SCHOOL OF
CIVIL ENGINEERING

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DEPARTMENT OF TRANSPORTATION

JOINT HIGHWAY RESEARCH PROJECT

JHRP-93/15
Informational Report

THE COMPONENTS AND BENEFITS OF
AN ADVANCED SURFACE ARTERIAL
TRAFFIC MANAGEMENT SYSTEM

Ted M. Andrews
Kumares C. Sinha

PURDUE UNIVERSITY

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To: V. P. Drnevich, Director, JHRP

September 3, 1993

From: K. C. Sinha, Research Engineer, JHRP

File 3-3-46

Attached is an informational report entitled, "The Components and Benefits of an Advanced Surface Arterial Traffic Management System". The research was conducted by Ted M. Andrews under my direction.

The report presents a detailed review of current technologies in Advanced Traffic Management Systems for surface arterials. Recommendations for surface arterial ATMS were made including a proposed application in the Indianapolis area.

It is felt that the research work will provide useful information to the INDOT and City of Indianapolis.

Respectfully submitted

A handwritten signature in cursive script, appearing to read "K. C. Sinha".

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Informational Report

THE COMPONENTS AND BENEFITS OF
AN ADVANCED SURFACE ARTERIAL
TRAFFIC MANAGEMENT SYSTEM

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EXECUTIVE SUMMARY

Traffic congestion has become an increasing problem on major surface arterial roadways. Demand for accessibility to adjacent land uses yields increased vehicular turning movement activity at driveways and intersections. As turning and cross-road traffic volumes increase, the need for traffic signalization will eventually be warranted. When numerous, independently operating traffic signals are present on a given arterial roadway, adverse effects can result. First, continuous movement along the arterial at a desirable speed may not be assured. Second, vehicular delay will increase because of the slower operating speeds and increased number of stops. Third, safety can be threatened as poor traffic flow (i.e. increased number of stops, etc.) may lead to potential vehicular conflict. Fourth, vehicle emissions may increase as a result of poor traffic progression and can have unfavorable consequences to the local air quality. Lastly, increased fuel consumption is possible as traffic waits along poorly timed arterials. Of the five effects mentioned, travel delay is the most conspicuous and readily measured. To offset these

effects, advanced traffic control systems have been developed to effectively and efficiently coordinate traffic flow along an arterial roadways or throughout an area.

In this study, a review of the most current technologies in Advanced Traffic Management Systems (ATMS) for surface arterial roadways was performed. An emphasis was placed on new and developing technologies which are likely to be available for use within the next five years. In addition, advanced traffic control systems presently within Indiana were covered. Finally, recommendations for surface arterial ATMS were made including a proposed application for major arterial roadways in the metropolitan Indianapolis area. Furthermore, the cost-effectiveness of a surface arterial ATMS was discussed. This included the consideration of the initial construction, maintenance, and operation costs of the system hardware and software as well as roadway user benefits and costs. A comparison of before and after surface arterial ATMS user benefits was made.

CHAPTER 1 INTRODUCTION

Traffic congestion has become an increasing problem on major surface arterial roadways. These facilities are typically found in urban/suburban areas and mainly function as a balance between the demands for wayside accessibility and through traffic mobility. Demand for accessibility to adjacent land uses yields increased vehicular turning movement activity at driveways and intersections. The additional demands of turning movement activity will not only increase traffic volumes on the subject arterial but will also potentially conflict with one of the main functions of the arterial roadway which is to provide moderate to high speed mobility within an area at a desireable level of service. As turning and cross-road traffic volumes increase, the need for traffic signalization will eventually be warranted (IDOH, 1988). When numerous, independently operating traffic signals are present on a given arterial roadway, adverse effects can result. First, continuous movement along the arterial at a desireable speed may not be assured. Second, vehicular delay will increase because of the slower operating speeds and increased number of stops. Third, safety can be threatened as poor traffic flow (i.e. increased number of stops, etc.) may lead to potential vehicular conflict. Fourth, vehicle

emissions may increase as a result of poor traffic progression and can have unfavorable consequences to the local air quality. Lastly, increased fuel consumption is possible as traffic waits along poorly timed arterials. Of the five effects mentioned, travel delay is the most conspicuous and readily measured.

Motorists in this country waste approximately 2 billion hours a year in traffic jams which equates to annual business losses of \$73 billion. Should this situation remain unchecked, a 400% increase in the number of hours spent in traffic delays can be foreseen by 2005 (Stephanedes, 1990). As discussed previously, the majority of these congested arterials are in urban/suburban areas; because of right-of-way and land development constraints, building or expanding the facility out of congestion is usually not possible. Hence, improved traffic control over the roadway network can be considered as a viable solution for traffic congestion.

Improved quality of traffic operations can be achieved by means of a traffic control system. A system typically consists of an arrangement of interacting components (i.e. signalized intersections, detectors, etc.) which forms a unified whole serving a common purpose: to effectively and efficiently coordinate traffic flow along an arterial or throughout an area (Homburger and Kell, 1984).

In this report, a review of the most current technologies in Advanced Traffic Management Systems (ATMS) for surface arterial roadways will be performed. An emphasis will be

placed on new and developing technologies which are likely to be available for use within the next five years. In addition, advanced traffic control systems presently within Indiana will be covered. Finally, recommendations for surface arterial ATMS will be made including a proposed application for major arterial roadways in the metropolitan Indianapolis area. Furthermore, the cost-effectiveness of a surface arterial ATMS will be discussed. This will include the consideration of the initial construction, maintenance, and operation costs of the system hardware and software as well as roadway user benefits and costs. A comparison of before and after surface arterial ATMS user benefits will be described.

CHAPTER 2 ROLE OF ATMS WITHIN IVHS

Advanced Surface Arterial Traffic Management Systems (ASATMS) is an off shoot of the Advanced Traffic Management System (ATMS) which is one of the four basic components of a Intelligent Vehicle / Highway Systems (IVHS). The other components of IVHS are: Advanced Traveler Information Systems (ATIS), Commercial Vehicle Operations (CVO), and Advanced Vehicle Control Systems (AVCS). ATMS involve the traffic control and surveillance of arterials, freeways, and corridors. These systems implement traffic control strategies such as efficient signal timing and roadway user information in a real time format. For an ASATMS, the emphasis is on the traffic control of the surface arterial roadways as they are influenced by traffic demands, intersecting roadways, freeways interchanges, accidents, construction/maintenance activities, and adjacent land uses. Relevant information regarding the operational status of the arterial network can also be made available to the traveling public.

CHAPTER 3 EVOLUTION OF TRAFFIC CONTROL SYSTEMS

In the past, there have been five basic types of traffic control systems. These systems, which can vary from being relatively small and simplistic to quite large and complex, will be briefly discussed at this time. The first type of system is non-interconnected and is the crudest form of a control system. It is made up of intersections with pre-timed controllers whose cycle lengths and offsets are set manually. There is no physical interconnection between the signals; should signals go out of step of the pre-determined timing plan, the signal(s) would need to be reset manually. The second type is a time-based coordinated system. Similar to the non-interconnected system, the signals are not physically interconnected. However, the signals use a common power company's supplied frequency to keep time accurately. With this form of interconnection, various timing plans can be established based on time of day (TOD) and day of week (DOW). The third type is a master-controlled, interconnected system. This system directly interconnects the signal controllers and synchronizes each controller from cycle to cycle with a one-way pulse signal sent out by a designated master controller. In the past, these systems were not traffic responsive and generally utilized TOD and DOW timing plans. The fourth

system is traffic adjusted and uses an analog computer as the master controller to control the system cycle length based on the traffic volumes. This system has become obsolete with the advent of the digital computer in traffic control. The fifth and last system is the digital computer signal control system. Historically, these signal control systems are distinguished by a centralized control computer and two-way communication with the computer and the individual intersection controllers and detectors (USDOT, 1983). The inherent speed, programmability, and extensive logic capability of the digital computer enables it to control, operate, and supervise a given traffic control system. These systems can range in size from 10-20 signalized intersections (for one arterial, etc.) to all or the majority of the intersections in a city. The basic components of a digital computerized system includes: the central computer facility, communications hardware, field equipment (i.e.: local signal controllers, detectors, etc.), signals and variable message signs, and transit and emergency vehicle identification equipment. These systems can implement signal timing strategies that either time based (Time of Day) or traffic responsive and can detect signal and detector failures remotely. There has been, in recent years, efforts to decentralize the digital computing system by having satellite computers be installed in the field. The principal reason for this is the elimination of total dependence on the main computer should communications or the computer itself fail (McShane and Roess, 1990).

Although all five types of control systems are in use today, the digital computer system is what is currently being installed on arterial roadway networks. An ASATMS would consist of some form of a digital computer system.

CHAPTER 4 ADVANCED TRAFFIC CONTROL SYSTEMS IN INDIANA

A variety of traffic control systems currently exist within the state of Indiana. Many of these systems have been developed independently from one another and are under jurisdictions ranging from municipalities to the state. At the present time, two hoosier cities, Evansville and Ft. Wayne, have had a functioning centralized traffic control system for a number of years. South Bend is in the process of installing an advanced traffic control system. The Indiana Department of transportation (INDOT) has a number of traffic control systems located within its districts in addition to the Borman Expressway's Freeway Traffic Management System (FTMS). In this section, an overview of the important traffic control systems currently existing in Indiana will be discussed. This will include the systems operated by the cities of Evansville, Ft. Wayne, and South Bend; the status of traffic control systems in the city of Indianapolis will also be disclosed. Finally, the Greenfield and LaPorte Districts of INDOT will be discussed since their work in traffic control systems is more comprehensive than in other districts.

Evansville

The city of Evansville has a computerized traffic control system which provides signal control throughout the city with the use of a central digital computer. The system was designed and constructed fifteen and eight years ago, respectfully. At the present time, 175 signalized intersections are on line, 50 of which are INDOT intersections (Savage and Wilhite, 1991). Ultimately, the Evansville system has the capacity to control 300 intersections; the controlled region can be divided into as many as 40 sub-areas with up to 31 timing plans for each sub-area. The system allows the timing plans to be selected manually, by time of day (TOD), day of week (DOW), and by traffic response pattern matching with a time of day backup. Data can be received from as many as 350 system detectors and 400 local detectors (JHK, 1986). The main computer configuration includes a MODCOMP classic processor, three magnetic tape drives, teletype and console printers, two CRT monitors, a wall-mounted display map and control panel. The Evansville system basically follows the FHWA Urban Traffic Control System (UTCS) program. The system is able to provide extensive reporting and logging capabilities to record normal operations as well as signal/detector malfunctions.

Communication between the central computer and traffic signals is achieved with four wire, full duplex, time division multiplexing cables owned by the city. Bell 3002 leased lines are used to interconnect with the INDOT intersections as well

as with out-lying city intersections recently added to the system. For each four wire circuit, as many as eight intersections and six system detectors and eight intersection detectors can be served. Critical Intersection Control (CIC), which reassigns split time on a cycle by cycle basis on highly congested intersection approaches, can be used on all intersections. Also, signal pre-emption can be activated from fifteen designated emergency services facilities (police, fire, hospital, etc.) with up to ten routes for each facility. Railroad crossing pre-emption is also available at selected locations.

In 1986, an engineering consulting firm performed a comparative analysis of the modernized traffic control system with a pre-system Evansville. From the analysis, it was found that overall traffic delay had been reduced by 8%. The resulting average speed was increased between 2% and 32%; the probability of a motorist from being stopped by a signal saw a 17% reduction. It was estimated that 2,887 person-hours per day were saved by the new traffic control system. In 1986 dollars, this time savings was translated to an annual benefit of \$3,288,200. Fuel consumption would also be reduced as much as 1,782,270 gallons a year. The combined savings in fuel and time was determined to be approximately \$5.5 million annually. When compared to the original installation cost (uniformly spread out over 10 years) of \$658,154 a Benefit/Cost ratio of 8.4 was achieved. In comparison, a B/C ratio was estimated during the signal system's design phase to be 3.2. Also, a

reduction of 922 tons per year of vehicle pollutants was estimated to reflect the reduction of stops and delays. Hence, the advanced traffic control system has been viewed as an excellent investment for Evansville (JHK, 1986).

Ft. Wayne

Ft. Wayne has had a traffic control system since the early 1970's. A pre-UTCS traffic control system was applied to 80 intersections within the central business district. A single main frame computer centrally controlled the pre-timed intersection controllers; the system monitored and altered the green times to ensure coordinated green phases. Communication was provided by a four wire cable exclusively installed by the city for the system. In the early 1980's another traffic control system was installed for the US 30 Bypass (Coliseum Blvd.), a facility not within the Central Business District (CBD). The newer system consisted of a Data General main frame computer with UTCS software developed by Eagle/Comtrack. The Data General system was designed to only use two wires to communicate with eight traffic signals. In 1988, excellerated efforts were made with Federal aide funding to merge both the CBD and bypass systems using the Data General computer as the main central computer. The original CBD computer was deactivated due to hardware failure. The resulting system has a designed capacity for 250 intersections and 500 system detectors (Davis, S., 1991). At the end of 1991, Ft. Wayne had 156 intersections on line with approximately 60% being

city signals. The remaining signals (i.e.: on the US 30 bypass, etc.) are under the jurisdiction of INDOT but are operated by the Ft. Wayne system. The newer system does have a wall-mounted display map of the city but is also equipped with color graphic capabilities to enable the main office to call up an individual intersection and monitor (via crt screen monitors) its performance in a real time format. The Data General system, similar to the Evansville system, can break the total network into groups of intersections and send out TOD, TOW, or traffic responsive timing commands on a group by group basis. This was a feature not available on the older CBD system. In addition, the Data General has an effective logging system which can log, on a 24 hour basis, the preprogrammed times when signals go to TOD, traffic responsive, flash, or when signals unintentionally conflict flash and when detectors become inactive or malfunction. The system not only can control pre-timed signals but also semi or fully actuated signals releasing them for isolated operation during non-saturated periods. With an exception to a few outlying signals, communication lines are owned and operated by Ft. Wayne with the balance provided by leased telephone lines. At the time of this study, no cost effective analyses of the Ft. Wayne system(s) were available.

Indianapolis

The city of Indianapolis currently has two closed loop traffic signal systems on two high trafficked arterials (Davis, J., 1991). The first system is on 38th street and controls approximately 12 signalized intersections (from Eagle Creek Park to Industrial Blvd.). The system was installed four years ago but its software was updated in 1991 by Econolite. The system consists of connecting the local traffic signals to a field master controller which, in turn, has interface with an personnel computer at IDOT's main office. The current status of the closed loop system can be reviewed at the office in addition to updating and downloading traffic control strategies. IDOT is presently using six different timing strategies on the 38th street system which are activated by traffic (traffic responsive). The second existing system in Indianapolis is found on Keystone Avenue between Haverstick Road and Fall Creek Parkway. This system contains 16 signalized intersections and was installed approximately seven to eight years ago. The Keystone Avenue system's set up is similar to the 38th street's; both systems were developed by the same manufacturer and software updated in the past year. The Keystone Avenue system has five timing strategies.

Indianapolis is installing five additional closed loop systems this year. The number of signals controlled per system will vary from three to approximately fifteen with an average of twelve. These closed loop systems are located at:

Post Rd. (Washington St. to Pendleton Pike)
82nd St. (Allison Point to Hague Road)
Allisonville Rd. (82nd St. to 96th St.)
86th St. (Allisonville Rd. to Center Rd.)
Shadeland Ave. (Fall Creek Rd. to 75th St.)

There are four additional closed loop systems in the design phase. It is the desire of IDOT to have these systems identical or compatible with one another. Although IDOT did have justification reports prepared for a few of these closed loop systems, no before and after cost-effective analyses were performed.

South Bend

The City of South Bend recently installed the first phase of a city-wide traffic control system. The first phase consists of the interconnection of 46 signalized intersections in the central business district. The second phase involves approximately 70 adjacent intersections which feed into the downtown area. The last phase will make up the interconnection of intersections on the outer limits of South Bend. The purpose of the system was to effectively coordinate and monitor traffic flow on the major arterial roadways during peak / off-peak hours and special events. Similar to Ft. Wayne, South Bend has a conventional grid street network and has major state routes and other surface arterials serving both inter/intra city travel. Although South Bend does have two by-pass routes on the west and south sides, these facilities are grade separated limited access in nature. The

traffic control system features a hierarchical framework between the city office and intersection. Three personal computers are at the top of the chain, each being connected to the system via a data port selector. Through the port selector, the PC's can interface with the master controllers in the field. The master controllers coordinate intersection control (i.e.: time of day, traffic responsive) as well as collecting traffic data from system detectors. The masters are connected to individual signalized intersections in a closed-loop fashion. For example in the first phase, 46 signals are connected to the system through 4 master controllers. What makes the South Bend system unique within Indiana is that it is fully connected by means of fiberoptic cable; the other existing systems use twisted pairs of copper wire or other cable types for interconnection. Furthermore, the first phase of the South Bend system directly connects the master controllers to the office PC's by means of fiberoptics, which is unique from the typical use of leased telephone lines (Walk, 1992).

