Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
TX-98/2971-S		

4. Title and Subtitle	5. Report Date
EVALUATION OF INNOVATIVE COORDINATION METHODS UTILIZING ITS TECHNOLOGY FOR TRAFFIC SIGNALS	October 1997
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
Steven P. Venglar	Research Report 2971-S
9. Performing Organization Name and Address	10. Work Unit No.
Texas Transportation Institute The Texas A&M University System College Station, Texas 77843-3135	11. Contract or Grant No. Study No. 7-2971
12. Sponsoring Agency Name and Address	13. Type of Report and Period Covered
Texas Department of Transportation Research and Technology Transfer Office P. O. Box 5080 Austin, Texas 78763-5080	Project Summary: September 1995 - August 1997
	14. Sponsoring Agency Code

15. Supplementary Notes

Research performed in cooperation with the Texas Department of Transportation.
Research Study Title: Evaluation of Innovative Coordination Methods Utilizing ITS Technology for Traffic Signals

16. Abstract

This project report summarizes research and implementation of signal system communications and improved signal control. An investigation of available signal system communication technologies and media identified spread spectrum radio as an effective, inexpensive, and flexible alternative. As part of the project, a radio communications system was selected and installed at five signalized intersections along US 281 in Falfurrias, Texas. Closed loop system software was then installed to coordinate the previously isolated, actuated intersections. The end result was improved traffic control, improved traffic flow, and remote system monitoring for those responsible for signal maintenance.

A second aspect of the project focused on developing real-time control functionality that would make use of the communications system. The Texas Department of Transportation's Dynamic Arterial Responsive Traffic System (DARTS) Specification provided a public domain, real-time signal coordination algorithm that suited this purpose. Simulators were developed by the Texas Transportation Institute to determine the effectiveness of DARTS installed in Falfurrias. Results show an average 18 percent reduction in travel time on US 281 and indicate the potential for DARTS to reduce arterial travel time. As an added project benefit, the simulation software developed for this project can be used to determine DARTS applicability at any given field site, and it can be used to train personnel in DARTS use and calibration.

17. Key Words	18. Distribution Statement
Traffic Signal, Traffic System, Signal System Communication, Coordination, DARTS, Dynamic Arterial Responsive Traffic System, Traffic Simulation, Traffic Control	No restrictions. This document is available to the public through NTIS: National Technical Information Service 5285 Port Royal Road Springfield, Virginia 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	90	

EVALUATION OF INNOVATIVE COORDINATION METHODS UTILIZING ITS TECHNOLOGY FOR TRAFFIC SIGNALS

by

Steven P. Venglar
Assistant Research Scientist
Texas Transportation Institute

Research Report 2971-S
Research Study Number 7-2971
Research Study Title: Evaluation of Innovative Coordination Methods Utilizing ITS Technology for Traffic Signals

Sponsored by the
Texas Department of Transportation

October 1997

TEXAS TRANSPORTATION INSTITUTE
The Texas A&M University System
College Station, Texas 77843-3135

IMPLEMENTATION STATEMENT

Based on the experiences and results of this research project, several suggestions can be made about future improvements or modifications to traffic signal control communications technologies and systems. The first implementation item is the recommendation that the word continue to be spread among traffic operations and maintenance personnel about the viability of radio communications for traffic signal control. Radio systems have now proven very reliable over time, and for the foreseeable future they appear to be less expensive to install than cable-based media. Spread spectrum radio proved to be an appropriate choice for the project at hand. It seems particularly applicable as a cost-effective means of providing flexible and reliable traffic signal system communications and coordination where no current accommodations or media are available for enabling traffic system communications.

The Dynamic Arterial Responsive Traffic System (DARTS), as specified by the Texas Department of Transportation, should be reinvestigated as a readily implementable, low-cost means of providing real-time coordination along major arterials with comparatively moderate cross street traffic volumes and reasonably spaced intersections. Though the idea showed promise when it was first conceived and installed, the advent of off-the-shelf, inexpensive closed loop system controller equipment and software appears to have curtailed interest in this promising coordination solution. If time and resources are available to develop DARTS-enabled controllers in the future (i.e., perhaps using the Caltrans 2070 Advanced Traffic Controller platform), it is suggested that Falfurrias, Texas, be one of the first sites where the technology is deployed.

The FACS/DARTS and TexSIM simulators developed from this project are a windfall that was unanticipated at the time the project plan was originally assembled. Now that these tools have been developed, they can be used to evaluate candidate field sites for DARTS installation. Engineers can determine whether or not a field site will see benefits, and if so, to what extent, before the investment is made in appropriate control equipment and communications hardware. Further, the simulators can be used as a tool for familiarizing operations personnel with DARTS and training them in system installation and calibration.

Finally, the logic and algorithm that compose DARTS should be investigated as a means of providing added controller functionality in other traffic control applications. Specifically, the advanced warning of platoon arrival and allowance for conflicting phase service (i.e., only in the presence of adequate phase service time) that form the heart of the algorithm may find application in railroad preemption scenarios and in the coordination of diamond interchanges with adjacent intersections. In each situation, a critical event (i.e., train arrival or platoon arrival at the interchange, respectively) that is currently not handled gracefully by controller hardware and software might be improved with advanced notice of event occurrence. Then, using DARTS' ability to measure and react to whether or not adequate time exists to service conflicting phases, an intelligent decision can be made about the transition to either the track clearance phase in the one case, or the arterial movements at the interchange in the other.

DISCLAIMER

The contents of this report reflect the views of the author who is responsible for the opinions, findings, and conclusions presented herein. The contents do not necessarily reflect the official views of policies or the Texas Department of Transportation (TxDOT). This report does not constitute a standard, specification, or regulation, nor is it intended for construction, bidding, or permit purposes.

ACKNOWLEDGMENTS

The author wishes to thank Gustavo Lopez of the Texas Department of Transportation's (TxDOT) Pharr District for serving as the Project Director for this research effort. TxDOT support for the project was also obtained from Nader Ayoub and Allison Meadors of the the Traffic Operations Division, Amadeo Saenz of the Pharr District, and Stuart Jenkins of the Pharr District. A special thanks is extended to Mr. Jenkins for his shared experience and efforts in equipment installation in Falfurrias.

Several key personnel of the Texas Transportation Institute also provided essential support and assistance during this project. Marc Jacobson of the Systems Applications Program spent tireless, enthusiastic hours creating a successful and user-friendly controller and Dynamic Arterial Responsive Traffic System (DARTS) simulator. Joseph Koothrappally also assisted with making the simulation efforts a success.

Bryan and Henry Beyer of NAZTEC, Inc. of Houston took time from their busy schedules to discuss past DARTS implementation products developed by NAZTEC and to investigate implementation possibilities for a radio-based communications system that would support a software version of DARTS.

Last but not least, gratitude is expressed to Harvey Beierle, retired TxDOT Signal Systems Manager for the San Antonio District, for taking a reprieve from his retirement activities to discuss the logic and function of DARTS as a real-time traffic control system.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

SUMMARY

The focus of the research effort was a method of improving traffic flow within towns like Falfurrias, Texas, where a major arterial route - in this case, US 281 - passes through a rural community. Examination of the environment in Falfurrias identified most traffic as through vehicles, and a high percentage of trucks that were bound for, or returning from, the border areas of South Texas. Local traffic flows were relatively light in comparison to the US 281 traffic load carried through the five isolated (i.e., uncoordinated), actuated signalized intersections in Falfurrias.

From among many technologies examined, spread spectrum radio was selected as a highly capable data transmission technology that was both less expensive and required less installation time than more common media, such as twisted pair cable. Subsequently, researchers installed radio communications equipment in Falfurrias. With the communications system in place, closed loop system software was installed to provide reliable, coordinated signal operations in Falfurrias.

Further research into signal systems identified the Texas Department of Transportation's Dynamic Arterial-Responsive Traffic System (DARTS) as one means of providing real-time coordination along an arterial. Fundamentally, the DARTS system allows each intersection to operate in its inherently efficient isolated, actuated mode until a need for main street progression exists. When loop detector sensors identify a platoon of vehicles, signals are sent to the DARTS system at each downstream intersection, and a green signal is arranged for the arriving platoon as it reaches each intersection. Provisions are made so that undue delays are not experienced by cross street vehicles and pedestrians.

Project timeline and resources prohibited the field installation of DARTS-enabled signal controllers in Falfurrias. To continue this experiment, a simulation system was devised to recreate the roadway, traffic, and signal conditions in Falfurrias. The Texas Transportation Institute (TTI) developed the Fully Actuated Controller Simulator (FACS) to model standard signal controller operations and added the DARTS system to this program. Previous research at TTI produced the TexSIM simulator, which was used in this project as a means of modeling the roadway geometry and traffic volumes found in Falfurrias. Researchers compared model output to field data collected in Falfurrias, and the validated models produced reliable travel times and intersection delays.

The DARTS functions were then "turned on" in the models in an effort to see how well the DARTS system would function in Falfurrias. Compared to uncoordinated conditions, the DARTS system produced an average US 281 travel time savings of about 18 percent. Slight delay increases were noted for cross-street traffic, but these increases were more than compensated for on an overall system basis by the time savings to through vehicles and border-bound heavy vehicles on US 281.

Based on success with both radio communications and the DARTS system, recommendations were made to deploy radio equipment and to renew interest and implementation of the DARTS algorithm. The FACS/DARTS and TexSIM programs developed as part of this project can be used to train personnel in DARTS functionality and calibration.

CHAPTER I.
INTRODUCTION

Signal systems, and signal system communication, have undergone a multitude of changes in the last several years. The National Electrical Manufacturer's Association (NEMA), which publishes and administers standards for a variety of electrical devices and interfaces, has recently released the TS-2 standard, the second generation of standards for electronic traffic signal control devices. In addition, increased availability and inventive use of communication media (personal communication systems, digital paging, two-way cable company communications, fiber optics, increased availability of wireless spectra, etc.) have made a variety of media and devices available for signal communications in a highly competitive market. Finally, as part of the nationally sanctioned Intelligent Transportation Systems (ITS) implementation effort, new standards and specifications are being developed for the protocols and devices used in ITS, including signal systems.

Amid the uncertainty of communications media alternatives, varying system functionality from multiple vendors, and initial and maintenance costs, municipal and state transportation engineers are often in a position where "best" decisions must be made surrounding improvements to local traffic signals and signal systems. Summarized below are a limited number of the concerns surrounding such a decision:

1. Initial, transition, and maintenance cost of signal system software and hardware;
2. Training operations and maintenance staff for new software and hardware use and maintenance;
3. Compatibility of system software and hardware with previous versions of vendor's software, and all other vendor's hardware and software;
4. Ability of vendor to successfully deliver product in a timely fashion;
5. Cost of vendor support services and training;
6. Vendor's ability to maintain product line and spare/replacement parts;
7. Cost of system changes/modifications post-award of contract to vendor;
8. Reliability of system software and hardware components; and,
9. Maintenance of spare parts inventory that can support (multiple) vendor's products.

While the above list is by no means representative of all major concerns in making an informed signal system choice, it is given here as an example of the complexity of an issue faced in every municipality and state transportation agency across the country. These decisions are increased in complexity and order of magnitude by the recent emergence of new technologies, standards, and systems control alternatives in the traffic control arena. This project summary report is intended to clarify the facts and document research into one major aspect of signal systems - the communications infrastructure.

ROLE OF COMMUNICATION IN SIGNAL SYSTEMS

Early implementations of electronic signal control at roadway junctions were simple timer devices that alternately activated the signal indications for intersection approaches for a predetermined, fixed length of time. As more and more of these devices were eventually used and relied upon in dense urban areas, it became necessary to find methods for linking the signal control devices together to allow traffic to safely and continuously move through major arterials, while maintaining the allowance of "green" time to cross streets. As these needs emerged, the devices actually used to perform the automatic changing of signal indications were themselves becoming more intricate and capable of performing additional functions.

Ultimately, traffic engineers devised methods to link the signal controllers of adjacent intersections. In the first installations, twisted wire pairs were used to create a synchronization circuit that would hold, or "freeze," a given signal indication at a slave intersection controller until the timing dial, or "clock," of the slave became synchronized with the timing dial of the master controller. Such systems not only required the communications media but also the mechanical and/or electronic means of manipulating one of the devices until the appropriate, pre-established conditions (i.e., synchronization with the master) were satisfied. Thus, the transmission of an electronic pulse through copper wire became the enabling mechanism for coordinating signal control devices.

As traffic control systems have evolved, a variety of methods have been used to interconnect signals along arterial streets and in networks. Currently, the technology available to transportation engineers allows signal interconnection using time-based interconnect, twisted pair cable, coaxial cable, spread spectrum radio, fiber optic cable, and other media. In addition, the communications media itself has become a more integral component of signal systems over time, as it enables remote monitoring of field controllers, downloading and uploading of controller settings, transmission of intersection traffic volumes, and even real-time, centralized control of intersection control functions.

COMMUNICATIONS ARCHITECTURES AND MEDIA

Communication Architectures

Communication architecture defines the system design in terms of how elements relate to one another and the general framework in which each element and system is located. Figure I-1 identifies generalized types of traffic control system architectures. Knowledge of real-world traffic control systems leads to an awareness that practical and political considerations impact how systems are designed to serve municipalities, and such systems are not optimally configured and utilized.

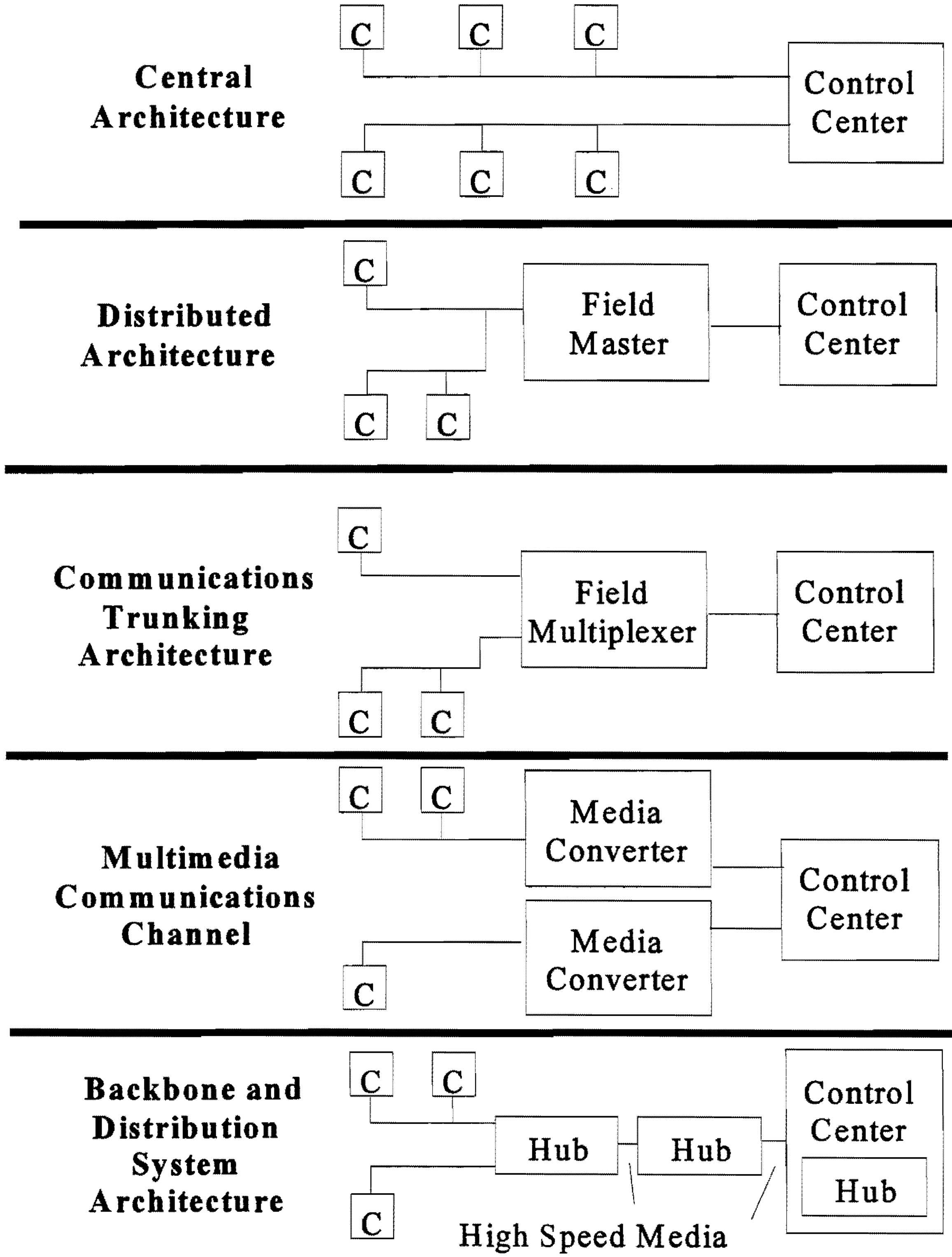


Figure I-1. Traffic Control Communication System Architectures

Communications Media

A wide variety of communications media options exist for use in the transportation field. For purposes of discussion here, media are broken down into the wireline (i.e., cable-based) and wireless (i.e., radio frequency) categories. Cost and ease of installation vary widely, depending on choice of media. A limited comparison of media for use in this research project is presented later in this research project summary.

Wireline

Though wireless communications media are gaining popularity in the transportation engineering community, land lines are by far the most commonly used media for transferring data between field devices and control centers and/or other field devices.

Dial-up telephone lines are a popular means of accessing control devices in small- to medium-sized cities and suburbs of large urban areas. The critical need easily filled by the dial-up phone line is access from a signal shop or traffic/control monitoring center to an on-street signal system master. For agencies with large coverage areas, the monthly charges for the on-site phone drop at the master controller are readily accepted in lieu of the large capital outlay required for installing an owned cable network.

As signal controllers are typically not outfitted to initiate a call, dial-up service is mainly used for occasional central monitoring of remote field devices and the downloading and uploading of new or modified signal timing plans for the intersections administered by the master. Communication between the master and local controllers is usually accomplished with agency-owned twisted pair, though other wire-based and wireless alternatives are becoming more common. In terms of system architecture, these systems are either central or distributed in nature. Institutionally, a major issue is that dial-up access to the master is not private; a simple phone call can link any remote device to the signal controller, whether the purpose is legitimate or not.

Land line access to field devices can also be accomplished using twisted pair cable. The cable may be owned by the operating agency, which makes the initial capital investment and then maintains the cable, or it may be leased by the city or state from the local telephone company. In this situation, the phone company provides the leased line service and maintains the cable plant, but the agency bears the economic burden of perpetual monthly service charges. Whether owned or leased, the lines are "permanently" at the disposal of the operating agency, unlike dial-up lines where a "call" must be initiated for data transfer to occur. Because of this functionality, leased or owned lines commonly serve as the communications media in traffic control systems where a central control computer continuously polls, or requests, traffic control data from the signal system masters and/or individual controllers in its system. Such systems are centralized in nature and typically request data from their constituent field devices once every second.

In addition to the potentially large number of cables terminating at the control center in large signal systems, a constant issue surrounding the use of twisted pair is noise. EMI/RFI (electromagnetic interference/radio frequency interference), which can be caused by electric motors, high-voltage lines, engines, radio or television broadcast equipment, and/or weather, has the potential to block or introduce errors into data transmitted over copper cable. The "twist" of twisted cable helps counteract these forces, as does shielding which can be added to surround the conductors in the cable, but the issue of noise and its impact on transmission efficiency remains an important issue.

Coaxial cable is one alternative to traditional twisted pair cable, but it is subject to the same EMI/RFI interference that afflicts twisted pair. One distinct advantage to coaxial cable is that it is a high capacity transmission media that is capable of transmitting live video signals. In advanced traffic control systems, the same coaxial cable that is used to transmit signal control data can also be used to feed live video of critical intersections back to the control center. This added functionality is possible only through additional cost. Supplementary devices, known as multiplexers, must be added to the line to mix the signals over the same cable.

The cable media that has lately gained the attention of the traffic engineering community is fiber optic cable (FOC). FOC is inherently a high bandwidth, or high transmission capacity, media in that it is based on sending pulses of light (as digital data) down an optical fiber. The cable is virtually immune to regularly encountered EMI/RFI and is as easy to install as other cable media. FOC has low attenuation (signal weakening over a distance), so fewer repeaters (or regenerators for FOC) are needed as compared to copper media. Further, as FOC is increasingly installed, the per unit installation costs continue to drop. Perhaps most fundamentally, FOC can carry very large amounts of digital data. And, as with other media, multiplexing can be used to combine data of multiple types (or from multiple devices) to bring video, traffic signal control, variable message sign, and other data back to a central facility. With its flexibility and carrying capacity, FOC is often organized in traffic control applications as a backbone and distribution system with trunking and multimedia possibilities (depending on communications system design).

