and RHODES would be forced to change to STANDBY mode. This would prevent RHODES from issuing signal phase settings that may be inconsistent with the current traffic conditions, a situation that would arise if RHODES lost its ability to predict arrivals from peer intersections.

4.3 Bench Testing of Field Test Setup

Figure 22 summarizes the overall field configuration. With all hardware and software issues resolved, the research team turned its attention towards making the final adjustments necessary to properly configure RHODES at the interchange test site. First, the team verified the proper operation of all equipment, including loop detectors, Autoscope cameras, RTMS detectors, the external modems and the 2070 itself.

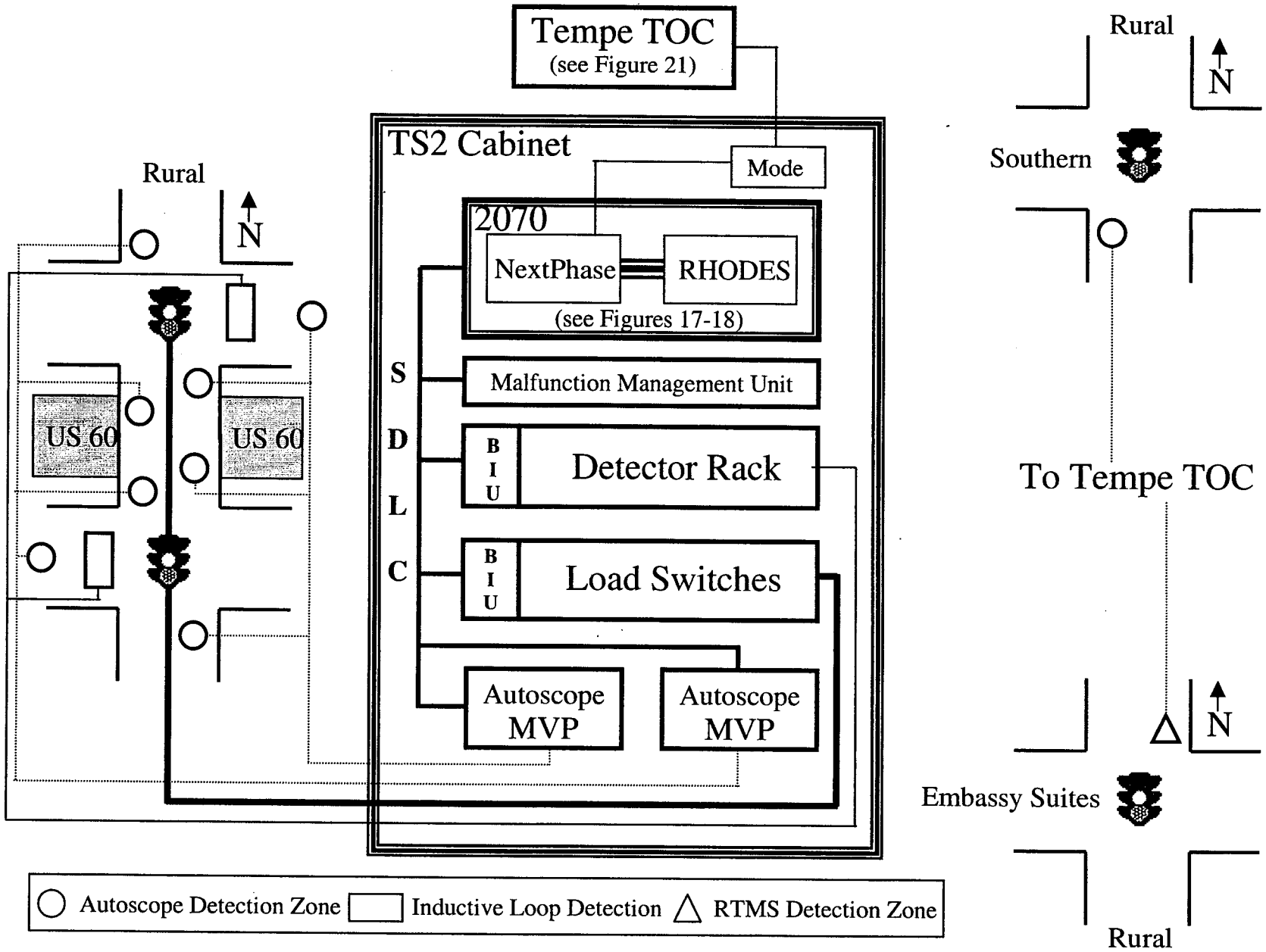


Figure 22 – RHODES Field Configuration

(A representative from the City of Tempe Traffic Signal Division was present at the traffic cabinet at all times during the operation of RHODES or when any hardware/software configurations were adjusted.)

Then, the team observed the system while in operation, in case any problems arose, so that any new issues could be dealt with quickly. In addition, the team fine-tuned some parameters used by RHODES, such as (1) travel times between upstream detectors and downstream queues, (2) queue discharge rates and (3) turning proportions, so that they were reasonable and reflected the experience of the vehicles passing through the interchange.

To aid in debugging and bench testing, the research team developed a static display tool, which proved to be extremely helpful, that displayed all of the data received by RHODES, along with its outputs and various statistics to track its performance and help identify possible problems (see Figure 23). Using a telnet session between a laptop PC and the Ethernet port of the 2070, the user could obtain a real-time representation of the intersection from the point of view of RHODES. This was very helpful when diagnosing problems, as it allowed the research team to isolate where any problem was occurring by comparing the cabinet equipment LEDs, the *NextPhase* output screen, actual traffic conditions and this display to identify discrepancies. Using this tool, it was a simple matter to verify that all detectors were functioning properly; that is, when a vehicle passed over either an inductive loop or virtual detector, one could easily check if RHODES has received an actuation. If it did not, the cause could be investigated immediately. Similarly, the research team was able to confirm the correct operations of the *Peer Decoder* program and the associated communications link by observing upstream traffic and matching the observations with the peer detector actuations received. Also, being able to visually compare the size of the actual queues and those estimated by RHODES, by quickly glancing at a meaningful onscreen display, made the process of fine-tuning parameters less tedious and less prone to error. In addition, some of the data shown in the RHODES display tool had also been made available on a *NextPhase* screen accessible via the 2070 front panel, in particular the current queue estimates, the current RHODES mode and the status of each peer intersection. Similarly, this data was transferred to the Tempe TOC via the RHODES status message for remote monitoring purposes.

During this bench test period, adjustments were made to almost all variable parameters in an attempt to ensure that they reflected actual conditions at the interchange. When the research team was satisfied that all subsystems appeared to be working well, the City of Tempe was requested to consider making RHODES operational. Since Tempe was satisfied with the system's performance thus far, it was ready to perform some additional tests of its own by leaving the intersection under unattended RHODES control for extended periods of time. This resulted in no additional reported problems other than some interesting observations concerning some differences between RHODES control and the existing method that will be

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                    RHODES 2.00a
          Real-Time Adaptive Signal Control System
        ATLAS Research Center, University of Arizona
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  19:18:36              US60 & Rural Avenue            08/03/2000
                          Tempe,  Arizona

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                      | -   -   - |            |
                      |           |            |  Peer   12345678
  SB Time: 00:00:30   |           |            | Status: . .
                      |           |            |
  OL Time: 00:00:00   |    1   6  |            |  Ped    12345678
                      |  SBR SBT  |            | Calls:
                      | X X - X - |            |
  ------------------+                          +------------------
                                                X WBR  1
    -         -                                 -              -
                                                - WBL  0
  ------------------+                          +------------------
                      | - -   - - | - X   X X |
  Current Mode:  SB   |           | NBrL NBrT |  Current Phase:  26
                      |           |   0    8  |
  Desired Mode:  OL   |           |           |  Desired Phase:  26
                      |           |           |
  Current Plan:   1   |           |           |  Signal  Stage: Grn
                      |   5    0  |           |
  Xition  Time:  32   | SBrT SBrL |           |  Elapsed Stage:  11
                      | X X   X - | - -   - - |
  ------------------+                          +------------------
            1 EBL  X
    -               -                                -          -
            0 EBR  -
  ------------------+                          +------------------
                      |           | - - - - - |
  Ph:  15 26 48 Cyc   |           |  NBT NBR  |  COP:  CPU  Intrvl
                      |           |   0   0   |
  Cur: -- 11 -- ---   |           |           |  Cur: -----   --
  Min: -- 10 -- ---   |           |           |  Min: -----   --
  Avg: -- 10 -- ---   |           |           |  Avg: -----   --
  Max: -- 11 -- ---   |           |           |  Max: -----   --
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 Q  SBT SBR | WBL WBR | NBrL NBrT | NBT NBR | EBL EBR | SBrL SBrT
Avg:  0   0 |   0   0 |   0    0  |   0   0 |  0   0  |  0    0
Max:  6   1 |   0   1 |   0    8  |   0   0 |  1   0  |  0    5

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 RHODES MESSAGES:
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Figure 23 – Screen Snapshot of the RHODES Display Tool

discussed later in Section 5. At this point, no further modifications were made and preparations were made for the evaluation period to commence.

4.4 Procedure to Turn RHODES On/Off

The RHODES implementation at the US60 and Rural Road is a complex system, and the process of implementing it has not been a simple one. As a result, the process of turning RHODES "ON" or "OFF" is more than just a matter of flipping a switch. Between the extraneous hardware/software elements involved and the many checks that must be performed, it was felt that the research team should provide a detailed procedure listing the steps to be followed when initiating/ceasing RHODES control at the interchange. In addition, the development of these procedures ensured that all parties were clear on the function of each component, how it would affect the overall system and how to respond should a problem arise. The complete set of procedures for initiating/ceasing RHODES control at the U.S. 60 & Rural Interchange is provided in Appendix 2.

5. PERFORMANCE OF TEMPE FIELD TEST

5.1 Field Data Collection

The University of Arizona issued a subcontract to TASK Engineering Company Inc. to collect data during the field test and evaluate the traffic performance of RHODES. TASK was chosen as a third-party evaluator to decrease any bias that ADOT (the research sponsor) or the RHODES research team (the developer of the traffic control algorithms) might interject if one of them conducted the evaluation. TASK provided a draft report in December 2000, which was subsequently updated in June 2001 [Howell, 2001]. Some of the material provided in this section is from the draft report, where verbatim material is given quoted italics.

Data was collected during two Thursdays, one week apart, in September 2000. During those days the interchange was run with RHODES in control – the *ON* scenario – for four hours at a time, and, at other times under usual semi-actuated time-of-day control used by Tempe – the *OFF* scenario. The data-collection periods with respective scenarios were as follows:

DATE	7AM-10AM (AM Period)	11 AM-2PM (Midday)	3PM-6PM (PM Period)
September 7, 2000	OFF	ON	OFF
September 14, 2000	ON	OFF	ON.

Much of the data was collected manually using 2- and 3-person teams. The *Highway Capacity Manual* (Transportation Research Board, 1998) describes a method for collecting traffic control delay data in the field. TASK states, "*This consists of teams of 2 persons each collecting queue data on each approach. The queue data is then used to calculate estimated control delay. Since there are 10 lane groups and two through approaches at the traffic interchange (see Figure 24), a team of 6 persons can collect approximately 60 minutes of data on each approach during a 3-hour peak period.*"

TASK reported that the following traffic parameters were calculated:

- Control Delay per vehicle, by lane group
- Control Delay per vehicle for the interchange as a whole
- 95th Percentile queues length in vehicles for each lane group
- Platoon Ratio, for each direction on the arterial
- Total traffic entering the interchange.

TASK states "*Control delay is the total delay to vehicles at a traffic signal, including stopped delay, move-up in queue time, lost time due to acceleration and lost time due to deceleration. Control delay is the best single measure of operations of a signalized intersection*". TASK used procedures from the *Highway Capacity Manual*, which required the collection of the number of cars in queue at designated intervals.

"*Queue lengths for 95th percentile measure the length of a back-up from the intersection. Long queue lengths should be associated with long control delays.*"

"*The platoon ratio is a measure of traffic signal progression. Platoon Ratio is defined by the Highway Capacity Manual chapter on signalized intersections.*"

Traffic counters were used to count total traffic volumes. These were used to compare the ON and OFF scenarios and to validate manually collected data. Figure 24 gives the location where queues and traffic counts were taken.

Since platoon ratio definition is dependent on cycle times, this measure is not reported in this document. Readers interested in this measure and details on procedures for the data collection are referred to the TASK report. TASK's discussion on data collection and the reliability of data is reproduced in Appendix 3.

5.2 Field Test Results

Figures 25 – 30 give the traffic volume data. Note the significant variations in traffic volumes, both with respect to the date and with respect to time of day. Although the data collection was conducted on the same day of the week in an attempt to recreate similar conditions, traffic varied significantly on the two days. TASK provided the 95th percentile queue sizes (i.e., these are exceeded only 5% of the time) as shown in Table 3. Except in a very few instances where the queues are rather large in the ON scenario, there appear to be no systemic differences between the ON and OFF scenarios. However, comparison of queues does not mean much unless some consideration is given to the traffic volumes that generate the queues. In addition, since queue length is highly nonlinear with respect to the arrival rates, small increases in arrival rate could result in large differences in queue lengths – as is the case here where we notice high traffic volumes (see Figures 25 – 30) when there are large queues. This issue becomes clearer when the control delays at various traffic volumes is considered below.