The first phase of the South Bend system became operational in the winter of 1991 and at the time of this writing was undergoing a six month period evaluation. No cost-effectiveness analysis results are available.

INDOT - Greenfield District

The Indiana Department of Transportation's (INDOT) Greenfield District is one of six state districts assigned to a designated section of Indiana. For the Greenfield District, its jurisdiction covers east-central Indiana that includes the Indianapolis area. The Greenfield District has more signalized intersections under its jurisdiction than any other district in the state. The Greenfield District currently has four computer driven traffic control systems that are closed loop in nature. The first system is on US 31 in Kokomo and controls thirteen intersections between State Route 26 and Morgan Road. Recently, the telemetry communications between master and individual controller was upgraded from twisted wire to fiberoptics. There are two other traffic control systems on US 31 that straddle the I-465 Interchange on the south side of Indianapolis. The first one is between Mills Avenue and Pleasant Run Parkway and consists of eight traffic signals. The second system, which is south of the I-465 Interchange, runs between Thompson Road and Countyline Road and controls thirteen signals. The last traffic control system is on Keystone Avenue; the system begins at the I-465 Interchange in northern Indianapolis and interconnects with several signals on Keystone north of the interchange. This system is manufactured by Traffic Control Technologies (TCT) and is the only non-Econolite system in the Greenfield District. All of the closed-loop traffic control systems have

direct access from the main office via telephone modem (Roller, 1991).

A closed loop traffic control system in essence consists of the interconnection of a field master controller with servant signal controllers by means of hard wire/fiberoptics communication. The master has the ability to transmit timing plan commands to the other controllers while receiving an acknowledgement of these commands, as well as diagnostic checks and system operating parameters from the local controllers (Shewski, 1988). Also, the field master controllers can be uploaded/downloaded with operating parameters by means of a Personal Computer located in the main office. This is different from the earlier "centralized" traffic control systems that enabled only one-way communication between the central computer and local controller. Closed loop systems are generally used to coordinate signals on a stretch of roadway since the common line of communication would benefit signalized intersections having an element in common: the same roadway. Another difference is found in the method of communication used between the main office computer and the field master(s). In the Evansville, South Bend, and Ft. Wayne systems, communication between the office computer and field masters was through dedicated wires owned by the city. In the Greenfield District, this type of office to field master communication was provided with modems over leased telephone lines. The reason for this was the fact that these closed

loop systems are not in the direct vicinity of the main office (e.g. Evansville, South Bend, Ft. Wayne) but rather are located throughout the district. The distance between the closed loop systems and the main office could be over 60 miles. Having a direct communication link with the system would be very costly. Because of this, Greenfield lets these closed loop systems run independently but will periodically "call them up" and upload/download information. All of the traffic control systems have the capability of storing information for such purposes. At the time of this study, no cost effectiveness analyses were performed on these Greenfield systems.

No additional closed loop systems were being designed or planned for installation in the Greenfield District. However, potential areas for such advanced traffic control systems could include US 40 between Cumberland Avenue and Post Road on the east side and US 31 north of 86st Street towards Carmel.

INDOT - La Porte District

The La Porte District of the Indiana of Transportation is located in the northwest part of the state; the district's jurisdiction basically covers the counties: St. Joseph, La Porte, Porter, Lake, Newton, and Jasper. The La Porte District is responsible for approximately 400 signalized intersections. In the district, there are 40 to 50 traffic control systems with 15 to 20 of these being closed loop in nature and are manufactured by Econolite (Shamo, 1992). It is

estimated that as many as 40 to 50 closed loop systems could be installed in this district. The remaining systems consist of the older hard wire interconnection design. There are several closed loop systems in the Hammond-Gary area. One INDOT system is on Calumet Avenue just north on the Borman Expressway Interchange and controls eight intersections including those signals for ramp traffic. Further north on US 41 (Calumet Ave.), the City of Hammond has approximately a dozen traffic control systems which include intersections on Calumet Ave.; INDOT-La Porte has the jurisdiction to review and approve Hammond's timing plans. In Gary, a unique closed loop system is controlled by La Porte. Two closed loop systems, one for US 12 & 20 (East - West), and one for Broadway Avenue (North - South), share a common intersection that being US 12/20 at Broadway Avenue. The master controller is positioned at this intersection. An "L" - shaped configuration of the closed loop systems results. The master assigns timing strategies to the two loop systems; depending on the traffic volumes at the master intersection, one loop system will be assigned the major phase split and will assume a primary status. The other loop system will be assigned the minor phase split (lower green time) and will be the secondary system. Another closed loop system is found on Ridge Road, a major east-west arterial roadway south of the Borman Expressway. INDOT - La Porte used to have jurisdiction of this system but was transferred to the cities of Highland, Griffith, and Munster when Ridge Road lost its US Route 6

designation. At the time of this writing, no cost-effective analyses of these systems were available.

The La Porte District, in conjunction with INDOT and the Federal Highway Administration, are currently in the process of installing a Freeway Traffic Management System (FTMS) on the Borman Expressway. The twelve mile stretch of Interstate 80/94 begins at the I-65 interchange in Gary and terminates at the Indiana/Illinois stateline. The principle purpose of the FTMS is to mitigate operating problems through the real-time detection and removal of expressway incidents. In addition, strategies for managing and minimizing congestion resulting from incidents are to be part of the proposed FTMS system (Cassidy and Sinha, 1990). The Borman Expressway's system, when installed, will consist of three basic components which would be monitored and controlled from a Traffic Operations Center (TOC) located in the vicinity of the expressway. The first component is traffic surveillance and would cover inductive loops, closed circuit television, radar detection, additional field reference marks (mileposts), and service patrols. The second component is motorist information; methods of relating information to the general public would include changeable message signs, highway advisory radio, and relevant traffic bulletins issued by local media. The third component of the FTMS system would be traffic management. Management systems would be used to reduce the effects of congestion resulting from incidents. With a data base developed with the assistance of the other two components, a

variety of contingency plans can be developed to deal with incident occurrences. These plans would involve a variety of agencies including police, fire, emergency medical, local DOT's. The motorist service patrols, mentioned in the traffic surveillance component, have an important function of detecting and removing expressway incidents. During the labor day weekend in 1991, the La Porte District began motorist service patrols on the Borman Expressway. These patrols, officially called "Hoosier Helpers" constantly patrol the expressway looking for disabled vehicles and accidents. The service patrol unit has the ability to call all relevant services (i.e.: police, fire, EMS, wrecker, DOT, etc.) via radio. In addition, the patrol unit is equipped to provide basic motorist needs such as fuel, water, tire and minor repairs. Over the first five and a half months of service, almost three thousand vehicles were serviced. At the present time, INDOT - La Porte has expanded it's "Hoosier Helper" fleet and is currently installing a test section surveillance equipment along the Borman for analysis purposes.

CHAPTER 5 ASATMS COMPONENTS

Advanced technologies that are presently available or are most likely to be developed in the foreseeable future in an ASATMS will be discussed in this section. The advanced technologies section is divided into four components. The first component overviews the hierarchical architecture of traffic control systems that are currently available or soon to be developed. The second component will cover the technical means of communicating data retrieved from surveillance devices and commands originating from computing centers located centrally or in the field. The third component will discuss the devices used for traffic surveillance and detection of vehicular traffic. Finally, in the fourth component, advanced types of communication devices available for interface between the traffic control system and motorist will be addressed.

Control Systems

A system is made up of an arrangement or combination of interdependent components that will interact for a particular purpose. For traffic control, the basic objective is to enable continuous movement and/or minimize travel delay along a roadway or corridor. A traffic control system will utilize

equipment, methods, and techniques to achieve its designated objectives. In this section, advances in traffic control systems will be investigated. Basic operating philosophies in traffic control will be overviewed. In addition, a variety of system architectures based on these philosophies will be discussed in detail.

Principal Control Philosophies

Traffic control systems have existed for a number of years and have been developed in differing levels of complexity and capability. Traffic control philosophies have changed over the years to reflect the progression of state of the art technologies. These philosophies can be grouped into four basic generations of traffic control systems.

The first generation of traffic control philosophy, developed in the early 1960's, was basically of the table look-up type (Homburger and Kell, 1984). Traffic signal timing plans were developed "off-line" from the system. The off-line techniques could either be manual in nature or computer program based. This type of traffic control philosophy enables a number of timing plans to be stored and activated by the system. The plans could either be selected on a Time-Of-Day (TOD) basis or by data received from traffic detectors. For the latter method, timing plans are changed as detector data exceeds pre-established threshold values. In recent years, an improved version of the first generation philosophy has been developed. Conveniently classified as

"1.5 Generation", these systems enable new timing plans to be developed at the discretion of a traffic engineer using a signal optimization program such as TRANSYT. However, the input data for the program is not collected manually but rather adapted from the flow data measured from the traffic detectors.

The second generation philosophy differs from that of the first generation mainly on how the timing plans were developed. Although still utilizing a background timing cycle, the second generation develops timing plans "on-line" from real time information such as detector data. Prediction models are used to predict short term (i.e. 15 minutes) changes in traffic demand. These predictions, together with current traffic conditions, are used in a optimization program to compute splits and offsets (Homburger and Kell, 1984). The second generation philosophy was primarily in vogue between the mid-60's and 70's. Evaluations on the second generation have indicated that the philosophy may not be as effective as what is desired (Euler, 1987). By design, second generation systems have the ability to change timing plans as frequent as 15 minutes. With transition times running as high as 5 minutes per transition, the benefits of implementing a better timing plan may be offset by the frequent transition times that are typically awkward in an operational sense. In many of the systems, the timing patterns could be changed too often. Also, the prediction techniques used to determine near term timing plans were too reliant on the most recent cycle

length. With traffic demand being quite variable from cycle to cycle, the prediction performance was not too effective. On the other hand, certain second generation systems used prediction models that "smoothed over" detector data during longer periods of time (i.e. 15, 30 minutes, etc.,). Hence, this prevented the system from predicting traffic situations because sudden changes in traffic demand were averaged out.

Third generation philosophy does not require a background cycle. This philosophy, first introduced in 1975, involves on-line optimization subject to frequent (i.e. 1-2 minutes) field sampling periods in between timing plan updates. The continuous updates would include offsets, splits, and cycle lengths (Head et al., 1992). Some third generation systems can group together subgroups of intersections based on whether if the cycle lengths are common. The cycle lengths are changed from cycle to cycle in steps of several seconds per cycle. Subgroups can be "married or divorced" if it is evaluated that such actions will benefit coordination (Euler, 1987). Despite the consensus in the traffic engineering profession that third generation systems have met expectations better than the second generation, some shortcomings have been identified. First, the third generation system is slow to respond to drastic, sudden changes in traffic demand. This shortcoming is similar to that found in systems harboring the second generation philosophy. Second, the system is totally dependent on real-time data collection from traffic detectors which are not necessarily a reliable source. The third

generation systems only consider traffic flow data and do not consider nor respond to origin-destination data.

The fourth generation philosophy is being formulated at the time of this writing. This philosophy has not been physically applied to a traffic control system yet but several ideas and objectives have been brought forth (Euler, 1987). One principal feature of fourth generation systems would be the flexibility to accommodate different control objectives in different time periods and or parts of the urban/suburban region. One objective would be the minimization of system total travel cost. This would address vehicle delay and stops in terms of vehicle operating costs. Another objective would maximize safety. Effective ramp metering and motorist information systems could be used to yield smooth freeway flow and inform the public of potential downstream incidents. Also, integrated ramp metering would assist in maximizing roadway equity by adjusting the metering rates upstream and downstream of an incident to increase effective traffic operations. Likewise, unnecessary travel can be minimized with integrated motorist information systems (i.e.: variable message signs, highway advisory radio, etc.) providing timely information before, during, and after the trip. Finally, the development, installation, and maintenance of fourth generation systems need to be minimized to increase the availability to interested transportation agencies and to increase cost effectiveness.

System Architecture

A coordinated traffic control system can be defined as two or more signalized intersections operating in a relationship that yields progressive traffic flow. What is necessary for coordination is an appropriate timing plan and the hardware/software for interconnection. There are several different ways to establish signal interconnection; Chapter 3 gave an overview of early and advanced traffic control concepts. Some of the earlier systems had no physical interconnection and relied mainly on synchronization between electro-mechanical controllers. As technology advanced, so did the sophistication of traffic control systems. Computers can now be found not only at a central control location but also at field locations in master and local controllers. Automation has made it possible to monitor and accommodate traffic demands in a real-time environment, something that the earlier non-interconnected systems were unable to do. However, one important factor is how the system is composed or arranged to achieve its objectives.

In this section, architectures of traffic control systems will be discussed. The architecture involves the design and structure of the traffic control system and how it is to function. During the past thirty years, different types of architecture have been developed for traffic control. Their designs were subject to the technology available, financial constraints, the size of the traffic network, and the control philosophy designated by traffic agencies. Only the

architectures applicable to advanced technologies will be discussed.

Centralized Computer Control Systems

One of the first approaches in developing an automated traffic control system involved the control of the traffic network at one central location. This system, schematically shown in Figure 1, generally has one computer at a central location (e.g. traffic office, etc.) that sends out timing strategies to the local controllers. The timing plans, which are stored within the computer's memory, can either be Time-Of-Day (TOD) based, manually implemented, or traffic responsive (Mitchell, 1988). In the traffic responsive mode, traffic information is gathered by the computer from traffic detectors. The detectors can either be placed on the immediate approaches of local intersections or be "system" detectors positioned mid-way between signalized intersections. The traffic data (i.e. volumes, occupancy rates, average speed, etc.,) is used by the computer to compare against stored threshold values unique to particular timing strategies. Once specific thresholds are met or exceeded, the corresponding timing strategy is activated and sent out to the local controllers.

Centralized traffic control systems possessed several advantages that were well received since their introduction in the early 1960's. The ability to update signal timing plans at one central location at one time was a significant

maintenance staff. Lastly, centralized control systems have the ability to store the collected traffic data for planning and traffic purposes.

Because of their early introduction, the majority of centralized traffic control systems fall under the philosophy of the first generation. Second and 1.5 generation philosophies have been applied to centrally controlled systems either by initial design or from the modification of older first generation systems. Third or fourth generation philosophies have not been applied to centralized systems due to the requirements for automation at locations other than that of the central office (i.e. signal controllers, field masters, etc.).

At the central computing location, a variety of combinations can be realized. There could either be a single mainframe or a grouping of a few mini-mainframes each with a designated task. These tasks were to reflect the specific design abilities of the individual computers; some computers would be better equipped for tasks such as fast computation rather than monitoring or memory storage (McShane and Roess, 1990). Typically, these central control traffic systems were equipped with wall-mounted display maps and could produce progress reports and store traffic data on magnetic tape. Depending on the size of the computer system, there would be at least one operator to supervise over and respond to emergency messages.

One of the first centralized control systems to be installed in North America was in Toronto, Ontario in 1963. It originally controlled 864 intersections and was considered to be the most comprehensive system in the world. Other traffic control systems were installed in the english communities of West London and Glasgow as well as in Munich, Germany in the mid sixties. In 1965, the first american system was activated in San Jose, California and originally controlled 59 intersections. The following year saw another installation controlling 77 intersections in Witchita Falls, Texas. By 1972, nine american communities had operational traffic control systems with twenty-three more being designed/installed. Seven years later, a total of 201 traffic control systems were either operational, under construction, or in design (McShane and Roess, 1990). Many of the early systems such as Toronto, Witchita Falls, and San Jose reported relatively high benefit-cost ratios and capital recovery times as low as six months. Before and after results with regards to vehicle stops, average delay, and average travel speed experienced favorable changes measured in double digit percentages. In Indiana, as mentioned earlier, two centralized traffic control systems were installed in Ft. Wayne and Evansville. These systems were designed using centralized control concepts that were in vogue in the 1970's.