Wireless

Wireless media are as varied in number as cable media choices. One of the most common alternatives for wireless coordination of traffic signals is time-based interconnect using an external or internal coordination unit. These devices can operate in several different ways, including picking up on the 60Hz frequency of the power line servicing the controller unit or picking up on one of the nationwide WWV clock transmissions from Fort Collins, Colorado. Regardless of how the device receives its time reference, it is simply necessary that one such device be maintained for each signal controller or master in the field, such that all intersections have access to a uniform time base. From this uniform reference point in time, coordination can be arranged for adjacent intersection control devices. The primary disadvantage to this type of coordination is that it must be monitored to ensure that the devices do not fail, and there is no capability for the signal technician or engineer to access the controller remotely; all timing changes and monitoring must be performed in the field.

Other wireless alternatives offer much more functionality than simple time-based interconnect and, in fact, offer the same features and use the same system software as cable-based systems. As a useful oversimplification, the wireless device, with its transceiver (transmitter/receiver) and antenna, replaces the cable. Table I-1 is provided to frame this discussion of wireless communication and to provide a reference for the radio communication bands described in this section.

Table I-1. International Telecommunications Union Frequency Band Names
Reproduced from (*1*)

Frequency Band Name	Frequency	Applications
Very Low Frequency (VLF)	3 kHz - 30 kHz	Very long-range point-point communications (over 1000 nautical miles)
Low Frequency (LF)	30 kHz - 300 kHz	Long- and medium-range point-point communications; radio-navigation aids, aeronautical mobile
Medium Frequency (MF)	300 kHz - 3 MHZ	Medium- and short-range communication. AM broadcasting; aeronautical mobile, radio-navigation, marine radiophone, Loran; international distress, disaster; amateur
High Frequency (HF)	3 MHZ - 30 MHZ	Medium- and long-range communication. International broadcasting; International point-point; air-ground; ship-shore; space research; amateur, citizens, radio astronomy
Very High Frequency (VHF)	30 MHZ - 300 MHZ	Short-range line-of-sight communication; over-horizon "scatter" communication. VHF television, FM broadcasting; space tracking and telemetry, satellites; aeronautical distress; worldwide radio-navigation; land mobile; amateur; radio astronomy
Ultra High Frequency (UHF)	300 MHZ - 3 GHz	Short-range communication; microwave relay; over-horizon "scatter" communication. UHF television, instructional TV; land mobile; weather satellites, meteorological aids; space tracking and telemetry; radar; worldwide aeronautical radionavigation; amateur; citizens; radio astronomy
Super High Frequency (SHF)	3 GHz - 30 GHz	Microwave relay; deep space, space research, telemetry, communications satellites; radar; aeronautical radionavigation; meteorological aids; amateur, citizens; radio astronomy
Extra High Frequency (EHF)	30 GHz - 300 GHz	Microwave relay; space research; radar; radionavigation; amateur, experimental; radio astronomy
None	300 GHz - 3000 GHz	Unallocated radio spectrum

Though the technology has been around for many years, and traffic control systems have used wireless devices as many as 30 years ago, it has only been within the last three to five years that their application in traffic control environments has become widely accepted. Among the primary reasons that implementation barriers have finally begun to weaken is that suppliers of radio equipment have finally created an audience aware of both the limitations and benefits of using radio communication.

Technical, institutional; and regulatory barriers affect radio acceptability (*2*). Technical issues include turn-around time, or the time require for a radio to open a channel; bandwidth, or the quantity of information that can be carried by the wireless device; and reliability, or the impacts of noise and static on the transmitted signal. Institutional issues mainly center around acceptance of the technology. Wires and closed circuits are easy to understand; signal-bearing waveforms are not. Regulatory barriers come in the form of heavy radio communication regulation by the Federal Communication Commission (FCC). Most transmitting frequencies are allocated by a lengthy licensing process, and the bandwidth itself is highly desirable and expensive.

Fortunately, solutions exist to most of the major barriers to the use of wireless devices. Error correction techniques exist that can improve data reliability far beyond the needs of traffic control systems. Bandwidth needs can be greatly reduced by relying more upon the processing power and clock accuracy inherent in most modern traffic controllers. Rather than requiring a central control computer or master controller to poll each intersection controller on a second-by-second basis (as is common today), communication may need to be initiated only once per cycle to maintain coordination. Further, communication can be "by exception" for the transmission of data from the local device to the master or central device. Essentially, this means that the central computer or master would request data that has been stored for hours or days in the local device rather than requiring constant communication for the transmission of local controller data, such as volume and occupancy information. Communication might even be initiated by the local device when its memory is nearly full of data or when an error occurs at the local site.

As operators and systems designers hear more success stories related to the application of wireless equipment and as more experience is gained in this application in general, institutional barriers will continue to weaken. Regulatory barriers are also falling. The FCC has opened spread spectrum radio bands for use without a license. Many radios that are commercially available for traffic control use these unlicenced frequencies. Many municipalities already have other frequency spectra already reserved (and licensed for municipal use by the FCC) for maintenance fleet dispatch radio, emergency dispatch and/or monitoring use, or transit dispatch applications. As cellular phones rise in popularity for these other applications, it is increasingly likely that these spectra are unused or will be unused, creating a clean, open-channel opportunity for the use of radio communication for signal control. Frequencies can also be leased from a commercial provider, but monthly use charges are incurred. Further, if the system is designed such that once-per-second polling of local devices is replaced with report-by-exception, usage-based radio spectrum leasing is a possible wireless alternative.

Agency-owned radio communications can take the form of an area radio network (ARN), a land-based microwave transmission system, or spread spectrum. ARNs operate in the 150 to 960

MHZ transmission bands, and they require licensing from the FCC. Using an ARN, an agency can control groups of signals and similar devices over a moderate-sized geographic area, but transmission rates are limited to about 9600 baud. In the past, these systems have been used to provide contact between maintenance headquarters and mobile maintenance vehicles.

Frequencies in the 928 MHZ to 40 GHz bands are described as microwave transmission bands. These bands also require licensing by the FCC, and they usually require line of sight between the transmitting and receiving units. Data rates can be much higher than ARNs, with a practical upper limit of around 155 Mbps for digital transmission. Because of their high data transmission capabilities, microwave systems are often used for communications trunking. This use is also a practical compromise of expense versus baud rate, as microwave systems often require installation on communications towers.

Spread spectrum radio became commercially viable in 1985 when the FCC opened the 902-928, 2400-2483.5, and 5725-5850 MHZ bands to spread spectrum application. Transmission in each of these bands is allowed without the need for licensing from the FCC. The technology earns its name from the fact that the signal is spread over a wide range of frequencies for transmission and then reassembled at the receiver. The two main forms of spread spectrum are direct sequence and frequency hopping transmission. Direct sequence modulates the original signal over a wide base signal, which continually changes between two states. Frequency hopping changes the carrier frequency over a multitude of different frequencies, and the receiver knows in advance what the order of the changing frequencies will be. One concern over the long-term use of the 902-928 band for signal applications is the fact that since the channel is open for use without a license (and, hence, is not controlled), it has the potential to become very noisy in the future as more and more devices use these easily-accessible frequencies.

Leased wireless services can take the form of cellular radio service, packet radio, or satellite transmission. Many users are already familiar with the "cell" technology that enables the use of cellular phones. Cellular radio modems can be purchased to provide communications for signal systems, but the technology and how it is commercially administered make it more viable in traffic applications for infrequent use, such as in portable changeable message signs. Based on the popularity of the service for cellular phone and the limited number of channels available for cellular use, it is unlikely, especially in the long run, that cellular is a cost-effective choice for signal systems. This is especially true if constant communications must be maintained between the central computer and the intersection controller (i.e., if "report-by-exception" is not employed).

Packet radio is a commercial radio service designed for data transmission rather than voice transmission, like cellular radio. Remote devices communicate with radio base station antennas owned or leased by the radio service provider. The radio modems and their interfaces may or may not be proprietary, but they must be purchased by the agency wishing to use the radio service. Like cellular radio service, packet radio is not cost effective in an architecture where continuous or near-continuous communication is required between intersection controllers and a central control or monitoring computer. Packet radio is best suited to temporary communication needs where frequency of use justifies the cost of the service contract with the packet radio provider and the cost of the radio modems.

Other wireless options are available, including transmission using satellites. A unique aspect of satellite usage is that providers typically do not link circuit length to pricing. Thus, though the service is not cost effective for continuous signal system communication, it may have applications in area-wide or statewide remote monitoring applications. The FCC has licensed the "C" band (5.925-6.425 GHz uplink, 3.700-4.200 GHz downlink) and "Ku" band (14.0-14.5 GHz uplink, 11.7 - 12.2 GHz downlink) for fixed service satellite communications. However, the limited number of providers and uncertainties involving channel pricing currently make this technology uncertain for future signal system application.

Despite the number of radio communication options available for potential use in signal system applications, only a few have been proven to provide cost-effective long-term service. These technologies tend to be those owned by the agency enabling wireless signal system communication. Regardless of which technologies are employed, it must be recalled that all radio transmission has inherent advantages as well as disadvantages. Table I-2 enumerates the pros and cons of wireless communication in signal systems.

Table I-2. Advantages and Disadvantages of Radio Communications Systems
Adapted from (*1*)

Advantages	* No need for physical medium (cable) * No cost of major land line installation and maintenance * Used to span natural barriers or provide communications link between points where right-of-way is not available * Flexible implementation * Commercial off-the-shelf equipment available * Used in a number of traffic control systems
Disadvantages	* Relatively complex design since local environment must be examined * Limited choices of operating frequencies based on regulatory issues * Path line-of-sight constraints in the microwave range (above 900 MHZ); clearance required of obstacles governed by propagation relationships, which must be examined * Fading considerations (signal loss over distance) * Turnaround time considerations (channel access time) * Limited bandwidth * Requires external antennas and cable * May require repeaters

Media Comparison

The selection of appropriate communications media depends on a myriad of factors. The most important of these factors have more to do with agency needs than the aspects of the media themselves. Ranking among the primary concerns are short-term and long-term needs for type and quantity of transmitted information; maintenance cost and personnel/time requirements for communications infrastructure; availability of existing capital for funding communications infrastructure; whether the finances are available immediately or spread out over multiple years; and, the architecture in which the field devices and communications equipment will be configured. Once these decisions or determinations have been made, the process of media selection can begin.

Table I-3 (below) is intended to clarify and compare some of the major characteristics of each type of wireline and wireless communications media. Given an appropriate system architecture and adequately designed provisions for communications trunking, all listed technologies are capable of handling the minimal communications requirements of modern day intersection controllers and field master controllers, even in a system requiring once-per-second communication.

Table I-3. Communications Media Comparison
Reproduced from (*3*)

Type	Media	Medium Range Data Speed (8+ km) (5+ miles)	Long Range Data Speed (24+ km) (15+ miles)	Full Motion Video Compatible	Relative Cost ($/bps)	Reliability
Wireline	Copper Twisted Pair	1.5 Mbps	1.5 Mbps	No	Low	High
	Coaxial Cable	100 Mbps	100 Mbps	Yes	Medium	Medium
	Multi-mode Fiber	500 Mbps	N/A	Yes	Low	High
	Single-mode Fiber	40 Gbps	40 Gbps	Yes	Low	High
Wireless	Digital Microwave	155 Mbps	155 Mbps	Yes	Medium	Medium
	Digital Packet Radio	250 Kbps	N/A	No	Medium	Medium
	Cellular	19.2 Kbps	19.2 Kbps	No	High	Medium
	Microcellular	N/A	N/A	Yes	Low	Medium-High

Studies were conducted for the City of Rockford, Illinois, to determine cost effectiveness and life cycle cost comparisons for several different communications media in a signal system application (*4*). Figure I-2 illustrates the results of this comprehensive comparison among leased telephone lines, agency-owned hardwire interconnect, and agency-owned radio interconnect. The study includes provisions for varying discount rates to evaluate the sensitivity of the cost values examined. As shown in the figure, agency-owned radio interconnect is approximately 40 percent less expensive than agency-owned twisted pair cable, and averages about 50 percent less expensive than leased phone lines for the discount rates examined.

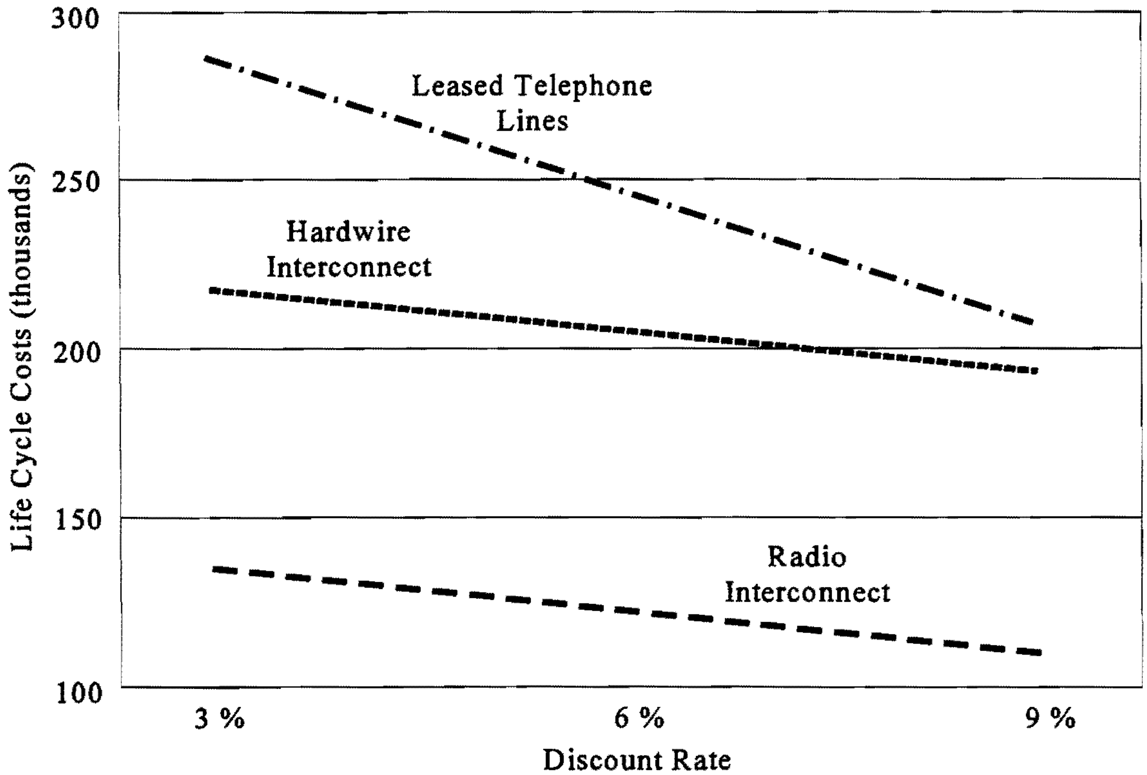


Figure I-2. Life Cycle Cost Comparison for Popular Signal Communications Media
Adapted from (*4*)

The conclusions reached in the study that produced Figure I-2 are an appropriate conclusion to this section of this project summary report:

> "The success of the on-site demonstrations conducted earlier this year indicate that radio interconnect for traffic signal communications is a viable alternative to standard communications media used today. Radio can be installed at a fairly reasonable cost as compared to hardwire installations or leased phone lines. Communications reliability is adequate for distributed systems; however, centralized (UTCS) systems should proceed with caution. It can be concluded that radio has the capability of satisfying specific communications requirements." (*4*)

INNOVATIONS AND FUTURE POSSIBILITIES

National Transportation Communications for ITS Protocol

The National Transportation Communications for ITS Protocol (NTCIP) is a family of standard communications protocols used for data transmission within and between Intelligent Transportation Systems (ITS). For purposes of clarification, the NTCIP can be envisioned as the language that is spoken between field devices, traffic control centers, and a variety of other electronic media and devices used in ITS, such that useful data transmission and reception can occur. Where possible, the NTCIP is based on existing standards in the telecommunications and computer industries. The NTCIP and related standards are intended to eventually provide a comprehensive family of communications protocols covering all ITS applications.

One component of the NTCIP covers signal systems and their communications. The end result of this effort will be an environment where signal system controllers and other devices from any manufacturer can be added to existing communications infrastructure and/or existing signal systems and retain full functionality, even if multiple agencies are involved. Researchers anticipate that the NTCIP effort, then, will eliminate current inefficiencies and equipment incompatibilities caused by out-of-date or incomplete standards development efforts of the past and the proprietary nature of existing equipment available for device manufacturers. It will help enable interoperability and interchangeability between devices and between systems from different manufacturers. It can provide more choice, more flexibility, and the ability to coordinate the operation of adjacent devices and systems.

The signal systems component of the NTCIP even includes options for user-defined messages. In essence, this aspect of the protocol allows for end users to create and implement unique solutions to transportation that are not already contained in the NTCIP. Because those solutions are developed within the overall NTCIP protocol, they can be easily incorporated into field devices that are NTCIP compatible and that have the processing power and programmability to accommodate the enhancements.

Advanced Transportation Controller

The Advanced Transportation Controller (ATC) is emerging as the next generation of traffic control devices to replace existing Type 170/179 and NEMA TS1 controllers. The most common vision of the ATC is that set forward in the California Department of Transportation's (Caltrans) 2070 specification. The Caltrans 2070 specification identifies the VMEbus industrial and process control computing platform as the architecture for the ATC.

Versions of the ATC have already been developed by multiple manufacturers in compliance with the 2070 specification. In each case, an outward chassis with keypads and interface panel houses a power supply, field input/output module, and VME circuit boards that contain processors and memory chips. Additionally, open slots in the VME allow for the addition of serial communications ports, modems of a variety of types, and a variety of other functional components for changeable message sign control, video detection systems, emergency vehicle monitoring and preemption, emergency call box operation, camera control, highway advisory radio, and even environmental monitoring.

Underlying the concept of the ATC is the desire for operating agencies to purchase an open architecture field device for traffic signal control. In the signal systems environment, open architecture allows for the use of off-the-shelf operating systems (i.e., not proprietary software), non-proprietary computer architecture, flexibility to accommodate future communication protocols (i.e., the NTCIP), interchangeability of controller components from different manufacturers, and the ability to add functionality with the simple addition of a modular component. Versions of the ATC are even available with interfaces to existing Type 170 and NEMA TS1 and TS2 cabinets.

The processing power of the ATC and its use of a non-proprietary operating system allow the traffic engineer to use high-level programming languages (i.e, C++) to develop custom software to solve a variety of traffic control problems. Further, such custom solutions will be portable to the ATCs maintained by any adjacent operating agency.

Real-Time Control Systems

The first attempts at network traffic signal control took place in the early 1970s under the federally sponsored Urban Traffic Control System (UTCS) program. Research under the UTCS program defined three generations of traffic control, simply referred to as first, second, and third. All generations of control identified under the UTCS program relied to some degree upon an extensive communications network capable of handling a central computer polling each local controller or master on a once-per-second basis.

First generation control consisted mainly of timing plans that were developed from off-line analysis programs and stored in computer memory. The plans could be called by time of day or by matching volume levels to current traffic demand. A hybrid known as first-and-a-half generation was also developed. This generation automated the timing plan development process and detected when precalculated timing plans should be modified. Numerous examples of first and first-and-a-half generation systems exist today. By design, these systems are centralized in nature. An example of a first-and-a-half generation system is the Automated Traffic Surveillance and Control (ATSAC) system in Los Angeles, California.

Second generation systems involved the real-time production and implementation of plans through on-line techniques based on surveillance data gathered from vehicle detectors. Timing plans are implemented periodically, on the order of once every 10 to 15 minutes. These systems are somewhat less centralized than first generation systems.

The third generation implements and evaluates a fully traffic-responsive, online control system. Signal timing parameters must be changed continuously in response to real-time measures of traffic variables. Third generation systems are being developed today as distributed intelligence systems. Optimized Policies for Adaptive Control (OPAC) strategies are an evolving example of this generation, and efforts are underway to enhance the OPAC strategies for network applications.

Numerous other examples of real-time or near real-time traffic control systems exist around the world today. Among them are SCATS (Australia), SCOOT (United Kingdom), UTMS (Japan), UTOPIA (Italy), PRODYN (France), and German systems. Many of these systems face the same implementation issues (i.e., advanced detection requirements, decentralization of signal control, extensive communications infrastructure) as those described earlier for systems in the United States.

Unique solutions have also been developed to attempt to improve one aspect or multiple aspects of traffic signal control problems in networks or along arterial roadways. The Dynamic Arterial Responsive Traffic System (DARTS) is an example of one such system that was designed by personnel of the Texas Department of Transportation (*5*). DARTS provides progression along an arterial roadway only when a platoon of sufficient size exists; when the DARTS system is not engaged, each intersection operates in isolated, actuated mode. The DARTS system will be discussed in greater detail in later sections of this report.