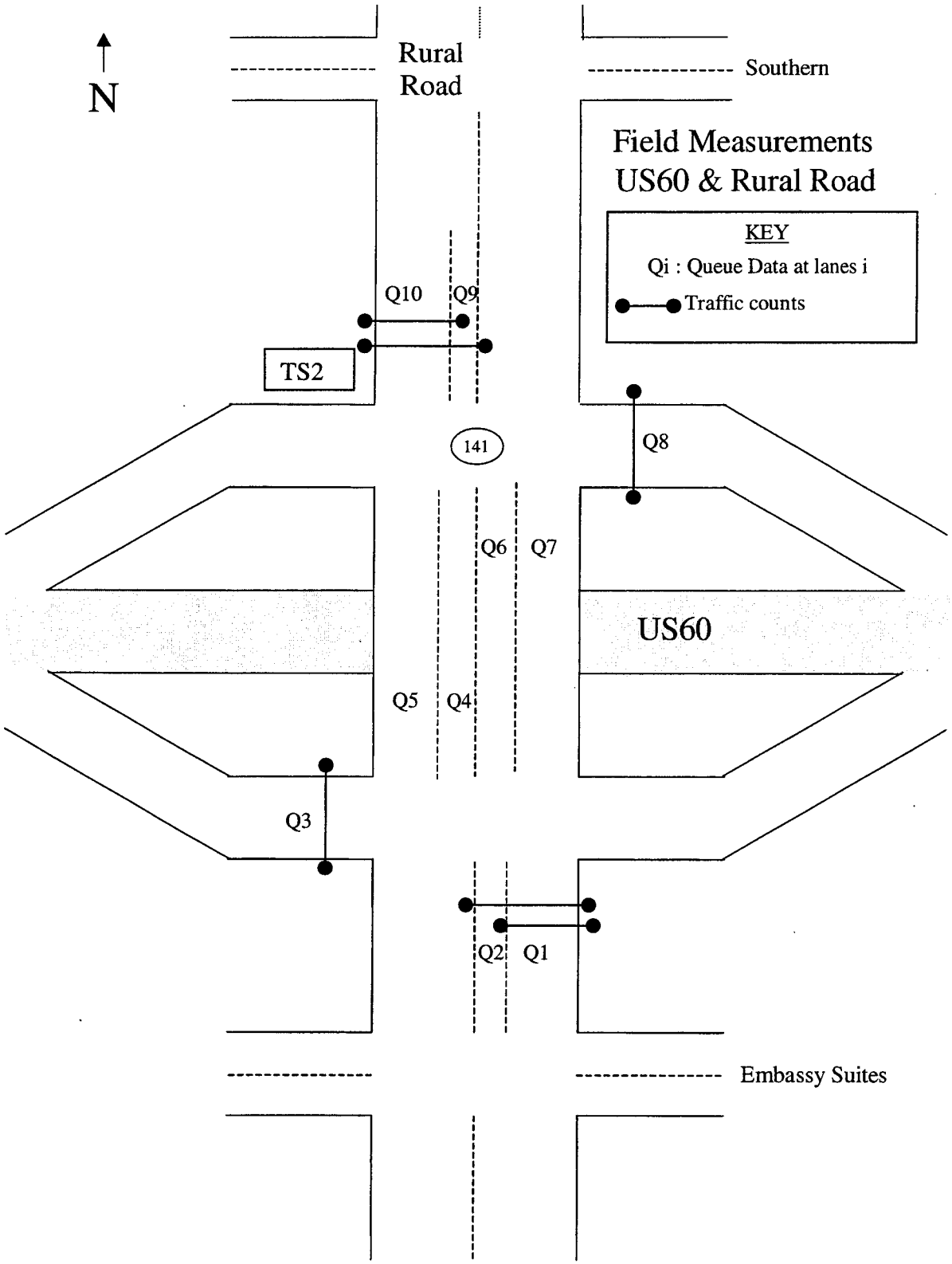

Figure 24 – Lane groups and location of queue data collection

Table 3 - 95th Percentile Queue Sizes (number of vehicles)

Location / 95th Percentile Queues	Q1 NB Thru	Q2 NB LT	Q3 EB Ramp	Q4 SB LT/B	Q5 SB Thru/B	Q6 NB LT/B	Q7 NB Thru/B	Q8 WB Ramp	Q9 SB LT	Q10 SB Thru
AM Period										
ON (9/14)	34.40	4.00	8.00	6.00	6.80	7.00	7.00	16.10	3.00	10.50
OFF (9/7)	32.00	4.00	9.00	7.45	8.00	11.40	9.00	13.00	2.00	8.00
Midday Period										
ON (9/7)	16.65	4.75	9.55	6.50	7.00	9.00	5.00	15.30	4.00	13.15
OFF (9/14)	8.00	3.00	7.00	6.00	8.00	8.00	6.00	15.00	3.00	12.00
PM Period										
ON (9/14)	18.25	4.00	11.00	5.00	10.90	8.00	5.00	21.00	4.00	41.00
OFF (9/7)	9.00	2.30	8.00	8.00	11.00	6.05	5.00	21.00	3.50	29.10

Key: NB: North Bound; EB: East Bound; SB: South Bound; WB: West Bound; LT: Left Turn; B: Bridge

TASK provided the delay per vehicle results given in Table 4. Differences of more than 10% between the OFF and the ON scenarios are given in bold. In the last column, the average delay is computed as the weighted average for all the approaches, where the weights are proportional to the traffic volumes. Hence, the last column corresponds to the average delay per vehicle for all the vehicles moving through the intersection. Therefore, although it appears that during the midday periods the OFF scenario has smaller delays, when vehicle volumes are accounted for (in the last column) the differences between the average delays are not significant. (Also, the midday OFF scenario data may have a systematic bias as will be argued below when we examine 15-minute data.)

Table 4 - Control Delay per Vehicle (seconds)

Location / Control Delay per Vehicle	Q1 NB Thru	Q2 NB LT	Q3 EB Ramp	Q4 SB LT/B	Q5 SB Thru/B	Q6 NB LT/B	Q7 NB Thru/B	Q8 WB Ramp	Q9 SB LT	Q10 SB Thru	Average (for all vehicles)
AM Period											
ON (9/14)	**18.37**	18.22	32.87	36.68	13.80	**26.47**	12.62	52.00	22.24	20.77	36.40
OFF (9/7)	21.04	19.35	32.75	37.99	14.66	39.94	13.17	**40.75**	**18.25**	**17.08**	34.74
Midday Period											
ON (9/7)	17.12	21.93	31.05	32.80	14.27	36.23	14.19	45.47	22.01	**16.83**	36.07
OFF (9/14)	**14.01**	**15.90**	**24.88**	30.04	**12.93**	**32.15**	**12.88**	**38.52**	20.43	21.23	36.36
PM Period											
ON (9/14)	15.84	20.47	31.35	**24.29**	13.44	33.64	12.74	61.34	19.93	28.77	41.50
OFF (9/7)	14.31	**15.91**	**26.03**	31.81	13.94	32.25	13.25	**45.03**	19.09	**22.76**	35.81

Key: NB: North Bound; EB: East Bound; SB: South Bound; WB: West Bound; LT: Left Turn; B: Bridge

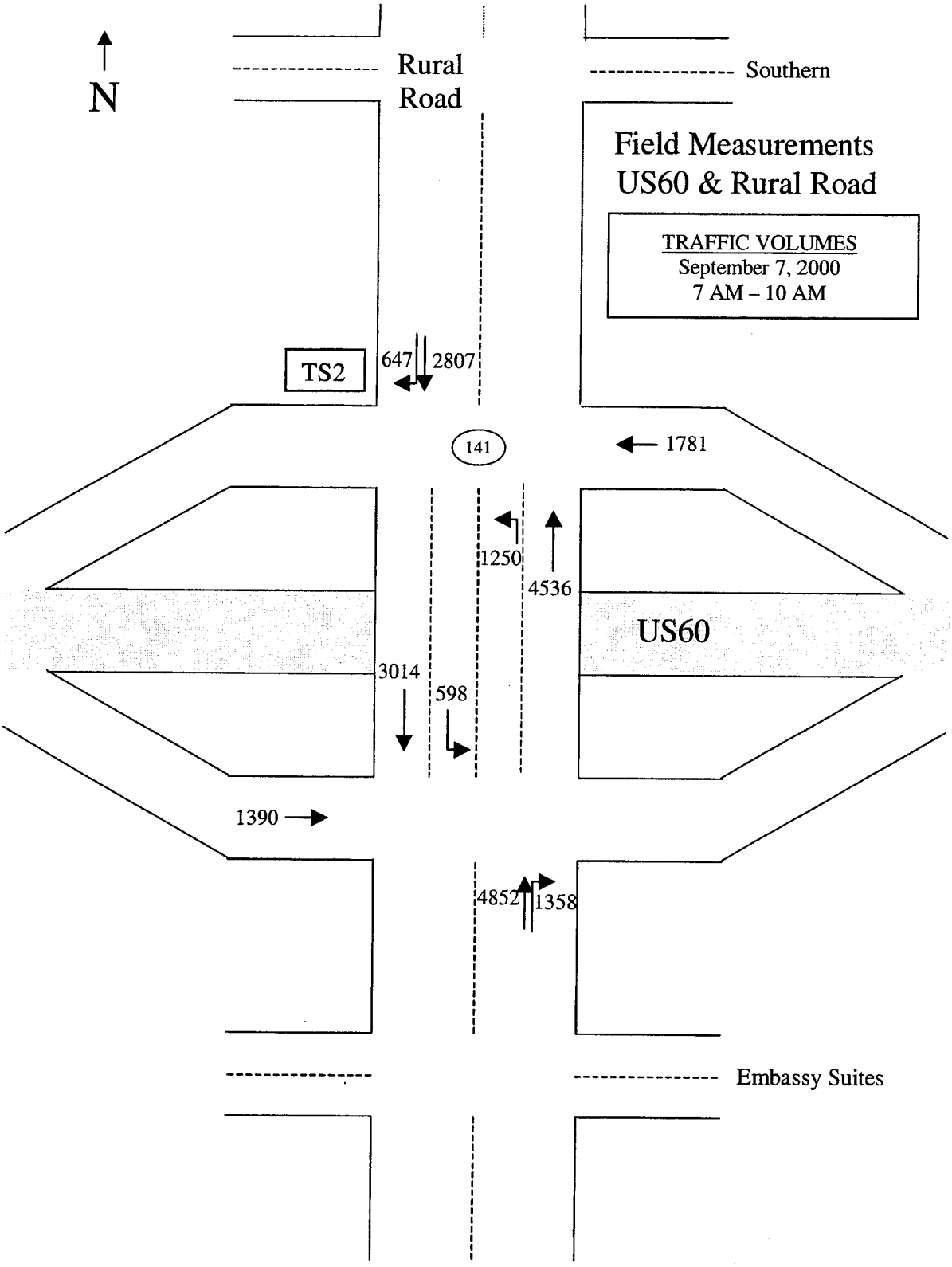

Figure 25 – September 7, 2000, 7AM-10AM, Total Traffic Volumes (RHODES OFF)

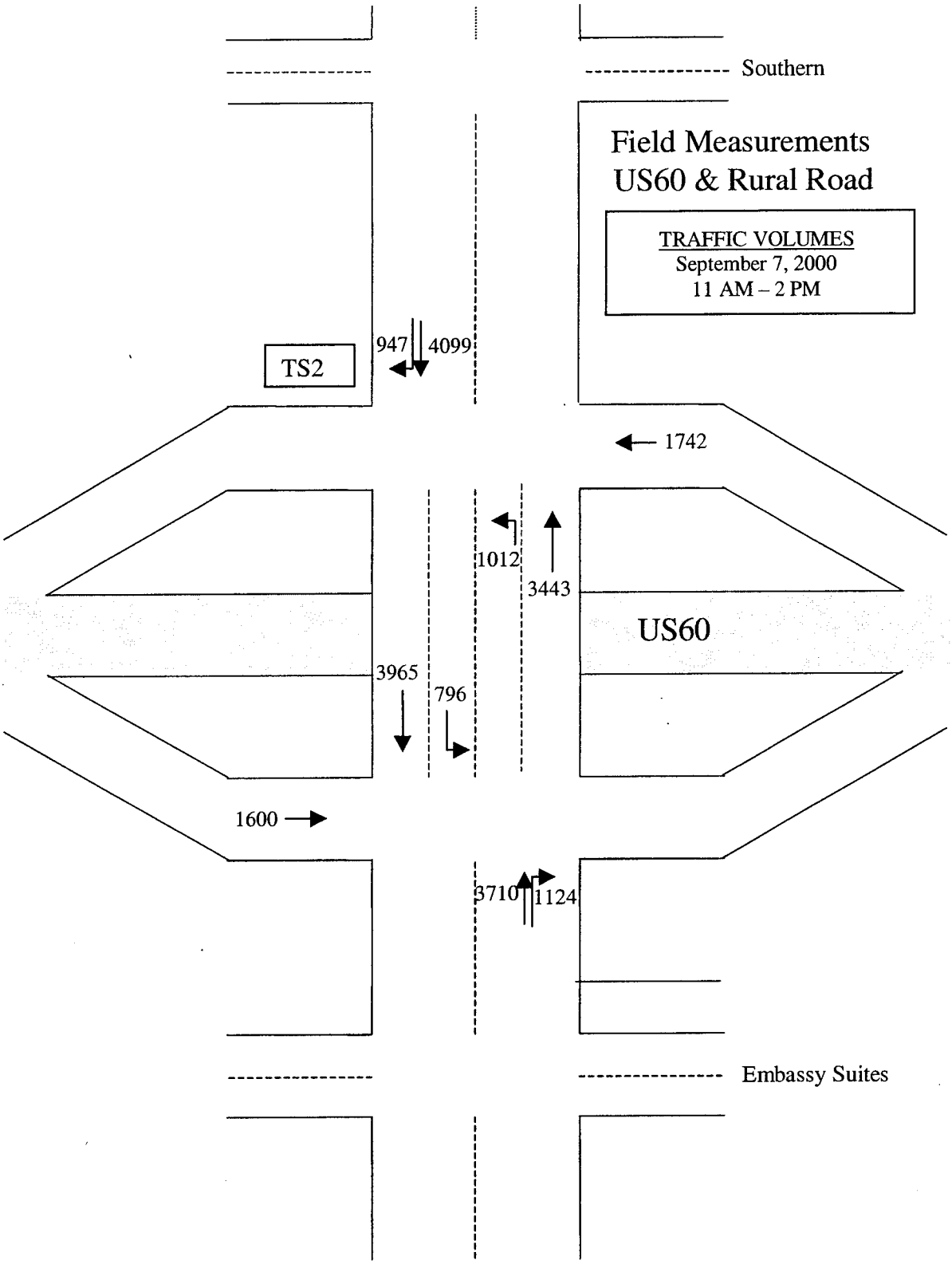

Figure 26 – September 7, 2000, 11AM-2PM, Total Traffic Volumes (RHODES ON)