Despite the early benefits of automated centralized traffic control, some noticeable disadvantages became apparent. The architecture of centralized traffic control

systems were influenced in part by the exclusive availability of central mainframe computers in the 1960's and early 1970's. These computers were relatively new in concept and considerably expensive, ranging from \$100,000 to several million (Barry, 1989). Because of this price constraint, the applications of early traffic control systems were usually restricted to large metropolitan areas. Applications to medium or small communities were awkward and very costly since the available main frame computers were generally suited to much larger, complex traffic networks. Also, the obsolescence of early computer systems was very rapid and conspicuous because of the transition into integrated circuit electronics and the ongoing refinement of hardware and software components. Early centralized traffic control systems became outdated soon after installation; nearly 30% of the originally installed UTCS central master systems are now out of service. Because of the early technology, main frame computers had noticeable limits to their computational and memory capabilities. Even if main frame obsolescence is not a critical issue, the growth and expansion of a traffic network may exceed the capacity of the given computer. A tradeoff decision may need to be made between keeping the existing over-burdened computer or replacing it with a more powerful but expensive main frame. Furthermore, the first traffic control software, like much of rest of early main frame computer software, was not user friendly. Another potential weakness of early centralized traffic control systems was the

their vulnerability to communication disruptions. On many of the centralized traffic control systems, the central computer possessed real time control over all the detectors and signal controllers. Commands and telemetry feedback was performed on a once per second basis. Should this line of communication between the central on the field equipment be broken, automated traffic operations would cease. Safeguards such as time of day timing plans stored in the local controllers prevented the total collapse of the system. However, even short temporary communication breaks could yield numerous and lengthy transition periods for the entire system which would result in inefficient operations. Lastly, changes in timing parameters at the local signal controller level were not possible. On many of the early systems, a combination of solid state and electromechanical pre-timed controllers could be found. Since all of the automation was at the central location, only commands relevant to timing plans (i.e.: cycle length, split, offset) were sent out to the controllers. There was not a practical way to change individual signal controller timing parameters (i.e.: amber, all red, left turn, walk, flashing don't walk, etc.). Also, electromechanical controllers could not have their timing plans changed from the central computer since the controllers cycle dials were physically pinned for specific timing plans. Hence, time consuming field changes would still be necessary because there was no compatible automated interface between central and field hardware.

Centrally controlled systems were the first traffic systems to be introduced. They were developed at a time when solid state electronics was making inroads into computers and local signal controller construction. However, microprocessors were in the process of being developed and refined. Although the above-mentioned disadvantages of early centralized control yielded awkward experiences to some participating agencies, the user benefits of automated traffic control were being revealed. As solid state and microprocessor technology became more affordable, applications were made to hardware other than that of the central computer.

Decentralized Computer Control Systems

With the advent of microprocessing and affordable solid state electronics, automated hardware components were introduced for field applications in highway traffic control. The result was a distributed or "decentralized" concept of command and control throughout a signal system. More computing could be performed in the field and less information was sent back to a central location (Mcshane and Roess, 1990). Although a central office computer was still necessary, the traffic signal network's exclusive or complete dependency on control was no longer the case. With decentralization, network communication is reduced since more computations and commands are being performed in the field. Hence, constant communication to the central office is no longer necessary and reductions in operation costs are achieved. Even if

communication lines should be broken, effective traffic operations are still possible due to micro-processed memory at the master and controller level. Electromechanical hardware has essentially been replaced by solid state integrated circuits.

The concept of decentralized control systems have existed for over thirty years. Early systems would typically consist of a master (usually located in the field), detectors, and a system coordination unit for local controllers (Shewski, 1988). Traffic data is relayed from the detectors to the master whereas traffic commands were sent from the master to the local controllers. However, no local controller feedback was sent to the master. Moreover, no communications link existed between the master unit and the traffic engineer in the central office. The resulting lack of communications between the central office and the system yielded incomplete or an "open loop" (Mitchell, 1988).

With the introduction of personal computers in 1980 as well as the application of distributed levels of microprocessors in master and controller units, two way communications between the field and central office was finally possible. As Figure 2 demonstrates, a "closed loop" configuration is developed between the central office PC and the local signal controllers. Traffic detector data is sent to the master through the local controller. As it can be seen, a communications link enables the master to send system operating parameters and controller diagnostic checks to the

office PC (Shewski, 1988). Likewise, the PC can transmit or download changes in timing plans to the master or timing parameters to individual controllers through the master. This feature was simply not available with the

Figure 2 Closed Loop System Components
(Shewski, 1988)

earlier centralized systems. Therefore, the use of the personal computer has enabled a two-way communications link between the main office and the local control forming a complete or a "closed loop". The frequency in communication within the loop typically varies (Haver and Tarnoff, 1991).

The master controller communicates commands and telemetry to its subordinate controllers on a once per second basis. However, communication between the master unit and the office PC could be as little as once per day depending on agency's need for upload / download of traffic data.

Closed loop systems form the principle example of a decentralized traffic control system. As demonstrated in Figure 2, logic and decision making capabilities are distributed among three major hierarchies (Mitchell, 1988):

- Local Signal Controllers
- Field Master
- Central Personal Computer
- Traffic Engineering Staff

This hierarchy enables data collection, analysis, and command controls to be performed at different levels. Data collection and timing plan commands and implementation is basically done at the local and master levels. These commands are generally frequent and repetitive in nature and can easily be performed with microprocessors. At the central computer, data collection, analysis, and changes to the system can be performed but not necessarily in real time. The applicable command and controls are infrequent in nature; second by second operations of traffic control are not totally dependent on these commands which are more for long term purposes. The top of the hierarchy is the traffic engineer, who ultimately makes the decisions on whether timing plans should be changed and implemented. These decisions, which are influenced by

decentralized traffic control could be applied in a large metropolitan area or a small community.

Closed-loop decentralized traffic control systems possess several advantages over the earlier centralized systems. First, because of their closed-loop nature, these systems are able to upload / download data and information. Timing plan and individual traffic signal parameters can be uploaded, changed, and downloaded from the central office in an efficient and quick manner. This is possible since there is compatible levels of automation between the central and field units. Similarly, more complete surveillance of the entire system can be performed. Not only can intersection and roadway segment traffic flow can be monitored but hardware telemetry checks can be performed to detect equipment failure. Second, decentralized systems are relatively inexpensive when compared to the centralized control systems. Closed-loop systems were originally developed by the signal controller manufacturers; compatibility between the manufacturer's software and its field masters and controllers was assured. All signal controllers and field master units available today can interface with decentralized systems. Because of this standardization and mass production, the cost of field equipment is low. The term "off the shelf", as used by many of the manufacturers, indicates interchangeable components that are readily available at low cost. It has been already mentioned that the central computing unit is a basic personal computer. Depending on the closed loop manufacturer, the

minimal requirements for the PC can range from that of a 286 processor to faster, more powerful PC's such as a 486. Even if a 486 PC was specified, it can be purchased at prices as low as \$2000. When compared in magnitude to the cost of main frame and minicomputers that control centralized systems, the acquisition of a PC can easily be fit in the budget of even the smallest of cities. Furthermore, the PC is not exclusively used for traffic control and can be used for other purposes. A background RAM (random access memory) is used for the closed-loop control while a foreground RAM can be simultaneously used for other tasks such as word processing, spreadsheets, engineering programs, etc.,. Third, closed-loop systems are expandable. As traffic and budget conditions warrant, additional signals and field masters can be added to the system. Finally, the signal manufacturer's control software has become more user friendly over time and is able to generate pre-programmed progress and activity reports. The report formats are standardized and can be altered to fit the needs of individual agencies.

There is one constraint to the use of closed-loop systems. The application of master controller units in the field have created a situation where all subordinate controller units must always be under the control of the master. The controllers must be subject to the same timing plan as dictated by the master. Because of the physical interconnection, the controllers cannot be transferred from one master to another. In other words, controllers cannot be

dynamically grouped and regrouped as warranted by changing traffic conditions. Although closed-loop systems are best suited for linear, arterial networks, the inability to dynamically rearrange traffic signals can hinder the ease of system expansion.

Similar to their centralized control counterparts, decentralized, closed-loop systems were originally introduced with first generation philosophy. Recent versions of closed-loop systems are available in second and 1.5 generation philosophies. Third and fourth generation systems have not been developed at this time.

Decentralized, closed loop systems can readily be found all over the United States. Due the relatively low cost, these systems have been applied in towns and small cities which originally escaped the applications of the expensive centralized systems. However, with the increasing power and automation of local controller units, master units, and the central PC, closed-loop applications have be performed in large cities and municipal regions. In Indiana, many closed - loop systems have already been installed by municipalities and INDOT with more in the planning and design phases. Before and after studies have been performed on the effects of closed-loop systems have on traffic flow (Westwood, 1990). It was found that the average increase in travel speed and travel time was into double digit percentages. This was also true for the percentage decrease in the average number of stops and average delay. For eleven suburban Minneapolis arterial

systems analyzed, it was predicted that the ten year benefit value to the driving public would be 45.35 million dollars while the estimated cost was 1.73 million dollars. This translated to a benefit/cost ratio of 26 to 1 over a ten year period.

Centralized Control with Distributed Intelligence

In the past several years, advances in technologies have yielded a new traffic control system. A centralized data base-driven system is utilized for primary command and control but automated hardware is also distributed in the field. One of the first developments of such systems came about with the installation of the Automated Traffic Surveillance and Control (ATSAC) system in Los Angeles (Rowe, 1987). The system was equipped with a supervisory computer and area computers assigned to specified locations in the network. Also, local electromechanical controllers were replaced with automated solid state ones. Microprocessor based 170 type controllers were first used because they enable complete versatility of control by using a wide range of software without hardware modification. Although the ATSAC system embraced 1.5 generation philosophy, the concept of centralized control with distributed intelligence could be applied in higher control philosophies.

Centralized control with distributed intelligence combines the favorable characteristics of both centralized and decentralized traffic control systems (Yauch, 1990). As shown

in Figure 4, the timing plans and parameters are downloaded to the individual intersection controllers. Although communications are maintained continuously with the intersections, second by second command data is eliminated because the timing plans and parameters have been downloaded into the controllers software. The frequency of these data downloads typically are as long as 30 minutes.

Figure 4 Distributed Intelligence Traffic Control System
(Yauch, 1990)

Telemetry feedback from the controllers to the central can be sent on a once per 30 second basis. Furthermore, centralized systems with distributed intelligence can store timing plan commands in the controller's software. Interruptions in communication will not be as disruptive as compared with traditional centralized control systems since local controllers' memory can store timing plans for the next 30 to 60 minutes. In addition, contingency timing plans can

also be downloaded to offset any long term communications loss. With the reduction in download communication frequency, an increase in the amount of monitoring and telemetry data returned to the central computer is possible. This can enable the system to develop comprehensive data bases as well as complex graphics displays for central office use.

Another key advantage that centralized control with distributed intelligence systems have is that controllers can controllers are not pre-arranged in groups such as closed-loop systems. With advanced automation at the controller level, downloaded timing plans and parameters enable controllers to re-arrange themselves in groups and subgroups as traffic conditions warrant. Hence, with distributed intelligence, a dynamic closed-loop traffic control system is created. As traffic conditions change throughout a given time period, intersections can be "married" or "divorced" from groups of traffic signals which share the same timing plan.

At the present time, there are two commercially available distributed intelligence traffic control systems. The Management Information System for Traffic (MIST) produced by Traffic Control Technologies can control between 20 to 2000 intersections. It interfaces directly with local controllers to provide full access command messages, detector and monitor information, and uploads and downloads (TCT, 1990). The second system has similar objectives, providing centralized transportation management and control while enabling distributed area wide on-street control (Eagle Signal, 1992).

Automatic Signal/Eagle Signal has recently introduced Master Office Network Area Responsive Control (MONARC) which can upload and download data into MONARC compatible controllers. There is an unlimited number of intersections per group with synchronization pulses for all groups referenced to a common time. In accordance with the definition of distributed intelligence control systems, MONARC allows intersections to be switchable between groups. In addition, MONARC can support all NEMA compatible and 170 type controllers. Closed-loop systems and remote communication units (i.e.: pre-timed controllers, changeable message signs, reversible lane controls, ramp metering, video imaging, etc.). There is a limit of 500 intersection controllers per office personal computer however, there is no limit on the number of computers in the office. Hence, such a distributed intelligence system is readily expandable. The MONARC system can not only upload and download commands to compatible controllers but it can also monitor non-compatible controllers, closed-loop systems, and a vast array of other traffic management and control systems. This commercially available system represents versatile and comprehensive traffic control; the MONARC could very well be the first of many versatile traffic control systems to be available from manufacturers.

Both the MIST and the MONARC systems can readily follow one of the control philosophies of first, second, and 1.5 generations. In order to achieve the real time traffic control as warranted by third and fourth generation

philosophies, additional automation at the central office and in the field is necessary. These more advanced traffic control systems are not commercially available and are being developed on an individual, site-specific basis. The typical objectives of these third (and eventually) fourth generation control systems are to respond to the stochastic elements of traffic behavior using appropriate controls at appropriate frequencies and monitoring the system at appropriate sampling rates.

The framework of a conceptual design is being developed for the city of Tucson, Arizona (Head et al., 1992). The prototypical system, known as RHODES, stands for Real-time, Hierarchical, Optimized, Distributed and Effective System. As Figure 5 shows, RHODES's hierarchical control architecture is made up of four levels of traffic control and real-time network monitoring. The hierarchy is based on the spatial and temporal response characteristics of stochastic traffic sources described over different time and distance scales. At the highest level of RHODES, is the Stochastic Traffic Equilibrium module. Its premise is that for over a period of time, travelers become somewhat aware of travel times, delays, and other associated characteristics of links and routes. What results is a stochastic equilibrium which provides a probable estimate of the predicted loads in the roadway links in the network. Because of the nature of this stochastic equilibrium can be viewed for the long term (i.e: hours, days, weeks etc.), decision making and computation of

Figure 5 Functional Flow Chart of RHODES
(Head et al., 1992)

stochastic equilibrium can be performed off-line.

In the second level of the RHODES's hierarchy is the Network Flow Estimator/Optimizer. It represents a high-level decision making platform for setting signal timings in order to optimize traffic flow in the network. This module needs to be more real time based since it is to estimate traffic flow profiles and perform new or revised timing decisions. It is envisioned that the decision horizon to perform these tasks would be within the range of several minutes.

Thus, the Network Flow Estimator/Optimizer generates target signal timing parameters to be used at the lower hierarchical modules. Allowable variances are included in these target timings because of stochastic fluctuations in traffic flow at the local intersection level are enormous in number, unknown and or cannot be modeled on a macroscopic level. Therefore, at the third level, entitled as

Intersection Dispatching, would include the use of artificial intelligence and learning theory to enable RHODES in learning the characteristics of individual intersections. This knowledge based expert system would allow the effective response to traffic fluctuations in real time that may occur within seconds or minutes. Finally in the fourth level, known as Traffic Light Actuation, is situated at the local intersection cabinet. Splits, phase sequences, and offsets are relayed to the controller. The key element to the success of this local module is the timely gathering and analysis of traffic data on all approaches so that decisions can be made well in advance to be beneficial.

One chief advantage that RHODES possesses is that can be proactive in operation. Many of the first and second generation systems reviewed in the past pages are traffic responsive; they simply react to traffic conditions as it happens. Because there is a lag time experienced in the field whenever timing commands are altered, these traffic responsive systems are slightly behind the actual traffic conditions. Should the rate of change in actual traffic conditions be high, traffic responsive control may prove to be ineffective. In RHODES, the stochastic traffic equilibrium component found in the top hierarchy in addition to the model based traffic predictions found at each level allows for proactiveness. RHODES can attempt to predict future demands placed in roadway network and to constructively accommodate these demands as they actually unfold. Furthermore, RHODES's Intersection

Dispatching module is intended to be reactive to second by second random fluctuations in both predicted and unpredicted traffic demand. But it is also implemented as a distributed control system that allows local control decisions at spatially separated locations. At the time of this writing, a prototypical version of RHODES has not been fully developed for simulation or demonstration purposes. The Arizona Department of Transportation is providing the research funds for its development. Once developed and tested with computer simulation, the tentative location for the first implementation and field testing of RHODES is the City of Tuscon.

There are other advanced traffic control systems following the third generation philosophy. A method known as SCOOT (Split, Cycle and Offset Optimization Technique) is a notable example. The basic concept is to adjust signal timings in small but frequent intervals (McShane and Roess, 1990). SCOOT employs the signal optimization logic found in the TRANSYT program to determine on whether if adjustments to current timing settings (i.e.: cycle lengths, splits, offsets) should be made. This ongoing optimization is performed in the background of SCOOT. Although originally introduced in Glasgow and Coventry, England, the only North American installation of SCOOT is found in Red Deer, Ontario.

In Australia, there are two traffic control systems that have distributed intelligence. The Sydney Co-ordinated Adaptive Traffic (SCAT) control is a three level, distributed

intelligence, hierarchical system using microprocessors and minicomputers. In SCAT, the roadway network is divided into a number of small subsystems, varying in size from one to ten intersections. The subsystems, developed as separate traffic entities, can function independently from one another with local automation. As traffic conditions change, the subsystems can be "married" to one another to form large, compound systems. Coordination between married subsystems would be performed by higher level regional computer. Similar to SCOOT, SCAT is designed to calibrate itself by adjusting timing plans and parameters in response to variations in traffic demand. Another Australian system, is similar to both SCOOT and SCAT but does not perform incremental cycle-to-cycle optimization. The Traffic Responsive Area Control (TRAC), developed by the Main Roads Department in Queensland, also embodies the use of subsystems. Each subsystem can have up to 12 stored timing plans. The best fitting plan, determined by average detector occupancy or similar performance measure observed from detector data, is downloaded to the subsystem by a regional computer. The TRANSYT program is used off-line to originally develop or modify these plans.