CHAPTER II.
PROBLEM IDENTIFICATION (CASE STUDY)

EXISTING CONDITIONS IN FALFURRIAS, TEXAS

Traffic congestion is no stranger to small, rural communities that have developed along major highways in Texas. Frequently, these communities are large enough to require traffic signals for safe traffic and pedestrian crossing of the highways but not large enough for congestion relief facilities, or bypasses. In these situations, the entire traffic load of the highway is carried along the "Main Street" of the rural community. Falfurrias, Texas, is one such community. It is located along United States Highway 281, approximately one hour north of the Mexico border region of south Texas and the Texas cities of McAllen, Harlingen, and Brownsville (see Figure II-1). Since US 281 is a major trade route to this region, a large percentage of heavy vehicles move through Falfurrias. Moreover, a large majority of the traffic that uses US 281 in the vicinity of the town is through traffic.

Intensifying the traffic situation along US 281 in Falfurrias is the large percentage of trucks that are laden with cargo headed for the border, or are returning to central Texas and/or other areas of the state or country after dropping off or receiving a load of cargo at the US-Mexico border. There is also a considerable amount of oil drilling activity in the central South Texas area, placing that many more heavy vehicles on US 281 for drilling activities, equipment maintenance, and oil retrieval and delivery. Again, a vast majority of these vehicles, in the neighborhood of 90 to 95 percent, are vehicles that will pass through Falfurrias.

Connecting with US 281 in Falfurrias are other important routes that access other cities, towns, and other transportation; two of these facilities, State Highway 285 (i.e., Rice Street) and Farm to Market Road 2191 (i.e., Noble Street) form signalized junctions with US 281. In particular, SH 285 links Falfurrias with the extremely active inland port of Laredo (via its connection with SH 359) to the west, and United States Highway 77 to the east, which allows access to the cities and ports of Corpus Christi and Brownsville.

Prior to this project, signal control in Falfurrias was traffic actuated at each of the five signals along US 281, including Rice St. and Noble St. However, none of the signals were coordinated to work together. Creating a traffic control environment that better served the public framed the objectives of this study and served as the goal against which project progress could be gauged.

Though delays are not excessive during most periods of the day in Falfurrias, queue lengths are important because of limited block spacing and truck presence. Also, significant amounts of cross-street traffic are present, with intensity increasing during school drop-off and pickup times. School activity also increases pedestrian activity, with most movements crossing US 281. In essence, cross street activity and pedestrian needs are pitted against higher through traffic volumes and heavy vehicle presence and storage needs along US 281. Frequency of heavy vehicles stops along US 281 has created some degree of pavement rutting along US 281, indicating that additional steps made to improve through traffic flow along US 281 also have the potential to increase the useful life of the pavement infrastructure.

The roadway geometry is also of concern in Falfurrias. US 281 is a four-lane facility with two lanes in each direction (see Figure II-1). Turning movements are not accommodated with turn bays at any of the intersections in town. Cross-street approaches are typically one lane approaches with the exception of Rice St., which has a left-turn bay on the east (i.e., westbound) approach and a shoulder that is used as a right-turn bay on the west (i.e., eastbound) approach. The proximity of buildings, sidewalks, and utility poles/facilities to the right-of-way line severely limit possibilities for expanding the US 281 cross section.

In the case of Falfurrias, it is especially unfortunate that a center two-way left-turn lane cannot be constructed. This improvement would safely harbor turning vehicles out of the way of much heavier volume through movements (which also have a large percentage of heavy vehicles); would easily accommodate the relatively light turning traffic needs at the signalized intersections in Falfurrias; and, would improve signal efficiency at Rice St., the busiest of the signalized intersections in town.

ALTERNATIVES FOR IMPROVEMENT

A variety of geometric and signalization improvements have the potential to increase traffic flow along US 281, decrease cross-street delay, and increase both vehicular and pedestrian safety. Unfortunately, the most common solutions to these problems often address only one of these needs - traffic flow improvements along the major artery. And, as discussed earlier, opportunities for adding turn lanes or turn bays along US 281 are very limited. Improvements in the operation of the signalized intersections that provide safer and more efficient movement for US 281 and cross street vehicles and pedestrians appear to be the best hope for improving mobility in Falfurrias.

Time-Based Coordination

Time-Based Coordination (TBC) offers the potential to provide progression to platoons of vehicles along US 281. Using a uniform cycle length at each intersection, the signal displays can be arranged in time, or offset, such that when a green signal indication is received at the first intersection, the platoon of vehicles is able to pass through all other intersections without receiving another red indication. Manual and computerized techniques exist to calibrate the settings at all intersections such that at least some degree of progression can be provided for traffic traveling in both directions along the major artery. The more complicated the signalization (i.e., the more signal phases, such as protected green arrows for left turns) at each intersection, the more likely compromises will have to be made in allowing for main street progression. In Falfurrias, the situation is relatively simple at all intersections with the exception of Rice St., where separate left-turn arrows are provided for both westbound and northbound traffic.

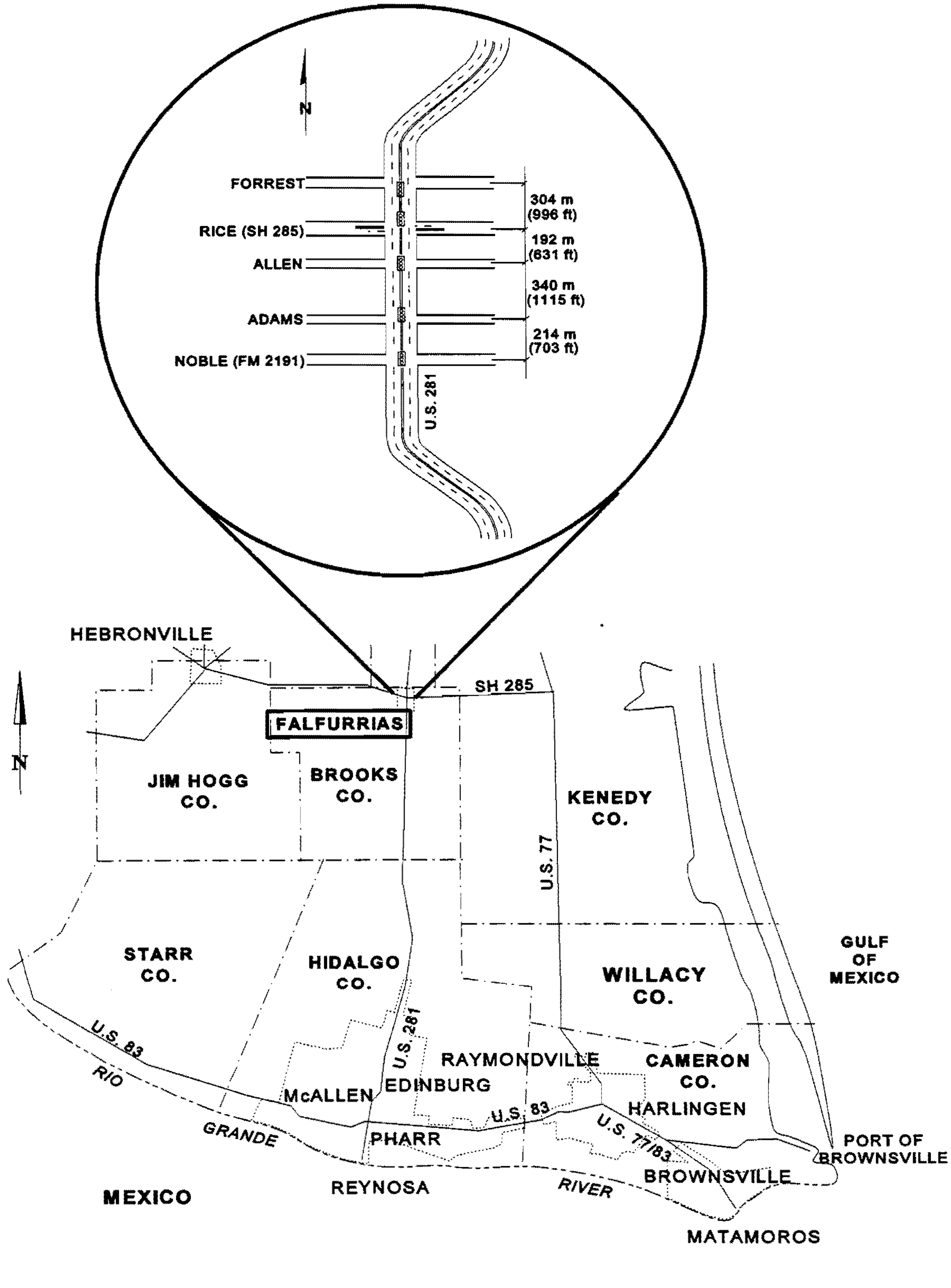


Figure II-1. Area Map and Traffic Network in Falfurrias, Texas

TBC would expedite the movement of traffic along US 281 through Falfurrias. However, the use of TBC restricts each intersection to a common cycle length. Unfortunately for cross-street motorists, this is likely to increase the amount of time they are delayed at the signal before receiving a green indication. As the intersections in town are currently running in an isolated and traffic responsive mode, local motorists may be dissatisfied if a movement were made to TBC control.

TBC control can be made more flexible by the introduction of separate timing plans for different times of the day. Based on time-of-day selection, the timing plans would become active at each intersection at the same time. For instance, during the early morning and late evening hours, a short cycle length may be selected so that all approaches to each intersection are serviced quickly, or the intersections may be allowed to revert to isolated, traffic responsive control. During the day, however, and especially during the peak traffic hours of the day, a longer, fixed cycle length would be introduced that allowed for traffic progression along US 281. And, during hours of the day when cross-street volumes are higher (i.e., during school entrance or release hours), extra green time can be allotted the cross streets for improved cross street vehicle and pedestrian movement.

The responsiveness that is possible even with a simple scheme like TBC cannot be achieved and maintained without the attention of the responsible agency. Each intersection and artery must be examined and information about the traffic volumes, roadway geometry, and signal system must be collected for each time of day that a different set of timing parameters is desired. Further, once any changes are made, the data must be recollected on a semi-regular basis to see whether or not significant changes have occurred, especially in terms of traffic volume changes. As most agencies are responsible for a large number of intersections, perhaps even in a large number of smaller communities, and most signal personnel also carry a variety of other responsibilities as well, it is unfortunately the case that a single timing plan is often all that is used at each site on a daily basis. For local motorists, the result is TBC signal control that is inflexible and appropriate for only a portion of the day. Further, in application to Falfurrias, the TBC is realistically only able to improve traffic conditions along US 281, one of three overall objectives for improved signal operation.

Closed Loop System

Closed loop systems (CLS) offer, as a minimum, the capabilities described above for a TBC system. Intersection controllers within a CLS are linked by any one or a variety of communications media such that each device is in contact with a master controller. The master maintains the coordination of the system by sending synchronization pulses to each controller, whereby offsets can be maintained and signal progression can exist along an arterial. Multiple timing plans can be used as required throughout the day, and the initiation of each plan is administered by the master controller. Special plans can even be designed for special events and initiated by the master on a certain day of the week, month, or year at a predetermined time.

CLS also have additional features that are important to the traffic engineer and/or signal system administrator. A phone line link can be enabled at the master controller and, via modem, a remote computer (i.e., at the signal shop or traffic control center) can access the master controller and receive status reports, traffic volumes, alarms, and a variety of other information about the system and each individual intersection controller. Without leaving the office, the engineer can call special timing plans, if desired and the need is identified, or simply monitor the traffic situation after receiving a phone call from a concerned citizen. Most CLS even have the capability of changing timing plans automatically once certain traffic volume or density thresholds are reached on system loop detector sensors.

CLS are state-of-the-art equipment for small to medium-sized communities. However, it must be recalled that they are only efficient if the timing plans are maintained on a semi-regular basis and if they are monitored to ensure that they meet the needs of the motoring public. Further, CLS are hinged to the cycle length concept, which means that each intersection, regardless of how much traffic it accommodates, must be based on the system cycle length, or the cycle length used by all of the intersections in the system. The effectiveness and the efficiency of the system are intimately linked to the experience of the system administrator and the amount of time that administrator is able to spend monitoring system performance and updating the signal settings as required.

Real-Time Control

Real-time control (RTC) has the potential to overcome all of the deficiencies cited above in TBC and CLS systems. And, as described earlier in this document, a variety of real-time control systems with unique features and system architectures exist. However, one impediment exists that virtually eliminates the possibility of implementing such a system in a small community, and that is cost.

Most RTC systems are designed for deployment in the complex signalized networks found in large urban areas. Not only is the software and logic of these systems proprietary and expensive, but equipment that is capable of executing the commands must be purchased and/or existing systems modified. Consultants are usually involved to design the system architecture, which almost always requires the creation or enhancement of a communications architecture that reaches down from a central administration and/or monitoring computer system to the individual intersection controller level. System design consultants are also involved in the setup and calibration of the system once it is physically installed. And, personnel of the agency procuring the system must be fully trained in system operation, maintenance, and troubleshooting.

One exception to the above general rule about RTC systems is the DARTS system, which was mentioned previously in this document and which will be discussed later in much greater detail. Though the system is not one that would typically be brought to the mind of a traffic engineer discussing RTC systems, it is deftly capable of solving the traffic problems found in Falfurrias, and the system logic is public domain information (i.e., it is freely accessible).

CHAPTER III.
COMMUNICATIONS SYSTEM COMPARISON AND SELECTION

MEDIA COMPARISON FOR FALFURRIAS, TEXAS

Researchers performed an analysis to determine the most cost effective communications technology for use in Falfurrias. Based on availability, cost, and the anticipated communications capacity needs for the project and for the future in Falfurrias, the list of available technologies was narrowed to two: agency owned twisted pair cable and radio interconnect. Even a rough cost and installation time comparison resulted in sufficient information for decision making (see Table III-1).

Table III-1. Comparison of Selected Communications Media for Falfurrias, Texas

Comparison Item	Radio	Twisted Wire Pair (in conduit)
Installation Cost (equipment and labor)	$19,000	$46,000
Installation Time (construction time only)	3 days	10 days

Radio communications equipment was selected for implementation based on significantly lower cost and installation time as compared to agency-owned twisted pair cable. Thus, though radio communication has only become widespread in signal applications within the past few years, this technology is less expensive and can be installed more quickly than cable media in situations like the one found in Falfurrias.

SELECTION OF RADIO EQUIPMENT

Once the decision was made to procure radio equipment, the task at hand became the selection of which type of radio equipment to purchase. Some of the options included spread spectrum radio or an area radio network that would use one of the frequencies allocated for highway maintenance use by the FCC (see Table III-2) as the means for allowing signal communication in Falfurrias.

Consultation with the manufacturer of the signal controllers in place in Falfurrias identified off-the-shelf spread spectrum radio equipment that was previously tested in a variety of conditions and at a variety of field sites with flawless performance. A recommendation from the signal equipment manufacturer was made to purchase that radio equipment, and that recommendation was carried through equipment procurement for the project. Not only did the acquisition of spread spectrum devices (i.e., which operate in the 902-928 MHZ band, unlicenced by the FCC) save researchers and TxDOT personnel the time and trouble of checking into and receiving FCC clearance to operate the radio equipment in Falfurrias as an area radio network (i.e., in licensed bands), it also saved future energy that would have been required to correctly configure and ensure compatibility of other devices with the signal controller manufacturer's equipment.

Table III-2. Frequencies Allocated for Highway Maintenance Under Part 90
Reproduced from (*1*)

Frequency Band (MHZ)	Class of Station
33-47	Base or Mobile
72-76	Operational Fixed
150-170	Base or Mobile
169-172	Mobile
450-470	Fixed
470-512	Base or Mobile
806-824	Mobile
851-869	Base or Mobile
928 and above	Operational Fixed, Base or Mobile
929-930	Base Only
1427-1435	Operational Fixed, Base or Mobile
2450-2500	Base or Mobile

For each intersection, a radio, radio power supply, antenna, cabling, and connectors were required (see Table III-3). Each radio is capable of transmitting at 9600 kbps, a relatively high data rate for signal system communications, which is usually accomplished in today's common closed loop system installations with 2400 kbps modems. The radios are also capable of full duplex communications, which means that they can receive and send signals simultaneously (i.e., rather than half duplex, which allows only transmission or reception at one time). As a final operations detail, the spread spectrum radios are direct sequence devices, which spread their data signal over a wide carrier signal, rather than frequency hopping devices, which send data over a mix of frequencies.

In essence, a high-speed, flexible, robust (i.e., transmission error resistant) spread spectrum radio communications system was purchased as part of the project and installed in Falfurrias.

Table III-3. Selected Equipment for Radio Communications Installation in Falfurrias

Item	Count*	Description
1	5	L-Band, 902-928 MHZ, 9600 kbps synchronous transmission radio modem
2	5	12V DC power supply for the radio modem
3	5	L-band, 902-928 MHZ, 15 dBi yagi (directional) antenna
4	5	RS232 interface cable (controller to radio modem cable)
5	5	Antenna mounting bracket
6	5	Coaxial cable and connectors, linking the antenna and radio

* Note: One full set of equipment installed at each of the five intersections

INSTALLATION OF RADIO EQUIPMENT

The radio equipment was installed on September 18-20, 1996. Figure III-1 illustrates the connectivity of radio components inside of the NEMA TS-1 cabinets found in Falfurrias. Each intersection has an antenna that is mounted atop the signal mast arm nearest the controller cabinet. Coaxial cable connects the antenna to the radio modem, which is located in the cabinet and receives power from the cabinet's 110V outlet. The modem is connected to the controller with an RS 232 interface cable to the controller's serial communications port.

The intersection controller at Forrest Street serves as the master controller and has a phone line connected to it (see Figure III-2). Via the phone line, the closed loop system can be monitored and the controller settings for all five intersections can be adjusted from a remote location. This is especially advantageous in Falfurrias, since the TxDOT Pharr District signal shop is located in Pharr, Texas, about 95 kilometers (60 miles) south of Falfurrias.