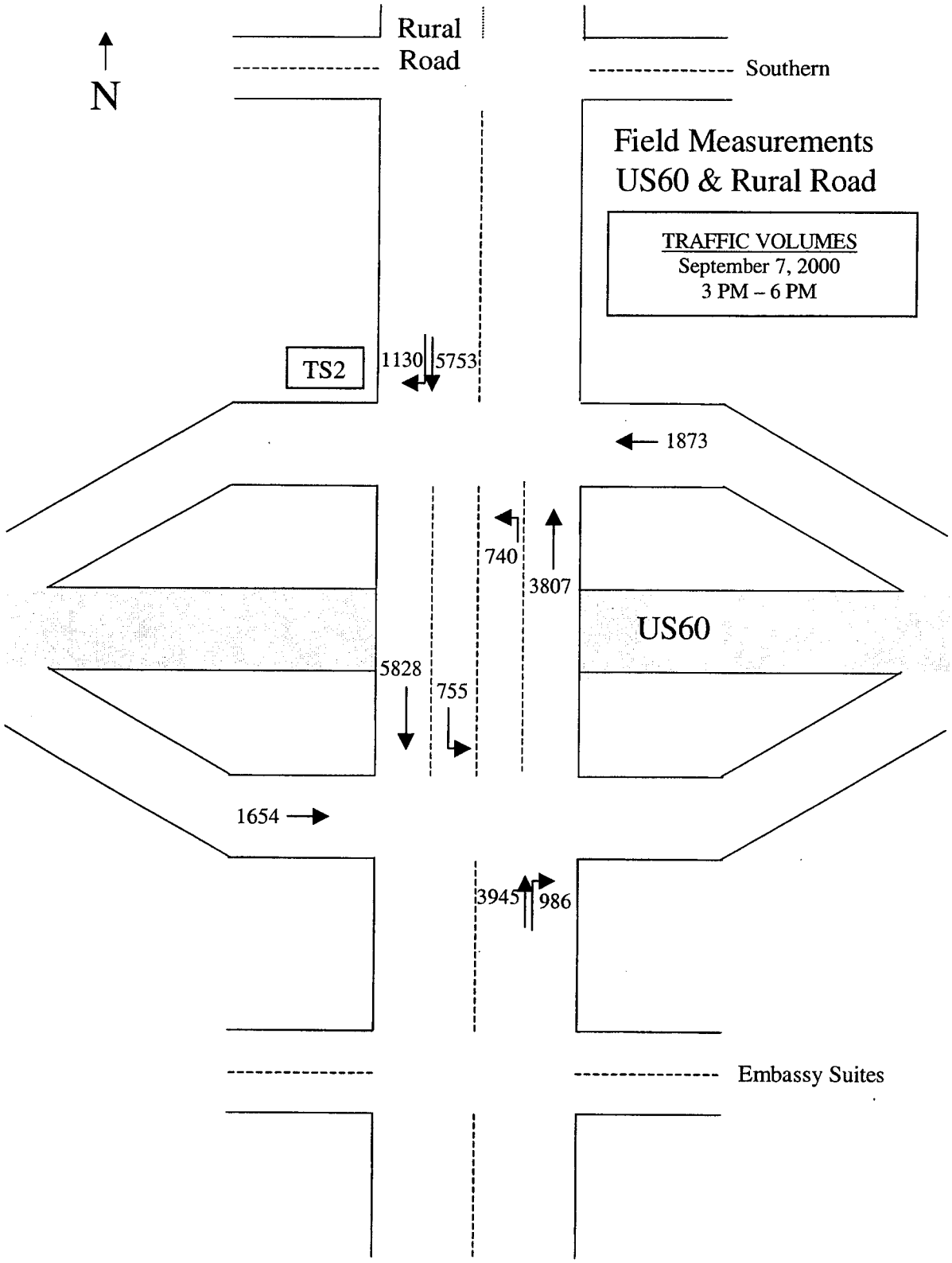

Figure 27 – September 7, 2000, 3PM-6PM, Total Traffic Volumes (RHODES OFF)

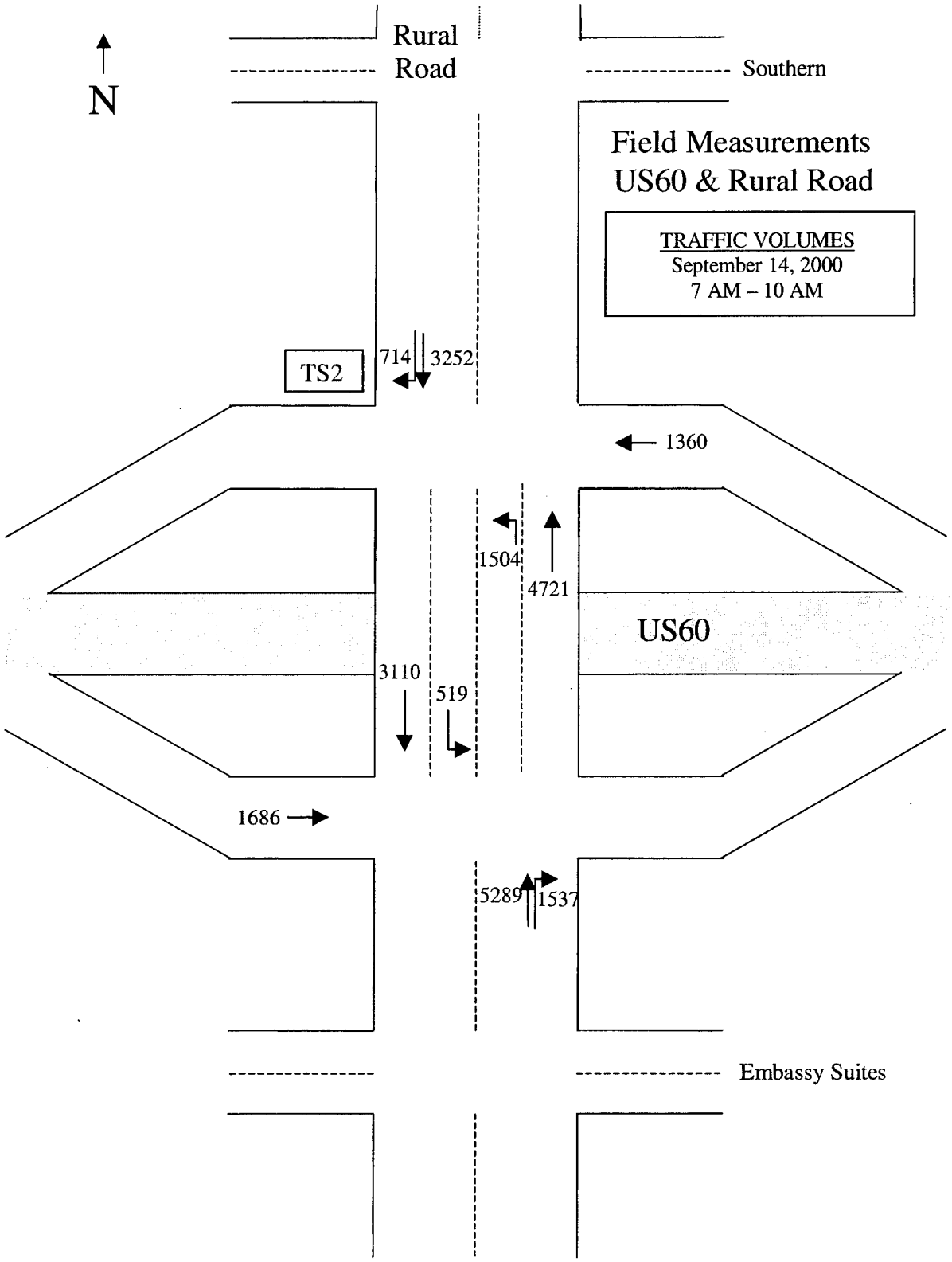

Figure 28 – September 14, 2000, 7AM-10AM, Total Traffic Volumes (RHODES ON)

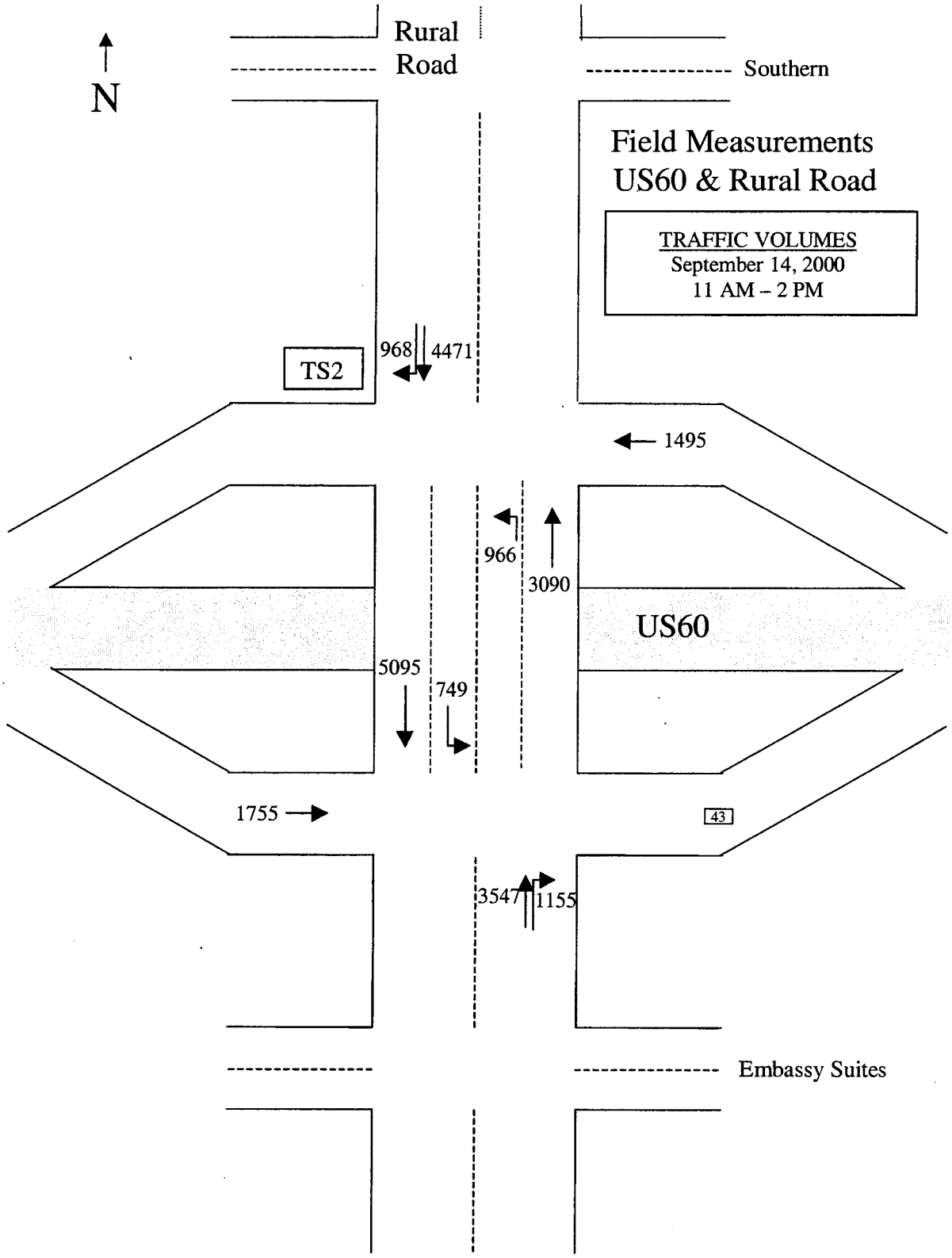

Figure 29 – September 14, 2000, 11AM-2PM, Total Traffic Volumes (RHODES OFF)