As traffic control philosophies become come sophisticated, so will the requirements for automated hierarchy. Of the four principle components of IVHS, it is agreed that ATMS is the most probable component to be installed first. It has been theorized that the use of paralleled computing would be a likely automated platform in

a fully operational IVHS system (Junchaya et al., 1992). If a complete IVHS project is intended for a particular roadway network, then special attention needs to be made to the design and operation of the ATMS since it must provide a foundation for the other IVHS components. This may require the use or the reservations for the use of a parallel computing architecture.

Local Area Networks in Traffic Control Hierarchy

So far in the discussion of traffic control architectures, emphasis has been placed on the hierarchy of the system. Levels in the hierarchy have been identified and the vertical integration between the levels have been distinguished (i.e.: central personal computer to master unit to local controller, etc.). This concept of control basically is restricted to the control of field equipment; the ability to perform additional facility support such as engineering and operations is absent. In order to satisfy the need for more powerful traffic control techniques including on-line, real-time, timing optimization, freeway-surface street integration, and data base management, the recent maturation of local area networks and multiuser computer systems have enabled traffic agencies the capability and affordability of managing traffic networks (Haver and Tarnoff, 1991). In this section, the concept of Local Area Networks will be discussed for the use at the central computing location in order to satisfy the growing processing needs.

A Local Area Network (LAN) is an arrangement of local workstations and a file server. The workstations can simply be personal computers with desktop processing power; the typical memory (RAM) could be 4-8 Megabits(MB) while the hard disk storage could be in the 40-80 MB range. The file server can essentially be a monitorless PC with a 8-10 MB RAM but with a very large hard disk storage size of 300 MB. The workstations and file server can be either physically interconnected or joined together by means of telephone modems. Hence, workstations don't necessarily have to be under the same roof but can be spread out over the agency's jurisdiction.

There are two initial developments in LAN's for traffic control. The first, Traffic Responsive and Uniform Surveillance Timing System (TRUSTS) was formulated for the traffic system in Taiwan. The second LAN, the Management Information System for Traffic (MIST) was developed in the United States and is commercially available from Traffic Control Technologies (TCT). The key difference between the two LAN's, shown in Figure 6, is that TRUSTS is based on the allocation of specific tasks to individual workstations. Under TRUSTS, there could include a wall-mounted PC, an on-line intersection color graphics PC, a master PC, subsystem PC's, an on-line timing plan generation or table selection PC, and a maintenance PC (Tsay, 1989). These specific task PC's can effectively be allocated to the appropriate engineering and operations staff. The MIST system performs these tasks

Figure 6 Local Area Networks in Traffic Control Systems
(Tsay, 1989)

from the central file server. Although both the MIST and TRUSTS LAN's communicate directly with local controllers as per the distributed intelligence philosophy, decentralized closed-loop traffic control systems can also benefit from LAN's (Econolite, 1991b). There are several important advantages that LAN's possess. First, all workstations have simultaneous access to the file server's system database. Since there is only one database, the stored information is always current. Once information is updated or revised, all workstation users benefit. The LAN can be structured that only a select number of workstations can update and change the database while others can only retrieve information but not revise it. Second, LAN's are easily expandable. As the traffic network increases in size and technological processing improves, new workstations and file servers can be added to

the LAN. This is significant since earlier traffic control systems would face complete replacement of its central computer unit as the network and processing loads increased. As mentioned in the centralized control section, such a replacement could be very expensive. Third, LAN's client-server concept permits the development of microcomputer based traffic control systems operating in either a stand-alone or networked configuration regardless of the size of the traffic network.

LAN's essentially are based on IBM compatible PC equipment. Because of the wide spread use of IBM compatible computers, nearly all traffic engineering software packages have been catered for this use. To enable the broad range of software, DataBase Management System (DBMS) software can easily be applied to the LAN's file server with a Standard Query Language (SQL) to assist user interface. With the combined utilization of DBMS and SQL interface, a broad and versatile flow of information is available to network users. Traffic operations, network status monitoring, on-line timing optimization, CADD applications, inventory and maintenance management and other relevant information can be effectively obtained and used to manage the traffic network.

Traffic Data Communication

An important issue with an automated traffic control system is the relaying of data and control commands throughout the system's network. Although the communication of data will

depend on the size and complexity of the traffic system, the initial and annual costs of communication can be substantial (McShane and Roess, 1990). Past experience has shown that communication components in traffic control systems can be as much as 20% of the initial cost. Likewise, up to 40% of the annual operating cost can be attributed towards communicating data for traffic systems. Hence, data communication is a significant part of the initial capital expenses and more so in operating costs. The quality and integrity of a communications system for a traffic control system can be influenced by the type of communications used, the magnitude of the system, the amount of data to be relayed, and on whether if the communication network is owned by the agency or leased through a utility. Direct two-way communications is desirable since it can provide the greatest degree of data collection and control over a given network. In this section, communication techniques for traffic control systems will be discussed.

There are two basic approaches to interconnect a traffic control system. The first method uses hardwire communications to physically interconnect a network. The second method incorporates "through the air" radio frequency techniques to communicate.

Hardwire communications used for traffic control systems have come in two principal forms, switched-voltage interconnect and modulated data (Yauch, 1990). The switched-voltage interconnect method uses a multiconductor (or

multiwire) cable to communicate. A typical multiconductor cable for a traffic control system would consist of approximately seven wires. Each conductor within the cable is dedicated to a specific task. The tasks can represent different cycle lengths, offsets, and a flashing mode (ITE, 1991b). Based on the size of the system, the commands to activate a particular task is performed by either a field master controller or a centralized network computer. Originally, switched-voltage interconnections were designed for one-way communication (exclusive TOD/DOW timing strategies). However, two-way communication between traffic signals/detectors and master controllers/central computers could be achieved by using larger cables with additional conductors.

The modulated data technique utilizes communications with as few as two conductors. Numerous messages/commands can be sent over the two conductors to signals/detectors that share the common conductors. This type of communication is performed by coding the information prior to it being transmitted. Once the transmitted information is received, the coded information is then decoded. This process, known as multiplexing, can send specific message signals by dividing the signal over a period of time (Time-Division) or can place the message signals on different "carrier" frequencies (Frequency-Division) (McShane and Roess, 1990). Modems are used at both ends of the communication link to encode/decode the signals. The modulated data technique has numerous

advantages. First, it uses less conductor cable than the switched-voltage configuration which reduces the initial cost. Second, the two-wire arrangement is compatible with communication systems found in utility lines such as telephone and television cable. Therefore, a highway agency can either install its own traffic conductor lines or use leased utility lines.

Coaxial cable used by private cable television franchises has become the principle alternative to leasing lines with a telephone utility. Throughout the 1980's, cable television has spread across the country and can be found in nearly every metropolitan area. Similar to twisted wire pairs, coaxial cable consists of a conductor wire installed within a larger cylindrical conductor. Insulating material is used to separate the two conductors to prevent shorting. The key advantage of cable TV is its significant capacity to carry information as compared to conventional twisted lines. The broadband coaxial cable has a large bandwidth potential to carry information. This bandwidth is divided into discrete communication paths called channels. These channels are used to carry both video such as individual television channels as well audio and data. Data and audio can be carried over bandwidth channels that are much smaller in size with respect to video channels. Even though cable television was originally designed for one-way communication (from cable office to subscriber), sub-split channel assignment can be performed to yield two-way communication (Alroth, 1992). This

configuration can enable a master controller to monitor and control up to 256 intersections with only two video channels. Cable modems can split the two channels into much narrower channels and enable the carrying of digital data or commands to groups of intersections (Basnett, 1982).

There are potential advantages of coaxial cable over the use of leased telephone cables. First, coaxial cable has a greater capacity than data-grade telephone lines. Voice-grade telephone lines is perhaps the lowest in quality (McShane and Roess, 1990). Second, telephone rates can and usually do increase over the inflation rate which can place unanticipated strain on a highway agencies operating budget. For example, a comprehensive traffic control network serving the District of Columbia was shut down in June 1976 on account of a massive telephone rate increase (Homburger and Kell, 1984). Third, cable television companies are actively pursuing the non-entertainment/data-oriented market. Cable franchises are generally willing to negotiate long-term contracts that are within the annual inflation rate. Fourth, cable franchises usually can include clauses in the contract that cover response times and repair times to malfunctions in cable equipment. These response times are generally lower and more convenient than what a telephone utility can provide. Fifth, because coaxial cable is used to carry video, closed circuit television or video-imaging surveillance can be accommodated. Sixth, the reliability of coaxial cable and its accessories has steadily increased over the past decade. And seventh,

television cable systems are already in place in metropolitan areas in the vicinity of major surface arterial roadways and freeways (Bowcott, 1987). These advantages, though noteworthy, do not necessarily imply that coaxial cable is superior over telephone lines. Depending on site specific conditions found within a municipality, telephone lines could be advantageous to use. The highway agency should consider the capabilities of the existing utility companies/franchises when considering a leased line contract.

Another communication method that uses the modulated data technique is fiberoptics. Originally used by telephone utilities for long distance trunk communications, multidrop applications enable this technology to be used for traffic control systems. A fiberoptic line is made up of two basic components: the core and the cladding. Both the core and the cladding are made from glass or plastic. The only difference between the two is that the core has an index of refraction value higher than that of the cladding. This characteristic permits light to travel through the core wire while not the cladding. Multiplexing is used to encode/decode signal messages; laser transmitters and receivers are used to send the data through the glass core. There are many advantages for fiberoptics (Alroth, 1992). First, its bandwidth is very large and range of frequencies greater than the highest radio frequencies available. One fiber has the same capacity as 900 pairs of twisted copper wire. Second, fibers have lower attenuation than copper wire and do not require amplifiers for

long distances. Third, the glass material is dielectric which makes the fiber unaffected to external disturbances such as lightning, solar flares, and electrical inductive fields. Fourth, the light weight and the small size of the fiber can allow lower installation costs. In fact, existing conduits can be used to house the fiber line. And fifth, fiberoptics are literally impossible to tap without being detected. Some of the disadvantages include the lack of industry standardization, the use of special transmitters/receivers, the increased quality necessary for installation, the complexity in splicing and termination, and the inability to have simultaneous two-way (duplex) communication on a single fiber. Two fiber lines usually are provided (one in each direction) to allow for duplex communication.

The second basic approach to interconnect traffic control systems involves transmitting data/information across the airwaves. This can be done with a variety of techniques which will be discussed at this time. Radio systems have become a particular interest over the years. Radio has the potential of using one of the new 800 and 900 MHz public service channels or on the popular commercial cellular telephone systems (Yauch, 1990). Radio systems that are equipped with digital data dissemination have the ability to transmit data as opposed to conventional voice transmission (OCDE, 1987). A typical radio arrangement for traffic control would consist of what is called a multiple address system. This would be comprised of a central node and several

satellite nodes. Communication is performed through the central node to the individual satellite nodes. The radio communication would include addressing parameters unique to each satellite node. Hence, individual satellite nodes could be singled out for specific communication commands (Ringler and Ernst, 1992). One-way digital radio systems can broadcast information to field devices like changeable message signs, similar traffic control devices, and to vehicles with mobile receivers. For large communications networks, data transmission rates can be lowered to maintain reliable service. Two-way radio systems have also been used in traffic control. These systems have the ability to receive and transmit surveillance and control information to numerous field points in the network. Data transmissions received from the field would also have unique address parameters identifying the originating satellite node. 20 signalized intersections were connected to a city-wide traffic control system in Daytona Beach with positive results. The signals in question could not be conveniently interconnected in a cost effective manner (Rivera, 1991). Field equipment needed for a radio telemetry system would include a transmitter/receiver, an antenna, and a coaxial cable. In prototypical applications, the transmitter/receiver has used the traffic signal controllers internal communications protocol to activate addressing and control functions (Ringler and Ernst, 1992).

When considering a radio transmission system for traffic control, several important factors should be considered. First, the availability of radio frequencies in the area needs to be known since licensing with the FCC will be necessary. Second, the size of the traffic control network will dictate the range of radio communication required. Third, the terrain of the surrounding area will influence the height and cost of transmission towers as well as the type of magnitude of radio frequency used. For example, a low frequency of about 150 MHz is better suited for mountainous areas due to the ability of radio waves to travel around and over objects. Fourth, the availability of transmission sites will be critical in the selection and design of a radio system. The use of existing facilities such as municipal building rooftops can be used to gain elevation while keeping installation costs low. If individual intersections will be receiving/transmitting information, the appropriate antenna can be mounted on the signal masts. Line-of-sight will be a constraint to transmission especially if microwave is used. One way to compensate for this is to use satellite communications as opposed to a ground-based system. Radio communications is a viable alternative to other forms of signal control interconnection. It can be installed at a reasonable cost and can be quite cost effective when compared with leased line communications with high annual costs. This form of radio communication is reliable with decentralized traffic control systems with automated field master controllers. However,

radio applications to traffic systems with only one control center (i.e. UTCS centralized), have not been widely made and tested.

Another method of communicating through the air involves infrared technology. This method of communication shows promise although improvement is needed in the reliability of transmission under foggy as well as the reduction of cost (OCDE, 1987).

The use of cellular radio systems is another alternative. It does offer a cost-effective approach since it uses an already available spectrum. Although originally used for voice communications, an increasing need exists for data transmission in a mobile environment (OCDE, 1987). This type of communication can be beneficial in an IVHS for it enables a traffic control system to communicate with individual vehicles.

Another type of radio transmission has recently been introduced for civilian use. A technique called Spread Spectrum and has been used for the past twenty years by the U. S. military in the scenario of intentional, smart jamming of an adversary's radio system. The principle idea behind spread spectrum is to transform a signal of a given bandwidth into a noise-like signal of a much larger bandwidth (Pickholtz, 1991). The larger bandwidth signal may represent a "fixed" spectrum that is currently available. By transforming additional signal bandwidths onto the much wider spectrum, spread spectrum can efficiently and effectively allow

additional users such as a highway agency to use the same bandwidth as other, existing users. Because spread spectrum uses already existing signal bandwidths, no FCC license is necessary. Also, spread spectrum units will not interfere with adjacent radio units that are being used for other purposes (i.e.: traffic signals, changeable message signs (CMS's), surveillance detectors, vehicle navigational units, etc.). INDOT in cooperation with the Hughes Aircraft Corporation are currently working on a spread spectrum-based communication system that is to be used on the Borman Freeway Traffic Management System (Shamo, 1992). Spread spectrum will be used to transmit data and video(AUTOSCOPE) that has been condensed for broadcast. It is anticipated that two-way communication will be used between the Traffic Operations Center (TOC) and AUTOSCOPE surveillance locations, CMS's, and agency mobile units. No cost estimate was available since spread spectrum has not been applied to traffic control. Spread Spectrum is a form of code division multiplexing and would be an effective method of reducing the number of frequencies needed for a large integrated traffic control system. This is important since frequency allocations are a valuable commodity especially in large metropolitan areas where numerous frequency users exist.

There are many different approaches to communicate data in a traffic control system. Similar to that of Surveillance Devices, not one type of communication technique is superior to the rest. Both hardwire and through-the-air data

communication methods have advantages and disadvantages depending on the criteria for the traffic control system. Some types of communications have existed for many years with a proven track record while developing systems such as spread spectrum are yet to be implemented. As mentioned in the beginning of this section, the quality and integrity of a data communications for a traffic control system will be influenced by the magnitude of the network, the amount of data to be relayed, and the type and ownership of the communication system. A highway agency must consider all options available for data communication. It should be emphasized that not just one communication method should be used for a traffic control system. Based on the site-specific factors, a combination of different communication methods can be used to form a base network for a traffic control system. An agency must acknowledge this possibility and conceptualize a hierarchical arrangement on how various communication methods can work together effectively.

Detection and Surveillance

Traffic detectors are used to sense vehicular demand. Two basic functions are to be fulfilled from the use of detectors. The first function is that the presence of a vehicle is to be determined. A presence detector will yield an output signal for as long as a vehicle is in the detection monitoring area. The second function that is to be preformed is the determination of the motion or passage of a vehicle.

A detector designated for passage yields a short-duration signal based on the motion of the vehicle detected. Usually, detectors are applied for either presence or passage; some detector applications can be used for both of the functions (Yauch, 1990). Although the initial application for detectors was for actuated-signal intersections, their data acquisition capabilities have made larger, macroscopic traffic control systems possible. Traffic detectors must have the capability to withstand extreme environmental conditions during an extended life span. However, a recent survey to highway agencies revealed a level of dissatisfaction concerning the reliability of current detection equipment (Yauch, 1990). Moreover, the limited operating budgets available for traffic agencies often place defective detectors on low priority. When a detector fails at an intersection or within a traffic control system, by-pass modifications are attempted to make up the lost degree of detection. What generally results is a traffic control system that is not truly responsive nor efficient to the needs of the traveling public.