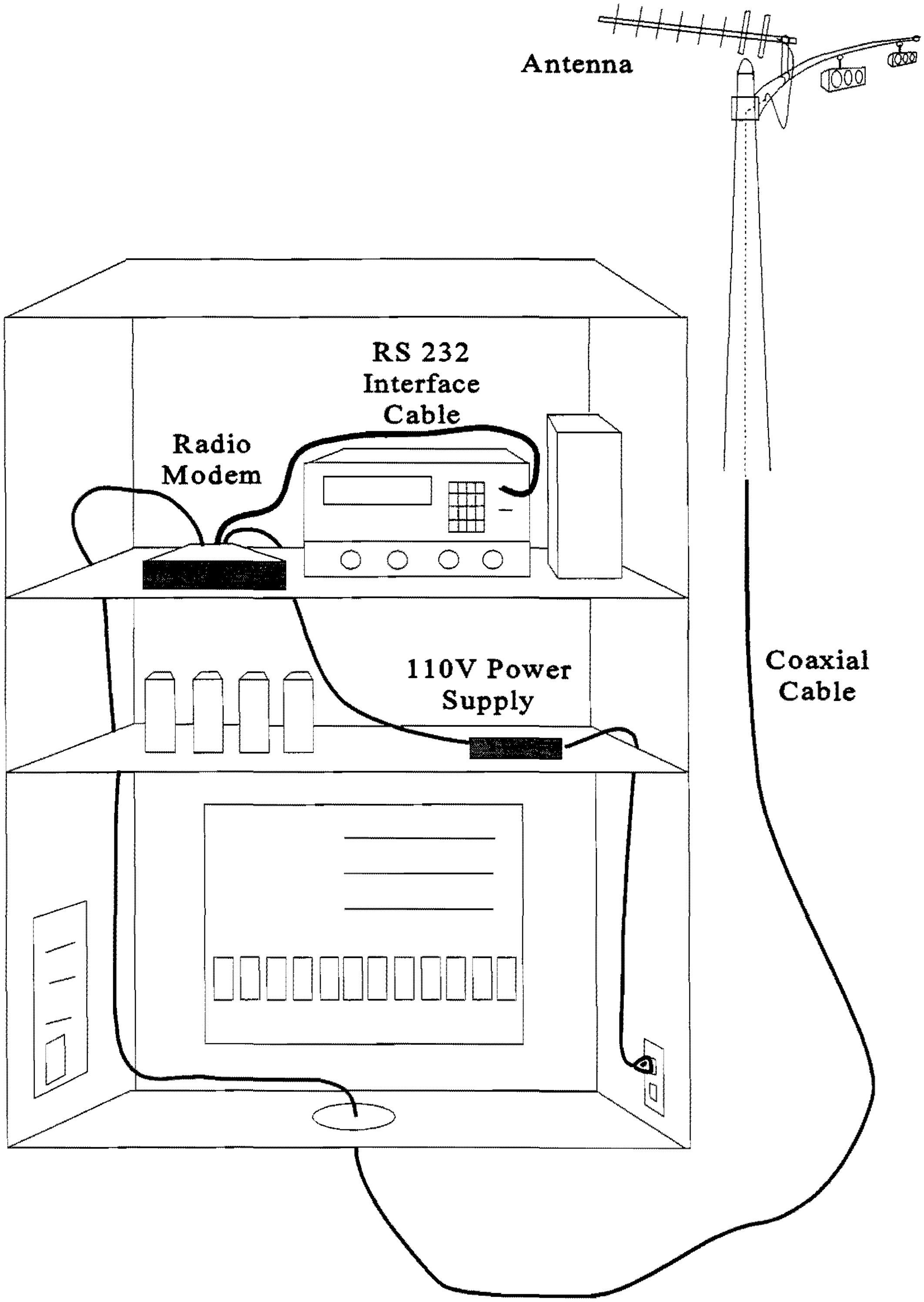


Figure III-1. Radio Communications Equipment Within a NEMA Controller Cabinet

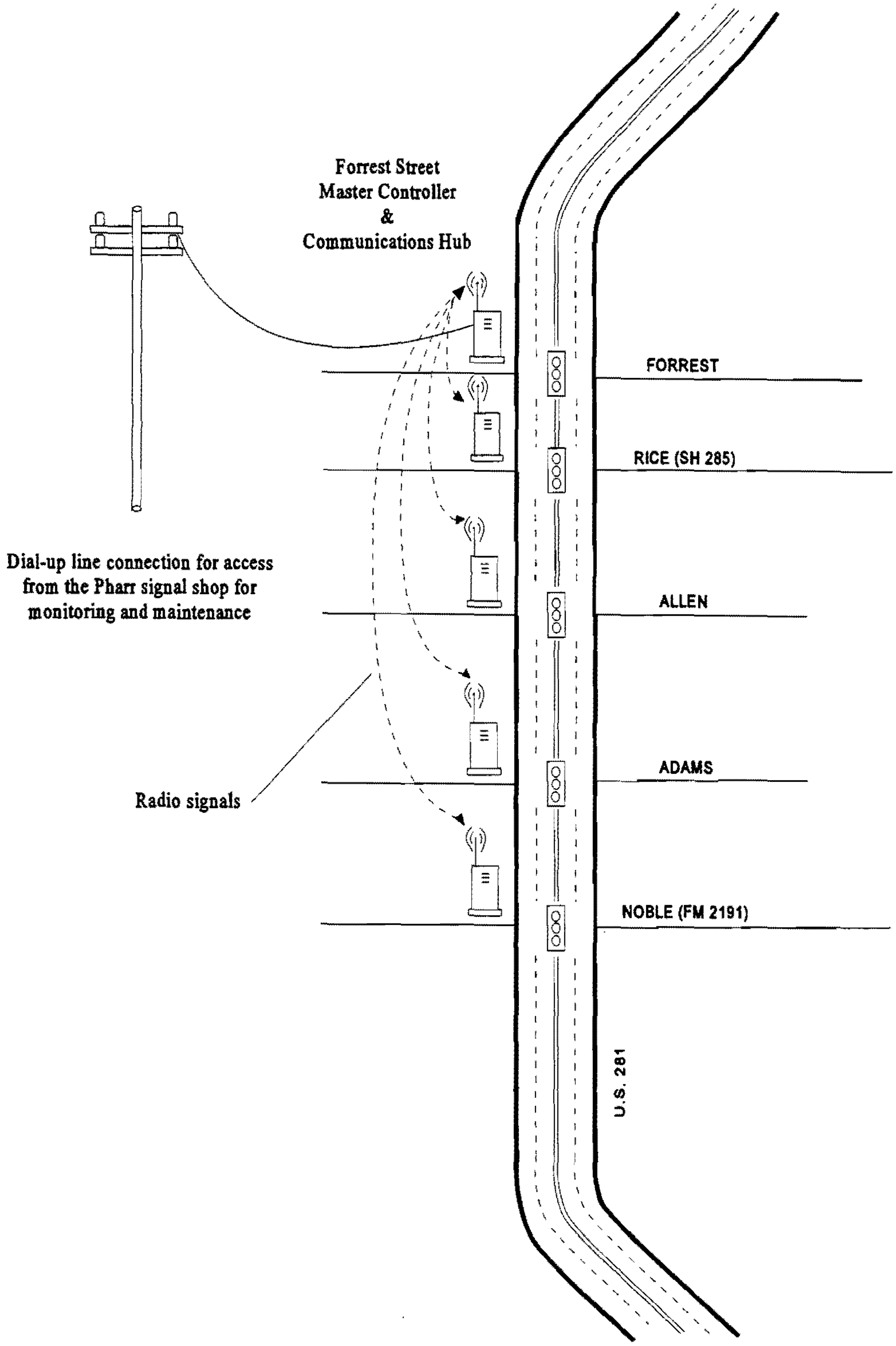


Figure III-2. Spread Spectrum Radio Communications System Design, Installed in Falfurrias, Texas

CHAPTER IV.
DEVELOPMENT OF DARTS-BASED REAL-TIME CONTROL SYSTEM

The DARTS (Dynamic Arterial Responsive Traffic System) was originally developed in the 1970s by Harvey Beierle of the San Antonio District, TxDOT, as a means of dynamically linking adjacent signalized intersections. A unique aspect of the system is that when the DARTS system is not active, the controller at each intersection operates in isolated, actuated mode. Thus, when coordination between adjacent intersections is not required, each intersection operates very efficiently in actuated mode. Control at each intersection is only coordinated, or influenced by DARTS, when Main Street progression is necessary.

DARTS FUNCTIONALITY AND DARTS DEVICES

Within DARTS, devices at each intersection send messages back and forth to one another about approaching traffic, and DARTS devices at the receiving intersection use this information to arrange a green signal indication for main street vehicles when they arrive at the next intersection. In past implementations, all communications for the system took place over multiple strands of twisted-pair cable. Commands were, for the most part, executed external to the signal controller as discrete electronic signals applied to the control cabinet's backpanel. In this manner, the external DARTS device was able to assume a level in the control hierarchy whereby it could influence the operation of the signal controller and bring about the desired DARTS results.

The external, or auxiliary, DARTS solid- state devices that have been manufactured in the past can be connected directly to any modern (NEMA standard) full-actuated traffic signal controller. One pair of conductors is needed to transmit the necessary platoon identification information from the upstream intersection, and another pair of conductors is required to transmit similar signals from the second upstream intersection (i.e., two intersections away). No modifications are required to a NEMA standard controller, if force-off and phase-skip features are provided.

Up to 14 electronic timing mechanisms are incorporated as parts of the DARTS system. Eight of these timers (i.e., Platoon Timer, Detector Disable Timer, T1, T2, T3, T4, T5, and T6) are allocated to platoon detection and platoon progression. The remaining six timers (i.e., TW1, TW2, QT1, QT2, PWT1, and PWT2) deal with measuring vehicle time waiting and queue length over detectors on the cross street and in left-turn lanes whose movements conflict with DARTS-progressed traffic, or with pedestrian waiting time on the cross street. Each of the following sections presents a functional aspect of the DARTS system.

Platoon Identification

For DARTS to initialize, a platoon must be detected on one and/or both of the main street approaches along the DARTS-equipped arterial (i.e., phases 2 or 6). A detector, designated as the

DARTS detector along the approach, must be occupied for at least the time specified in the Platoon Timer (PT) prior to a green signal being given to that approach. If the PT has been active for the minimum time and the main street approach (say, phase 6) receives the green, an inbound platoon start (IPS) signal is received at the downstream intersection and an alternate platoon start (APS) signal is received at the next downstream intersection.

Platoon Progression

Upon receiving an IPS signal, the DARTS system at the downstream intersection begins timing its intervals (T1, T2, T3, T4, T5, and T6) so that, ultimately, a green signal indication at that intersection on phase 6 is ready for the approaching platoon. The APS signal received at the next downstream intersection performs similar functions, again to provide a green at that intersection when the platoon arrives. Timers proceed in numerical order until the last timer (T6) is reached, at which time the platoon should have safely passed through the intersection. Figure IV-1 indicates which timers are employed as the platoon moves toward the downstream and next downstream intersections.

During the T1 interval, the platoon is predicted to travel to a point beyond which there will be insufficient time for the downstream controller (i.e., the one receiving the platoon) to terminate the Main Street green on phase 6, present the associate change interval, service a conflicting phase (with a minimum green for phase 4 or phase 5), and return to the Main Street green before the platoon arrives. Also, the detector disable timer operates, which starts simultaneously and runs concurrently with timer T1. During this interval, the phase 2 and phase 6 detectors will be disabled, and in the apparent absences of calls, phase 2 and phase 6 will gap out; other phases can be serviced when a demand exists.

After the T1 timer ends, the T2 timer initiates. This interval should end when either the platoon arrives at the outermost phase 6 detector or when the platoon is at a location which allows for the longer minimum green of phase 4 or phase 5 plus an appropriate change interval and display of phase 6 green plus driver perception-reaction time before arrival of the platoon at the downstream intersection, whichever is earlier. If the controller is in phase 6 green at the beginning of the T2 interval, DARTS places a continuous call on phase 6 to extend the green throughout the T2 timed interval. If the controller is beyond the phase 4 minimum green and a phase 5 call is present, DARTS will force the controller to terminate phase 4 and immediately service phase 5. If the controller is in the phase 4 minimum green or in phase 5, DARTS sends no command to the controller.

At the conclusion of T2, T3 begins timing. This interval is set as the longer of the minimum green plus the associated change interval for phase 4 or phase 5 plus driver perception-reaction time. DARTS provides an alternative platoon identification feature for a moving platoon that approaches the downstream intersection during T3 interval. If the phase 6 detectors are being actuated, and phase 6 green is displayed, the DARTS at the intersection receiving the platoon sends a platoon identified message to the DARTS at the next adjacent downstream intersection.

Intervals T4 through T6 have functionality similar to T3 but may use different programmable options to accommodate a static platoon. For further explanation of system details, the full TxDOT DARTS specification (*6*) can be found in Appendix A.

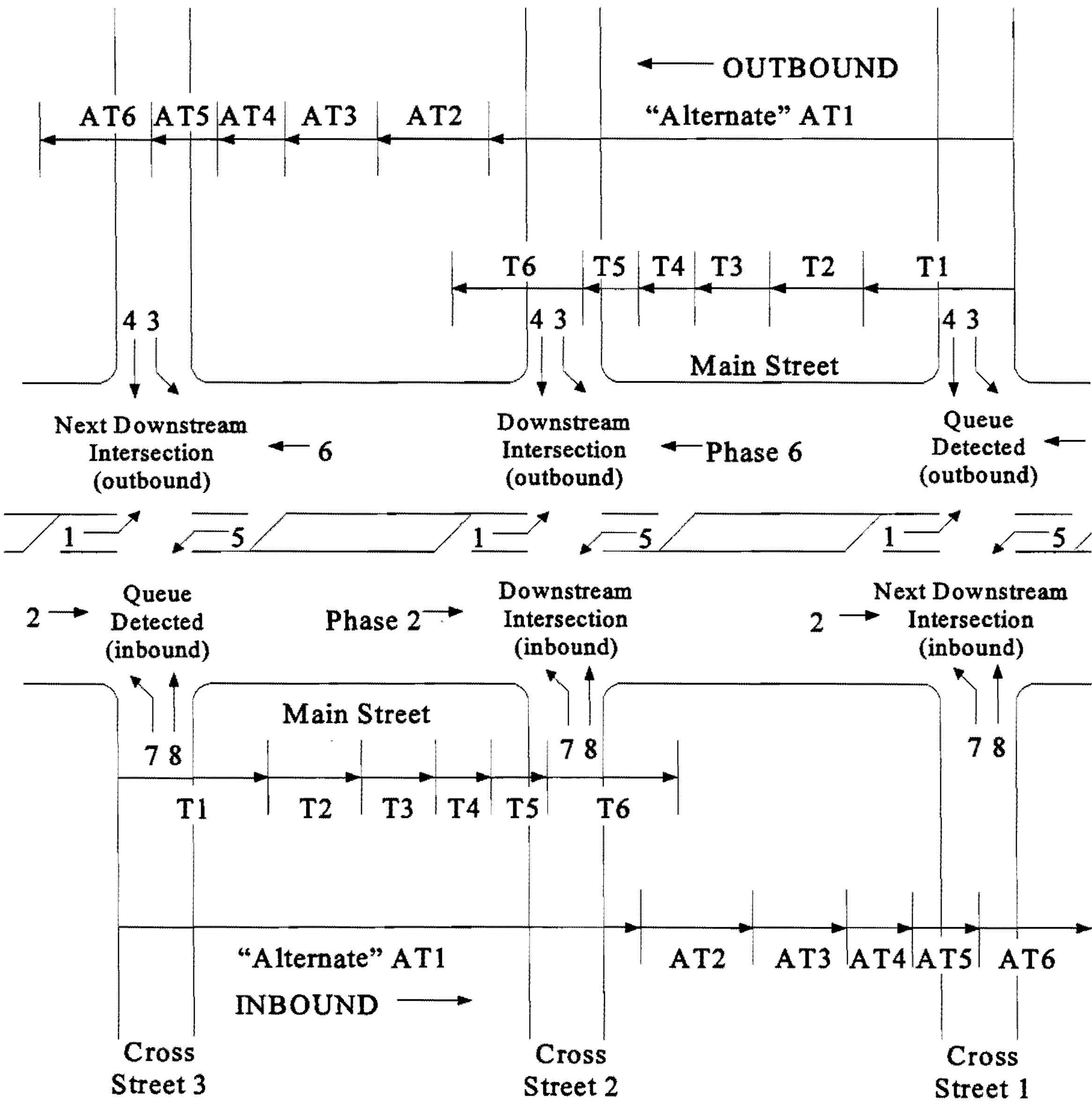


Figure IV-1. DARTS System and Timer Reference Diagram

Conflicting Phase Evaluation

To prevent intolerable delays and excessive queue buildup from developing on the conflicting phases or pedestrians, DARTS includes a series of timers which monitor the time that detectors on the approaches that are served by the conflicting phases are occupied. On each conflicting phase, one time-waiting timer (TW) is connected to a presence detector near the intersection, and a queue-length timer (QT) is connected to another presence detector that is set back from the intersection far enough to identify a excessively long queue on that approach. TW1 and QT1 monitor phase 5 approach, and TW2 and QT2 monitor phase 4 approach. Similar to the timers employed for vehicular movements, the PWT1 and PWT2 timers track delay for pedestrians on the phase 4 and phase 8 approaches. If they are occupied longer than the interval set on the timer, the phase 2 and phase 6 detectors are temporarily disabled, and the controller is allowed to extend the green on the excessively-affected phases up to maximum extension for that phase. When these phases have been serviced, DARTS commands to the phase are resumed. To provide progression for platoons of traffic in the opposing direction, all DARTS functions explained so far are duplicated (i.e., for the phase 2 approaches).

ADAPTATION OF DARTS TO SOFTWARE LOGIC SYSTEM

The complete system logic DARTS was formatted in a flowchart (see Figure IV-2) to locate all decision points in a single reference location. The flowchart is shown here to illustrate that the logic is complex in nature but can be arranged in a way that is relatively easy to understand. Due to scaling reductions that were required to reduce the flowchart for inclusion in this report, specific details are difficult to read in the figure.

Both the flowchart and the TxDOT DARTS Specification (see Appendix A) were used to guide the software coding of the DARTS system. A software program that included NEMA TS-1 controller logic, DARTS capability, and a user interface were developed so that DARTS settings could be entered into the computer. In this way, those wishing to become familiar with the DARTS system could use the software as a tutorial or as part of a traffic simulation package. The controller logic and DARTS simulation made possible by this software coding effort eventually became a key element of this project. Further, the fact that the DARTS system is now available in software (rather than just the original solid state unit originally envisioned) means that it can be readily incorporated into the controllers sold by any manufacturer willing to port the DARTS code to their controller.

DEVELOPMENT OF DARTS SIMULATION ENVIRONMENT

The simulation environment developed to simulate the varying control environments found in Falfurrias, Texas, combined two programs into one unified simulation package. The first program, known as TexSIM, was used to model the roadway features and vehicles. The second program, known as FACS, was developed for this research project to simulate NEMA TS-1 ring-based controller logic and the DARTS logic found in the TxDOT DARTS specification. Minimum system requirements for running the two software programs include a 486/66 MHZ computer using the Windows 95® operating system, 16 Mb of RAM, and 15 Mb of free hard disk space.

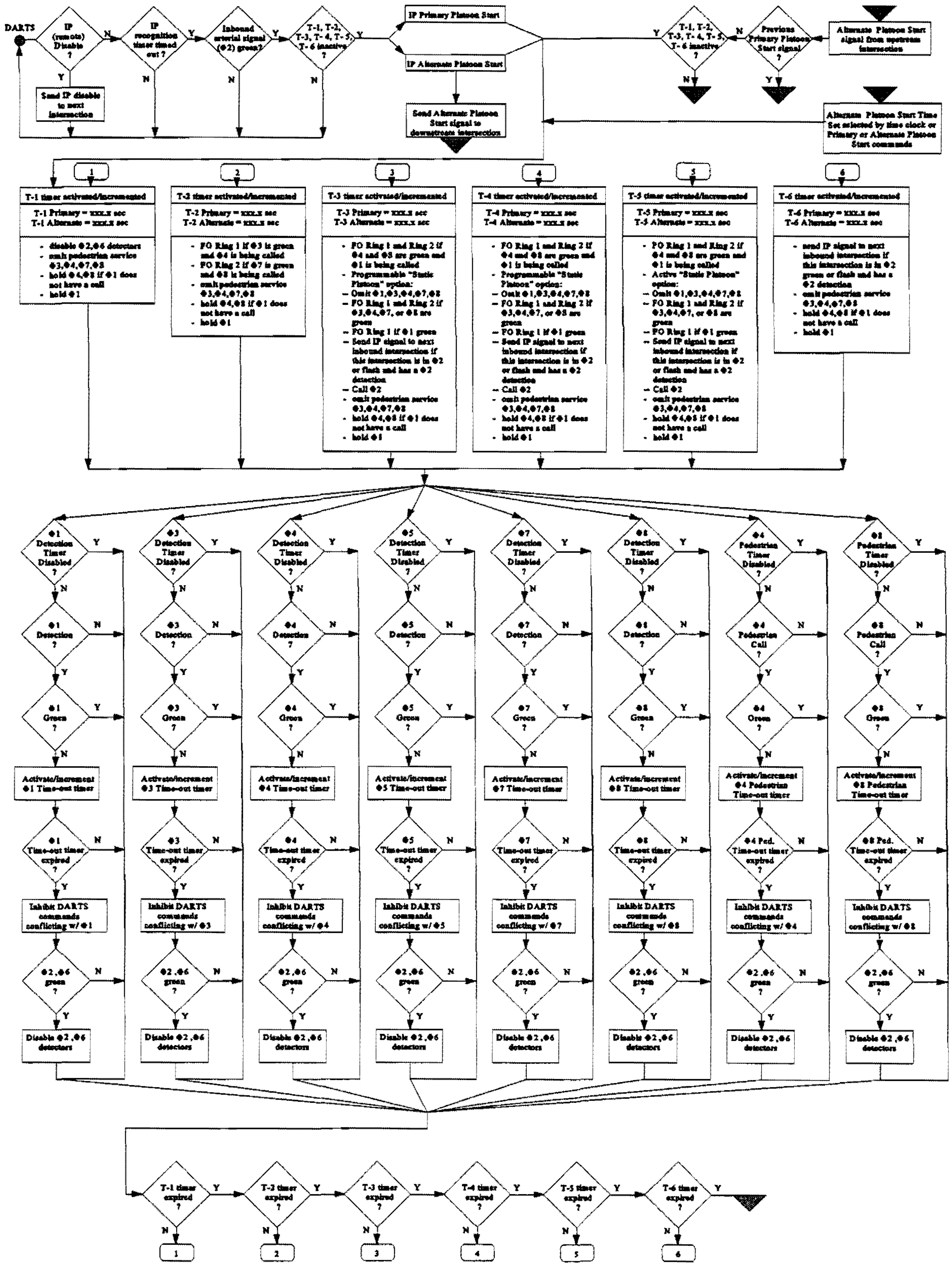


Figure IV-2. DARTS Algorithm in Flowchart Format

TexSIM Simulator

The TexSIM microscopic simulation model was developed by the Texas Transportation Institute to help analyze complex traffic signal systems and multi-modal operations. Every aspect of the transportation system, such as the vehicles, signals, detectors, and intersection approaches, are modeled as separate objects. The object-oriented model design allows for the flexibility to model many complex situations.

A network is defined in TexSIM by connecting certain intersections (nodes) to one another with one or more approaches (links). Each intersection can handle up to 16 approaches, and each approach can include several full length lanes in addition to shorter turn-bays. Traffic volumes to be simulated, as well as the percentage of trucks in the traffic stream, are specified for all the external approaches to the simulation model. For each internal approach, or approach to an intersection, the appropriate turning movements are specified.

The latest version of the model, TexSIM 4.0, was used in the analysis performed for this research. This model includes a graphical representation of the network that is being simulated. In addition to the graphics provided, several measures of effectiveness are also produced for each approach in the model. These measures of effectiveness include delay, number of stops, length of maximum queue, detector occupancy, and the space mean speed.