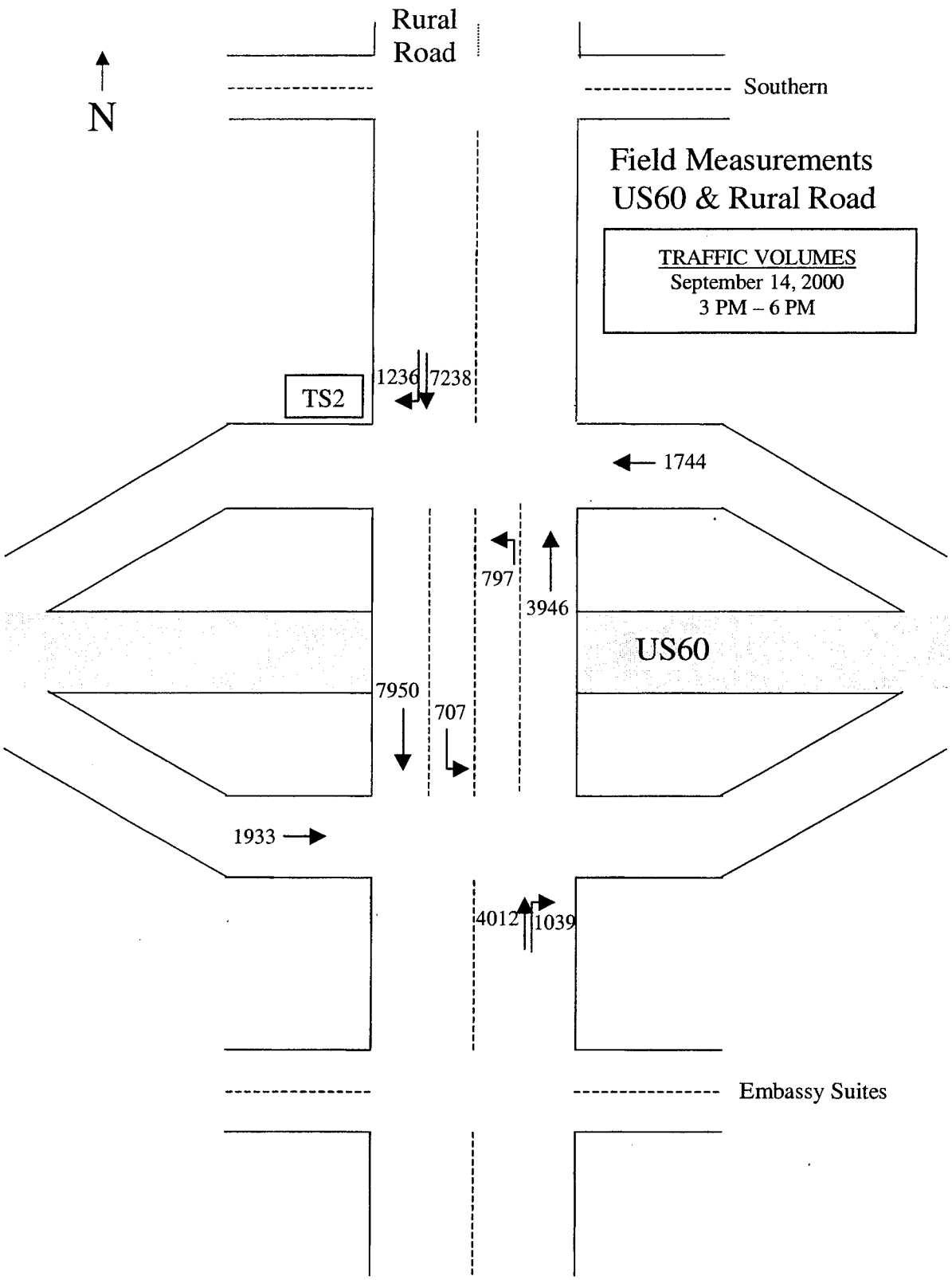

Figure 30 – September 14, 2000, 3PM-6PM, Total Traffic Volumes (RHODES ON)

The research team requested that TASK also provide 15-minute data on traffic volumes and delays. TASK was able to provide this information for the middle hour of each data collection period (i.e., 8AM-9AM, 12PM-1PM and 4PM-5PM). Tables 5 and 6 give this data. Inspection of the data shows that regardless if RHODES is OFF or ON, the delays for "straight-through" traffic are in a different "ball park" than the delays for the "left-turn" traffic. A quick plot of delays versus volume confirmed this. Subsequently, the research team developed Figures 31 and 32 for accurate plots of delay-versus-volume for the through traffic and the left-turn traffic.

Table 5 - OFF scenario: 15-minute Control Delay (s/veh.) and Volumes (veh/15 min.)

Location	Q4			Q5			Q6			Q7		
	South-Bound Left-turn on Bridge			South-Bound Through on Bridge			North-Bound Left-turn on Bridge			North-Bound Through on Bridge		
Time	AM	Midday	PM	AM	Midday	PM	AM	Midday	PM	AM	Midday	PM
Delay (s)	NA	19.21	41.02	NA	14.55	14.15	NA	30.68	30.29	NA	12.98	12.48
Volumes	NA	152	91	NA	301	447	NA	83	50	NA	306	380
Delay (s)	NA	16.97	22.05	NA	12.50	14.57	NA	34.42	20.67	NA	13.18	13.22
Volumes	NA	231	45	NA	496	458	NA	71	43	NA	288	359
Delay (s)	NA	16.74	25.35	NA	12.52	13.85	NA	34.26	32.50	NA	12.95	12.74
Volumes	NA	192	56	NA	437	506	NA	96	61	NA	281	312
Delay (s)	NA	20.42	35.41	NA	12.85	13.34	NA	27.35	47.69	NA	12.45	14.86
Volumes	NA	134	60	NA	603	563	NA	73	54	NA	322	300

(NA : Data not available because at that particular AM period data was not collected in 15 min. periods.)

Table 6 - ON scenario: 15-minute Control Delay (s/veh.) and Volumes (veh/15 min.)

Location	Q4			Q5			Q6			Q7		
	South-Bound Left-turn on Bridge			South-Bound Through on Bridge			North-Bound Left-turn on Bridge			North-Bound Through on Bridge		
Time	AM	Midday	PM	AM	Midday	PM	AM	Midday	PM	AM	Midday	PM
Delay (s)	21.62	55.16	28.76	12.89	15.19	13.96	23.05	36.9	35.47	13.38	13.63	12.58
Volumes	39	62	50	280	401	457	108	75	51	526	312	396
Delay (s)	48.94	20.64	23.14	15.59	13.35	13.03	28.3	25.94	35.42	11.89	13.57	12.97
Volumes	51	63	65	257	338	491	95	81	62	478	280	353
Delay (s)	46.76	36.85	20.2	13.26	14.91	13.59	25.99	40.34	34.27	12.14	14.04	12.23
Volumes	53	52	45	243	326	470	103	87	73	509	302	332
Delay (s)	24.55	24.81	22.49	13.52	13.13	13.33	20.55	34.6	24.85	13.06	15.57	13.17
Volumes	46	69	63	199	348	568	74	85	47	402	293	352

By and large, the plots for the "through" traffic show very little difference between the OFF and the ON scenarios. Given the fact that the average delays at the intersections were between 12s and 16s for all the volumes up to 2400 vehicles/hr, it may be imputed that:

- the through-capacity for both the semi-actuated and RHODES controls was high enough so that the intersections are operating in the "flat" part of the delay versus volume curves for queuing systems, and
- RHODES performed as well as Tempe's current finely-tuned semi-actuated coordinated control

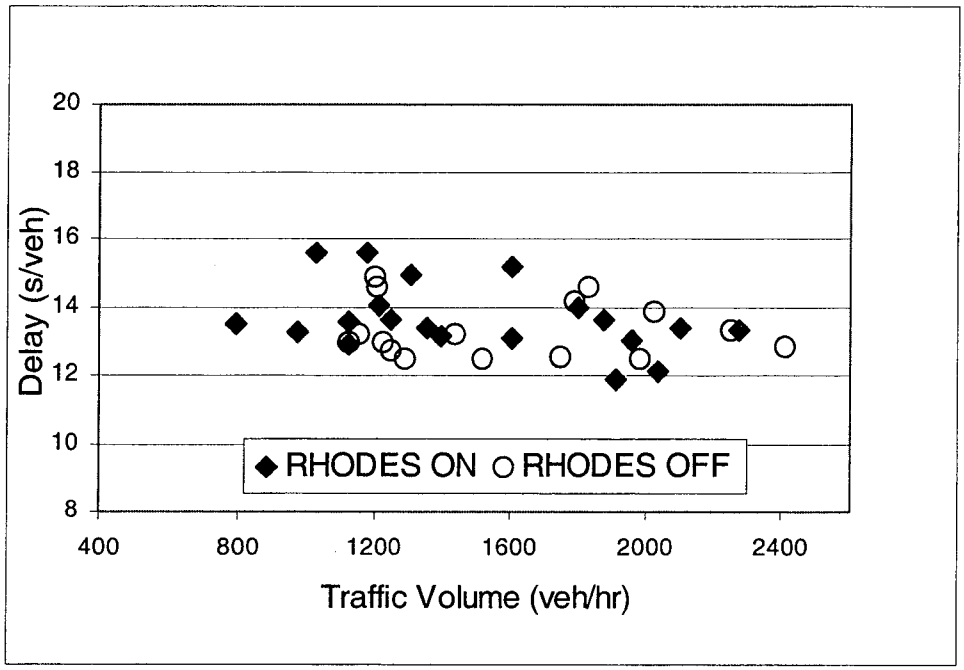

Figure 31 – Through movement delays

These plots cannot be directly compared with the simulation results of Figure 13. In this case the delays are for the vehicles at each intersection whereas in the simulation results the delays are for "trips" where the cumulative stopped delay of each vehicle that goes through the interchange (including the on-ramps delays if any) is considered. Nonetheless, if does show that the trip delays in the simulations were around the numbers that would be expected from the intersection delays observed in the field. For example, the average delay for straight-through trips for the two intersections is the sum of the delays at each intersection, and this was between 24s and 32s in the field data, approximately the delays obtained in the simulation results.)

The left-turn data indicates larger average delays with smaller traffic volumes. This is to be expected since the queue discharge rate for left turning vehicles is slower than the straight-through vehicles (and hence queue "service time" is larger). If one examines the data for the southbound midday period (on September 14th) with RHODES OFF, substantially lower delays for very large volumes will be noticed. The fact that all of these "outlying" data points were taken at the same time and are significantly different

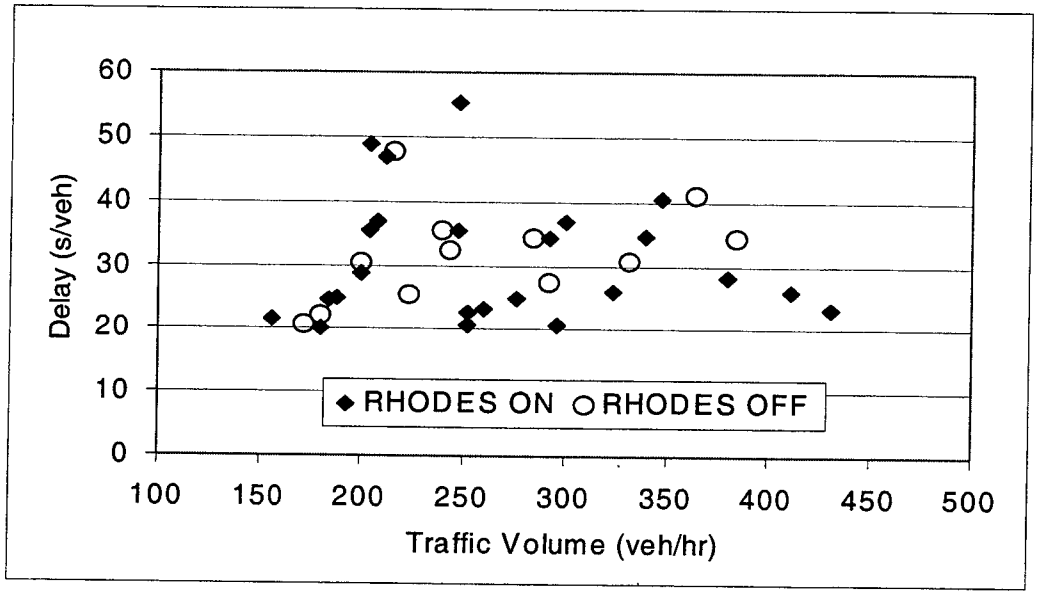

Figure 32 – Left-turn movement delays

than the rest, even with the other OFF scenario data, makes them suspect. (Perhaps the data gatherers during this time had different training or were distracted.) Thus, this data are outliers and most probably in error. Figure 32 gives the plot of left-turn delays (the outliers are not included; they would be outside the figure with volumes of over 500 vehicles/hr. and delays of 20s and less). Again, there does not appear to be significant differences between the ON and OFF scenarios, except that it could be argued (by simply looking at Figure 32) that the ON scenario (RHODES) may have slightly better traffic performance than the OFF scenario (semi-actuated control) for volumes at the higher end (350-450 left-turn-vehicles per hour).

5.3 Further Observations on the Field Test

Considering the above results obtained in the field, it may be stated that for the periods that data was collected with RHODES enabled, RHODES performed as well as the current well-tuned semi-actuated control. However, RHODES was run with only <u>one</u> set of parameters, which did not vary with time-of-day, unlike for the current approach. In addition, RHODES did not require the collection of a large amount of data and the running of an off-line optimization model, such as TRANSYT-7F, to determine optimal cycle times, offsets and splits for different times of day. With RHODES, the matching of signal phasing to detected traffic was done "on-the-fly", in real time. Also, RHODES was constrained by City of Tempe's operational requirements that did not allow (1) phase skipping and (2) adjustment of minimum/maximum green times; it is likely that relaxation of these constraints would have improved RHODES performance.

RHODES works better when it has larger prediction time horizons. When the prediction horizon is long, more phase duration alternatives are evaluated in the CAPRI optimizations, thereby giving, in general, a better (calculated) objective function value. In this field test, except for those from Southern/Rural, the count measurements were from detectors that were 7-10 seconds upstream, from the two off-ramps and from Embassy/Rural. This allowed RHODES to obtain good predictions for only a time horizon of 7-10 seconds, the remaining part of the decision horizon assumed average arrival streams. The research team believes that if either more detections from the neighborhood were available or if the RHODES prediction model was enhanced with a better representation of "arrival streams" then it is possible that RHODES performance would be improved further.