The use of detectors is vital to the performance of a traffic control system. Detectors enable the system to "see" or sense traffic demand. The quality and capabilities of a detector system will have direct bearing on the performance of a traffic control system. In the following paragraphs, detectors that are currently available as well as those soon to be developed will be discussed.

The most common type of detector used today is the inductive loop detector. An inductive detector is a wire loop embedded under the surface of the pavement and subjected to a predetermined frequency signal. When a vehicle passes over the loop, a change in the inductance and corresponding frequency of the signal is experienced. The change is detected and converted to a relay actuation (Homburger and Kell, 1984). The loop detector is well suited for computerized traffic control systems due to its accuracy, wide spread use, and its ability to detect both passage and presence. Hence, a number of variables such as volumes, occupancy, speed, stops, queue lengths, and arrival times can be generated albeit with differing degrees of accuracy (ITE, 1991a). Inductive loops are generally installed approximately two inches below the pavement surface; some installations have been made deeper into the pavement structure in the presence of reinforced steel with desirable results (Herstein and Shapiro, 1991). In addition to their versatility, the cost of inductive loops are relatively low making them available to nearly every highway agency. Despite the wide spread use, inductive loops do have disadvantages. The installation process can disrupt traffic operations not to mention the damaging effect on the pavement surface. Also, loops do have a relatively high incidence of failure, particularly in areas with severe winters.

There are other types of in-pavement detectors that are in common use. A magnetic detector is composed of a small

coil of wire surrounded by a protective coating, and installed under the pavement surface. Magnetic detectors operate on the principal of the change in the lines of flux in the earth's magnetic field. As a vehicle passes over the detector, the constant lines of flux are deflected by the vehicle, creating a small voltage to be developed in the coil. The voltage activates a relay to register an actuated impulse. Although in common use, the magnetic detector can only function as a passage detector since the vehicle must be in motion in order to be detected (USDOT 1983). Another type of detector that also uses the earth's magnetic field to detect vehicles is the magnetometer. Different from magnetic detectors, magnetometers measure the focusing effect of the earth's magnetic field as influenced by a ferrous object (metallic object). Since the focusing effect does not change whether the vehicle is in motion or not, the magnetometer can be used to measure both passage and presence. The magnetometer probe and wire require less pavement saw-cutting to install in addition to being more effective than inductive loops in poor conditioned pavements (ITE, 1991a).

Several types of detectors do not require to be installed in the pavement but rather are installed above or on the wayside of the traveled lanes. Radar detectors function on the basis of the Doppler effect. A microwave signal is emitted from the detector and is deflected back by an approaching vehicle. A change in the feedback frequency is caused by the moving vehicle and is picked up by the receiver.

Because the radar detector requires motion, detection is restricted for passage (Yauch, 1990). The Ultrasonic detector transmits a high frequency tone towards approaching traffic. The presence of vehicles causes the frequency beams to be reflected back at different frequencies. The detector senses the change and registers an actuated impulse. Unlike the radar detector, the ultrasonic detector can be used for both passage and presence (USDOT, 1983). Infrared Detection is a recent development for traffic systems. There are two different types of infrared detectors. The first type is called a passive infrared detector and basically senses the thermal infrared radiation emitted by warm objects as they pass by the detection zone. An increase in thermal radiation activates the actuation output. The passive infrared detector can only be used for passage purposes. The second type is called an active infrared detector. This detector emits an infrared light source toward the subject traffic lanes. Approaching vehicles will reflect the infrared light back to the detector where the signal is analyzed and the presence of a vehicle is detected. Different versions of the active detector are available for stopline and intersection approach detection (ITE, 1991a). The radar, ultrasonic, and infrared detectors have the advantage of being mounted above or next to the traveled way. The pavement and therefore traffic operations would not be adversely disrupted by the installation or the maintenance of detector hardware.

The development of new and advanced detectors has yielded two types which show promise for the future. The first is a Self-Powered Vehicle Detector (SPVD). This detector is an advanced magnetometer equipped with a low power radio link to a receiver which can be located as much as 500 feet away. No lead-in or interconnecting cables are needed. The cylindrical device is installed beneath the surface of the traffic lane and relies on a battery source to communicate with the receiver. The SPVD can measure vehicle passage, presence, count, and occupancy; speed measurements are possible if two SPVDs are used in tandem. Although the advantages of SPVDs include low cost, ease of installation, and a reduced disruption to traffic flow during installation, the principal disadvantage of the SPVD is its relatively low battery life. Prototypical models had only a one year life span. Currently, two year batteries have been developed (ITE, 1991a). As longer life batteries are used, the SPVD, with its simplicity of installation and lack of physical interconnection, make it an attractive alternative to inductive loops provided that the price can be competitive (OCDE, 1987). The second type of detection system currently being developed is based on video image processing. In the past, video cameras have been used for freeway surveillance. Human operators would view and interpret the images for incident detection. The procedure proved to be laborious and tiresome yielding human error and inconsistencies in judgement. Currently, the concept of video surveillance is being automated. In this process, an

electronic camera is set up overlooking a section of roadway. Based on the images received by the camera, a microprocessor determines vehicle presence or passage in real time. The video system has the ability to detect traffic in various locations within the field of vision of the camera. Interactive graphics are used to allow the user to place detection lines across the traffic lanes as viewed by the camera. These lines are not physically placed on the pavement but rather masked over the image received by the camera. When a vehicle crosses one of these lines, the microprocessor generates a signal. The key advantage is that numerous detection lines can be placed on one camera giving one camera site the ability to take the place of numerous detectors such as inductive loops. Because of this advantage, video image processing has also been called a Wide Area Detection System (WADS) since area detection, not point detection, is performed. Other advantages include the ease of hardware installation and the modification of the detection lines, the elimination of placing detectors under the surface of the pavement, and the potential reduction of disrupting traffic operations during installation and or maintenance activities. In the last several years, improvements to prototypical WADS have resulted in reliable and accurate data processing with relatively low and allowable degrees of error; the systems can function favorably under adverse lighting and weather conditions. One WADS system is currently being marketed in the United States (Econolite, 1991a). This WADS, known as

AUTOSCOPE, has many potential applications which include freeway surveillance, incident detection, traffic counting/classification, ramp metering control, and bus/emergency vehicle recognition. AUTOSCOPE consists of four principal components: a camera, a video monitor, a supervisory computer (IBM compatible PC), and an AUTOSCOPE processor. Similar to the prototypes, AUTOSCOPE can monitor such traffic parameters as vehicle presence/passage, speed, flow rate, volume, occupancy, vehicle headway, and can distinguish between passenger cars, single-unit trucks, and tractor-trailers. One AUTOSCOPE field assembly which can monitor four cameras has an initial cost of \$40,000. An AUTOSCOPE based surveillance system is presently being designed to serve as part of the Borman Expressway's Freeway Traffic Management System.

Although WADS was originally designed for freeway traffic surveillance, it has also been tested with success on approaches to signalized intersections (Michalopoulos et al., 1990). The field data processing capability of WADS enables it to provide real time information to an associated traffic control system. The signal processing provides outputs comparable to conventional loop detectors. Therefore, presence and passage can be used to determine such intersection/arterial roadway variables as speed, occupancy, volumes, queue lengths, etc. (ITE, 1991a). WADS applications could be made at major intersections or on oversaturated arterial corridors. Because of its area detection

capabilities, it is likely that one camera per approach could be used in lieu of numerous stopline and approach inductive loops. It is estimated that the average installation cost per intersection would be 30 percent lower than for loop detectors and the average maintenance cost would be 35 percent lower (Michalopoulos et al., 1990).

In summary, many types of vehicle detection are available for use in traffic control systems. As discussed, certain detectors have various advantages over other types given certain applications. This does not necessarily mean that one type of detector is superior over the rest. It should be recognized that all detectors mentioned are generally reliable and can yield accurate information on a site specific basis. However, the cost effectiveness of the type(s) of detectors used can be a significant factor given the size, complexity, and operational requirements of a traffic control system. A combination of detection devices, not just one device, can yield effective data to make the system function desirably.

Roadway User Communication

User communications provides relevant traffic information to motorists or other facility users. To effectively inform the public of prevailing traffic conditions is a crucial element for an advanced traffic control system. It is the only interface that the traveling public has with an automated control system. Three principal functions are served by alerting motorists to congestion and incidents (Cassidy and

Sinha, 1990). First, roadway safety will be improved since motorists will be informed of upstream accidents and congestion. Motorists will approach the subject areas with increased caution and attention. Second, efficient roadway use can be possible with an effective motorist communication system. Motorists can be informed of not only of incidents but also potential alternative routes to use in lieu of the subjected route. Individual delay times would decrease as well as system-wide reductions in congestion and delay due to the effective use of under-utilized alternative routes. Third, an effective user communication system would gain use and acceptance by the public and an improved public opinion of the highway agency would result.

There are four categories in which real-time user communications can be applied (Dudek, 1987). The first category is for recurring problems. This is essentially peak hour congestion as well as special events that occur on a regular basis (i.e. sporting events, conventions, etc.,). In either case, the traffic patterns and flows can be empirically established and therefore predicted. Real time user communications can be used to assist in informing the traveling public of the congestion status of the principal and alternative routes. The second category involves nonrecurring problems. This would include traffic accidents, maintenance operations, and other unpredictable incidents. These types of incidents can create considerable congestion on the effected roadway and result in under-utilized parallel roadways. Real

time information can significantly help in alerting motorists in incidents well upstream from the incident and the resulting congestion. Depending on the roadway network, alternative routes around the incident can be displayed to the motoring public. The third category deals with adverse weather conditions that may be specific to the area. Conditions such as fog, snow, and other weather conditions which can create safety hazards can be revealed to the motorists well before they reach the effected area. The last category is for special operational features on the roadway. Traffic features such as reversible lanes, high occupancy vehicle (HOV) lanes as well as physical elements like draw bridges, weight stations, and toll booths can have their current status displayed to the public with a real time information system.

Different modes of communicating with the traveling public are either currently available or being developed (Dudek et al., 1989). Although these modes have been mentioned for use in FTMS and complete IVHS applications, they have potential use in ASATMS. These modes of communication include the following:

- Changeable Message Signs
- Radio
- Television
- Computer Terminals
- Telephone Dial-up Service

In this section, advanced technologies in regards to motorist communications in an advanced traffic control system will be discussed.

Changeable Message Signs

Changeable Message Signs (CMS) are roadside signs designed to dynamically change their messages to reflect existing or future traffic conditions (Payne and McCasland, 1988). CMS's, also known as Variable Message Signs (VMS), can be used to communicate routine information such as roadway construction zones and lane closures as well as unique traffic information accompanied with suggestions of alternative routing to by-pass congestion and accidents. Some CMS applications have dealt with variable speed limit signing to accommodate the changing conditions of traffic volumes, weather, road surfaces, and lighting (Sumner, 1988). CMS's have historically been used on freeways in congested urban corridors. However, applications of CMS's have been made on surface arterials and other roadways in the vicinity of major freeway/expressway interchanges (Baxter, 1989). Furthermore, CMS's have been applied in conjunction with conventional guide signs to compliment their message. One or two lined CMS's are physically attached within or at the bottom of the base guide sign. This application is different from conventional use where a multi-lined CMS would give exclusive information independent from other guide signs.

A number of different methods have been used for the development of CMS. Initial techniques have been incandescent bulb matrix, electromechanical drum, and rotating panel. In recent years, other technologies involving fiberoptics, light-emitting diodes, and flip disk matrix have been used for CMS

(OCDE, 1987). There has been an emphasis on the latter three CMS types due to the increased flexibility in messages that can be displayed. Both the flip disk and fiberoptics CMS have moving mechanical parts at the field site. This is especially true for the flip disk matrix; matrix disks must be "flipped" from its dark to reflectorized sides to form a message. Sometimes these individual disks can get stuck increasing maintenance costs. Agencies with flip disk matrix CMS often "exercise" the signs in the early morning hours to loosen up any potential stuck disks. The fiberoptics CMS require shutters to mechanically open and close character pixels to form messages. Although this particular feature may be prone to failure, fiberoptic CMS manufacturers claim that up to 50 million cycles are possible under severe environmental conditions (Shamskhov, 1991). In contrast, Light-Emitting-Diode CMS is fully solid state in construction and is not prone to any mechanical breakdown.

In a comparison with conventional guide signs, the fiberoptic and LED CMS's performed favorably in regards to target value, legibility, and viewing comfort (Upchurch et al., 1992). A study that involved a population of motorists viewing the three types of CMS's in different lighting conditions {i.e.: mid-day, nighttime, back-lit, and front-lit (washout)} found that the flip disk matrix CMS had unacceptable performance in most categories. Although the fiberoptic CMS's fared slightly better in overall performance than the LED CMS's, it was recommended that either CMS system

should be considered for use in a traffic management system. In another study, fiberoptic and LED CMS's were evaluated for more detailed features including: legibility/brightness, color, component reliability, power consumption, temperature sensitivity, viewing angle, maintenance requirements, and life cycle expectancy (Shamskhov, 1991). The analysis did not reveal a fatal flaw for either CMS system nor was a clear preference for one system over the other found. Both systems were comparable in regards to legibility/brightness, power consumption, maintenance, and life cycle cost. Hence, either the fiberoptic or the LED system is recommended for CMS use; it would be advisable for highway agencies to conduct a comprehensive test program to help decide which system to use based on the agencies' own needs and criteria.

Radio

Another method to communicate with the motoring public is through radio. Radio, both private and public, can effectively be used since nearly all vehicles already have AM/FM receivers. Highway Advisory Radio (HAR) is operated by the agency and can give detailed information on congestion, accidents, and detour alternatives. HAR can supplement the information given on CMS; messages on CMS's can direct motorists to the HAR should traffic conditions warrant additional information. HAR can be transmitted through a "leaky" coaxial cable installed in a freeway median. This low power transmission may be effective for motorists on the given

roadway but will not reach motorists on other roadways. Also, the "leaky" cable may have a high installation cost. Another method of transmission of HAR involves the use of traditional broadcast methods. This can be accomplished easily if the jurisdictional authority has access to existing transmission facilities. In Minneapolis, the Minnesota DOT utilizes a public radio station operated by the Minneapolis Public School system. MnDOT can reach nearly all locations in the twin cities area and has received favorable feedback from the public (Sinha and Cassidy, 1990). Should an agency decide to install its own transmission facilities, initial costs can be lessened if the agency mounts its transmission tower atop a tall building. Such an approach not only gains the height necessary for adequate transmission but also reduces the cost of the transmission tower requirements (Rivera, 1991).

Commercial radio can likewise broadcast traffic reports to motorists using the arterial/freeway network. Nearly every existing traffic management system has communication links with local radio stations (Cassidy and Sinha, 1990) and nearly every metropolitan area has several private radio stations that report traffic information. Information can be supplied to radio stations in a real-time format; traffic updates can be performed from this information on a periodic, regular basis (e.g. 10 minutes, etc.,). A concurrent use of HAR and commercial radio would increase coverage since not all motorists may wish to change their radio to an HAR frequency due to its "information only" format.

Television

Television can also serve as a communication medium between an advanced traffic control system and the motoring public. Information regarding road conditions can be sent through cable or transmitted to individual television monitors located in either private residences, work locations, and other high traffic generators. Traffic conditions presented in text or graphics can enable motorists an advanced look of local/regional traffic conditions prior to their departure from home or work. A pilot system has been in use in the Los Angeles area since 1990 (Reid, 1990). The system, known as Commuter Television or COM-TV, has television receivers placed in the lobbies of several major downtown Los Angeles office buildings. A rolling text concept was used to convey traffic information, similar to how stock information, weather reports, and sport scores are relayed. It utilized the Vertical Blanking Interval (VBI) of the television signal which is the same way that closed captioned information for the hearing impaired is communicated (Lum et al., 1989). With the television screen being up-dated every several seconds, the motorist can select the relevant screen for the designated area of travel. Once in route, the motorist can obtain up-to-date traffic information from radio stations also equipped with the same commuter television system.. The principal purpose of COM-TV is to provide timely traffic information for motorists to make educated decisions regarding the best route to take. Although this service begins to overlap into other

IVHS components namely AVCS and ATIS, it does educate the motorist in regards to the roadway network.