While the model includes the capability to simulate both pre-timed and actuated signals, these features were not used in this research. Instead, the model was adapted to allow the traffic signals specified at each intersection to be controlled by an external program. This allowed the desired control and communications strategies to be more easily simulated. The outputs from the detectors that can be specified on any TexSIM approach are sent to this external controller program. The controller simulator, in turn, tells TexSIM the status of each signal phase. The simulated vehicles in TexSIM then react to the changing signal indications as if they were produced by the model's own signal logic.

FACS/DARTS Simulator

The Fully Actuated Controller Simulator (FACS) was developed by the Texas Transportation Institute to investigate different control strategies that could be implemented using available traffic signal controllers. The simulator replicates most common features available in NEMA type eight-phase dual-ring fully actuated controllers. The software can be used to evaluate pre-timed, coordinated pretimed, semi-actuated, and fully actuated control strategies for up to six intersections simultaneously.

Currently, the FACS software supports two modes of operation: pre-timed sequence evaluation and network simulation. The network simulation mode interfaces with the TexSIM simulator to provide measures of effectiveness for a network that is operated under a particular signal strategy. This mode also allows for evaluation of semi-actuated and actuated controller operation since the TexSIM simulator can be used to generate detector calls to the FACS controllers. When in actuated mode, the FACS controller logic has the capability to skip phases when there is no demand or to place certain phases on recall so that they will receive green time even if no vehicles are present.

In addition to the standard controller capabilities that are included in the FACS software, the first version of the program includes a module to evaluate the implementation of the Dynamic Arterial-Responsive Traffic System (DARTS). The goal of DARTS is to coordinate the timings of two or more fully actuated controllers for the purpose of maximizing the progression of the through vehicles along the signalized arterial. The coordination is accomplished using the phase hold, phase force off, and detector disable functions available in standard NEMA controllers.

The DARTS module within FACS takes the place of the external DARTS device that can be installed at an intersection to work with the controller. The logic continues to use the standard hold and force commands and provides a communications channel to allow a controller from one intersection to "talk" to the controllers upstream and downstream. Thus, this logic could be implemented in a controller in the field with only slight modifications. Using the DARTS module in FACS in coordination with TexSIM will provide a measure of how effective the DARTS system is in minimizing motorist delay compared to other strategies, such as coordinated pretimed operation.

CHAPTER V.
SYSTEM IMPLEMENTATION ALTERNATIVES

As presented in Chapter III of this project summary report, researchers selected a direct sequence spread spectrum radio communications system from a wide variety of traffic signal communications media and installed the system in Falfurrias, Texas. As presented in Chapter IV, the DARTS system provides for real-time traffic signal control response to platoons of vehicles that would benefit from progression along an arterial, like US 281 in Falfurrias. This chapter presents the events and activities directed toward enabling DARTS functionality in the signal controllers in Falfurrias using the installed radio communications system.

ROLE OF NAZTEC, INC.

The signal controllers found in Falfurrias were manufactured by NAZTEC, Inc. of Houston, Texas. NAZTEC, Inc. is also the only company that produced a solid state DARTS system (i.e., based on the TxDOT DARTS Specification) as a commercially available product. In hopes of developing a partnership to facilitate the research, TTI contacted NAZTEC, Inc. about this project. Interest in the potential of the DARTS system and a desire to see DARTS functionality enabled in software, rather than in hardware, led to a sharing of information.

Several alternatives were discussed as a means of implementing DARTS as a software-based system rather than as solid state electronic timers and hardware. The simplest software solution was that of the simulator, which was already developed as a part of the project. The most complicated solution involved the addition of DARTS as a control option within the NAZTEC controller, made possible by the development of a modified controller EEPROM. Much like closed loop system software, DARTS could be configured from the controller's front panel, or it could be monitored and administered remotely. Unfortunately, restrictions of time and limited project resources did not allow the porting of the DARTS code to NAZTEC controllers for purposes of this research project.

ALTERNATIVES FOR ENABLING DARTS

The following sections discuss two of the most realistic and implementable alternatives for testing the DARTS system as part of this project. The first alternative leverages the development effort that resulted in the development of the FACS/DARTS simulator. Alternative two makes use of an external device to supplement existing controller operations with DARTS functionality, using the radios installed in Falfurrias as the communications media.

Alternative 1

TTI developed a controller logic/DARTS simulator known as FACS to simulate what would have occurred in the field had the DARTS system logic been coded into a standard NEMA controller. Also, TTI previously developed a road and vehicle simulator known as TexSIM to simulate cars, road lanes, and detector calls. Used together, these two simulators can simulate the roadway, vehicles, and DARTS controller that were envisioned for installation in Falfurrias (see Figure V-1).

It is possible to calibrate the TexSIM and FACS simulators from field data collected by TTI to function like the true roadway network in Falfurrias. Researchers can then conduct DARTS testing in the lab using the simulators. Results could be obtained and compared for uncoordinated operations (before the radio controlled closed loop system was installed), pretimed coordinated operations (since the radio controlled closed loop system was installed as part of the project), and finally DARTS coordinated operation (from the simulators).

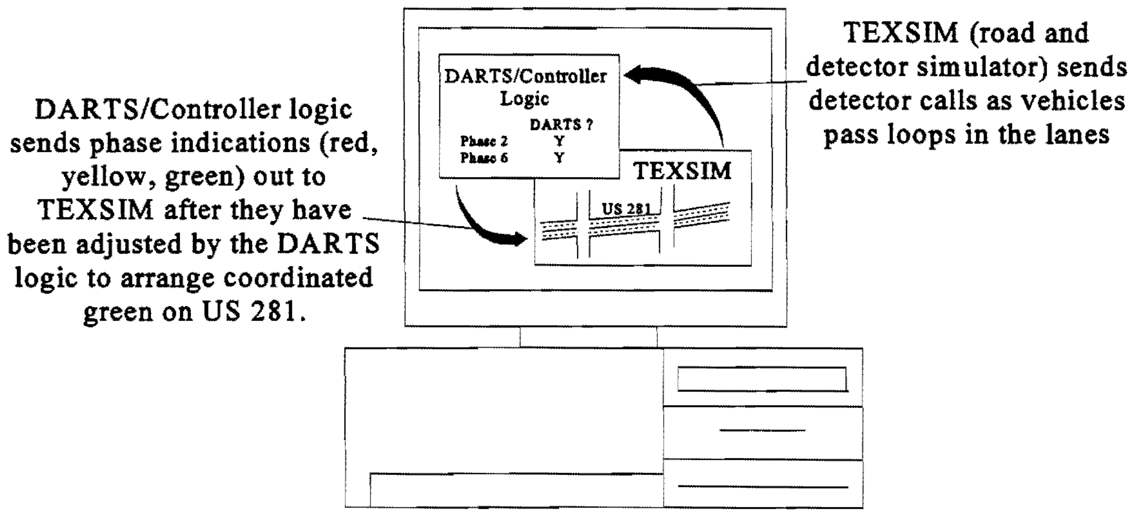


Figure V-1. DARTS Implementation in a Simulation Environment

Alternative 2

Another alternative is purchasing a "black box" controller that can serve the same DARTS logic functions as discussed, but would be outside the NAZTEC controller found at each intersection in Falfurrias (see Figure V-2). These devices would connect to the back panel of the cabinet and the modem, and they would transmit the necessary messages to make DARTS coordination work.

Time and energy would be required to develop the software to make this black box serve its role in the field system, but the implementation would be unique (i.e., not easily reproducible for

TxDOT). The "black box" system would be usable for any NEMA TS-1 or TS-2 cabinet, but any further implementation would require the purchase and coding of additional external controller units. In reality, the industry is actually trying to eliminate such "black box" solutions with better designed cabinet hardware (i.e., NEMA TS-2), flexible controllers (i.e., those based on the 2070 specification), and new protocols (i.e., the NTCIP). Due to practical restraints on the time and budget available for the project, researchers identified this alternative as the only way to make the DARTS system work in the field.

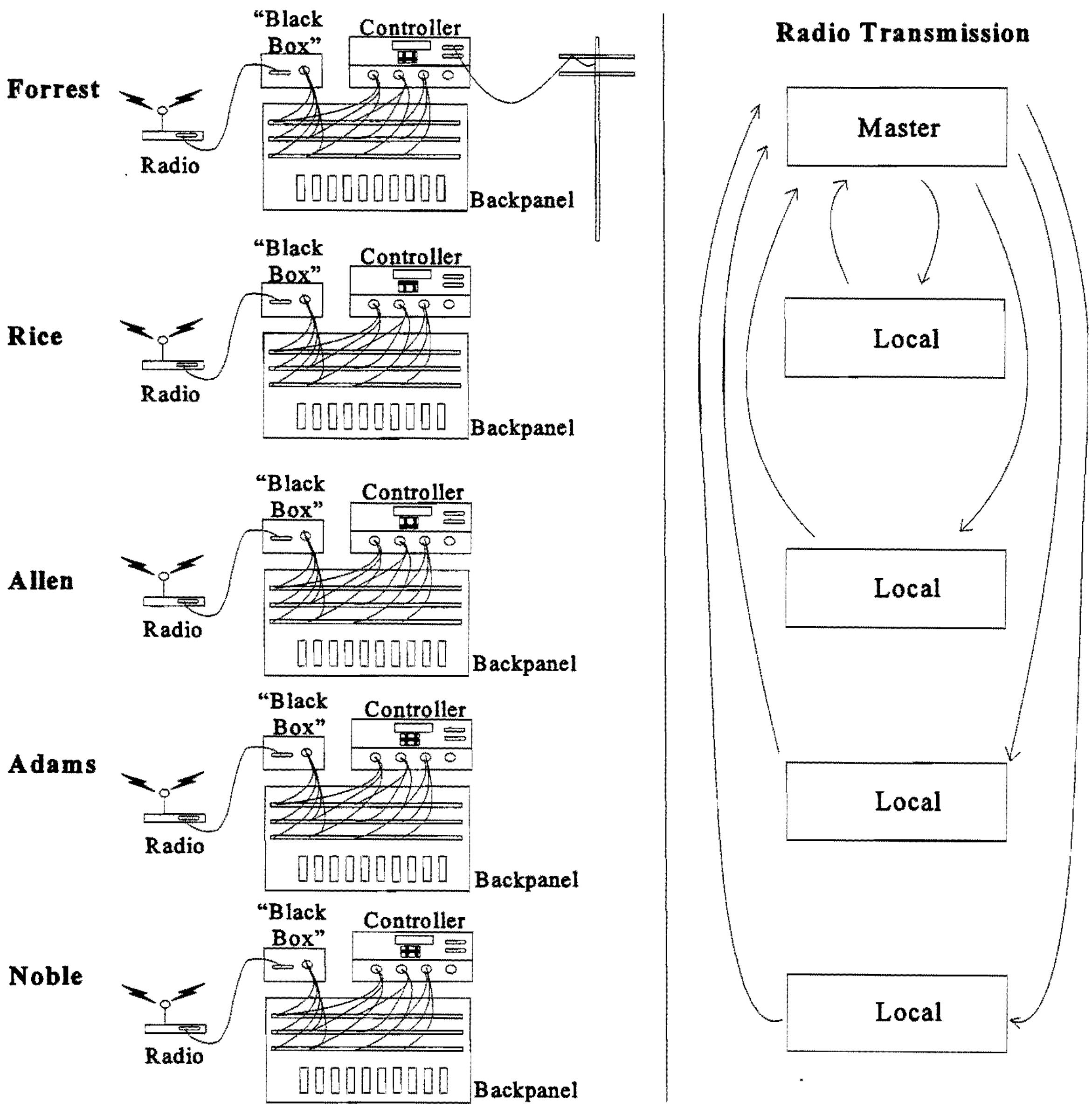


Figure V-2. "Black Box" Controller Alternative to Provide DARTS Functionality

USE AND VALIDATION OF MODELING

Intending not to retrace steps in the previous work in the development and implementation of the DARTS, researchers opted to use simulation rather than the "black box" alternative for DARTS testing in Falfurrias. A field implementation would have been of immense benefit in creating a "hands on" environment for the testing and calibration of the DARTS system and radio communication in Falfurrias. However, researchers were of the opinion that in the long term it was better to focus on the software coding of the DARTS specification and the creation of a DARTS simulation and testing environment that could be used to identify DARTS and/or real-time control potential in any location rather than focusing unique development effort on one particular site. In addition, the radio communications system installed in Falfurrias as part of the research allowed for the use of closed loop system software in Falfurrias. Thus, some measure of improvement in signal coordination and monitoring was already realized in Falfurrias due to the project.

As simulation took on an increasingly important role in the project, and because a before-and-after study was an outlined task in the project, a series of field data collection studies took place in Falfurrias. Three data collection efforts were originally envisioned:

1. Before the installation of any equipment in Falfurrias, with all intersections operating in isolated, actuated mode;

2. After the installation of the radio equipment in Falfurrias, with all intersections coordinated using a master controller in a closed loop system environment; and,

3. After the closed loop system was enhanced through the addition of real-time control functionality which, for the purpose of the project, was the DARTS system.

As the DARTS system was not actually implemented in the field as part of the research project, simulation was used to determine how effective the system would have been had it been installed. To validate this effort and ensure that the simulation results were comparable to field results, researchers compared data from the first two field data collection efforts to simulation data for the same conditions. The roadway geometrics, traffic volumes, and controller settings for both isolated, actuated conditions and fixed-cycle (i.e., closed loop) conditions were entered into the simulator. Analysts compared the modeled results to measures of system performance recorded during the field data collection. Tables V-1 and V-2 contain the field and modeled data, respectively. Researchers then performed a statistical analysis to determine whether or not significant differences existed between the field data and the modeled data. In addition to presenting the modeled data, Table V-2 also presents the outcome of the statistical analysis.

Table V-1. Field Data for Isolated and Closed Loop Operations in Falfurrias, Texas

Type of Control	Type of Data	Intersection	Average		Standard Deviation		Samples	
			AM	PM	AM	PM	AM	PM
Isolated, Actuated	Total Delay (secs/veh)	Rice	18.89	19.22	4.94	4.17	8	8
		Noble	7.86	7.21	2.30	2.08	8	8
	Southbound Travel Time on US 281 (seconds)	Forrest to Rice	54.92	52.40	12.48	12.97	12	15
		Rice to Allen	21.25	22.60	6.38	8.10	12	15
		Allen to Adams	35.58	27.33	11.93	7.03	12	15
		Adams to Noble	22.83	24.60	5.73	5.03	12	15
		TOTAL	**134.58**	**126.93**	**19.38**	**23.33**	**12**	**15**
	Northbound Travel Time on US 281 (seconds)	Noble to Adams	24.58	22.13	7.87	5.42	12	15
		Adams to Allen	28.08	34.60	6.72	9.92	12	15
		Allen to Rice	35.75	32.07	10.05	9.97	12	15
		Rice to Forrest	26.42	26.00	6.53	5.46	12	15
		TOTAL	**114.83**	**114.80**	**15.95**	**12.80**	**12**	**15**
Closed Loop System (semi-actuated)	Total Delay (secs/veh)	Rice	22.67	29.36	5.83	9.45	8	8
		Noble	15.45	12.84	5.49	2.76	8	8
	Southbound Travel Time on US 281 (seconds)	Forrest to Rice	43.83	40.38	10.79	6.71	12	13
		Rice to Allen	32.33	19.23	8.44	5.99	12	13
		Allen to Adams	32.83	24.15	6.32	5.26	12	13
		Adams to Noble	18.83	27.38	3.07	5.35	12	13
		TOTAL	**127.83**	**111.15**	**18.77**	**16.21**	**12**	**13**
	Northbound Travel Time on US 281 (seconds)	Noble to Adams	19.67	20.62	2.19	3.86	12	13
		Adams to Allen	31.25	27.08	4.49	2.90	12	13
		Allen to Rice	25.08	37.85	7.61	9.59	12	13
		Rice to Forrest	25.50	23.08	3.12	5.09	12	13
		TOTAL	**101.50**	**108.62**	**11.06**	**13.78**	**12**	**13**

Table V-2. Modeled Data and Statistical Comparison to Field Data

Type of Control	Type of Data	Intersection	Model Output		Computed Confidence in Matching Field Data	
			AM	PM	AM	PM
Isolated, Actuated	Total Delay (secs/veh)	Rice	18.25	20.63	0.36	0.83
		Noble	8.34	7.02	0.73	0.40
	Southbound Travel Time on US 281 (seconds)	Forrest to Rice	52.23	49.30	0.23	0.19
		Rice to Allen	20.82	24.95	0.41	0.66
		Allen to Adams	38.49	25.61	0.80	0.12
		Adams to Noble	21.73	23.48	0.25	0.32
		TOTAL	**133.27**	**123.34**	**0.41**	**0.21**
	Northbound Travel Time on US 281 (seconds)	Noble to Adams	27.23	21.79	0.88	0.38
		Adams to Allen	29.03	33.81	0.69	0.52
		Allen to Rice	36.29	37.65	0.57	0.97
		Rice to Forrest	27.86	25.14	0.78	0.55
		TOTAL	**120.41**	**118.39**	**0.89**	**0.92**
Closed Loop System (semi-actuated)	Total Delay (secs/veh)	Rice	24.46	33.07	0.81	0.87
		Noble	13.00	11.32	0.10	0.06
	Southbound Travel Time on US 281 (seconds)	Forrest to Rice	44.75	39.91	0.62	0.45
		Rice to Allen	30.53	19.74	0.23	0.59
		Allen to Adams	30.98	27.29	0.15	0.99
		Adams to Noble	19.39	26.17	0.74	0.19
		TOTAL	**125.65**	**113.11**	**0.34**	**0.68**
	Northbound Travel Time on US 281 (seconds)	Noble to Adams	20.43	19.06	0.89	0.09
		Adams to Allen	32.19	27.20	0.77	0.48
		Allen to Rice	23.07	37.45	0.18	0.42
		Rice to Forrest	25.52	21.94	0.51	0.20
		TOTAL	**101.21**	**105.65**	**0.46**	**0.20**

For both isolated, actuated operations and closed loop system operations, the data shown under Model Output in Table V-2 are the model's attempt to replicate output produced in the field (i.e., Table V-1). The Table V-2 column "Computed Confidence in Matching Field Data" is a statistic that measures how likely the modeled data are to fit into the range of values actually present in the field. Researchers suggest interpreting the data at the 90 percent confidence level, meaning that values less than 0.05 or greater than 0.95 are suspect and, within reasonable limits, fall out of the range of data values found in the field data.

Review of the model output for Total Delay under isolated, actuated conditions at Rice Street shows a value of 18.25 in the AM peak. A glance back at the field data in Table V-1 produces an average value of 18.89 for this same data point in the field. Based on the standard deviation and number of samples found in the field data, the determination was made that the model's value of 18.25 has a confidence value of 0.36, which is well within the acceptable criteria of not less than 0.05 and not greater than 0.95.

Examination of the confidence values calculated for the modeled Total Delay and Total Southbound and Northbound Travel Times for both isolated, actuated operations and closed loop operations shows that all major modeled values fall within the acceptable confidence criteria. The only modeled values that fall outside of the confidence limits are two of the travel times between intersections (i.e., Allen to Rice in the PM peak for isolated, actuated conditions; and, Allen to Adams in the PM peak for closed loop conditions). Though these modeled values statistically are considered different from the corresponding field values, the overwhelming evidence that other delay and travel time values are acceptably modeled (especially the total travel times) led researchers to conclude that the TexSIM and FACS modeling is an acceptable proxy measure of field conditions.

CHAPTER VI.
DARTS MODELING

USE OF SIMULATOR FOR FALFURRIAS, TEXAS

With the simulator's ability to accurately and appropriately model field conditions verified, researchers began the steps necessary for modeling DARTS using the simulator. The TexSIM program used the same setup and configuration settings for traffic volumes and geometry as the previous simulations, but detectors had to be added for the extra sensing requirements of DARTS. The FACS/DARTS simulator was configured with the appropriate DARTS timer settings as described earlier in this report and in the TxDOT specification, which can be found in Appendix A.

Researchers generated data sets for DARTS simulation of both the AM and PM peak periods in Falfurrias, Texas. The models were executed, and measures of system effectiveness were produced, including delay at each approach to each intersection and travel times along US 281. To produce a relative interpretation of how the DARTS system functioned versus non-coordinated (i.e., isolated, actuated) operation at each intersection, the simulated DARTS AM and PM peak period runs were compared against simulated data sets that used the same traffic volumes and roadway geometrics under isolated, actuated control.

RESULTS

As modeled data sets and outputs, the simulation data for the DARTS comparison to isolated, actuated operation was not restricted to the same limitations on personnel and time that affected field data collection. In other words, a vast quantity of data was produced by the model for the various simulation runs. Comparison statistics were compiled from the TexSIM output files, and they are found in Tables VI-1 and VI-2 for isolated, actuated and DARTS operation, respectively.