The RHODES model implemented in Tempe assumed fixed turning ratios, queue-discharge rates, and travel times from upstream detectors. Current research into future RHODES enhancements include "on-line" estimation of these parameters – these modifications would have improved RHODES' performance further.

In the original design of RHODES and in the simulation evaluations, queues at ramps were also considered in setting phase durations. If one considers the delays at the signals as well as at the ramp meters, then, as the simulations show, the RHODES system should do better for <u>all</u> traffic using the interchange. Unfortunately, the detections from the on-ramps were not available at the 2070 Controller that was controlling the interchange. If they were available and the delays at the ramp meters were measured, then it would have been possible to evaluate the types of results as per the simulations.

It is useful to note two other visual observations. When RHODES was controlling the interchange but no data was being collected, Tempe Transportation Department on-site personnel and the RHODES team noticed the following:

- On one occasion, a single lane at the bridge was blocked off for some ADOT maintenance work. RHODES continued to adapt and control traffic with no apparent degradation in traffic flow.
- On one occasion an emergency vehicle pre-empt went into effect. The Tempe Transportation Department on-site personnel felt that RHODES recovered faster from the pre-empt transients than the current system.

Although the above observations were not during heavy traffic and may only be considered "anecdotal", it is reassuring to note that the Tempe Transportation Department on-site personnel expressed satisfaction

with RHODES' performance, especially given that this was its first operational test and many obstacles on the hardware/software integration had to be overcome.

Based on the evaluation of the data gathered, and the observations of the Tempe Transportation Department on-site personnel, the research team concludes that RHODES is a promising approach for real-time responsive traffic signal control. This is further attested by TASK in their statement "*The RHODES program was not able to improve the traffic performance at the field survey site, over and above the traffic level of service resulting from a well executed timing plan by traditional methods. Nevertheless, RHODES shows promise of increasing the performance of traffic signals.... In addition RHODES ability to quickly generate new traffic control plans in response to changing conditions is a potential advantage.*"

6. OVERALL EVALUATION

In this section of the report, an overall evaluation of the RHODES-ITMS system is provided based on the field test results described in Section 5, as well as other observations and considerations.

In considering the implementation of any traffic control system, one must evaluate (1) its potential benefits and (2) the marginal costs of implementing the system to achieve these benefits. The benefits for a traffic control system could include (i) an improvement in traffic performance, (ii) an improvement in the transportation of people, goods and services, (iii) an increase in safety, (iv) a decrease in energy consumption, and (v) an improvement in air quality. Though not quantitatively shown in all cases, it will be argued below that RHODES has the potential to positively influence all the above benefits.

On the other hand, these benefits do not come freely. RHODES requires additional technological systems (i) to get more traffic data -- in terms of more and better detectors, (ii) to move this data fast to where it is utilized – in terms of communication systems that are faster and of higher capacity, and (iii) to process this data quickly – in terms of more powerful computing systems. These technological systems cost more than what are currently in place in cities like Tempe. In addition, there are the costs of training, maintenance and operation of a system, whether or not it includes traffic adaptive features.

Although the primary scope of the project was only to implement RHODES-ITMS and evaluate the resultant traffic performance in the field (the subject of Sections 3-5 of the report), in this section an overall evaluation of the system will be provided that includes the field-test results and considerations of other potential benefits and costs. To do so, the actual and anticipated traffic performance improvements from RHODES will be discussed first. Next discussed will be the other potential traffic control functions that may be available once the required infrastructure and RHODES architecture has been implemented. In concluding this section, we will comment on other benefits and marginal costs that may be associated with the implementation of RHODES.

6.1 "Adaptive" Control and System Responsiveness

While the focus of RHODES is to "adapt" to prevailing traffic conditions, the motorists themselves also adapt, over time, to traffic conditions. The ability of RHODES to adapt to the various types of changes in traffic patterns is measured by its "responsiveness", in terms of <u>how well it adapts</u> and <u>how fast it adapts</u>. However, these changes in traffic patterns are due to both the inherent stochasticity of traffic flows and *driver adaptation.*

Long-term driver adaptation (the kind considered in static traffic equilibrium models used for network planning), is when groups or percentages of travelers start choosing different routes to go around or avoid a long-term disruption, such as major road construction. In this case, RHODES may be enhanced to learn the changes in underlying traffic parameters, such as turning ratios, and hence, in turn, adapt to long-term driver adaptation. In this case, the requirement for "responsiveness" is only on how well RHODES adapts, and not how fast.

The mid-term, or tactical, driver adaptation occurs when travelers make local lane or route change decisions to avoid a temporary disruption, such as traffic incidents or an unusually large congestion level. For example drivers may go "around the block", or make a turn earlier than originally planned, to avoid an incident downstream. If the network of detectors and RHODES signals covers this local re-routing adaptation, then RHODES will respond well to this type of driver adaptation. In the Tempe field test site, if incidents occur just upstream of the upstream detectors (see Figure 33), then the change in flow to the interchange will be detected by RHODES which will set signal timing appropriately. Another type of mid-term traffic disruption is when an emergency vehicle pre-empt goes into effect. During that time some phases get extended or gapped out and hence the traffic flow pattern is altered for a few minutes. However, neither an emergency pre-empt nor the type of incident illustrated in Figure 33 took place during the data collection period, and hence this element of traffic performance was not evaluated in the current field test. Nevertheless, as mentioned in the last part of Section 5, anecdotal evidence suggests that RHODES does respond well to these types of traffic disruptions.

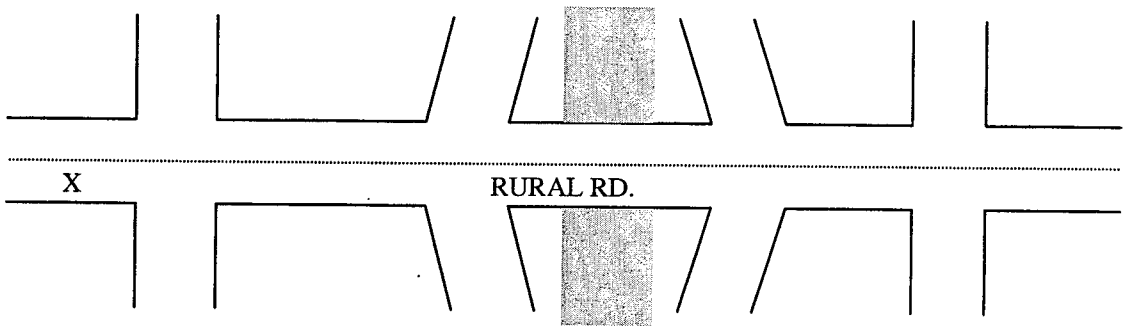

Figure 33 - Illustrative midterm traffic disruption (X indicates a traffic incident).

Finally there are the short-term, minute by minute, traffic fluctuations that are inherent in traffic flow, even when the long term and midterm patterns are statistically equilibrated. These are referred to as *recurrent* traffic conditions and the current RHODES-ITMS system is, in fact, designed to respond timely to the attendant traffic fluctuations.

6.2 Traffic Performance for Recurrent Conditions

Obviously for RHODES to even be considered as a viable traffic control system it must perform at least as well as the widely prevalent second-generation UTCS-type system. Presumably it does better.

Field data gathered by TASK during the field test show that RHODES does as well as the current time-of-day (TOD) semi-actuated coordinated system. As was pointed out by TASK in their report [2001], the current system performs very well, providing a high level of service given the large volume of traffic using the interchange on a regular basis. However, this level of performance has been attained with constant fine-tuning over an extended period of time, as Tempe's Transportation Staff have worked to continually improve the performance of the interchange to keep up with changing conditions. Currently, three different fixed-cycle signal timing plans are used at this location in an attempt to adapt the traffic controller' s performance to changing conditions during morning rush hour, evening rush hour and other remaining times. RHODES, on the other hand, does not need any time-of-day information, as it continually adapts to changing conditions throughout the day, instead of adjusting at specific time epochs.

TASK's data shows that the current version of RHODES, with a limited amount of fine-tuning of the few parameters, was able to perform as well as the current well-tuned TOD coordinated system used by Tempe.

6.3 Potential New Traffic Control Functions

Given the well-defined architecture of the current RHODES system (see Figure 3) it is possible to add other traffic control features such as *transit priority*, *emergency vehicle priority/preempt* and *railway-vehicle grade crossing control*. The RHODES-ITMS implementation in Tempe was only at the intersection/interchange level within the RHODES hierarchy, and the CAPRI module considers only a single category of arrivals: vehicles. Figure 34 shows a simplified illustration of how bus priority may be implemented. Buses will be another category of arrival that has to be served by the interchange signals and as such may be given a different "weight" as compared to other vehicles. For example, if the traffic/transit management objectives were to have on-time performance for buses, then a weight may be given that depends on the lateness of buses and the number of passengers. Figure 35 illustrates the implementation of bus priority in RHODES.

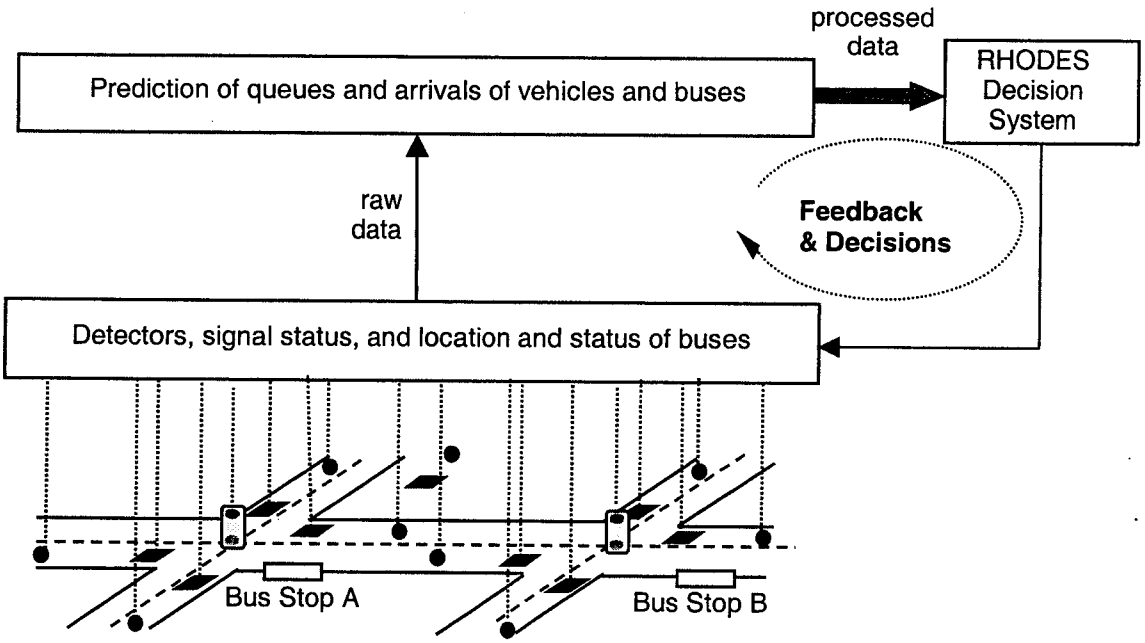

Figure 34 - Simplified illustration how bus priority may be included in RHODES

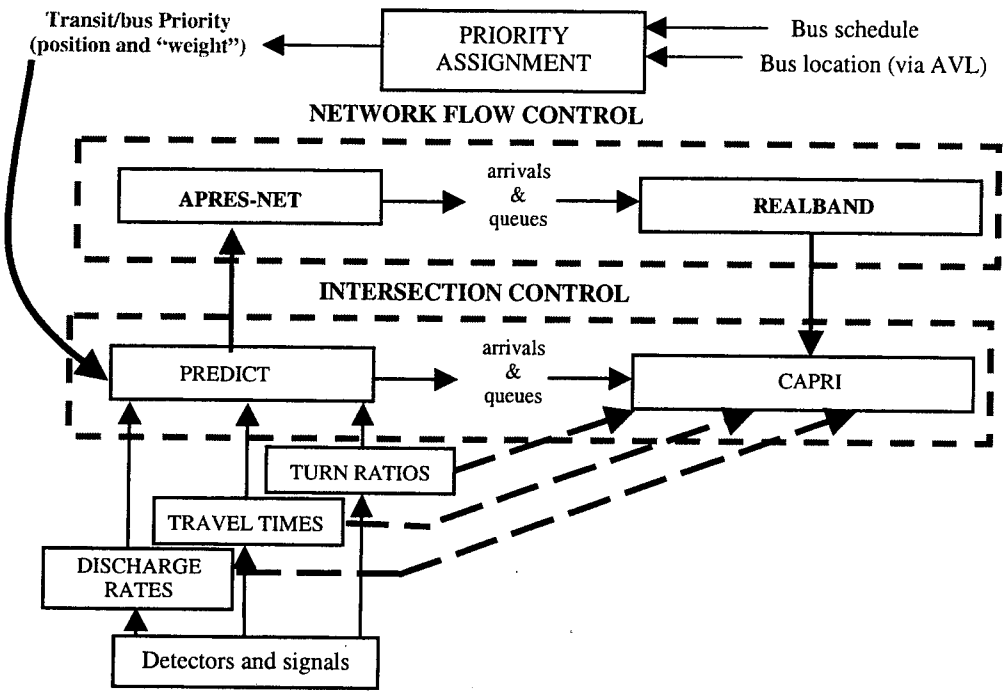

Figure 35 - Implementation of Transit Priority within RHODES Architecture

Priority for emergency vehicles means providing a path through the network with no stops. By constraining the intersection to provide the appropriate green phase when the emergency vehicle approaches the intersection, RHODES can "prime" the intersection so that there is minimum disruption for other traffic (a hard emergency pre-empt, as provided by many current systems, can also be implemented to provide a redundant safety feature). Figure 36 illustrates how an emergency pathway may be provided within the RHODES architecture.