Computer Terminals

Computer terminals can likewise be used to convey traffic information to the public. Through the use of modems, personal computers, either at home or work, can gain access to traffic information from a central computer located in the central traffic office (Lum et al., 1989). Computer terminals can also serve as display terminals at work sites and other high traffic generator locations. Such a system exists for a major shopping center in Houston, Texas (Thompson and Holcombe, 1991). The system, known as INFOBANQ, provides timely traffic information to shopping center employees regarding congestion, roadway construction, accidents, and disabled vehicles. Although this service can provide information on a regional level, the emphasis is placed on the freeways and arterial roadways in the vicinity of the shopping center. Ten display terminals are placed throughout the shopping center. The terminals have direct interface with a source computer located at the traffic advisory office situated in the shopping center. The source computer is updated with information received from various sources including state highway radio patrols, local transit authorities, law enforcement and other emergency services. Once the source computer is updated with new traffic information, it dials up the display terminals and downloads

the appropriate information. Another similar system exists in the greater Seattle, Washington area (Morse and Forbis, 1991). Developed by Washington DOT, the system uses a centralized computer to make available to the public a color-coded traffic map of Seattle area freeways. The centralized computer analyses freeway loop detector information and compiles the information to a traffic density format. The information can be accessed by users through the use of ordinary modems. The individual personal computers have two WSDOT programs stored in memory. One program is to generate a base roadway network map while the second program compiles the sent traffic information and loads it onto the base map. Because of on site program and color requirements, participating PC's need to be have VGA graphics and at least a 386 machine. Although this information service originally developed for traffic reporters, other users include transit authorities, a shopping center, large traffic generating businesses, and traffic engineers in the public and private sector. The automated display map is up-dated with new information every minute by the centralized computer enabling real-time traffic information.

Telephone Dial-up Service

The previously discussed service is possible through a telephone dial-up service. Other methods of motorist information services can use this same type of communication. However, because of the amount of real time information

necessary to provide detailed instruction, a voice-only transmission is unlikely. Instead, phone dial up services will probably be automated and use some sort of computer on the receiving end to display or interpret the information.

In summary, a information system for motorists will be a necessary component of an advanced traffic control system. However, additional research may be needed to develop an appropriate Motorist Information System (MIS). Studies have revealed noteworthy findings with regards to the effectiveness of MIS. One study covered the effectiveness of a radio broadcast information system geared toward the availability of parking in parking structures and lots in an English city's central business district (Polack et al., 1991). The study found that despite the high awareness if the broadcast service, which was transmitted periodically on private radio stations, the impact on parking behavior was restricted. The analysis of a survey showed that the vast majority of the motorists using the service while en route to the city did not modify their initial parking intentions regardless if the service indicated heavy congestion. These particular motorists appear to be prepared to tolerate the congestion and the searching for parking spaces. The survey also found that the motorist's initial decision on which parking facility to use was made during the pre-trip stage. On the other hand, motorists that used the broadcast service to influence their parking plans during the pre-trip stage did, on average, experience reduced congestion and search time for parking

spaces. Unfortunately, this group was a minority in the population of motorists that used the radio broadcast service. Another study, performed at the University of Washington, investigated on whether the motoring public can be referred as a homogeneous population (Wegner et al., 1990). The study found that the majority of the surveyed commuters indicated that they receive some kind of traffic information prior to morning departure and that more than half of them received this information immediately after awakening. The study also found that despite that the motorists were aware of traffic information services, it yielded little impact on their decisions before departure. Most of the motorists surveyed were not prone to change to an alternative route, mode, or departure time. This low rate of commute modification could be attributed to the approximate hour in lag in time between the receipt of traffic information and decision to modify just prior to departure. Furthermore, the study disclosed that motorists generally made a decision to use an alternative route based first on information received en route. Also, approximately twenty-five percent of those that use alternative routes actively seek out information on the primary and alternative routes more than 30 minutes before departure. Not surprisingly, those motorists that were more likely to use alternative routes could effectively describe the routes by road name. Commuters that were less likely to use alternative routes displayed a lack of familiarity of the road names of the principal route and instead referred to

roadside landmarks. In summary, the study concludes that an effective motorist information system needs to consider a number of factors including the commute distance, available pre-departure time, commuter personal characteristics, commuters' knowledge to primary and secondary routes, and commuters' responses to stress.

Both of the mentioned studies show a pattern where motorists neglect to use traffic information until the commute. Unfortunately, this type of use limits the potential of an information system since the options for alternative routes decrease as the trip proceeds. Also, only a small percentage of motorists used traffic information received during the pre-trip phase to potentially change travel plans. These studies reveal the motoring public as a diverse group of people influenced by attributes like personal characteristics, degree of familiarity with the roadway network, trip purpose, trip length, and stress response. In essence, an automated traffic information system is providing information to a non-automated audience. Unlike an automated ATMS, the travelling public is unable to receive, analyze, nor react to real time traffic information in a predictable, efficient, and automated fashion. Also, individual members of the motoring public will react to the same type of traffic information differently since each member has different objectives.

The components of an effective MIS contributing to desirable motorist decision-making should be examined (Koutsopoulos and Lotan, 1990). An information system can

either be static or dynamic in regards to its ability to provide the motoring public with real-time traffic information. Static information systems can only provide historic information based on past experience. Dynamic systems, on the other hand, yield real time information on the current traffic conditions. In general, dynamic information systems are much more effective than static systems in informing motorists of incident location, type, and severity. Furthermore, information systems can range from descriptive or prescriptive. Descriptive systems provide information on specific roadway segments or segments within a particular region or zone. Prescriptive systems suggest to road users on the best available route to use. An effective MIS used in an advanced traffic control system may utilize not one, but all components. The MIS would obviously benefit from the dynamic component since the initial objective of MIS's is dynamic. However, the inclusion of the static component would assist in complimenting the dynamic component by generating a forecast of the traffic conditions that motorists would most likely face during a certain time period. The static component, despite not being able to identify accidents/incidents in real time, will be able to generate a historic incident scenario the number, locations, and approximate times of typical incidents. Because the static component is based on historic information, these "forecasts" can be disclosed to the public before the typical morning pre-trip period. Perhaps disclosure could be made as early as the night before (via

cable television-traffic channel, radio, etc.,). Likewise, descriptive and prescriptive components can also be combined with the static and dynamic components to yield relevant information to the public during pre-trip, en route, and post-trip stages.

Because the development of motorist information systems are in their developmental infancy, different approaches to informing the motoring public should be considered. Additional study and research may be needed to determine the extent of an effective MIS. Although the current strategy towards MIS is based on real-time, lag-time information systems may prove to be beneficial in informing the public. As it has been previously discussed, motorists do not respond to real time information in an efficient and predictable manner because they are not automated like their traffic control counterpart. Perhaps lag-time information systems, used in conjunction with real-time systems, could assist in informing and educating the public in regards to its capabilities.

CHAPTER 6 TRAFFIC MANAGEMENT COMPONENTS FOR ASATMS

So far in this report, the discussion of advanced technologies in traffic control systems has been addressed. The formulation of control architecture, communications and surveillance components makes up the physical nature of the traffic control network. The hierarchical structure in itself is not management but it provides a means for an effective traffic management system for surface arterial roadways. The management components for an ASATMS, which can include facility inventory, operational status, traffic monitoring, traffic control, integration, geographic information systems (GIS), and multi-jurisdictional interaction will be overviewed; a detailed discussion on traffic management is beyond the scope of this report. Many of these management tools have already been part of existing traffic systems. They can be found in commercial available "off the shelf" decentralized closed-loop systems or in custom designed centralized main-frame systems. Regardless of what traffic control system is used, effective management should have a prominent role. Management assists in how agency personnel will interact with the system and how to utilize the traffic data for decision and planning purposes. This interaction will most always occur at the top hierarchy of the traffic

control system. Because of the large scale automation that is part of this top hierarchy (i.e.: mainframes, minicomputers, LAN's, etc.), effective software development can create a management system to fit the specific needs of the traffic agency.

Network Inventory

It has been previously discussed that a traffic control system is made up of four basic components: control architecture, data communications, surveillance, and user communications. Within each component, however, there can exist hundreds, perhaps thousands, of smaller parts that perform specific functions and tasks. A complete database inventory of all the finite elements that make up a traffic control system can give the highway agency increased control over the network. First, this information can be used as a principle roster for parts. Parts currently in use as well as spare parts in the maintenance shop can all be accounted for. Information entered for each part can include: part description, manufacturer, serial number, date purchased, date installed, date rebuilt, and the current location of the part. This information can either be entered manually or be entered by means of a bar-code system. Some forms of this network inventory are obtainable in commercially available traffic control systems (Eagle, 1992). Traffic personnel, through the use of the maintenance or main office PC, can view the contents inside a controller cabinet at an intersection.

Second, a comprehensive parts inventory can assist in preventive maintenance programs. Data regarding Mean Time To Failure (MTTF) and Mean Time Between Failure (MTBF) can be obtained by the parts manufacturers. This information can be used to compare the current service times of parts and to notify the maintenance personnel when specific parts are approaching or exceeding the MTTF. Advance notice can be programmed to be given to enable maintenance crews sufficient time to replace and reorder the affected parts. This feature can be most effective for vital parts in which failure in the field is undesirable (i.e.: controller mother boards, conflict monitors, signal lamps, etc.,). Third, the network inventory can give sufficient information to enable the traffic agency to rearrange parts in the field for the benefit of compatibility. Parts of the same manufacturer or compatible manufacturers can be grouped together in the same section of the traffic network to yield a more homogeneous control environment.

Facility Status

One of the major traffic control system components is its architecture. The physical layout of the traffic control system enables field data to be collected and control commands to be sent out. Likewise, the status of the traffic control network can be determined and sent to the main computing location(s). Status can deal with the operational nature of traffic; data collected in the field can determine volume,

speed, occupancy rate, and current signal timing plans. Nearly every traffic control system reviewed in this report performs these tasks in one form or another. However, the status of the traffic control facility itself is of emphasis in this section.

Facility status involves the operational condition of the traffic control network equipment. Advanced traffic management systems have been equipped to perform self diagnosis on the hardware and software. Failures in detection devices, controllers, on communication links can be detected with custom or commercially available systems. Some of the more recent closed loop systems can be programmed to prioritize the nature of the results of the diagnostic check (Econolite, 1991b). Such incidents as a detector loop inactivity report in the early morning hours can be reported to the main office perhaps once per day while a report of a intersection on all-way flash mode or an open cabinet door would warrant immediate notification. Facility status can be performed by two approaches. In the first method, the system can be programmed to perform scheduled diagnostic checks in which the main computer or master controller would interrogate its subordinate units. The second approach involves a subordinate unit, usually a controller, that will "call up" to a master unit or main office when a malfunction is detected. The local controllers possess the sophistication to self-diagnose its cabinet, searching for failures in the mother board, expansion boards, conflict monitor, load switches,

amplifiers, detector loops, etc.. Some manufacturers have produced self-test accessories for the cabinet. One device scans the amperage of the traffic light lamp circuits (IPC, 1991). When a lamp burns out, a conspicuous change in the circuit current results. The device can notify the master of the main office through the controller's modem and maintenance crews can be sent out to correct a potentially hazardous situation.

Effective status testing of the traffic control facility can enable the agency to determine how well the system is functioning with respect to its hardware. Should failures or malfunctions occur, the problems can be more or less pinpointed and corrections be made in an expeditious manner.

Traffic Control and Monitoring Management

In this section, the management applications in the control and monitoring of traffic will be discussed. Management techniques can enable a more flexible and versatile use of traffic control and monitoring. The use of advanced technologies, namely powerful automation, can allow for the effective application and optimization of timing plans as well as the recognition of traffic patterns and incidents. Artificial intelligence applications can be applied in traffic control systems to provide these types of services; the management of traffic control can be greatly enhanced with powerful automation assisting agency personnel with differing educational backgrounds.

Traffic Control

The management of traffic control is essential to the success of an advanced traffic control system. Traffic control involves the use of signal timing plans and how the plans are developed and implemented. Two basic elements of traffic control management will be overviewed. Timing plan implementation consists of the selection and use of timing plan strategies. Timing plan generation and optimization addresses the development of timing plan scenarios and how the plans can be improved in a real-time or a lag-time environment.

Timing Plan Implementation

There are several different management techniques that can be applied towards traffic control. Versatility and flexibility in traffic control can result from the use of one or all of these management techniques. One of the first methods that can be used is manual mode. This involves the manual selection of timing plans by the traffic agency personnel. This technique is basically reserved for special traffic events (i.e.: parades, sporting events, community events, etc.,). The use of manual plan selection, although useful in certain situations, is discouraged for frequent use since long term traffic control can be adversely effected to the point where conventional traffic responsive modes may not be effective.

Another technique that is used for the management of traffic control is Time-Of-Day (TOD). This technique utilizes fixed timing plans that are activated for use on a pre-set scheduled basis. The schedule and the accompanying timing plans were developed from either a traffic optimization program, engineering judgement, or a combination of the two. Once generated, TOD of Day of Week (DOW) plans are subject to obsolescence depending on the changing behavior of traffic. The TOD/DOW plans therefore need to be updated on a period basis. TOD/DOW plans represent the "best fit" for typical traffic conditions; they cannot accommodate unforeseen traffic incidents. Because TOD/DOW plans lack time sensitivity, they are usually generated off-line of the system with data either manually or automatically collected.

The most common technique use in advanced traffic control systems is traffic responsive. In the traffic responsive mode, traffic information is gathered by a traffic computer from field detectors. The detectors can either be placed on the approaches of local intersections or be "system" detectors positioned mid-way between signalized intersections. The traffic data (i.e.: volume, occupancy rates, average speed, etc.,) is used by the computer to compare against stored threshold values unique to particular timing strategies. Once specific thresholds are met or exceeded, the corresponding timing strategy is activated and sent out to master units or local signal controllers. This technique can be refined in being proactive by using past historical traffic information

in postulating future traffic patterns by acknowledging previous traffic events (McShane and Roess, 1990). If typical traffic patterns can be well established in advance by referring to historical data, threshold checks can be made during a period of time to indicate on whether the current traffic conditions reflect historic trends. With typical traffic patterns known in advance, proactive or "forecasted" traffic plan sequences can initially be considered for use but subject to change should traffic conditions warrant.

It should be emphasized that not just one of the above techniques is superior to the rest and should exclusively be used. Depending on the traffic behavior in a network, a combination of all three (i.e.: manual, TOD/DOW, traffic responsive) can be used to accommodate different needs. Manual operation should be used for special traffic scenarios that are rare and unusual. Traffic responsive operations should be used when a basic traffic pattern exists, but enough fluctuation is present to require similar timing plans to be used to effectively meet the network's needs. TOD plans should be used when conspicuous, predictable patterns are identified. This can be useful when there are rapid increases in traffic volumes at predictable times in the day. An example of this would be the change in work shift at a factory along an arterial road. It can be accurately predicted when the new shift begins and when the old shift workers leave the factory. In general, this can create a rapid increase in traffic volumes on the roadway; the traffic responsive

technique would not be able to effectively meet the traffic demands because it is responding to and slightly lagging behind the actual traffic demands. TOD plan could be activated just for the factory shift scenario. The TOD override command could be sent out to the effected signals approximately 5-10 minutes before the shift change. By the time the factory workers are leaving the factory site, the signals are already coordinated in their favor. Once the factory traffic disperses, traffic responsive operation can be returned. This technique can effectively be used when there is sufficient historical information on conspicuous traffic patterns that would warrant TOD instead of traffic responsive.

Timing Plan Development and Optimization

Timing plans can originate from different sources. Timing plan development can be subject to engineering judgement, agency policy, and computerized assistance. These sources can be used individually or combined together for a traffic network that is complex, simplistic, or just an isolated signalized intersection. Formal and technical approaches should be used to assure an educated and credible starting point in initial timing plan development.

There are many signal timing software packages that are available today. Many perform the task of plan development and optimization simultaneously. Some programs such as SOAP84 and the Highway Capacity Software are suited to individual intersections while other programs like TRANSYT, MAXBAND and

PASSER accommodate many intersections forming traffic systems. Not only could these traffic software packages develop timing plans, but could also evaluate traffic performance and optimize timings. Many of these programs originally required extensive field data collection and laborious input files; timing plans were quite labor intensive and were produced on a "off-line" basis.