Examination of Tables VI-1 and VI-2 shows that cross-street delay, southbound travel time, and northbound travel time are displayed for both isolated, actuated operations and DARTS operation. This side-by-side comparison brings to light several important results. First, the cross street delay at intersections in the DARTS simulation were slightly higher, but not much higher, than cross street delay for intersections operating in isolated, actuated mode. Researchers anticipated this result since the arrangement of phasing for progressive movement on the main street will almost always place restraints or conditions on cross street green.

The most significant and exciting statistic that researchers discovered was in the comparison of travel time between isolated, actuated operations and DARTS operation. By itself, actuated operation at a single intersection is virtually optimal; however, this mode of control makes no allowance for "main street" arterial progression. DARTS was specifically designed to improve coordination in such a traffic control environment.

Table VI-1. TexSIM Output for Isolated, Actuated Operation in Falfurrias

Operation	Type of Data	Intersection	AM	PM
Isolated, Actuated Operation	Cross-Street Delay (seconds/vehicle)	Forrest	13.79	11.87
		Rice	23.30	26.04
		Allen	11.75	14.59
		Adams	10.96	13.95
		Noble	11.99	13.69
	Southbound Travel Time on US 281 (seconds)	Forrest to Rice	52.23	49.30
		Rice to Allen	20.82	24.95
		Allen to Adams	38.49	25.61
		Adams to Noble	21.73	23.48
		TOTAL	**133.27**	**123.34**
	Northbound Travel Time on US 281 (seconds)	Noble to Adams	27.23	21.79
		Adams to Allen	29.03	33.81
		Allen to Rice	36.29	37.65
		Rice to Forrest	27.86	25.14
		TOTAL	**120.41**	**118.39**

Table VI-2. TexSIM Output for DARTS (Coordinated) Operation in Falfurrias

Operation	Type of Data	Intersection	AM	PM
DARTS (Coordinated)	Cross-Street Delay (seconds/vehicle)	Forrest	16.24	16.78
		Rice	26.61	24.67
		Allen	14.38	13.94
		Adams	12.17	17.25
		Noble	13.61	15.70
	Southbound Travel Time on US 281 (seconds)	Forrest to Rice	49.62	37.64
		Rice to Allen	16.03	19.98
		Allen to Adams	23.14	19.27
		Adams to Noble	20.43	20.75
		TOTAL	**109.22**	**97.64**
	Northbound Travel Time on US 281 (seconds)	Noble to Adams	27.77	15.83
		Adams to Allen	23.59	27.80
		Allen to Rice	35.74	25.88
		Rice to Forrest	24.94	14.83
		TOTAL	**112.04**	**84.34**

A comparison of the simulated travel times found in Tables VI-1 and VI-2 shows not only that DARTS produces a significant travel time savings, but also that it can be effective in Falfurrias for both the AM and PM peak periods and in both directions. These results are further emphasized in Table VI-3, which shows the percent travel time saved for both peak periods in each direction. Table VI-3 also presents another comparison statistic, known as system average total delay per vehicle. Simply, this value is the total system delay in seconds divided by the number of vehicles entering the simulation. The end result is an overall measure of system performance.

As shown in Table VI-3, the AM peak period showed roughly the same system delay for isolated, actuated operation and for DARTS. In this instance, travel time savings due to DARTS on the main street (i.e., US 281) were balanced by slightly increased delays on the cross street. However, in the PM peak period the progression provided by DARTS proved so effective (i.e., reduced delays to so many US 281 vehicles) that even the overall system delay dropped by over 10 percent. A glance back to Tables VI-1 and VI-2 verifies that under DARTS operation, cross street delays did increase slightly, but not inordinately, in both peak periods.

A previous evaluation was conducted for the DARTS system (7) in 1981. The results obtained from this evaluation were inconclusive as to the benefits attributable to DARTS operation. However, an earlier version of the DARTS algorithm was used in the field installations studied in that evaluation effort. For the current research, the latest revision of the DARTS specification was used. The previous evaluation report also indicated a high potential for the system as an inexpensive means of coordinating actuated controllers, and a postscript cited benefits similar to those found in the current research in subsequent installations (i.e., using the updated DARTS).

Table VI-3. Modeled Delay and Travel Time Savings Using DARTS in Falfurrias

Time	Measure of Performance	Isolated, Actuated Operation	DARTS Operation	Savings due to DARTS
AM Peak	System Average Total Delay per Vehicle	14.49	14.39	Negligible
	Southbound Travel Time on US 281 (seconds)	133.27	109.22	18.0 %
	Northbound Travel Time on US 281 (seconds)	120.41	112.04	7.0 %
PM Peak	System Average Total Delay per Vehicle	13.23	11.82	10.7 %
	Southbound Travel Time on US 281 (seconds)	123.34	97.64	20.8 %
	Northbound Travel Time on US 281 (seconds)	118.39	84.34	28.8 %

CHAPTER VII.
CONCLUSIONS AND RECOMMENDATIONS

Research as part of this project has extended into a number of areas pertaining to traffic signal control. Comprehensively, topics include system communications, technologies and media for communication, existing methods for improving arterial and network signal operations, detailed examination of a unique real-time coordination system, and a real-world implementation and simulation test of this system. The focus of the research effort was a method of improving traffic flow within towns like Falfurrias, Texas, where a major arterial route - in this case, US 281 - passes through a rural community.

Examination of the environment in Falfurrias identified most traffic as through vehicles, and a high percentage of trucks that were bound for, or returning from, the border areas of South Texas. Local traffic flows were relatively light in comparison to the US 281 traffic load carried through the five signalized intersections in Falfurrias. Improvements to roadway geometry were restricted by right-of-way availability and short building setbacks, placing the need for improved operations upon the signal system. Evaluation of the signals revealed that each intersection was operating in isolated, actuated mode, and that no communications links existed between the traffic signal controllers at the five intersections.

Improvement in operations along US 281 could practically be realized by the establishment of system communications. From among many technologies examined, spread spectrum radio was selected as a highly capable data transmission technology that was both less expensive and required less installation time than more common media, such as twisted pair cable. Thus, as part of the project, radio communications equipment was installed in Falfurrias. With the communications system in place, closed loop system software was installed to provide flexible, reliable coordinated signal operations in Falfurrias.

Further research into signal systems identified the Texas Department of Transportation's Dynamic Arterial-Responsive Traffic System (DARTS) as one means of providing real-time coordination along an arterial. Fundamentally, the DARTS system allows each intersection to operate in its inherently efficient isolated, actuated mode until a need for main street progression exists. When a platoon of vehicles is identified by loop detector sensors, signals are sent to the DARTS system at each downstream intersection, and a green signal is arranged for the arriving platoon as it reaches each intersection. Provisions are made so that undue delays are not experienced by cross street vehicles and pedestrians. As part of this project, DARTS was pursued as a means of testing a real-time control algorithm using the radio communications system installed in Falfurrias.

Project timeline and resources prohibited the field installation of DARTS-enabled signal controllers, so a simulation system was devised to recreate the roadway, traffic, and signal conditions in Falfurrias. The Texas Transportation Institute (TTI) developed the Fully Actuated Controller Simulator (FACS) to model standard signal controller operations and added the DARTS system to this program. Previous research at TTI produced the TexSIM simulator, which was used in this project as a means of modeling the roadway geometry and traffic volumes found in Falfurrias. Thus, within a computerized simulation environment, both the roadway environment (TexSIM) and radio communications traffic signal control system (FACS) were independently and thoroughly modeled.

The models were validated and verified, or shown to be accurate and realistic representations of field conditions, by comparing their output to field data collected in Falfurrias. To the satisfaction of researchers, the models produced reasonable and reliable travel times and intersection delays.

The DARTS functions were then "turned on" in the models in an effort to see how well the DARTS system would function in Falfurrias. Compared to data for isolated, actuated conditions, the DARTS system produced between a 7.0 and 28.8 percent travel time savings on US 281, depending on time of day and direction of traffic flow. Overall, average travel time savings during the peak periods was about 18 percent. Slight delay increases were noted for cross-street traffic as the DARTS system arranged for progression on US 281, but these increases were more than compensated for on an overall system basis by the significant travel time savings to through vehicles and border-bound heavy vehicles on US 281.

Based on the successful radio installation, computer simulation tool development, and DARTS test that resulted from this research effort, the following recommendations are made:

1. Spread spectrum radio should be considered as a cost-effective means of providing flexible and reliable traffic signal system communications and coordination where no current accommodations or media are available for enabling traffic system communications. Individual radio modems for traffic system application are available for as little as $2000.

2. DARTS, as specified by the Texas Department of Transportation, should be reinvestigated as a readily implementable, low-cost means of providing real-time coordination along major arterials with comparatively moderate cross street traffic volumes. If time and resources are available to develop DARTS-enabled controllers in the future (i.e., perhaps using the Caltrans 2070 Advanced Traffic Controller platform), it is suggested that Falfurrias, Texas, be one of the first sites where the technology is deployed.

3. The FACS/DARTS and TexSIM simulators developed from this project should be used to evaluate candidate field sites for DARTS installation. Further, the simulators should be used as a tool for familiarizing operations personnel with DARTS and training them in system installation and calibration.

4. Finally, the logic and algorithm that compose DARTS should be investigated, developed, and field tested as a means of providing added controller functionality in other traffic control applications. Specifically, the advanced warning of platoon arrival and allowance for conflicting phase service (i.e., only in the presence of adequate phase service time) are applicable in railroad preemption scenarios and in the coordination of diamond interchanges with adjacent intersections.

REFERENCES

1. Robert L. Gordon, Robert A. Reiss, Walter M. Dunn, and David R. Morehead. *Communications Handbook for Traffic Control Systems*. Report No. FHWA-SA-93-052, U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., 1993.

2. John M. Vetterling. Wireless Communication for Traffic Signals. In *ITE Compendium of Technical Papers 1995*, Institute of Transportation Engineers, pgs. 179-183.

3. David H. Kiel. Fiber Optics for ITS. In *ITS World*, Advanstar Communications, May/June 1997, pgs. 38-40.

4. Jon T. Ringler and Stephen K. Ernst. Radio Interconnect for Traffic Signal Control Systems. In *ITE Compendium of Technical Papers 1992*, Institute of Transportation Engineers, pgs. 60-65.

5. Robert L. Gordon, Robert A. Reiss, Herman Haenel, E. Ryeron Case, Robert L. French, Abbas Mohaddes, and Ronald Wolcott. *Traffic Control Systems Handbook*. Report No. FHWA-SA-95-032, U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., 1996.

6. Traffic Engineering Section. Specification for Dynamic Arterial-Responsive Traffic System (DARTS). Specification NO. 6-90-3050, District 15, Division of Safety and Maintenance Operations, Texas State Department of Highways and Public Transportation, 1990.

7. Clyde E. Lee. Evaluation of the Dynamic Arterial-Responsive Traffic System (DARTS). Research Report No. FHWA/TX-82/25+243-1F, Center for Transportation Research, August 1982.

APPENDIX A
TxDOT DARTS SPECIFICATION

**TEXAS
STATE DEPARTMENT OF HIGHWAYS
AND PUBLIC TRANSPORTATION**

FOR

**DYNAMIC ARTERIAL-RESPONSIVE TRAFFIC SYSTEM
(DARTS)**

1.0 SCOPE

The intent of this specification is to describe a dynamic system of full-traffic actuated controllers being coordinated on an intersection to intersection basis by maintaining a progression point for the start of artery green, the length of which shall be determined solely by the traffic signal controller in the normal vehicle passage extension manner. Thus, there will be no fixed progression bandwidth or background cycle length, with the start of artery green being established in terms of artery platoon arrival information and the termination of green taking place by gap-out or max-out in accordance with standard practice.

2.0 METHOD OF ACHIEVEMENT

To carry out this process, each controller unit is equipped with solid state digital Dynamic Arterial-Responsive Traffic System (DARTS) which shall have two main functions: (1) to determine the presence of a platoon from either direction and thereby send signals downstream to adjacent controllers when such a determination is made, and (2) to receive information from upstream controller coordination units of the approach of a platoon and proceed to clear its conflicting phases as necessary to provide the arriving platoon a green signal. When traffic on a conflicting phase reaches excessive stacking or time-waiting values, the arterial progression shall be inhibited until that phase has been serviced.

3.0 FUNCTIONAL REQUIREMENTS

3.1 The DARTS at each intersection shall be capable of transmitting and receiving various messages, to and from other controllers. The message received shall be used to start various time intervals, which in turn shall be used to guide intersection controllers to provide arterial progression.

3.2 Each DARTS shall generate and receive the following messages and then respond to these messages as explained below. The Inbound Platoon Start (IPS) signal (Phase 2) is generated and sent to the next intersection when:

(1) the inbound artery detector has caused the inbound platoon recognition timer to time out; and

(2) the inbound artery signal is green; and

(3) the following six sequential intervals, T-1, T-2, T-3, T-4, T-5, and T-6 at this intersection are inactive.

Each time the IPS signal is generated, an output is transmitted on both the Primary and Alternate Platoon Start interconnect line pairs.

3.3 The following sequence of intervals is initiated when an IPS signal is received at an intersection equipped with DARTS. Each interval shall provide the following outputs, some of which shall be programmable:

T-1 - During this interval, by programmable option, the outputs from Phase 2 and Phase 6 detectors are disabled. A programmable option shall also be provided to omit pedestrian service in Phases 3, 4, 7, and 8 during this interval.

T-2 - At the start of this interval, a programmable option shall impose a signal of 500 ms in length upon Ring 1 Force Off if Phase 3 is green and Phase 4 is being called. This programmable option shall also impose a signal of 500 ms in length on Ring 2 Force Off if Phase 7 is green and Phase 8 is being called. A second programmable option shall impose a Pedestrian Omit signal to Phases 3, 4, 7, and 8 during this interval.

T-3 - At the start of this interval, a programmable option shall impose a signal of 500 ms in length upon Rings 1 and 2 Force Off if Phase 4 and Phase 8 are green and Phase 1 is being called. A second programmable option called Static Platoon shall be provided to:

1. Omit Phases 1, 3, 4, 7, and 8; and

2. Apply Force Off to Ring 1 and 2 if Phases 3, 4, 7, or 8 are green; and

3. Apply Force Off to Ring 1 if Phase 1 is green; and

4. Send an IPS signal to the next inbound intersection if this intersection is in Phase 2 green or flash and has a Phase 2 detection; and

5. Call Phase 2 at this intersection.

Pedestrian service to Phases 3, 4, 7, and 8 shall be omitted during this interval.

T-4 - This is a separate interval with the same features as T-3 with separate programmable options as defined in T-3 for this interval.

Pedestrian service to Phases 3, 4, 7, and 8 shall be omitted during this interval.

T-5 - This interval has the same features as Interval T-3 with the Static Platoon option active. These features shall be present in every Inbound T-5 interval.

Pedestrian service to Phases 3, 4, 7, and 8 shall be omitted during this interval.

T-6 - A programmable option shall send an IPS signal to the next inbound intersection if this intersection is in green or flash and has a Phase 2 detection.

Pedestrian service to Phases 3, 4, 7, and 8 shall be omitted during this interval.

3.4 A programmable option shall be provided during all of the above intervals that will:

1. Hold Phase 4 and Phase 8 if Phase 1 does not have a call; and

2. Hold Phase 1.

3.5 Another programmable option shall be provided to impose the above signals to the unit when the next inbound, downstream intersection is in its intervals T-1, T-2, T-3, T-4, T-5, or T-6.

3.6 All functions defined for the inbound requirements above shall be duplicated for the outbound progression requirements. All references to inbound become outbound, and all timers and timed intervals are provided independently for outbound use only. The references to the phases are mirrored (i.e., Phase 2 = Phase 6, 6 = 2, 1 = 5, 5 = 1, 3 = 7, 7 = 3, 4 = 8, 8 = 4).

3.7 When a Primary Platoon Start Signal is received, DARTS shall immediately advance to Interval T-1 and begin timing the primary time set. It shall then advance sequentially, through T-2, T-3, T-4, T-5, and T-6, stopping at each interval for the duration of time programmed in the primary time set. Platoon Start Signals for either primary or alternate time sets, which may arrive during any of these intervals, will have no further affect on the sequence or timing.

When an Alternate Platoon Start Signal is received, DARTS shall immediately advance to Interval T-1 and begin timing the alternate time set. It shall then advance sequentially, through T-2, T-3, T-4, T-5, and T-6, stopping at each interval for the duration of time programmed in the alternate time set. Platoon Start Signals for either primary or alternate time sets, which may arrive during any of these intervals, will have no further affect on the sequence or timing.

3.8 A separate Queue Timer and Time Waiting Timer shall be provided for each of phases 1, 3, 4, 5, 7, and 8. Queue Timers will time when detection is recognized over the Queue Detectors of the appropriate phase. Time Waiting Timers will time when detection is recognized over the passage detector of the appropriate phase. These timers shall not time during the appropriate green. When the Timer(s) times out, as a result of continuous detection for the programmed time period, the DARTS commands which are in conflict with that phase shall be inhibited until that phase has terminated green. The detectors for phases 2 and 6 shall be disabled if either of these phases is green during the time-out condition.

3.9 A separate Pedestrian Time Waiting Timer shall be provided for each of phases 4 and 8. The timer(s) shall begin timing when a pedestrian call is received. Should either of these timers time out, all DARTS commands shall be inhibited until the appropriate WALK signal is serviced. Phases 2 and 6 detectors shall be disabled if either of these phases is green during the time-out condition.

3.10 There shall be provided an alternate set of time increments for both the inbound and outbound directions for T-1, T-2, T-3, T-4, T-5, and T-6. The alternate set of time increments shall be initiated by both of the following methods:

1. An Alternate Platoon Start Signal is received before a Primary Platoon Start Signal is received and T-1 through T-6 intervals are not active.

AND

2. The Alternate Platoon Start Time Set is selected by time clock for either Primary or Alternate Platoon Start commands. When this time clock input is active, the alternate time set shall prevail for either Platoon Start Inputs.

3.11 When a remote Inbound or Outbound Disable is received at an intersection, this message shall regenerate that disable signal and transit same to the next intersection. This feature shall permit either the inbound or outbound (or both) DARTS commands to be disabled for the system.

3.12 PROGRAMMABLE OPTIONS

(1) Disable Phase 3 Queue and Time Waiting Output

This inhibits the output generated by a Phase 3 time waiting or queue time-out when active.

(2) Disable Phase 4 Queue and Time Waiting Output

This inhibits the output generated by a Phase 4 time waiting or queue time-out when active.

(3) Disable Phase 7 Queue and Time Waiting Output

This inhibits the output generated by a Phase 7 time waiting or queue time-out when active.

(4) Disable Phase 8 Queue and Time Waiting Output

This inhibits the output generated by a Phase 8 time waiting or queue time-out when active.

(5) Disable Phase 1 Queue and Time Waiting Output

This inhibits the output generated by a Phase 1 time waiting or queue time-out when active.

(6) Disable Phase 5 Queue and Time Waiting Output

This inhibits the output generated by a Phase 5 time waiting or queue time-out when active.

(7) Disable Phase 4 Pedestrian Time Waiting Output

This inhibits the output generated by a Phase 4 ped. time waiting time-out when active.

(8) Disable Phase 8 Pedestrian Time Waiting Output

This inhibits the output generated by a Phase 8 ped. time waiting time-out when active.

(9) Inbound Static Platoon Recognition Simulation

When this function is active, an inbound platoon recognition timer time-out will activate the Phase 2 static platoon circuit.

(10) Inbound Static Platoon Recognition Simulation

When this function is active, an inbound platoon recognition timer time-out will activate the Phase 6 static platoon circuit.

4.0 INTERFACE REQUIREMENTS

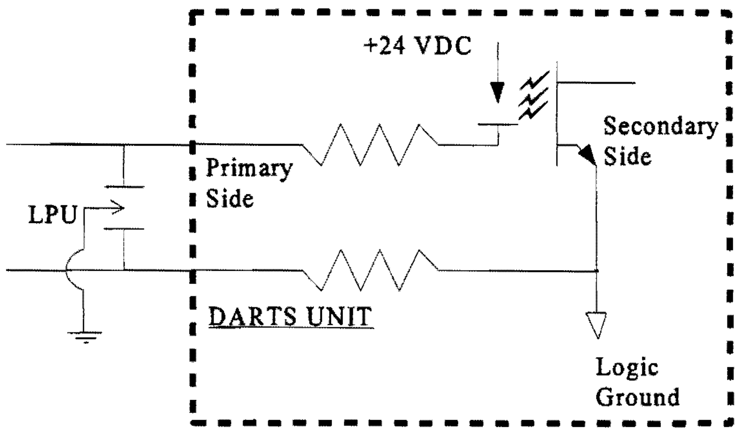
4.1 DC Power Supply

The DARTS shall be powered by the DC supply voltage supplied by the traffic controller with which it is incorporated. This DC supply shall be 24 volts DC. A separate power supply to supply power to the opto-isolaters shall be provided if necessary to meet the current draw requirements.