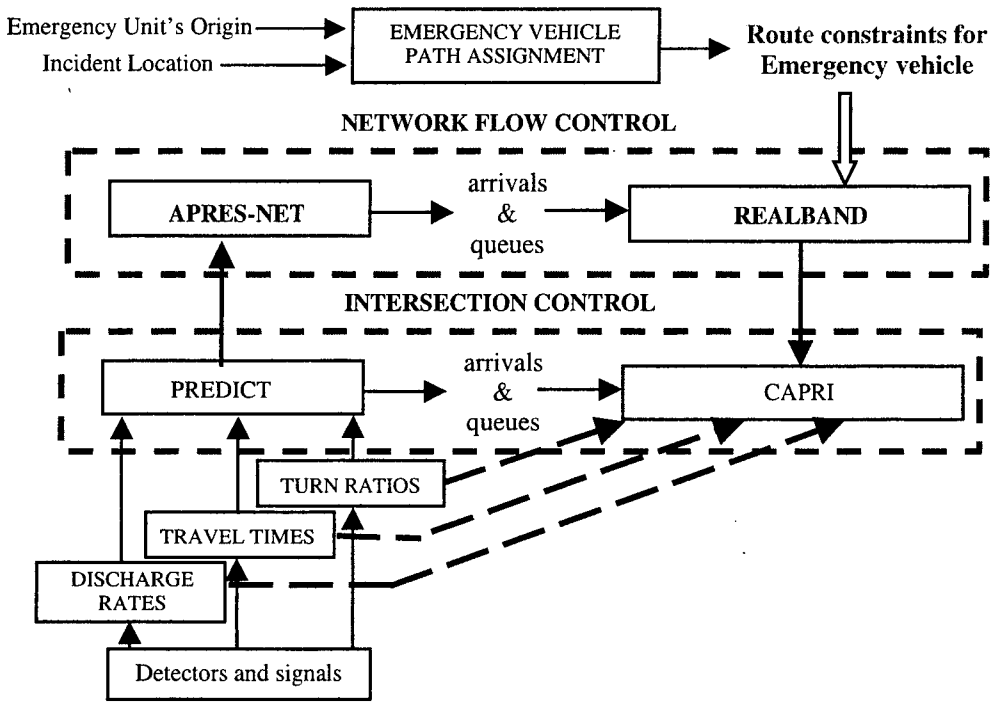

Figure 36 - Implementation of Emergency Vehicle Preempt/Priority within RHODES Architecture

Finally, consider the movement of trains through a set of at-grade crossings. With upstream detection (on the rail tracks) of train movement, one can predict, several minutes in advance, the times that the crossing will be occupied by a moving train and be blocked to vehicular traffic. Given this information, RHODES can time the signals at the intersections of the railroad crossings to minimize disruption of the surface traffic. Again, a hard signal preemption may be included as a redundant safety feature to make sure that vehicles do not cross the tracks at that time. In other words, RHODES priority would decrease the number of vehicles waiting to cross the intersection when the train approaches, thereby decreasing the exposure to a vehicle-train incident and increasing safety. Figure 37 illustrates how signal priority/preemption at railroad crossings may be implemented in the RHODES architecture.

The main point of this section is that even though the traffic control functions discussed above were not implemented in the current version of RHODES, they can be implemented in future versions. Then, by responding to categorized arrivals at the intersections and railroad crossings, RHODES can provide further benefits to the overall traffic performance.

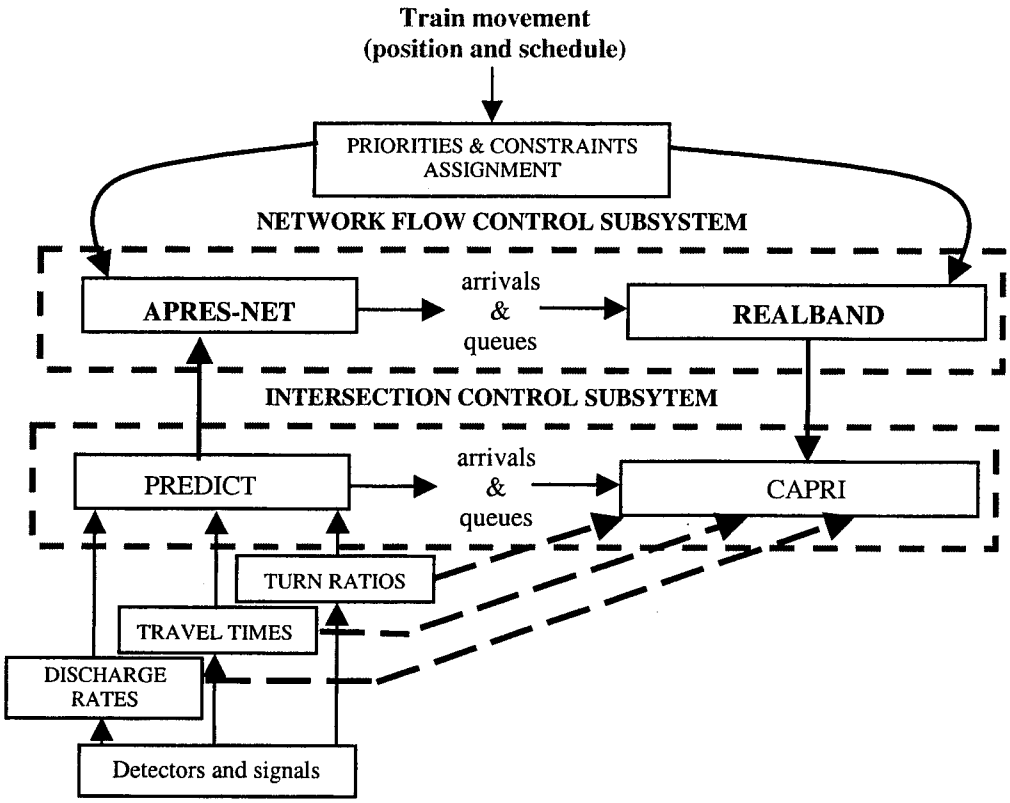

Figure 37 - Implementation of Railway At-grade Crossing within RHODES Architecture

6.4 Other Benefits

In the RHODES algorithms, estimates of travel times, delays and queues are updated using second-by-second real data. These are computed internally in the algorithms, so that the optimization routines may maximize given performance measures that are functions of these variables. It is possible to communicate these variables to (i) the TOC for better monitoring and management of traffic and (ii) traveler information providers so that drivers can get more and better information to make better route and departure time decisions. Thus, the use of RHODES-derived measures could also enhance travelers' driving experience.

There may also be additional safety benefits because with RHODES the intersections/interchanges (and the railway crossings) will have less traffic waiting when emergency vehicles (and trains) preempt the signals and disrupt traffic flow.

Since standing queues of vehicles contribute negatively to air quality, system-wide RHODES installation may improve air quality, because RHODES can implement objectives of minimizing queue sizes. Finally, both travel time delays and large queues make gasoline consumption less efficient; RHODES can alternatively implement an objective that reflects the minimization of energy consumption due to delays and queues.

6.5 Costs

Quantifying the cost of developing timing plans for a current second-generation UTCS system is difficult, as the associated effort consists of a series of refinements made over a long period of time for a variety of reasons. Usually, the costs for developing timing plans are included within the Operations and Management (O&M) budget of a city's transportation division and are therefore difficult to break out individually for any specific intersection. RHODES, however, does not require continuous manual refinement of timing plans to maintain its performance level, thereby freeing transportation staff for other tasks. Unfortunately, it is difficult to put a dollar amount on the cost of maintaining such timing plans, making it difficult to quantify the cost savings from using RHODES in lieu of semi-actuated TOD control.

Easier, perhaps, is putting a dollar amount on the cost of a RHODES installation versus the more traditional second-generation control. While both have different equipment requirements, in either case, a traffic cabinet, controller and basic detection capability are required. RHODES however, does have specific requirements regarding the controller and software involved. In particular, RHODES is currently limited to operating in a 2070 Advanced Traffic Controller environment, utilizing the *NextPhase* controller software to interface with the cabinet hardware. In addition, an additional processor, the MEN Card discussed earlier, is required to provide the memory and processing capability required by RHODES. Furthermore, if the existing detection capability is insufficient, that is, the required type and/or number of detectors for RHODES' *PREDICT* algorithms are not implemented, additional detection must be installed, though there is no requirement regarding the specific detection technology that needs to be used, (i.e., induction loop detectors, video detection, microwave detection, etc.). As a result, while maintenance of timing plans may be decreased, there may be an increased cost to maintain these additional detectors.

Additional features may also be added as desired, as with any traffic control method, but these elements are sufficient for basic RHODES operation. Estimates of the marginal cost for a new RHODES installation range from $30K - $65K, depending upon (i) whether integration with an Advanced Traffic Management System (ATMS), such as *icons*, is desired, (ii) the complexity of the installation, and (iii) requirements for any non-standard feature, such as additional communications capability and traffic monitoring.

However, this is in addition to the cost of installing a traffic management system, such as the Computran traffic control system in Tempe, which would cost several hundreds of thousands of dollars. Thus, RHODES may seem an expensive alternative, especially if one considers the field-test data that showed no significant difference between the results of the two control methods. However, there are two general reasons to believe that RHODES may be a better alternative to second-generation control. One is that the data-collection was performed solely during two days, each day for three three-hour periods experienced at the field test site. While the two systems were comparable in performance during these peak periods, no data-collection and evaluation was done for the remaining 15 hours of each day that the interchange was in use. In addition, the field data itself showed the need for an adaptive control method. By comparing the traffic volumes between the two days during which the systems were evaluated, it can be observed that there are significant traffic variations, even though the two days were just one week apart! While the current second-generation method has been adjusted to perform well during average peak periods, it is limited in its ability to adjust to conditions outside of the range of peak traffic volumes. Also, as discussed above, the current methods are limited in their ability to respond to mid-term and short term disruptions in traffic patterns, while RHODES adapts, in a timely fashion, to such variations in traffic flows. Once RHODES has been installed and is in place, no adjustments will need to be made in response to incidents resulting in lane closures, normal and abnormal fluctuations in directional flows and/or traffic volumes or signal preemption.

The other general reason why RHODES may be a preferred alternative to second-generation control is the range of various other benefits that are discussed above, including the option to include other traffic control functions within the RHODES architecture, and the potential improvements in safety, air quality and energy consumption.

7. PROJECT CONTRIBUTIONS

Although the main focus of the project was to implement RHODES and measure the resultant traffic performance, the contributions of the project were of much greater dimension and extent. The following is a list of the major contributions, in bulleted form:

- **Second-by-second traffic responsive**. To the authors' knowledge, this is the first implementation of a traffic adaptive control system that measures traffic variables every second and computes durations for traffic signal phases to be implemented for the next few minutes.

- **Hierarchical and Distributed Modular Architecture**. The RHODES architecture that was implemented is both hierarchical to account for the natural time constants of obtained traffic measures, and distributed to exploit the spatial aspects of traffic activities and local processing of these measurements. Furthermore this architecture allows for straightforward modular expansion that can include several other traffic control functions such as transit priority and railway grade crossing preemption.

- **Integration of Adaptive Features in the 2070 Controller**. This is the first time that a standard traffic control system was implemented that includes second-generation UTCS (*NextPhase* in our case) with an adaptive feature (RHODES in our case) which can be turned ON or OFF by a traffic engineer.

- **Implementation of a 2070 within a TS2 Cabinet**. Although it was not something that was specifically included in the planned tasks by the research team (since it was assumed in the project proposal that this would have been done by the time the field test required it or it would be easy to do so when the time came), the effort to implement a 2070 Controller in a TS2 was considerable and this was the first time it was ever done. (As of this report, there have been a few 2070 implementations, but these have been within a NEMA-TS1 Cabinet).

- **Implementation of a communication system for second-by-second decision making**. The communication system that was developed and implemented, which consisted of sending data from upstream detectors to a central traffic control system (in our case the Computran System at Tempe) to the controller at the interchange, with latency of a less than a second, and the subsequent implementation of signals, again with the latency of less than a second, is a new engineering design and was implemented for the first time through this project.

- **Implementation of a system that requires low maintenance by traffic engineers**. As discussed in the last section, the effort to develop timing plans for a current second-generation UTCS system consists of a series of refinements made over a long period of time. A system such as RHODES, however, does not require continuous manual refinement of timing plans to maintain its performance level, thereby freeing transportation staff for other tasks. (On the other hand, there may be some additional cost to maintain the extra detectors required by RHODES.)

- **Workforce expansion**. Over the course of the project several UA graduate students were involved with the research, development and deployment of a real-time transportation system, and some of them completed a Master's thesis/project or a doctoral dissertation. After graduation, these students, now with significant background and experience in traffic and systems engineering, have gone into the workforce, thereby considerably expanding the workforce in traffic systems engineering.

- **Real-time decision-making and optimization**. This project also extended the cutting edge in systems engineering by (i) developing a system design framework for real-time decision systems and (ii) the subsequent implementation and deployment of a system that uses a client-server framework for automated real-time optimization (in our case real-time dynamic programming).

8. LESSONS LEARNED AND DIRECTIONS OF FUTURE WORK

8.1 Lessons Learned

The precursors for this project were the earlier RHODES development projects [Mirchandani and Head, 1994, Head and Mirchandani, 1994, Head and Mirchandani, 1997] where the research team developed algorithms and software and tested them using simulation models. Given the team's knowledge of the computer/communication architecture available at the City of Tempe's TOC, and the possibility of support from the Traffic Engineering Department and its vendor (Computran Inc.) for Tempe's traffic management system, it was envisioned that the application of RHODES-ITMS for the US60/Rural interchange would be straightforward. The development of the simulation model for the interchange and the RHODES-ITMS algorithms was indeed straightforward, and these were done in time and on budget.