Many signal timing programs are now available that allow an interface between timing software and traffic signal control systems. One closed-loop system can download traffic detector data into Arterial Analysis Package (AAP) software and can generate revised timing plans off-line (Econolite, 1991b). Another software, known as SCOOT, has evolved from the optimization TRANSYT model (Robertson and Bretherton, 1991). SCOOT (Split, Cycle, Offset, Optimization Technique) shares the same optimization criteria that TRANSYT has in the past but goes further to perform real-time calculations. SCOOT attempts to measure the cycle to cycle traffic flow profiles for each arterial segment in real time. Likewise, SCOOT updates an on-line model of vehicle queues at intersections. Also, SCOOT performs cycle to cycle optimization of the current timing plan. Time increments as large as four seconds are allowed to change the cycle length, split, and offset; an increment limit was needed to reduce the variability in timing plan changes subject to traffic flow. Up to 10,000 optimization decisions can be made with SCOOT on a 100 intersection network. Because of the traffic flow

variability, location of detectors, and arbitrary timing increment settings, a few of the timing decisions will be wrong but most of them will be right. Another type of algorithm emphasizes an adaptive traffic control system for coordinated arterial streets (Nguyen, 1989). Coordinated arterial street operations require the use of three parameters: cycle length, split time, and offset. These parameters are rigid; they cannot be changed in magnitude without the breakdown of desirable traffic progression. A system, known as SCATS (Sydney Co-ordinated Adaptive Traffic System), utilizes dynamic offset setting procedures for an adaptive coordinated traffic signal system. SCATS determines the available bandwidth range between adjacent traffic signals. The optimum offset is selected from this bandwidth range. The process is repeated for adjacent, successive intersections to ensure traffic coordination. Likewise, the cycle length and split times are updated every cycle to respond to traffic needs. This system can increase the flexibility of traffic management systems by easing the constraints for coordinated systems.

It should be noted that a interactive software program that interfaces with the traffic network in real-time will be subject to the availability of traffic detectors and the degree of real-time traffic control. The detectors are the only way for the network to "see" the traffic conditions; more detectors would provide more accurate detection but would also be very costly. In addition, a comprehensive real-time

traffic control would be the most costly in the communications sense. Program applications could be made to allow lag-time, off-line, localized real-time, or a combination of the three for network traffic control management.

Traffic Monitoring

There are two basic elements in traffic monitoring, pattern recognition and incident detection. Pattern recognition involves with identifying and recognizing of traffic patterns for the benefit of traffic control. Incident detection is primarily concerned with detecting incidents that most likely would disrupt traffic operations (i.e: accidents, disabled vehicles, etc.,). Although both forms of traffic monitoring have been applied towards freeway traffic management systems, similar applications can be made towards surface arterial roadways.

Pattern Recognition

One of the control modes that a traffic control system can use is the traffic responsive mode. As the term implies, the system responds to traffic conditions. Although the detector data is collected in real-time, the response time can take several minutes to be fulfilled. For example, once a master controller sends out a new timing plan, the subordinate controllers need to coordinate themselves in proper synchronization. Based on the number of traffic signals involved, this coordination period could be as long as several

minutes. In essence, the traffic responsive mode operates in a lag-mode although minor. The system may be approximately five to ten minutes behind actual traffic conditions. If the rate of increase in traffic conditions (i.e: flow, occupancy, etc.) is relatively high, a traffic responsive system may not be truly effective.

In order to obtain a dynamic or real-time traffic control system, the prediction of traffic characteristics such as flow, speed, headway, and occupancy must accurately made. For example, traffic characteristics are measured by detectors at regular time intervals. The time frame of the characteristics can be thought of as t . To achieve dynamic traffic control operations, the time frame $(t + 1)$ must be predicted. The most traditional form of prediction has come from linear regression and extrapolation models. These types of mathematical models served best situations where conspicuous trends were found. In a traffic network, prominent trends can be observed in short time frames (i.e.: morning, afternoon peak periods, etc.). However, over longer time periods such as days, weeks, months, and years, constant traffic trends may not be clearly defined. Traffic characteristics (i.e.: flow, occupancy, speed, volume, headway, etc.) do change over long periods of time; the lack of stationary values over long time frames makes these traffic characteristics random variables. Recently, nonlinear and time-variate types of prediction models have been applied with promising results (Lu, J., 1990). These forms of longer term stochastic process models

can assist traffic management in developing a proactive traffic control system, one that responds to traffic conditions before they occur. A database driven system would be extremely useful since it could store and retrieve traffic data from the past.

Incident Detection

Incident detection has been primarily used on freeway traffic management systems. Freeways form the principle trunk arterials in a given metropolitan area. It is important that the level of service on freeways be maintained. Incidents can occur on these facilities that can disrupt service. Incidents can include traffic accidents, disabled vehicles, debris on the road, and the like. The early detection of such incidents can enable rapid response by traffic, police, fire, and emergency medical agencies.

On surface arterial streets, incident detection is not as obvious. In freeway operation, traffic flow is to be uninterrupted; conspicuous changes in lane occupancies, vehicle speeds, and headways can easily be detected by roadway loops and cameras. Likewise the point of incident can be made from the detector data. Surface arterial roadways include the use of traffic signals which periodically stop traffic flow. Because vehicular flow is regularly segmented by traffic control devices, incident detection is different from the freeway application. Despite the fact that surface streets have numerous access points, signalized or unsignalized,

incidents such as those mentioned above can still have a detrimental effect on surface traffic operations.

Instead of overbuilding a surface arterial network to accommodate capacity stemming from incidents, a management system can be suited to the surveillance of incidents (Han and May, 1989). For a incident system to be effective, the following must be achieved:

- The rapid detection of the incident
- The determination of important information concerning the nature of the incident
- The deployment of appropriate action

It is difficult to predict when and where an incident is to take place. Hence, a traffic management system capable of detecting incidents would be the most practical alternative.

Incidents on surface streets can be more complex than on freeways. The following are some of the more common incidents likely to be experienced on surface roads:

- Accidents
- Stalls
- Double or illegal parking
- Signal malfunctions
- Detector malfunctions
- Bus stops

Accidents could be the most common type of incident occurring on surface streets. These facilities have countless at-grade intersections which involve conflicting vehicle movements that are potentially hazardous. Accidents can differ in magnitude which can block a single lane or an entire intersection

approach. Most surface roadway accidents do occur at or in the vicinity of intersections.

Vehicle stalls generally take place on the approaches to intersections where the vehicle may have to stop and idle. Stalls usually block a single lane but can still have detrimental effects on traffic. Double parking is very similar to stalls in that it blocks a single lane. However, double parking occurs where street parking is permitted and not necessarily at intersections.

Traffic signal malfunctions effect arterial operations on its approaches which can lead to adversely effecting adjacent intersections. Detector malfunctions can also disrupt operations by reducing the ability of the traffic control system from "seeing" actual traffic conditions. As a result, ineffective timing plan strategies may be implemented. Current traffic signal hardware is available to detect such equipment failings.

Bus stops can temporarily disrupt traffic. This is especially true on two lane, two way facilities that have no pull off area. The knowledge of the location of bus stops and the bus schedules will assist in determining this incident.

Other events such as sporting events, parades, bad weather can have adverse effects on the surface roadway network. The determination of their characteristics could assist in future detections.

An effective incident detection mechanism with a traffic management system can yield many benefits. Operational

problems can be identified and solved faster, resulting in shorter incident durations and reductions in network delay and travel time. Detected accidents can be rapidly responded to which could increase the chances of survival of the injured. Double parked incidents can be relayed to the appropriate authorities for expedited law enforcement. Signal and detector malfunctions can be quickly corrected by notified maintenance crews. Hence, incident detection can serve as a support system for operations and maintenance.

Four principle things are needed to be known in order to deal with surface arterial roadway incidents. They are the Who, What, When, Where attributes of the incidents. If unusual patterns or trends in detector input data can be correlated to incidents, then the identifying of specific incidents is possible with automation. Decision tree algorithms can be developed to compare incoming detector data to incident threshold levels corresponding to specific incident types. The threshold values need not be stationary but can change in magnitude throughout the day to reflect the current traffic conditions (i.e.: a lane blockage in the afternoon peak hour would yield higher threshold values as opposed to a lane blockage in the late evening hours).

The effectiveness of incident detection is influenced by the quality and or quantity of the detection system. The more detection devices in the field, the more the system will be able to "look" for incidents. So far inductive loops and various forms of surveillance cameras have been used for

freeway incidence. Another detection device that has potential is a roving field manager. The "Hoosier Helper" service vehicles in use on the Borman Expressway are an excellent example of this form of detection. The roving field manager can visually see things that the loops and cameras cannot; the mobility enables the field manager to traverse the network unrestricted. In addition, the field manager can be equipped with radio communications to relay information back to a central operations office. Specific information can be sent to the agency staff and control computer systems as to the type and location of the incidents and what initial strategy could be implemented. The "Hoosier Helper" service has already shown promise on the Borman Expressway; similar applications can be made on the interstate freeway system in Indianapolis as well as the major surface arterial roadways.

Artificial Intelligence

What is known as artificial intelligence is a subfield of computer science involving the symbolic, automated inference from given facts and data. The reasoning process performed by the computer is symbolic but the end result is a computer system capable in behaving in ways that humans would recognize as intelligent behavior between one another (Cohn and Harris, 1992). Artificial intelligence in traffic control and monitoring can be used to increase the capabilities of the traffic control system as well as the accompanying management. Four basic applications in artificial intelligence can be

found in traffic control and monitoring (Han and May, 1989). They are expert systems, fuzzy set reasoning, machine learning, and decision support systems and will be discussed at this time.

Knowledge Based Expert Systems (KBES) have been one of the more developed segments in artificial intelligence. This system uses expertise and experience from earlier research in the topic, in this case traffic control. Expert systems rely on what are known as knowledge bases that incorporate extensive factual and historical data (i.e.: volumes, timing plans, detector thresholds, etc.) collected from the traffic network. With the experience and information stored in the knowledge base, the KBES's "inference engine" utilizes decision algorithms to arrive at a best course of action. Although KBES would be beneficial in traffic control and incident detection, other applications such as initial traffic control designs for signalized intersections have been introduced (Pattnaik et al., 1991). The best possible timing plans can be initially developed for new or altered intersections. KBES is very beneficial in traffic control because of the wide range of experience levels that can be found in traffic agencies. Most traffic control systems are designed by consulting firms or traffic signal manufacturers. Advanced, sophisticated traffic engineering principles are incorporated in the system's software. However, once the traffic system has been installed, the agency staff may not have the same educational nor experience backgrounds as those

who designed it. A KBES can serve as an effective interface between individuals in the agency that may not possess the knowledge that an expert would have.

The second form of artificial intelligence is fuzzy set reasoning. Fuzzy set theory is a generalization of the mathematical set theory in which a partial set is permitted. This technique can assist in the comparison of field data and with threshold values. In real situations, not all threshold values can be met to activate certain control or incident measures. Also, the discrete number of threshold values can yield significant "jumps" between them. Fuzzy set theory can be applied towards threshold rates in order to ease a transition between adjacent threshold values and the corresponding courses of action.

Another type of artificial intelligence is known as machine learning. In this technique, a decision tree algorithm is used in the initial setup of the traffic control system. The computer learns from on-line experiences instead of solving from theoretical means. By using the initial threshold values set by traffic engineers, the computer observes and records input data from the field and appropriately alters the threshold values. Over a period of time, the computer refines the threshold values, the course of action, and sorts out patterns for new situations. This type of machine learning would be very useful in traffic control. Once timing plans are initially developed, their effectiveness will decline over time as traffic volumes change. With

machine learning, a traffic control system can constantly update its timing plans by continuously incorporating field data in its threshold updates. An example of this would be the refinement of a specific and unique timing scenario like the monday morning peak period. The system can use data collected from every monday morning to upgrade the threshold rates and timing plans; the past monday data can be used or a set of the last dozen or so mondays can be used to assist in averaging and providing insight in new patterns. Other timing periods can be treated similarly.

The last form of artificial intelligence to be discussed is decision support systems. Once an incident or unusual traffic pattern is identified, the question now is how to deal with it. Once incidents are detected, different courses of action are available. They will be subject to time, location, type of incident, resource availability, and so on. A decision tree algorithm can be developed to follow actions that would be taken by an experienced agency traffic operator in a control center. A sophisticated decision support system could operate in real time and 24 hours a day, something that most agencies are not funded nor staffed for. Likewise, the system can give notice of pending decisions to on-duty traffic operators for the benefit of approval and possible override.

Integration with Freeway Traffic Management Systems

Freeways and surface arterial roadways perform similar tasks yet possess different attributes. Both types of

facilities provide rapid mobility to a region or metropolitan area. Traffic management systems have been developed for both types of facilities but interaction between the systems have not reached its potential. In this section, approaches in integrating the two traffic management systems will be discussed.

Freeways, by definition, have grade separated interchanges for access; access is provide by means of entrance and exit ramps. Freeway interchanges are usually spaced no less than a quarter of a mile but could be spaced several miles apart in a metropolitan area. It is at these interchanges where traffic exits or enters the freeway. Nearly all freeway interchanges connect with major surface arterial roadways. The exit and entrance ramps provide physical integration between freeways and surface arterials.

One of the first forms of traffic regulation between surface arterial roadways and freeways is ramp metering. Ramp metering regulates the amount of traffic entering the freeway from the entrance ramps (Robinson and Doctor, 1989). A traffic signal is positioned on the entrance ramp and is used to control the frequency and amount of traffic entering the freeway. There are three basic ramp metering techniques that can be used. First, the metering rate of ramp flow could be based on time-of-day, historical traffic data. The second type of regulation measures the amount of freeway mainline capacity available for on-ramp traffic. Loop detectors are located on the freeway lanes upstream of the merge area and on

the entrance ramp. Based on the measured freeway volumes, a metered rate is calculated for the ramp signal. The last type of ramp meter control is pro-active in nature. This type of control, however, is primarily intended for the prediction of congested bottlenecks on the freeway downstream from the on-ramp (Berg and Nihan, 1990).

The basic purposes for ramp metering is to regulate the amount of traffic entering the freeway to prevent freeway congestion and bottlenecks. Freeway speeds can be kept uniform while congestion related accidents are reduced. In addition, ramp meters can break up platooned traffic from nearby intersections. Considerable turbulence can be created if several vehicles enter the freeway that is near capacity. By reducing this traffic turbulence, a reduction in merge area type accidents (i.e: side-swipes, rear-ends, etc.) is possible. Ramp meters can operate independently from one another or be interconnected with forms of centralized control. With interconnection, system-wide ramp metering rates can be coordinated to produce the most desirable freeway conditions (Hibbard et al., 1990). For example, when a congestion incident is detected on the freeway, ramp metering rates upstream of the incident adjust to allow fewer vehicles to enter the freeway. Likewise, ramp meters downstream from the incident allow for more vehicles to enter. While loop detectors located at the ramp traffic signal allow for presence and passage of vehicles, a queue detector loop is positioned up-stream on the ramp. This loop is generally

located in the vicinity of the intersection of the ramp and the surface street. Its purpose is to detect when a sufficiently long queue of ramp vehicles reaches this critical level at which time the metered rate changes to increase ramp flow. An "advance" queue detector could also be positioned on the approaches to the cross street/ramp intersection to increase the advance detection and prevent possible queue backup onto the arterial street (Havinoviski, G.N., 1991). An alternative to changing the metered rate, surface street vehicles could be diverted to adjacent or other on ramp locations. These "forced" diversions are possible if the existing surface roadway network is capable in routing vehicles effectively and easily (i.e.: frontage roads, service streets, etc.,).

Ramp metering has been developed primarily for the benefit of freeway operation. Although traffic assignment computer models have been developed to simulate possible queue back-ups and diversions on adjacent surface streets (Yagar, 1989), these effects have been secondary. In addition, there has not been sufficient research on how off-ramp freeway traffic effects surface streets. Freeway operations embody continuous vehicle flow with no traffic control devices. Although surges in traffic volumes do occur on freeways, the lane densities are relatively uniform with no induced platooning. Vehicles which do leave the freeway, however, are subjected to signalized intersections where traffic is periodically stopped. The potential exits for vehicles to

back up onto the freeway if the off-ramp volumes are high and the intersection(s) is positioned relatively close to the ramp throat. Integration between the freeway and surface roadway management systems is needed to reduce the potential awkwardness that could occur with the exit ramp traffic. The FHWA is currently performing studies that will yield guidelines for integrating freeway surveillance and control systems with ramp metering and adjacent surface street traffic signal systems (Euler and Lindley, 1989). At the time of this writing, no publications have been released from these studies.

One possible scenario of freeway/surface street integration would be the timely exchange of freeway volume data to adjacent traffic control systems. Relevant traffic information can be sent to downstream exit ramp intersections to enable the signal systems to coordinate for the approaching ramp traffic that is still on the freeway. The relevant information could be based from several sources such as origin-destination studies, upstream entrance ramp volumes, upstream freeway volumes or lane densities, and time-of-day historical information. The key to the success of integration is the advance notification of approaching exit ramp traffic. The sooner upstream patterns are identified, the sooner downstream traffic control systems can be altered to effectively accommodate the approaching traffic before it arrives.

Geographic Information Systems

Geographic Information Systems, known as GIS, can assist management in the compilation and review of data. In essence, GIS has been applied where there are numerous physical features of interest spread out over a region. GIS has been used to gather, compile, and retrieve information on items of interest. GIS has been used by agencies and large companies in the past for purposes related to surveying, structures, highways and the like. For traffic control systems, GIS offers the similar advantages in data compilation and storage since traffic networks have physical attributes and are spread out over large metropolitan areas.