4.2 Inputs

All inputs, with the exception of the optical isolated interconnect line circuits, shall be ground true and shall be active when pulled down to less than 1/3 of the normal pull-up voltage of 24 VDC. They shall then remain down until the pull-down is released and the pull-up voltage exceeds 2/3 of the normal 24 VDC. When the outputs from the controller which are used as inputs to the DARTS unit, such as Greens, Checks, etc., are activated or pulled down from their normal voltage of 24 VDC, they shall draw between 0.4 ma and 1.0 ma, inclusive. Similarly, when the remote inputs, such as intersection detectors, queue detectors, etc., are activated or pulled down from their normal voltage of 24 VDC, they shall draw between 2.0 ma and 3.0 ma, inclusive.

All inputs from interconnect line pairs shall be received through the use of optical isolators and the local 24 VDC supply voltage.

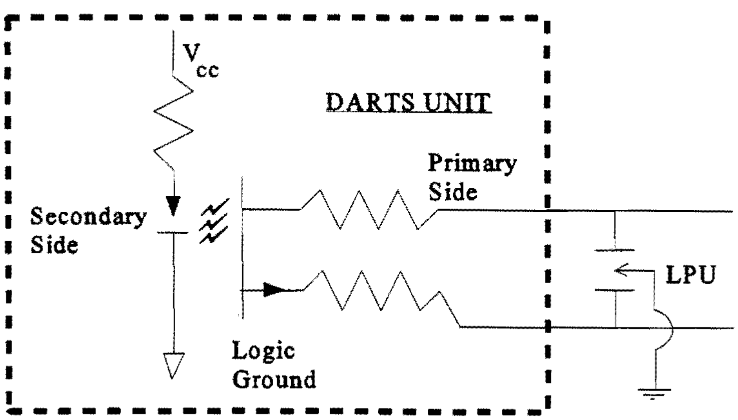


(one twisted pair of 24 AWG phone wire per message)

4.3 Outputs

All outputs with the exception of the optical isolated interconnect line circuits shall be ground true with a minimum current rating of 50 ma, each at 30 VDC, and shall drive to within 2 VDC or less.

All outputs to interconnect line pairs shall be transmitted through the use of optical isolators, and the receiving intersection's 24 VDC supply voltage.



5.0 INTERFACE PANEL

5.1 Darts/Pre-emption Panel

The input and output harness(es) from controller connector(s) shall terminate on terminal blocks mounted to a sturdy metal panel large enough to amply contain all functions necessary for proper operation. This panel shall be mounted on the upper portion of the left sidewall in the controller cabinet. Terminals shall have minimum 6 x 32 screws 5/16 inch long.

All harnesses shall be minimum of #22 AWG THW stranded wire terminating on terminal strips that are clearly and neatly labeled and correspond to cabinet prints.

The following components shall be mounted on interface panel:

1. Isolation relays with a rating of 120 VAC/5 AMP contact rating for pre-empt functions complete with fuses and test switches.
2. Sixteen lightning protection devices EDCO SRA-64A-030 or equivalent.
3. Switches for inbound and outbound disable.
4. Phone jack.
5. 120 VAC relay and fuse for the VOC flash input operation.

6.0 DESIGN REQUIREMENTS

6.1 Input/Output Requirements

The minimum input and output requirements for DARTS operation shall terminate on DART/Pre-emption panel and are to be as follows:

1. 120 Volts AC
2. AC Common
3. Chassis GND
4. Logic GND

Inputs

1. Primary inbound platoon start (+)
   Primary inbound platoon start (-)
2. Primary outbound platoon start (+)
   Primary outbound platoon start (-)
3. Alternate inbound platoon start (+)
   Alternate inbound platoon start (-)
4. Alternate outbound platoon start (+)
   Alternate outbound platoon start (-)

5. Disable inbound coordination (+)
Disable inbound coordination (-)

6. Disable outbound coordination (+)
Disable outbound coordination (-)

7. T-1, T-2, T-3, T-4, T-5 OR T-6 ON Inbound Next Downstream Intersection (+)
T-1, T-2, T-3, T-4, T-5 OR T-6 ON Inbound Next Downstream Intersection (-)

8. T-1, T-2, T-3, T-4, T-5 OR T-6 ON Outbound Next Downstream Intersection (+)
T-1, T-2, T-3, T-4, T-5 OR T-6 ON Outbound Next Downstream Intersection (-)

9. Inbound (Phase 2) static platoon detector

10. Outbound (Phase 6) static platoon detector

11. Phase 1 queue detector

12. Phase 2 queue detector

13. Phase 3 queue detector

14. Phase 4 queue detector

15. Phase 5 queue detector

16. Phase 6 queue detector

17. Phase 7 queue detector

18. Phase 8 queue detector

19. Force to alternate time set (Inbound)

20. Force to alternate time set (Outbound)

Outputs

1. Primary inbound platoon start (+)
Primary inbound platoon start (-)

2. Primary outbound platoon start (+)
Primary outbound platoon start (-)

3. Alternate inbound platoon start (+)
Alternate inbound platoon start (-)

4. Alternate outbound platoon start (+)
Alternate outbound platoon start (-)

5. Disable inbound coordination (+)
Disable inbound coordination (-)

6. Disable outbound coordination (+)
Disable outbound coordination (-)

7. T-1, T-2, T-3, T-4, T-5 OR T-6 ON Inbound This Intersection (+)
T-1, T-2, T-3, T-4, T-5 OR T-6 ON Inbound This Intersection (-)

8. T-1, T-2, T-3, T-4, T-5 OR T-6 ON Outbound This Intersection (+)
T-1, T-2, T-3, T-4, T-5 OR T-6 ON Outbound This Intersection (-)

9. Inbound T-1 On

10. Inbound T-2 On

11. Inbound T-3 On

12. Inbound T-4 On

13. Inbound T-5 On

14. Inbound T-6 On

15. Outbound T-1 On

16. Outbound T-2 On

17. Outbound T-3 On

18. Outbound T-4 On

19. Outbound T-5 On

20. Outbound T-6 On

6.2 Interval Time Increment Requirements

Timing intervals for the DARTS functions shall be programmable by keyboard entry. The following time intervals shall be provided:

0-5 seconds in 1-second increments or smaller
Primary T-1 Inbound
Alternate T-1 Inbound
Primary T-1 Outbound
Alternate T-1 Outbound

0-60 seconds in 1-second increments or smaller
Primary T-2 Inbound
Alternate T-2 Inbound
Primary T-2 Outbound
Alternate T-2 Outbound

0-30 seconds in 1-second increments or smaller
Primary T-3 Inbound
Alternate T-3 Inbound
Primary T-3 Outbound
Alternate T-3 Outbound

Primary T-4 Inbound
Alternate T-4 Inbound
Primary T-4 Outbound
Alternate T-4 Outbound

Primary T-5 Inbound
Alternate T-5 Inbound
Primary T-5 Outbound
Alternate T-5 Outbound

0-15 seconds in 1-second increments or smaller
Primary T-6 Inbound
Alternate T-6 Inbound
Primary T-6 Outbound
Alternate T-6 Outbound

0-5 seconds in 1-second increments or smaller
Phase 1 Queue
Phase 2 Queue
Phase 3 Queue
Phase 4 Queue
Phase 5 Queue
Phase 6 Queue
Phase 7 Queue
Phase 8 Queue

0-120 seconds in 2-second increments or smaller
Phase 3 Time Waiting
Phase 4 Time Waiting
Phase 7 Time Waiting
Phase 8 Time Waiting
Phase 1 Time Waiting
Phase 5 Time Waiting
Phase 4 Ped. Time Waiting
Phase 8 Ped. Time Waiting

0-15 seconds in 1-second increments or smaller
Inbound Platoon Recognition (Phase 2)
Outbound Platoon Recognition (Phase 6)

6.3 Darts Display

The alpha numeric display shall indicate when the following functions are active.

	Outbound		Inbound
1.	T-1 Timing	1.	T-1 Timing
2.	T-2 Timing	2.	T-2 Timing
3.	T-3 Timing	3.	T-3 Timing
4.	T-4 Timing	4.	T-4 Timing
5.	T-5 Timing	5.	T-5 Timing
6.	Phase 2 Detector	6.	Phase 6 Detector
7.	Phase 2 Time Waiting Time Out	7.	Phase 6 Time Waiting Time Out
8.	Phase 2 Queue Detector	8.	Phase 6 Queue Detector
9.	T-6 Timing	9.	T-6 Timing
10.	Phase 5 Detector	10.	Phase 1 Detector
11.	Phase 5 Time Waiting Time Out	11.	Phase 1 Time Waiting Time Out
12.	Phase 5 Queue Detector	12.	Phase 1 Queue Detector
13.	Phase 5 Queue Time Out	13.	Phase 1 Queue Time Out
14.	Phase 7 Detector	14.	Phase 3 Detector
15.	Phase 7 Time Waiting Time Out	15.	Phase 3 Time Waiting Time Out
16.	Phase 7 Queue Detector	16.	Phase 3 Queue Detector
17.	Phase 7 Queue Time Out	17.	Phase 3 Queue Time Out
18.	Phase 8 Detector	18.	Phase 4 Detector
19.	Phase 8 Time Waiting Time Out	19.	Phase 4 Time Waiting Time Out
20.	Phase 8 Queue Detector	20.	Phase 4 Queue Detector
21.	Phase 8 Queue Time Out	21.	Phase 4 Queue Time Out
22.	Static Platoon	22.	Static Platoon
23.	Platoon Recognized	23.	Platoon Recognized
24.	Platoon Start	24.	Platoon Start
25.	Alternate Timing	25.	Alternate Timing
26.	Disable	26.	Disable
27.	Phase 6 Detector	27.	Phase 2 Detector
28.	Pedestrian Time Waiting Time Out	28.	Pedestrian Time Waiting Time Out

6.4 Darts Coordination Connectors' (Inputs)

	Function		Function
1.	+24 VDC	20.	+24 VDC
2.	Alt. Outbound Plat. Start	21.	Disable Inbound Input
3.	Alt. Inbound Plat. Start	22.	Disable Outbound Input
4.	Prim. Outbound Plat. Start	23.	T1-T6 on Inbound Input
5.	Prim. Inbound Plat. Start	24.	T1-T6 on Outbound Input
6.	Inbound Alt. Time Input	25.	Special Det. P8
7.	Outbound Alt. Time Input	26.	Special Det. P6
8.	Logic GND	27.	Logic GND
9.	Static Outbound Detect. P6	28.	Special Det. P4
10.	Static Inbound Detect. P2	29.	Special Det. P2
11.	P8 Queue	30.	Reserved
12.	P7 Queue	31.	Reserved
13.	P6 Queue	32.	Reserved
14.	P5 Queue	33.	Reserved
15.	P4 Queue	34.	Reserved
16.	P3 Queue	35.	Contact Flash
17.	P2 Queue	36.	Spare A Input (Flash)
18.	P1 Queue	37.	Spare b Input (DARTS Stop)
19.	Spare C Input		

6.5 Coordination Connectors' (Outputs)

	Function		Function
1.	T2 Outbound Lamp	14.	T6 Outbound Lamp
2.	T1 Outbound Lamp	15.	Disable Outbound Output
3.	T6 Inbound Lamp	16.	T1-T6 On Inbound Output
4.	T5 Inbound Lamp	17.	T1-T6 On Outbound Output
5.	T4 Inbound Lamp	18.	T3 Outbound Lamp
6.	T3 Inbound Lamp	19.	T4 Outbound Lamp
7.	T2 Inbound Lamp	20.	T5 Outbound Lamp
8.	T1 Inbound Lamp	21.	Spare
9.	Disable Inbound Output	22.	Spare
10.	Alt. Outbound Plat. Start	23.	Spare
11.	Prim. Outbound Plat. Start	24.	Spare
12.	Alt. Inbound Plat. Start	25.	Spare
13.	Prim. Inbound Plat. Start		

APPENDIX B
FULLY ACTUATED CONTROLLER SIMULATOR (FACS) USER'S GUIDE

FACS Users Guide

The Fully Actuated Controller Simulator (FACS) was developed by the Texas Transportation Institute to investigate different control strategies that could be implemented using available traffic signal controllers. The simulator replicates most common features available in NEMA-type eight-phase dual-ring fully actuated controllers. The software can be used to evaluate pre-timed, coordinated pretimed, semi-actuated, and fully actuated control strategies for up to six intersections.

The current version of the FACS software includes a module to implement the Dynamic Arterial-Responsive Traffic System (DARTS) in the controller. This module takes the place of an external DARTS device that has been used to communicate commands to the controller. All of the input information required by the published Texas Department of Transportation (TxDOT) DARTS specification is included as inputs in the FACS DARTS module.

This user's guide describes how to program the FACS controllers to be operated in pretimed, coordinated pretimed, or actuated mode with or without the DARTS system active. The FACS program is designed to be used with TexSIM 4.0 to provide a method for predicting the effectiveness of certain signal control strategies. The steps required to interface with TexSIM are also discussed.

The FACS User Interface

The main interface screen for the FACS program is shown in Figure 1. The menu bar allows access to all of the commands needed to work with FACS. The standard file access commands are present under the File Menu. Files to describe the signal timing for the FACS program are stored with a ".FAC" extension. The current version of the software does not support any printing capabilities. The Intersection Menu is used to add intersections or edit the signal timings at the various intersections. The Edit Menu currently does not support any function.

The toolbar just below the menu bar allows quick access to the most commonly used commands. Most of the commands, as shown in Figure 2, are the same as those on the menu. The toolbar, however, also contains the button that is used to start and pause the simulation.

Adding Intersections

The first step in creating a FACS timing plan is to add the intersections to the network. Currently, FACS can support a maximum of six intersections. After "Add" is chosen from the Intersection menu or the Add Intersection button is clicked, the user is prompted for the name of the intersection to add. Once entered, the name appears in the list below the toolbar.

Note: In order for the TexSIM interface to work properly, the intersections must be added to FACS in numerical order based on the intersection number used in TexSIM.

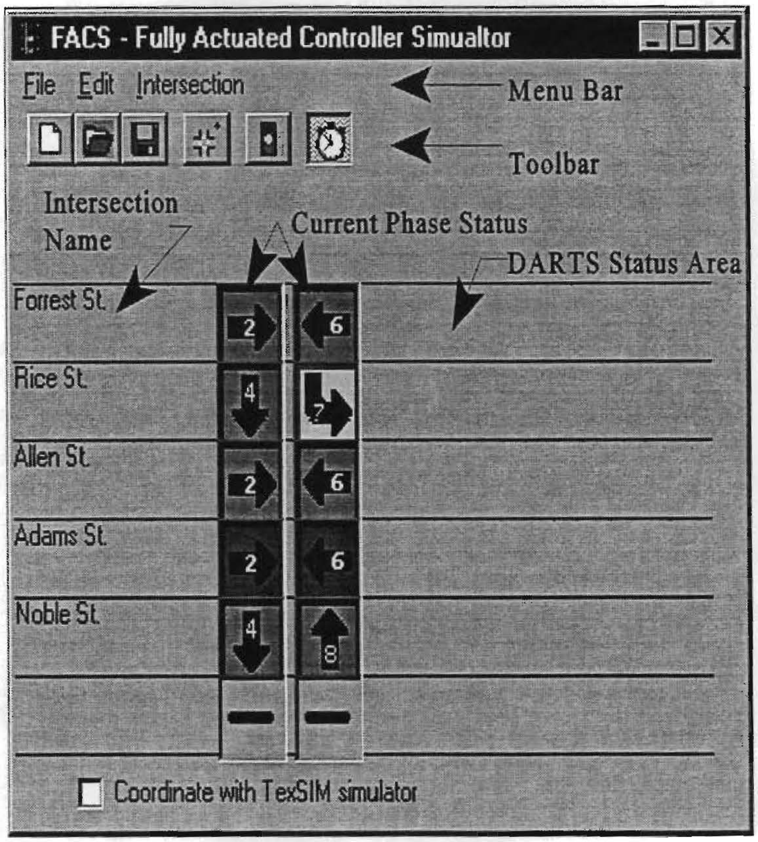


Figure 1. The Main User Interface Screen for the FACS Program.

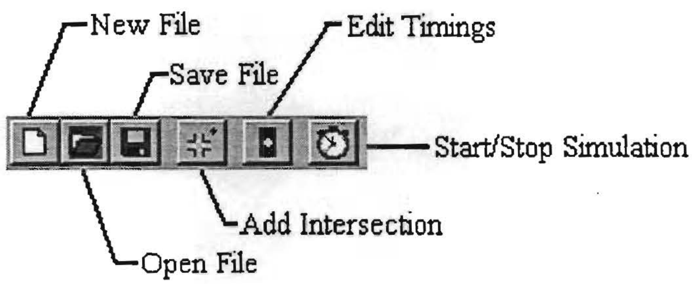


Figure 2. The FACS Toolbar.

Entering the Signal Timings

Once the appropriate number of intersections has been added, the next step is to set the FACS controller at each intersection. This is accomplished using a series of data entry screens that are intended to resemble the programming screens found on many real NEMA-type controllers. To begin setting the controller timings, either choose "Controller Settings" from the Intersection Menu or click on the Edit Timings button on the tool bar. The resulting dialog box is shown in Figure 3.

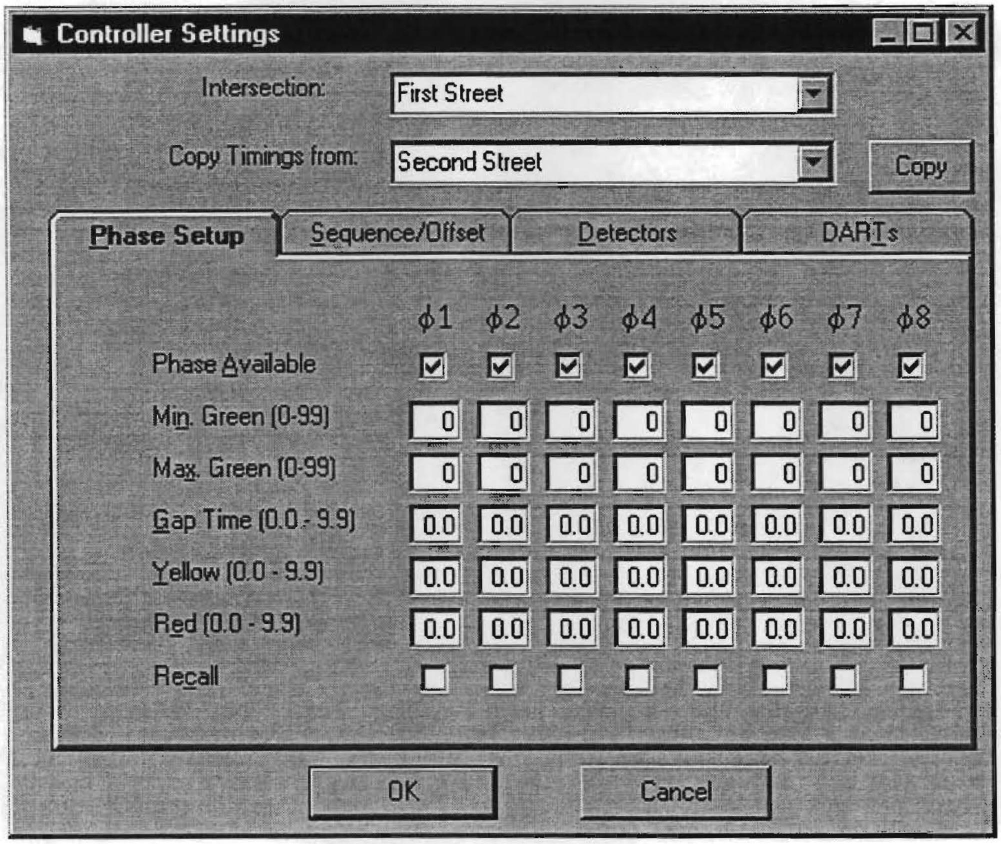


Figure 3. The Phase Setup Data Entry Screen.

The top and bottom portions of the dialog box are common to all data entry screens. The **Intersection** list box is used to select which intersection controller to edit the timings for. The timings for each intersection can be entered before closing the dialog box. The **Copy Timings From** list box is used to copy all of the settings from the specified intersection to the intersection that is being edited when the **Copy** button is pressed. Finally, the **OK** button closes the dialog box and saves the changes, and the **Cancel** button disregards any changes that have been made.

Note: Using the copy button will overwrite all settings (even those on different data entry screens than the one that is displayed) for the intersection that is being edited with the timing of the selected Copy From intersection.

Each of the four data entry screens will now be discussed in detail.

Phase Setup

The Phase Setup data entry screen that is shown in Figure 3 is used to specify timings for each phase. If a particular phase is not used (i.e., no separate left turn phases on an approach), the **Phase Available** box is left unchecked for that phase. If a phase is used, the following timings are specified:

Minimum Green Time - The minimum number of seconds to display the green signal once the phase becomes active. For pretimed operation, this entry is used to specify the green time for the phase.