However, the research team faced many obstacles in the implementation of the hardware and software within the TOC and the field. Over the duration of the project, the focus of the effort changed from algorithm and software development to communication system design and system integration. This significantly delayed the completion of the project. The team had to learn new material on communication technologies/systems, system security, data-transfer protocols, etc. Furthermore, the Project's specific application and the communication requirements were challenging and, after the fact, the team realized that the design of a reliable, real-time-capable communications system is much more difficult than was originally anticipated. It involves many significant new issues, which were quite different than the traffic engineering and algorithmic issues that the team had dealt with earlier. From specifying the requirements for the number and type of interfaces needed, to procuring the equipment, to actually installing and testing it, obstacles, both technological and organizational, continually arose and had to be dealt with. With a project such as this, involving a variety of agencies and people of varying backgrounds, the key factors to overcoming obstacles and successfully implementing state-of-the-art technologies and methods were:

1. A champion within the host organization who provided leadership and smooth interfacing to help "make things work" (Jim Decker of the City of Tempe, in our case)
2. A set of technical advisors who were interested in the success of the project and were helpful with suggestions and actions that supported the research team's efforts (the TAC members, in our case)
3. Subcontractors who were as interested in seeing the proposed system work as was the research team (Siemens Gardner Transportation Systems and Computran, in our case)
4. And the team's determination to apply the state of the art in every aspect of the project.

Perhaps the most important aspect of this project is the team's newfound respect for the various interface issues that must be resolved whenever integrating a variety of hardware/software systems produced by various vendors/manufacturers. From reading this report, it should be clear that a very large part of the work involved in this project was focused on the various interfaces that needed to be developed. From overcoming the problem of installing a 2070 inside a TS2 Type 2 cabinet, to interfacing the *NextPhase* software with RHODES, to obtaining upstream detector data from the Computran TCS located at the Tempe TOC, a variety of interfaces were designed, created, tested and redesigned until they worked properly. The team clearly did not anticipate the magnitude of the interface issue at the time this project was proposed and initiated, but has come away with a much better appreciation of this aspect of system integration as a result.

In concluding this subsection, we must mention some organizational issues that came up and, perhaps, must be dealt differently in any future effort of this kind. Given the total effort budgeted for the project, there is the constant issue of how much time should be devoted to "getting the job done" versus how much time should be spent on communicating via TAC meetings, minutes, and presentations to keep interested parties informed. While communication is very important, there are cases where it can also lead to added delays. As an example, there were many times when the team had to spend large amounts of time on technical obstacles, especially dealing with interface issues, and it had to use a fine-tooth comb and "forensic-type" investigation to see how they would be overcome. Still, they had to spend significant effort to let the TAC know of these problems and the team was sometimes not able to make the TAC appreciate the magnitude of the problem and/or the need for its resolution. Fewer TAC meetings, and the use of timely "mini-status" reports which briefly provide the status of tasks and problem/obstacle resolutions, as a mechanism to keep the team and the TAC involved without spending an inordinate amount of time for presentations was helpful in diverting more effort to resolve the original problems/obstacles.

Finally, the dependence of some tasks upon the completion of others had a major impact upon the schedule adherence of the project, reducing the ability of partners (ADOT, Tempe, Siemens Gardner Systems, Computran, etc) to work in parallel on some tasks. While improved program scheduling and management may have helped somewhat, the very nature of the tasks to be completed and the existing organization of the participants dictated the situation, in large part. In addition, one should note that each partner is involved in a myriad of projects, of which this was only one. This presented a problem at times, as various deadlines unrelated to the current project intruded at inopportune times.

8.2 Directions of Future Work

RHODES has now been successfully field-tested, and it is shown to be a viable traffic control method with many potential benefits. However, there remains much work to be done before it is fully accepted and widely implementable.

First, more field data must be gathered and RHODES' *real-time responsiveness* needs to be evaluated. While the evaluation performed by TASK Engineering follows standard practice, albeit for a single intersection, the research team feels that this method is insufficient for evaluating an interchange operating with an adaptive traffic control systems, such as RHODES. As a real-time adaptive system, RHODES is capable of providing optimized signal timing in a variety of traffic conditions and its traffic performance evaluation should reflect this. It is for this reason that the team has proposed a follow-up project to re-evaluate the traffic performance of RHODES as implemented at the US60 & Rural Road interchange. Towards this end, we are in the process of developing an evaluation design for adaptive traffic control systems that fully explores the potential advantages of such a system. This design involves additional data collection during a series of scenarios to represent traffic conditions that may arise at any time, including lane closure, major volume fluctuations and signal preemption. Including these types of events within the existing evaluation procedure, while making additional modifications to ensure that a comprehensive set of data is collected, would allow agencies to make informed decisions when comparing the performance of an adaptive control system with a more traditional one.

Along these same lines, the difference between real-time systems and off-line methods should be investigated to aid in the design and development of future real-time systems, which include the consideration of many issues currently not faced in the design of off-line systems. Some of these issues are:

1. What should be the time resolution in the real-time system (milliseconds, seconds, minutes, etc.)?
2. What should be the prediction horizon (decision rolling horizon)?
3. What should be the control time horizon (decision roll period)?
4. What type of communication system is needed (capacity, speed, etc.)?
5. What computing platform is needed?

Given the experience in the design, development, and implementation of RHODES, it will be useful to develop a framework for designing real-time decision systems in the transportation industry.

The RHODES-ITMS system included only <u>two</u> intersections under RHODES real-time control strategy. It will be useful to investigate the RHODES performance for a set of intersections on an arterial and its

performance in a grid. Fortunately, the research team has planned two new projects, which are supported by FHWA, ADOT, and UA, that extend RHODES to an arterial (Speedway Blvd. in Tucson) and a grid (two sets of arterials that cross each other, also in Tucson).

Finally, one of the original goals of RHODES-ITMS was to provide integration between the freeway traffic management and surface street traffic control. RHODES-ITMS integrated with MILOS [Gettman, Head and Mirchandani, 1999] provides an opportunity to achieve this goal. However, to test this integrated freeway/surface-street management, we must first test the control concepts in the laboratory using simulation models (a straightforward effort) and then implement them in the field (a greater challenge). The latter effort must be supported by enhanced communications/computation capability and infrastructure, and more importantly, by assistance and support of participating agencies. Future research should be in this direction -- to provide integrated management of surface street signals, ramp meters and variable message signs, to make the movement of all categories of vehicles appropriately efficient for each category, and to make the trip taking behavior of drivers and travelers smoother and safer, with less impact on air quality and energy consumption.

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APPENDIX 1

TIMING AND OTHER PARAMETERS FOR US-60 & RURAL ROAD

Time-of-day plans for US-60 and Rural Road (in seconds):

Time	Cycle Time	Offset	Phase 15	Phase 26	Phase 48
7AM – 8.30AM	110	80	24	34	52
3.30PM – 6.30PM	110	85	21	34	55
Other times	94	80	20	33	41

Turn ratios and travel times (in seconds) from upstream detectors:

Approach (see Fig A)	Turn Proportions			Travel Time from upstream
	Left turn	Through	Right Turn	
Approach 1	0	.88	.12	30 s
Approach 2	.66	0	.34	8 s
Approach 3L	1.0	0	0	5 s
Approach 3T	0	1.0	0	5 s
Approach 4	0	.83	.17	8 s
Approach 5	.40	0	.60	6 s
Approach 6L	1.0	0	0	5 s
Approach 6T	0	1.0	0	5 s

Queue discharge rates (vehicles per second) by lane group:

Approach (see Fig A)	Discharge rates in GREEN (vps)			Discharge rates in RED (vps)		
	Left turn	Through	Right Turn	Left turn	Through	Right Turn
Approach 1	0	1.8	0.5	0	0	0.3
Approach 2	0.25	0.25	0.25	0	0	0
Approach 3L	0.4	0	0	0	0	0
Approach 3T	0	1.5	0	0	0	0
Approach 4	0	1.8	0.5	0	0	0.3
Approach 5	0.25	0.25	0.25	0	0	0.3
Approach 6L	0.4	0	0	0	0	0
Approach 6T	0	1.5	0	0	0	0

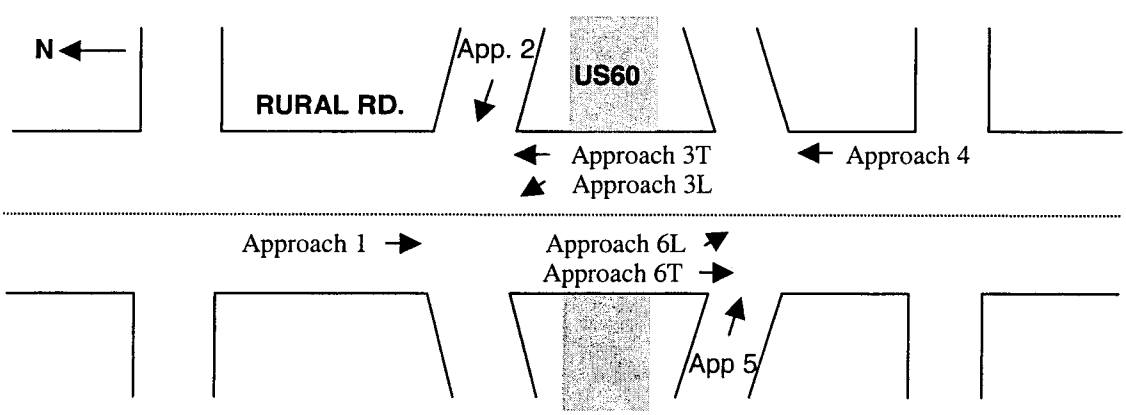

Figure A - Designation of Approaches at the Interchange

APPENDIX 2

RHODES INSTALLATION INSTRUCTIONS
For US60 and Rural Road in Tempe, Arizona
(August 2000)

Part A: Installation of the 2070 Advanced Traffic Controller in a TS2 cabinet

1. Install the 2070:
    a. Put the intersection into a flash condition.
    b. Physically remove the existing traffic controller from the cabinet and replace it with the 2070 controller.

2. Connect SDLC:
    a. Connect the cabinet's 15-pin SDLC cable to the 15-pin connector on the end of the SDLC adapter, ensuring that the spring clips are securely connected to the latching blocks.
    b. Connect the 25-pin connector of the SDLC adapter to the SDLC port of the 2070 (located to the left of the NEMA A connector), ensuring that the spring clips are securely connected to the latching blocks.

3. Connect Power:
    a. Connect the cabinet's NEMA A connector to the round A connector on the base of the 2070.
    b. Verify that the base unit is receiving power by checking the position of the toggle switch located in the lower right corner, above the fuse assemblies. If the switch is in the *on* position, but the indicator light is not lit, verify that step 3a was completed properly. If the indicator light is still not lit, check the fuses located below the switch to verify they are intact. If they are in proper working order, there may be something wrong with the base unit; replace it, or the entire 2070, before continuing.
    c. Verify that the top unit is receiving power by checking the LCD screen and/or the active light to the left of the two front panel keypads. If both are dark, open the front panel by pulling the black door latch (on the left side of the LCD) to the right, and examine the status of the power switch and indicator light. If the switch is in the *on* position, but the indicator light is not lit, verify that the power cord leading from the 2070-4 Power Supply Unit (located in the rear of the 2070) is plugged into the 2-outlet receptacle in the base unit. If it is, but the power indicator is not lit, there may be a problem with the 2070-4 unit; replace it, or the entire 2070, before continuing.

4. Start the 2070:
    a. Remove the cabinet's flash condition and reset the MMU to begin controller operations.
    b. From the NextPhase main screen, go to 3) *Status* and 1) *PhaseTim* to verify the controller is timing the intersection properly.

Part B: Installation of the RHODES Traffic-Adaptive Signal Control System

5. Verify Integrity of Peer Data Connection (TOC-side):
    a. Confirm that the following are in place:
        i. A serial connection from port 16 of Digiboard #3 (the Computran output port) to the RHODES PC serial port labeled *from Computran.*
        ii. A serial connection from the RHODES PC serial port labeled *to modem* to the StarComm modem
        iii. An RJ-11 connection from the StarComm modem to the twisted pair leading out to the traffic cabinet

iv. The RHODES PC powered up and the user currently logged on (the Administrator password is the Enter key)

b. Launch the *Peer Decoder* program by clicking on the desktop shortcut on the RHODES PC. Once the program window is open, click on Start under the Action submenu to begin decoding the Computran data for transmission to RHODES.

c. If the *Peer Decoder* software is properly receiving the Computran data, the response for each *CompuMsg* should be *Good*. If you see a response of *Read Timeout*, recheck the serial connection between the Computran System and the RHODES PC.

d. Confirm that the StarComm modem is receiving power via the AC adapter.

e. Check to see if the StarComm modem has established a connection to the cabinet-side modem by examining the LEDs on the modem's display (MR, TR, OH, CD and HS will be lit). (NOTE: If the modem is unable to establish a connection, the cabinet-side modem may not be powered up, so continue with step 6.)

f. Once a connection has been established, the *Peer Decoder* software should begin sending data to the 2070 in the cabinet. This can be verified by examining the SD light on the StarComm modem's display to make sure it is blinking, indicating the transmission of a message each second.

g. If the cabinet-side connection is already in place and operational, the RD light on the StarComm modem's display will also blink, indicating the reception of a message from the 2070 each second. The received data can be verified by examining the *Peer Decoder* display on the RHODES PC. If *ITMS_Response* is *ITMS_Good*, then a good connection to the 2070 has been established and is operational. However, if the message type is instead *ITMS_Error*, with a status of *CommResponseError* or *CommResponseNone*, then a connection to the 2070 could not be established and an inspection of the cabinet-side connection (as in step 6) is required.

6. Verify Integrity of Peer Data Connection (Cabinet-side):

a. Confirm that the following are in place:

i. A 2070 controller installed at the cabinet

ii. An RJ-11 connection from the twisted pair leading into the traffic cabinet to the StarComm modem

iii. A serial connection from the StarComm modem to the 2070 serial port labeled *Peer Data Connection* (located in the rear of the controller)

b. Confirm that the StarComm modem is receiving power via the AC adapter.

c. Check to see if the StarComm modem has established a connection to the TOC-side modem by examining the LEDs on the modem's display (MR, TR, OH, CD and HS will be lit).

d. Once a connection is established, the 2070 should begin sending data to the TOC. This can be verified by examining the SD light on the StarComm modem's display to make sure it is blinking, indicating the transmission of a message every second. In addition, if the TOC-side connection has been setup properly, the RD light will blink, indicating the reception of a peer data message each second.

e. Verify that the peer data are being received by RHODES.

i. From the NextPhase main screen, go to 3) *Status*, 9) *More* and 3) *AdptStat*. (This screen displays the Peer Status as a series of 8 flags, one for each of 8 potential peers. A blank entry means that the specified peer is not being used, an "X" indicates a failure and a "." (dot) indicates the peer is functioning properly.)

ii. Verify that peers 1 and 4 are operating correctly.

7. Verify RHODES initialization:

a. From the NextPhase main screen, go to 3) *Status*, 9) *More* and 3) *AdptStat*. (This screen displays the *mode* that NextPhase would like RHODES to be in, the *state* in which RHODES is currently running and the remaining time (in seconds) which must elapse before RHODES may run in Online mode.)

b. Verify that RHODES is currently running in Standby mode and that the *OnLineRdy* time is 0.

c. If the state indicates either NoRhodes or NoAdapt, RHODES has failed to initialize properly and can only be reset by restarting the 2070 (which will put the cabinet into flash). This may indicate a configuration problem with the MEN processor in the 2070, so contact the RHODES Project team if the problem persists.

8. Start RHODES (at the cabinet):
   a. Verify that the *OnLineRdy* time is 0 before continuing. (NOTE: If this is not done, then after the end of the current cycle, RHODES will start in phase 15 and remain in that phase until *OnLineRdy* time reaches 0.)
   b. From the NextPhase main screen, go to 1) *Control*. (This screen indicates the current control configuration of the NextPhase 2070 controller software. A *ControlMode* of *Sched* indicates that the 2070 is running Time Based Coordination in Scheduled mode, while *Manual* indicates that the 2070 is running under external control; in this case, under RHODES control. When running under *Sched* mode, the *FreePln* indicates the current plan, while under *Manual* mode, *ManPln* indicates the current plan.)
   c. On the right keypad, depress the "–" key repeatedly until *ControlMode* indicates *Manual*. Next, depress the **ESC** key, then the **YES** key to save this change.
   d. From the NextPhase main screen, go to 3) *Status*, 9) *More* and 3) *AdptStat* to verify that the *mode* has changed from Standby to Online. (NOTE: RHODES will not switch to Online mode until the end of the current cycle, i.e., the end of phase 48.)
   e. Next, from the NextPhase main screen, go to 3) *Status*, 9) *More* and 3) *AdptStat* to verify that the *state* has changed from Standby to Online, i.e., RHODES is now controlling the intersection.
   f. From the NextPhase main screen, go to 3) *Status*, 9) *More* and 4) *AdptQue*. (This screen shows the current queue estimates used by RHODES when making decisions regarding the optimal phasing plan to follow. (NOTE: While viewing this screen, hit the **ENT** key on the right keypad to view the current phasing information and **ESC** to go back.)

   The sixteen movements are labeled as follows:

SBL	Southbound Left	**SBT**	Southbound Through	**SBR**	Southbound Right
WBL	Westbound Left	**WBT**	Westbound Through	**WBR**	Westbound Right
NBrL	Northbound Bridgedeck Left	**NBrT**	Northbound Bridgedeck Through		
NBL	Northbound Left	**NBT**	Northbound Through	**NBR**	Northbound Right
EBL	Eastbound Left	**EBT**	Eastbound Through	**EBR**	Eastbound Right
SBrL	Southbound Bridgedeck Left	**SBrT**	Southbound Bridgedeck Through		

9. Halt RHODES (at the cabinet):
   a. From the NextPhase main screen, go to 1) *Control*. On the right keypad, depress the "+" key repeatedly until *ControlMode* indicates *Sched*. Next, depress the **ESC** key, then the **YES** key to save this change. (NOTE: This change will become effective at the end of the current phase and will have the effect of putting RHODES in Standby mode and returning the interchange to TBC.)

10. Start RHODES (at the TOC):
   a. From the NextPhase main screen, go to 1) *Control*. On the right keypad, depress the "+" key repeatedly until *ControlMode* indicates *Remote*. (Note: When the 2070 is in *Remote* mode, the controller will continue to operate the current active plan until it receives a command from *icons* to do otherwise.) Next, depress the **ESC** key, then the **YES** key to save this change.
   b. On the RHODES PC located within the TOC Computer Room, begin by verifying that the NT Service "ITMS TrafficControl" is running. To do this, open up the Services control panel and scroll down to ITMS TrafficControl. Verify that the service has a status of *Started*. If it does not, highlight the ITMS TrafficControl service entry and click on the *Start* button to activate the service.
   c. Next, from within the *icons* main window, click on the *Control* menubar command, then *Manual Assignment* in the drop-down menu. Within the *Manual Assignment* window, click on the "+" sign next to the Tempe system to display the associated intersections and

highlight US60 & Rural. Next, click on the *Add Row* button to create a new assignment command for this controller. This will cause a new row to be created with default entries. Click on *Action* and select *PAT:* from the list of options which appears. Then, position the cursor just after the ":" after *PAT* and enter the number "1" (without the quotes). Next, click on the empty space under the entry *EN* to enable this assignment. Then, click on the *Apply* button, followed by the *OK* button to close the window. You should now notice the current plan, on both the *icons* and *PeerDecoder-RHODES Status* screens reflect the fact that the 2070 is now in Plan 1, which effectively turns RHODES on. To put RHODES back into Standby mode, repeat the above procedure, but changing the # value after *PAT:* to the desired plan. In order to revert to *Sched* mode, step 10a will also need to be repeated, this time changing from *Remote* to *Sched* mode.

APPENDIX 3

DATA COLLECTION AND DATA RELIABILITY

(Excerpted from TASK Engineering Inc. Final Report)

DESCRIPTION OF DATA COLLECTION EFFORT

Traffic data were collected for two scenarios, one with the existing traffic signal control system, called the *Off scenario*, and the other scenario with the RHODES software controlling the traffic signals, called the *On scenario*.

The traffic data were collected on two weekdays in September, exactly one week apart. Data was collected for the 7:00 AM to 10:00 AM, 11:00 AM to 2:00 PM and 3:00 PM to 6:00 PM peak periods, using the existing signal control procedures. It is assumed that these procedures are optimal for the existing traffic flows and signal timing theory.

By collecting data on the same day of the week in the same month, we hope to minimize temporal variations in the data. On the first weekday, Thursday, September 7, 2000, *Off scenario* data were collected in the AM and PM periods, and On scenario data were collected in the Midday period. On the following Thursday, September 14, *On scenario* data were collected during the AM and PM periods, and Off scenario data were collected during the Midday period.

The following traffic parameters were calculated for AM and PM peak periods for the *Off* and *On scenarios*:

- Control Delay per vehicle, by lane group.
- Control Delay per vehicle for the interchange as a whole.
- 95th Percentile queues length in vehicles for each lane group.
- Platoon Ratio, for each direction on the arterial.
- Total traffic entering the interchange.

Control delay is the total delay to vehicles at a traffic signal, including stopped delay, move-up in queue time, lost time due to acceleration and lost time due to deceleration. Control delay is the best single measure of operations of a signalized intersection. The lower the control delay per vehicle, the better. The procedure for estimating control delay from field data is found in Appendix III of Chapter 9 of the 1998 update of the *Highway Capacity Manual*, [Transportation Research Board, 1998, Page 9-117]....

Queue lengths for 95th percentile measure the length of a back-up from the intersection. Long queue lengths should be associated with long control delays. In addition, long queue lengths have the potential of effecting operations at upstream intersections and driveways, or of overflowing storage bays. Either phenomena creates secondary delays. Traffic arriving on freeway off-ramps can be assumed to arrive at a platoon ratio of 1.0.

The platoon ratio is a measure of traffic signal progression. A platoon ratio above 1.0 indicates positive signal progression. Higher platoon ratios indicate better progression. Platoon Ratio is defined by the *Highway Capacity Manual* chapter on signalized intersections [Transportation Research Board, 1998, Page 9-11]. It is:

$$R_p = P(C/g_i)$$

where,

R_p	=	Platoon Ratio
P	=	proportion of all vehicles in movement arriving during the green phase.
C	=	Cycle length
g_i	=	effective green time for movement i.

For any given intersection, control delay and queue lengths are expected to be functions of traffic flows. So for the before and after scenarios to be comparable, they must have nearly identical traffic flows.

The *Highway Capacity Manual, 1998 Update*, describes a method for collecting control delay data in the field (Chapter 9, Appendix III). This consists of teams of 2 persons each collecting queue data on each approach. The queue data is then used to calculate estimated control delay. There are 10 lane groups and two through approaches at the traffic interchange, so a team of 6 persons can collect approximately 60 minutes of data on each approach during the three-hour peak period.

The same group of data collectors can collect Platoon Ratio data on the cross street approaches during the same time period. Queue lengths are directly calculated from the same data used to estimate control delay. Traffic counters are in place on each approach to count total traffic. This is used to compare the before and after time periods and as a check on manually collected data.

Table 1 shows an example schedule for data collection for the AM period.

Table 1
Example Schedule for AM period
RHODES-ITMS Field Test

Start Time	7:00 AM	7:30 AM	8:00 AM	8:30 AM	9:00 AM	9:30 AM
Team 1	P2	Q9	Q9	Q10	Q10	P2
Team 2	P1	Q1	Q1	Q2	Q2	P1
Team 3	Q3	Q3	*	*	Q8	Q8

* Collect Q4 and Q5 at intervals, and Q6 and Q7 at interval midpoints.

TASK Engineering together with Traffic Research & Analysis collected the data manually. This method is chosen over use of video cameras to reduce the expense. Manual data collectors also have a better view than a video camera, and can move up and down the queue to collect data. Another method of collecting delay data is by floating car travel time study; similar to the data we are collecting now for the City of Mesa. However, the chosen method will probably be more accurate because it counts delay for a much larger number of vehicles and can collect delay for all movements through the intersection.

The specific steps in the project are:

Task 1. Scheduling and training. Data collectors receive 2 hours training on procedures and schedule.

Task 2. *Off Scenario* data collection. Three teams of 2 persons each collect queue length and platoon arrival data at U.S. 60/Rural Road interchange from 7:00 AM to 10:00 AM, 11:00 AM to 2:00 PM and from 3:00 PM to 6:00 PM on a typical weekday.

Stopwatches were used for timing, which created a source of error because data collectors punched the end of one period followed by the start of the next. About one second was lost between the two punches. A correction factor was used in the data reduction process to expand queue length data to account for the missing time.

Arriving vehicles were counted using electronic counting devices for the busier movements. This also provided an accurate accounting of time.

Task 3. *On Scenario* data collection. Four teams of 2 persons each collect queue length and platoon arrival data at U.S. 60/Rural Road interchange from 7:00 AM to 10:00 AM, 11:00 AM to 2:00 PM and from 3:00 PM to 6:00 PM on a weekday exactly one week after the before scenario.

Task 4. Data Reduction. The data collected in task 2 and 3 is used to calculate the statistics described above.

Task 5. Draft and Final Report.

RELIABLITY OF DATA

Traffic arriving at several approaches could be compared directly with machine counts at the same location. This was possible for 36 one-hour periods. For these 36 periods, the manual count was lower by an average of about 34 vehicles. An undercount is reasonable, since humans can expect to miss an occasional vehicle at high volumes. The undercount is influenced by two large undercounts on through traffic on the overpass. This was the most difficult count due to high volume and uncomfortable conditions. Counters were also collecting extra data during this count. Even including the two high counts, the standard deviation of 143 is about 19 percent of the average manual count.

The standard deviation of the measured control data for the On scenario is also related to the reliability of the data. Large standard deviations may be due to errors in data collection or variation in real results. For 10 of the 12 cases, the standard deviation was less than 16 percent of the mean. For two cases, it was between 40 and 50 percent. The two cases with highest standard deviation as a percent of mean were a left turn move with lower volumes. Hence, higher variation might be expected in the data.

Time interval data was difficult for data collectors to get correct. Stopwatches were used to record 18 second intervals. At the end of one interval, a data collector pressed a stopwatch, called the time, and then pressed reset. A second or so was lost each time interval between the time the watch is pressed to stop one interval and the time it is pressed to start the next. So if only 190 queues were recorded in an hour, the actual time interval was slightly more than 18 seconds. An adjustment to the data was made to account for this variation in time interval.

At the end of the data collection period, counters were instructed to keep count of cars that did not clear during that time period, and record them for as many intervals as was needed for them to leave the intersection. This instruction was difficult for data collectors to understand, and so was usually not included. Because the time period counted was relatively long, 60 minutes, this source of error is probably not high.