Maximum Green Time - The maximum length of time that the green signal should be displayed for a phase under actuated control. (This should be set equal to the minimum green time for pretimed operation.)

Gap Time - The maximum headway between vehicles that will keep the signal green as long as the maximum green time has not expired. (Not used for pretimed operation.)

Yellow - Length of the yellow change interval.

Red - Length of the all-red clearance interval, if one is required.

Each phase also has a **Recall** check box. In actuated mode, this box is checked for each phase that should not be skipped and receive some green time even if no vehicles are detected on the approach. For pretimed operation, the **Recall** box should be checked for each available phase.

Sequence / Offset

The Sequence/Offset data entry screen that is shown in Figure 4 is used to specify the particular phase sequence that is used at the intersection and the offset for the start of the main street ($\phi 2+\phi 6$) green.

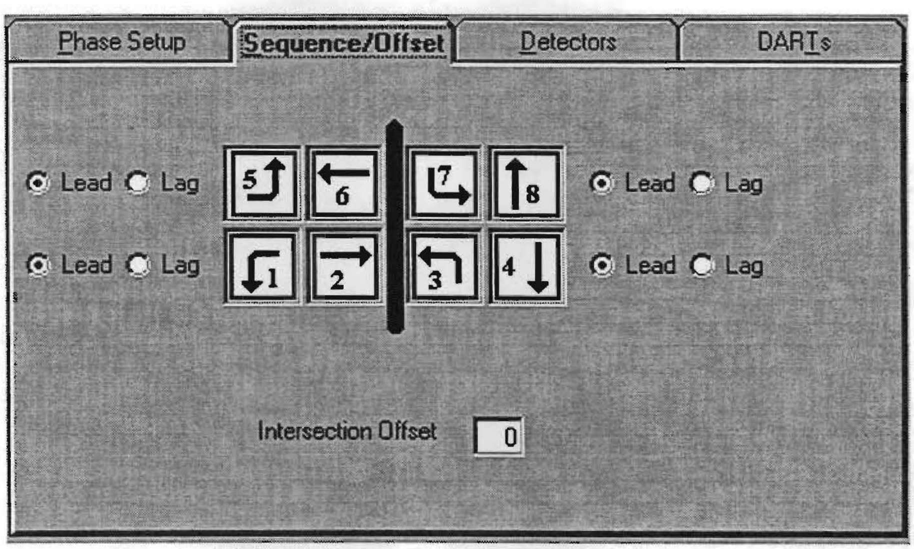


Figure 4. The Sequence/Offset Data Entry Screen in FACS.

The buttons marked **Lead** and **Lag** are used to determine where the left turn phase occurs in the sequence in relation to the corresponding through movement. The arrows indicate the direction of movement affected by the phase. The numbers refer to the NEMA movement numbering scheme. No phase on one side of the vertical black barrier in the diagram can run concurrently with any phase on the other side. Also, only one phase on a ring on the same side of the barrier can be active at one time (i.e., $\phi 1$ and $\phi 2$ cannot run concurrently).

If the intersection is part of a pretimed coordinated system, an offset to the start of the main street green can be provided. The master intersection in the system should have an offset of zero. All offsets must be positive values.

Detectors

The Detectors data entry screen is used to link specified TexSIM detectors with their appropriate phase. This data entry screen is shown in Figure 5.

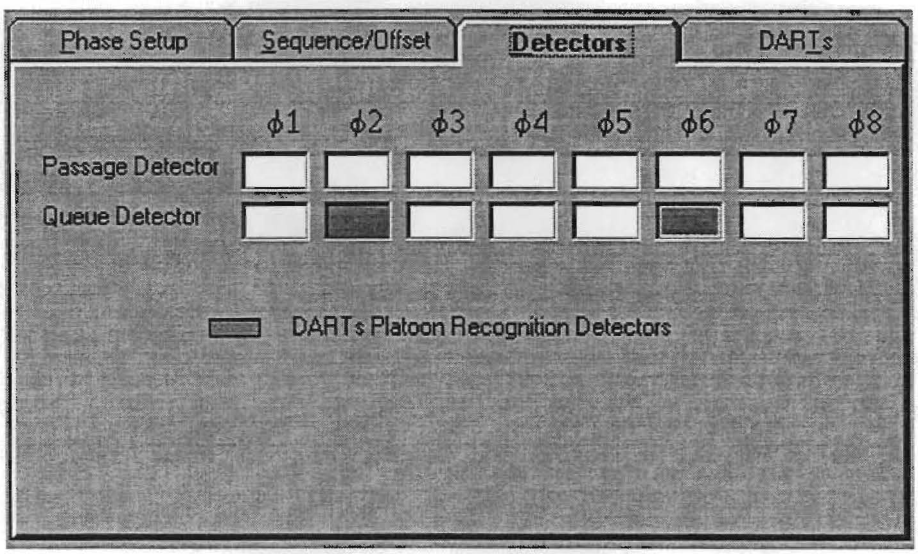


Figure 5. The FACS Detector Data Entry Screen.

Two types of detectors are currently supported by the FACS program. The **Passage Detector** is used to alert the FACS controller that there is a call for a phase. A call is generated by TexSIM whenever the detector is occupied. The **Queue Detectors**, on the other hand, are used by the DARTS module of FACS to determine if the delay experienced by vehicles on the cross streets is too high while the main street is being held in green. The queue detectors that are connected to $\phi 2$ and $\phi 6$ are used by the DARTS algorithm to determine if a platoon has formed on the main street approach.

The FACS program can support detectors that are in one lane or spread across two lanes. If a single lane detector is used, its TexSIM detector number is entered into the appropriate box on the data entry screen. Since TexSIM will only allow a detector to occupy a single lane, the following procedure is used to configure a two-lane detector:

- Set up two detectors in TexSIM, one in each lane to be detected.
- Assign the detector in the second lane a detector number that is ten plus the number of the detector in the first lane.
- Enter the value that is 100 plus the number of the detector in the first lane into the appropriate detector box on the data entry screen.

Detector numbers greater than 100 alert FACS that two detectors need to be examined for the particular phase. If a particular detector is not used for one or more of the phases, the data entry box is simply left blank for that detector.

DARTS

The DARTS module that is part of FACS is used to implement the Dynamic Arterial-Responsive Traffic System in each FACS controller on a network. The DARTS tab in the Controller Settings dialog box provides access to the data entry screens for the DARTS module. The data entry screen for the Inbound DARTS control is shown in Figure 6.

The Inbound data entry screen is used to configure the various timers and options that are available to operate DARTS in the inbound direction. In FACS, the inbound direction is the direction in which the through movement is served by ϕ2. The names of the six timers are listed across the top of the text boxes for the primary and alternate DARTS timers. The primary timers will be activated at an intersection if a primary inbound platoon signal is received. On the other hand, if an alternate platoon signal is received, the alternate set of timers will be used.

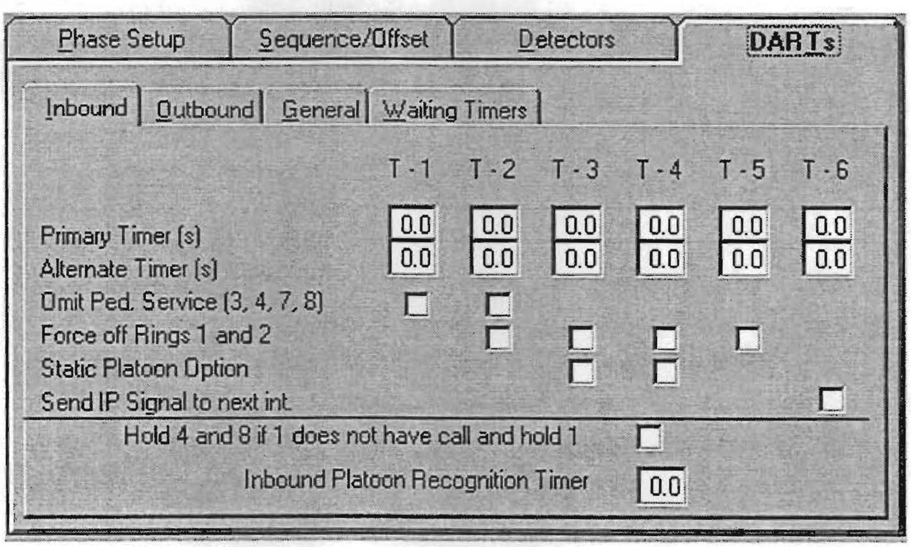


Figure 6. The Inbound DARTS Data Entry Screen.

Several options are available during each of the six DARTS time periods. If a particular option is available for a time period, the check box can be used to indicate if that option is desired. If a check box is not present, the option is either not available for the particular time period or is included in the DARTS specification to be active during the particular time period.

The final entry on the dialog box is for the **Platoon Recognition Timer**. If the inbound platoon recognition detector (the queue detector for $\phi 2$ on the Detectors data entry screen) is occupied for the length of time specified, the appropriate DARTS commands will be sent to the downstream intersection. The Output data entry screen has the same information as that for the Inbound. The through movement served by $\phi 6$ is considered the outbound direction.

The general DARTS settings can be found on the tab marked **General** on the DARTS data entry screen which is shown in Figure 7. These options control whether the DARTS system is active at a particular intersection and, if so, which direction is active. The list boxes at the bottom of the dialog box are used to determine which intersection will receive the DARTS notification if a platoon is detected. Primary DARTS platoon signals are sent to the **First Downstream Intersection** and alternative DARTS platoon signals are sent to the **Second Downstream Intersection** when a platoon is detected.

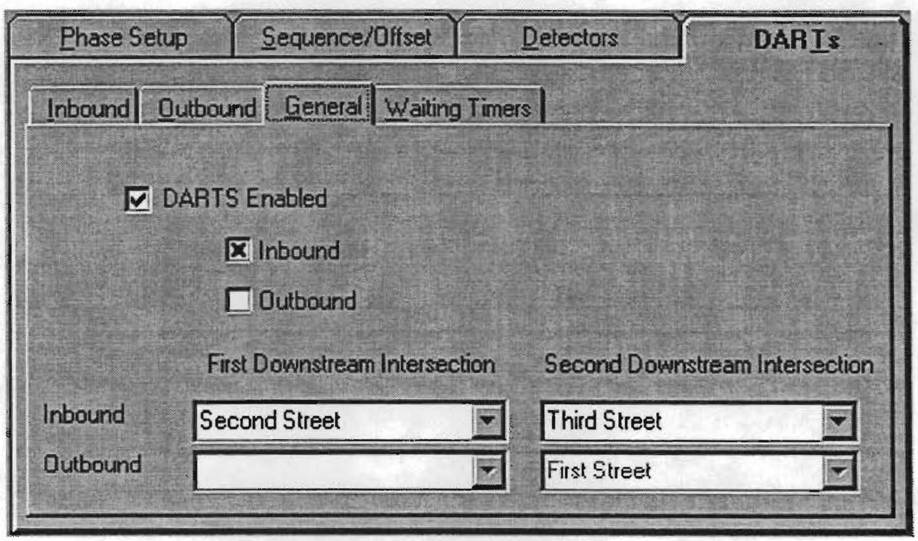


Figure 7. The Data Entry Screen for General DARTS Parameters.

The final settings required for the DARTS system are the duration of the timers used on the cross streets to determine if they need to be serviced to avoid excessive delay. The settings for these timers are entered on the **Waiting Timers** data entry screen, shown in Figure 8.

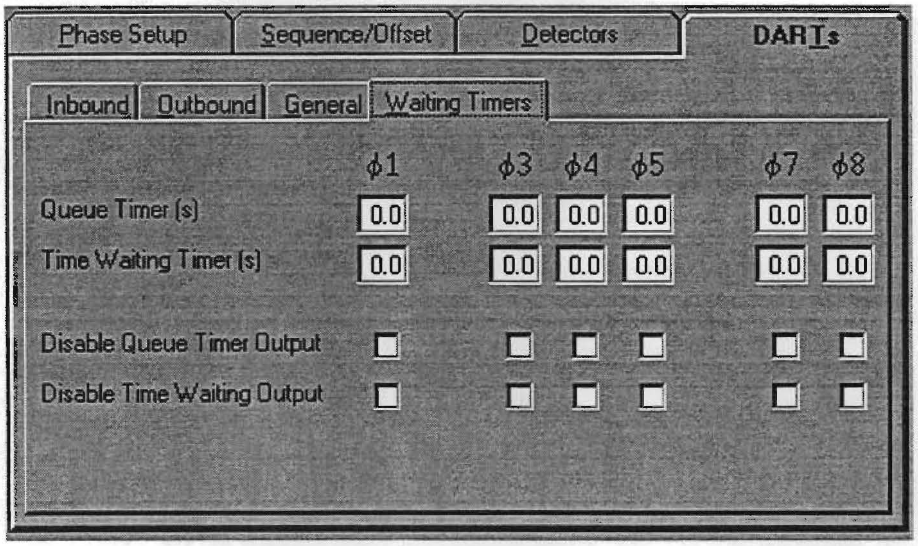


Figure 8. The Data Entry Screen Used to Specify the DARTS Waiting and Queue Timers.

This screen is very similar to that which is used to enter the detector numbers for each phase. Any phases that conflict with the through movements on the main arterial can have a time waiting timer and/or a queue timer to measure how the arterial progression is affecting the cross streets. The time waiting timer measures how long the passage detector for a phase has been active. The queue timer measures how long the queue detector for a phase has been active. If a vehicle is over either detector longer than the time specified on this data entry screen, the DARTS commands are inhibited, and the cross street vehicles are allowed to proceed. The check boxes at the bottom of the dialog box can be used to disable either timer for any of the phases. If these boxes are checked, the respective timers will not be used to determine if the DARTS commands should be inhibited.

Running the Simulation

After all of the settings for the FACS controllers at each intersection have been entered, the simulation is prepared to run. The FACS software can be used to test pre-timed strategies at the intersections without interfacing with the TexSIM simulator. If this mode of operation is desired, simply leave the check box marked **Coordinate with TexSIM Simulator** unchecked (see Figure 1). If the detector outputs and measures of effectiveness generated by TexSIM are desired, leave this box checked.

To start FACS, click on the Start/Stop Timing button on the toolbar. If coordination with TexSIM is not desired, the simulation will begin immediately. However, if TexSIM is being used, it must be properly set-up as discussed below before the simulation will begin. In either case, once the simulation has started, the Start/Stop button can be used to pause the simulation if desired.

As FACS runs, the currently active phases at each intersection are shown on the main interface screen (refer to Figure 1). The arrow directions and numbers correspond to the standard NEMA phase numbering sequence. The color of the box surrounding the arrow corresponds to the status of the phase. A red box is used to indicate the phase is timing its red clearance portion.

If the DARTS module is being used in conjunction with TexSIM, various messages may appear from time to time in the DARTS Status Area to the right of the signal status displays. The codes that appear are defined as follows:

IPC - indicates a vehicle is currently over the inbound platoon recognition detector
IPD - a platoon in the inbound direction has been detected; downstream signals have been notified
OPC - indicates a vehicle is currently over the outbound platoon recognition detector
OPD - a platoon in the outbound direction has been detected; downstream signals have been notified
T# - the current primary DARTS interval that is being timed where # is 1 to 6
T# A - the current alternate DARTS interval that is being timed where # is 1 to 6

If TexSIM is being used, the FACS program will automatically close at the conclusion of the TexSIM simulation period. After this time, the output files from TexSIM can be examined to determine the appropriate measures of effectiveness. The FACS program can also be terminated at any time by choosing **Exit** from the File Menu.

The Controller Matrix

Once the simulation is started, the **Controller Matrix** dialog box appears on the screen, as shown in Figure 9. This box provides information on the current status of each phase according to the controller at each intersection. The list box at the bottom of the window can be used to choose which intersection to examine.

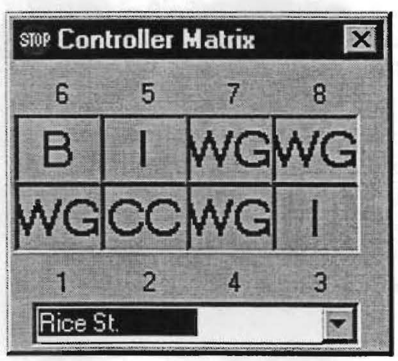


Figure 9. The Controller Matrix Box.

The numbers that appear in the window correspond to the phases used at the particular intersection. The following codes are used to describe the status of each phase:

B - the phase is BUSY either in minimum green or extended
I - the phase is IDLE (i.e., no cars are waiting) and displaying red
CC - the phase CAN CHANGE and will do so as phases terminate or another vehicle is detected
CG - the phase is CHANGING and is either displaying yellow or red clearance
WG - the phase WANTS a GREEN signal due to waiting traffic or the phase is set on recall
WT - the phase is WAITING for conflicting phases to end; it is the next phase to receive the green

Interfacing with TexSIM

In order for the FACS program to work properly when being used in conjunction with TexSIM, a TexSIM data file needs to be created to describe the network to be modeled. This data file specifies the geometric layout of the network and places the detectors used by FACS in their appropriate locations. For more information on how to create the data file, on-line help is provided.

After clicking on the Start/Stop timing button for the first time in FACS, it is necessary to load the simulation file into TexSIM. Once the file has been loaded, click on the green **Start Simulation** button to start TexSIM and FACS. Figure 10 shows an example TexSIM screen.

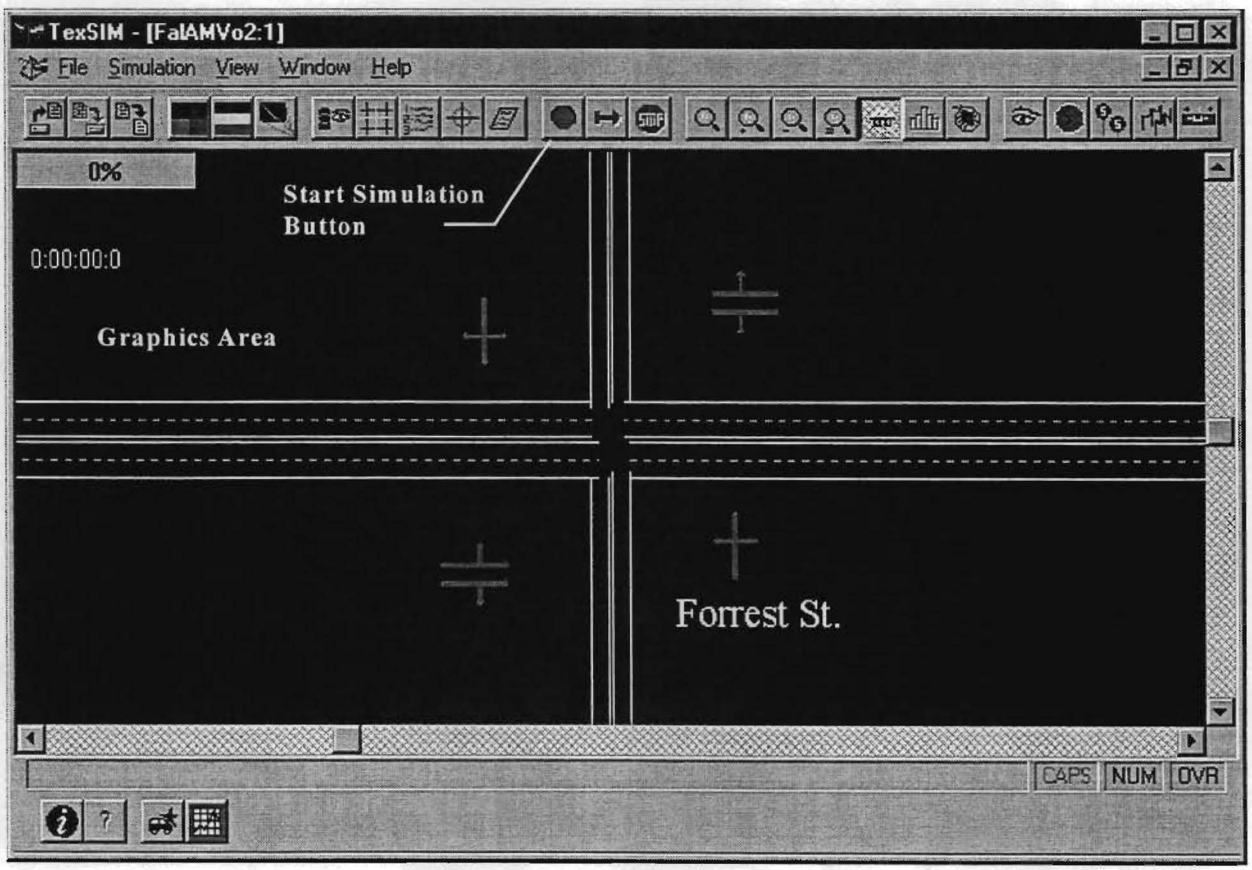


Figure 10. The TexSIM User Interface.