Currently, GIS applications are beginning to be applied in traffic control systems. Many of the commercially available closed-loop systems have some form of a GIS to enable the agency operator to view the traffic network on a computer screen. Systems from Econolite, Eagle, Traffic Control Technologies and others offer the ability to view the entire network or to "zoom in" on a given intersection. Real time, vital information is also displayed such as the current timing plan in use, the number of seconds into the given green phase, and the functional status of adjacent detector loops. Some systems allow one to view the inside contents of the controller cabinet for inventory and maintenance purposes (Eagle, 1992). The existing use of GIS in traffic control systems, propriety based or custom made, has reduced the need

for wall mounted network maps that were so prevalent in earlier systems.

GIS in traffic control systems offer several advantages (Logie, 1992). First, a GIS offers the ability to view a network at any given scale. The zoom in/out nature of GIS does not restrict an agency to accepting a "standard scale". Second, different types of data can be stored in GIS, regardless of its magnitude or importance. GIS has the potential to store data that may be relevant to the large network (i.e.: street names, ADT's, average speeds, etc.,) while having the ability to store data that is site specific (i.e.: traffic flow, accidents, signage, etc.,). Third, GIS allows for the easy update of information. As the network increases or is altered by traffic signal improvements, the updated information can readily be performed. Also, GIS can store data that changes as a function of time. Many databases only allow for current information to be displayed. GIS can enable the viewing of data over time which can be valuable for traffic applications where time-series and forecasting analyses are used.

With the use of WIMPS interface (i.e.: Windows, Icons, Mouse, Pulldown menus, and Scroll bars), a GIS can effectively serve as the primary administrative tool on accessing real time and historical information (Insignares and Terry, 1991). The use of these pull down menus allows the agency to perform both traffic and non-traffic related tasks like word processing, spreadsheet, database, real-time data observation,

fine tune control parameters, etc.. The use of the pull down menus allows for traffic control analysis, geographic analysis, and report generation can be performed off screen in the "background". GIS can eventually interface with other software; periodically stored traffic count data could be downloaded to a network/signal optimization program on a scheduled basis. Despite advanced traffic control systems having numerous components, a GIS can provide effective data interface. ATMS has the basic control components: architecture, detection, data communications, and user communications. Within each component there is a multitude of small elements such as controllers, detector loops, changeable message signs, to name a few. Maintenance personnel can pull up data regarding as-built construction plans of intersections, signal equipment inventory data, cabinet wiring plans, and maintenance records. Traffic personnel can access traffic flow and volume data, timing plan data, signal parameter data, and accident record data.

Multi-Jurisdictional Interaction

Traffic control systems are directly influenced by the jurisdictional agency where they are found. Each jurisdiction, (i.e.: town, city, county, state, etc.), can have a specific philosophy towards traffic control, signal design, installation, operation and maintenance activities. This philosophy is usually unique to each individual agency in order to meet its specific objectives and goals.

In a large metropolitan area, municipalities and their associated traffic control jurisdictions are adjacent to one another and are virtually separated by finite borderlines. Approximately five percent of the traffic signals in an urbanized area can be found on these jurisdictional boundaries and it has been estimated that at least fifteen percent of a jurisdiction's signals have direct influence on traffic operations in adjacent jurisdictions (Helmer, 1990). Despite these jurisdictional boundaries being transparent to motorists, the absence of consistent traffic control philosophies between adjacent jurisdictions' traffic control can be quite evident. Therefore, jurisdictional boundaries should not adversely effect the expectations of roadway users nor their use of the system (Cranford, 1992).

When traffic congestion crosses jurisdictional boundaries, it is essential that the local agencies work together to plan, develop, and implement traffic control strategies to effectively meet the traffic conditions (Helmer, 1990). Committees representing the area-wide traffic agencies can be formed to exchange information regarding existing and proposed traffic signal systems, operational strategies, and formulate the development of standards and specifications for new traffic control installation. It is important for the committee to determine what each traffic agency is doing and what impact it will have on the entire traffic network area.

The principal objective of this inter-jurisdictional committee is to plan, develop, operate, and maintain traffic signal systems such that regional traffic flow improvements will be enhanced. There are several short term goals that can be done to achieve this objective (Helmer, 1990). First, major arterial roadways that cross jurisdictional boundaries can be identified and classified. Second, an inventory of existing traffic equipment from each agency can be made available to assist in matching up compatible hardware. Third, existing coordinated signal systems or isolated intersections are inventoried to identify the development of regional coordinated networks. Fourth, effective capital improvement projects can be produced for the major arterial roadways in which traffic impact on adjacent communities would be evident. Traffic volume data can be collected periodically and used by the committee to develop optimized signal timing plans for the existing/proposed systems (Carvell et al., 1992). Fifth, a regional traffic control network can be developed based on existing and proposed agency hardware/software. This could imply regional control by means of a Traffic Operations Center (TOC), or agency control with field master units, or basic coordination with agencies by means of a common time reference. Long term goals for the committee could include the standardization of equipment, the planning of alternative routes, regional-wide pre-emption of traffic signals, and intelligent highway applications to long, regional corridors.

Multi-jurisdictional coordination between adjacent agencies is desired to improve regional traffic flow. However, such cooperation maybe difficult since many agencies have limited resources and capabilities and may be unable in effectively contend with actions from adjacent jurisdictions. Likewise, local elected leaders tend to support and fund projects that produce direct, tangible results in the short term (Cranford, 1992). Multi-jurisdictional committees should divide the work into small doable tasks to yield measurable benefits at a reasonable return on investment in order for elected leaders to support the these committees.

CHAPTER 7 PROPOSED ASATMS FOR THE INDIANAPOLIS AREA

An application of an advanced traffic management system for surface arterial roadways will be presented in this section. The designated location for the proposed application will be the greater metropolitan Indianapolis area. The selection of this area was due to the absence of comprehensive advanced traffic control systems in Indianapolis as well as the potential need for them. There are more surface arterial roadways in the metropolitan Indianapolis area than in any other comparable area in Indiana. Also, considerable short and long term growth is expected to be fulfilled in land development and population. The freeway and surface arterial roadway network will need to effectively accommodate the increased demand. In the following sections, existing roadway and traffic conditions as well as congestion and projected growth will be discussed. Also, the need for advanced traffic control systems for surface arterial roadways in Indianapolis will be identified. Finally, applications in regards to traffic control architecture, data communications, detection and surveillance systems, and user communications will be presented for the proposed Indianapolis ASATMS.

Existing Roadway and Traffic Conditions

The metropolitan Indianapolis area, shown in Figure 7, contains approximately 3,900 miles of roadway (IDMD, 1991). Of overall total mileage, 137 miles are made up of freeways and other limited access highways, 730 miles are arterial roadways, 400 miles are collector/distributor roadways, and 2,600 miles are local roads and streets. As seen from Figure 7, the surface roadway network basically follows a conventional grid-type network. The Fall Creek, Eagle Creek, and White River traverse through the metropolitan area and partially disrupt the continuity of the grid network in the northeast, near west, and southwest portions of Indianapolis. A comprehensive Interstate freeway system also exists in the Indianapolis metropolitan area. Freeways such as I-65, I-70, and I-74 provide interstate access to the region while I-465 completely encircles Indianapolis. The I-465 ring route not only alleviates intercity business freeways through redundancy, but also provides access to outlying communities in the metropolitan area. Marion County, which makes up the majority of the metropolitan Indianapolis area, contains 3,100 miles of roadway with the city of Indianapolis responsible for 2,907 miles. The balance of the mileage is under the jurisdiction of INDOT and surrounding cities such as Carmel and Greenwood. Over 18,500 intersections exist in Marion County with 1,100 controlled by traffic signals.

Figure 7 Indianapolis Arterial Roadway Network
(IDMD, 1991)

This roadway network carried an average of 2.3 million trips per day. The analysis, based of the 1990 current day assignment, resulted in a average trip travel time of 17.11 minutes per trip and an average trip length of 7.39 miles. Furthermore, almost half (47%) of the vehicular travel occurred on the freeway/expressway system, 46% used the arterial roadways, and the remainder (7%) utilized the collector/distributor and local streets. In a broad sense, the vast majority of the surface arterial roadways have Average Daily Traffic (ADT) volumes under 20,000 vehicles (IDMD, 1989). Some sections of the more significant arterial roadways (i.e.: Meridian, College, Fall Creek, Keystone, Northwestern, Washington, Allisonville, Shadeland, Washington, etc.) have ADT's between 20,000 and 40,000 vehicles. Likewise, most of the interstate freeways have ADT's of at least 40,000 vehicles. Sections of I-465 on the north, northeast, and west sides of Indianapolis as well as I-65 and I-70 in the vicinity of downtown have ADT's approaching or exceeding 100,000 vehicles per day.

Congestion and Projected Growth

Despite the Indianapolis metropolitan area possessing a comprehensive freeway and arterial roadway network, traffic congestion and forecasted growth can hinder its overall performance. A measure of current traffic congestion was performed by the Indianapolis Department of Transportation (IDOT). In 1990, IDOT conducted a capacity analysis for 161

signalized intersections in its jurisdiction. The intersections were assessed a level of service designation, which is a qualitative measure of traffic flow subject to travel speed, travel time, delay, freedom to maneuver, safety, and driver comfort. A level of service "A" indicates free flow traffic operations whereas a level of service "F" indicates unacceptable gridlock performance. For signalized intersections, levels of service less than that of "C" indicate that the average stopped delay for vehicles is exceeding 40 seconds per vehicle. In general, this level of service is unacceptable. Of the 161 intersections that IDOT analyzed, 64 were operating below a level of service "C" with 32 of the 64 below a level of service of "D" (IDMD, 1991). Although this analysis represents less than ten percent of the total intersections in Indianapolis, the results do reveal a high number of intersections, with respect to the sample size, that are not performing favorably.

In 1986, a travel demand simulation model of Indianapolis was developed (IDMD, 1986). The purpose of the model was to investigate the performance of the roadway network with respect to trip generation, trip distribution, modal split, vehicle occupancy, traffic assignment, socio-economic forecasts, and environmental analyses. The projected study year was 2005. The roadway links were classified by roadway function including freeway, expressway, 2-way arterial, 1-way arterial, etc.. The results of the trip assignment revealed volume to capacity ratios that were, for the most part, below

1.00 although many segments experienced v/c ratios in excess of 1.00. In essence, most freeways had v/c ratios between 0.5 and 1.00 while the majority of expressway class facilities were between 0.75 and 1.00. Both of these roadway types did have segments whose v/c ratios exceeded 1.00 but were not in the majority. The other roadway types, namely the 2-way and 1-way arterials saw a greater spread of v/c ratios including those above 1.00. Figure 8 shows excessive v/c ratios on the Indianapolis roadway network for the projected year 2005. The v/c ratios in this travel demand simulation model primarily deal with the combined effect of intersections and adjacent roadway segments. Since intersection performance is not detailed in this simulation model, it is difficult to effectively assess intersection performance. It can be estimated that intersection performance is as favorable as the roadway segment's level of service.

Another measure of performance for a roadway system is based on Vehicle Miles of Travel (VMT). VMT is a measure of demand for travel. Based on the travel demand simulation model, it is predicted that the VMT for the Indianapolis area will increase at an average rate of 1.64 percent over the 1980-2005 period (IDMD, 1991). Furthermore, the estimated 1990 VMT for the Indianapolis area is approximately 6,418 per person. The Department of Metropolitan Development has estimated that the urban area population density for Indianapolis is approximately 2,000 people per square mile. Figure 9 illustrates a relationship between urban area

Figure 8 Excessive Volume / Capacity Ratios
for the Indianapolis Roadway Network for the Year 2005
(IDMD, 1986)

population density and the annual area VMT. This figure is based on sampling many metropolitan areas across the country. From Figure 9, given the Indianapolis population density of 2,000 people, the annual VMT should be between 5,000-6,000. With the estimated 1990 VMT for Indianapolis area at 6,418 per person, it can be concluded that Indianapolis has a higher than average annual VMT per person than other U.S. cities with similar population densities.

Source:
Measures of Effectiveness for Multimodal Urban Traffic Management,
Vol. 2. U.S. Department of Transportation

Figure 9 Relationships Between Population Density
and Vehicle Miles of Travel
(IDMD, 1991)

Lastly, the growth in development in the Indianapolis area will continue although not uniform (Greiwe and Peoni, 1992). The northeast side will continue to be a high grow area especially in the Fall Creek Park northeast of I-465. Likewise, the north side in the vicinity of Carmel and Noblesville will experience continued grow and development. With the addition of the United Airlines Maintenance Facility

and the Postal Service Transfer Facility at the Indianapolis International Airport, the west and southwest sides will experience considerable growth. Decatur Township is most likely to be a recipient of attracting industrial, commercial, office, and lodging developments. The south side of the Indianapolis area is a potential area for high growth similar to that on the northeast sides. There has already been commercial growth along the US 31 south corridor. Commercial development can continue as well as residential, industrial, office, and warehouse developments. Growth is very likely on the south side but its magnitude is still unclear; the south side can be looked at as a "sleeper" area for growth. It should be noted that many elements of the above mentioned developments, namely the airport expansions, were not considered nor forecasted in the travel demand estimation model from 1986. Hence, the analysis of v/c ratios from that study may not be accurate for the year 2005.

In summary, there are capacity shortcomings that the Indianapolis area is currently experiencing and will experience. Likewise, the annual VMT growth rate signifies normal trends but Indianapolis's annual VMT is larger than other cities with similar population densities. Finally, the future growth of certain areas in Indianapolis will be substantial and will place considerable demands on the roadway network.

Need for a ASATMS in the Indianapolis Area

The need for an advanced traffic control system was first recognized by the city of Indianapolis in the early 1980's (IDMD, 1991). The Indianapolis Department of Transportation performed a signal system study in 1981; the study stemmed from previous air quality and energy conservation studies that concluded that the interconnection of optimally-timed traffic signals yielding desirable progression on the roadway network is a high priority. Although the 1981 study identified predictable traffic patterns on the Indianapolis roadway network, considerable fluctuation was also noted on daily and weekly basis. Because of this variance, a traffic responsive signal system for Indianapolis was recommended. The study reported that 450 or approximately 45 percent of the total intersections were already interconnected by hardwire and utilizing fixed time or time of day techniques. The study recommended that over 90 percent of the intersections should be interconnected. In Figure 10, the recommended areas for traffic control interconnection systems are illustrated. It can be seen that the majority of these areas occur on the major arterial roadways. IDOT used specific criteria in determining the location for traffic control on arterial roadways. First, common traffic flow characteristics were identified between given roadway segments and adjacent segments. Second, the proximity of control areas and segments to each other were considered. Third, the proximity of signalized intersections within a given roadway segment was a

Figure 10 Recommended Subsystem Control Areas
for Indianapolis
(IDMD, 1991)

factor. Fourth, the impact of traffic flows were subject to engineering judgement. Fifth, current traffic signal timing controls and adjacent land use demands were also considered.

The 1981 IDOT signal control study also investigated nine different traffic control alternatives for signal interconnection. It was concluded that a blend between first and second generation traffic control philosophies of the FHWA Urban Traffic Control System (UTCS) would be the most desirable for the final system. Therefore, the need for a traffic control system has been identified and the use of automation is recommended to effectively respond to traffic demands.

In 1983, the then Indiana Department of Highways (IDOH) estimated benefits that a traffic responsive system would have in the Indianapolis area (IDMD, 1991). The following benefits were reported:

- Reduced fuel consumption: 25,000 gallons per day
- Reduced travel time: 5,000 hours per day
- Reduced vehicle operation costs: \$35,000 per day
- Reduced exhaust emission: 28 tons per day
- Reduced accidents: 400 per year

It was also stated that the traffic control system was expected to generate quantifiable benefits to the roadway users of more than \$20 million per year.

The estimated benefits were developed in the early 1980's when the technology in traffic control systems was constrained. The originally proposed system, if installed in the early 1980's, would be a centralized control system.

Since then, decentralized closed-loop traffic control systems have been introduced and revised. With the introduction and the refinement of personal computers and micro processors, traffic control systems have become more powerful, flexible, but not as expensive as the earlier systems. In addition, the demand and growth forecasts for Indianapolis have changed in the last ten years; the growth in the north, northeast, and the potential growth from the airport expansion was not visualized in the early 1980's. The need for a comprehensive traffic control system for surface arterials is more evident than it was ten years ago. The benefits listed above reflected those obtainable with centralized, main frame systems. The benefits, if estimated today, would probably be higher because more powerful, decentralized traffic control systems can be inexpensively acquired.

Development of Proposed ASATMS Components

An advanced traffic management system for surface arterial roadways in the Indianapolis metropolitan area will be presented in this section. The proposed system encompasses traffic control concepts and technologies which have not only been discussed earlier in this report, but also represent the current and near future trends in advanced traffic control. The proposed system is broken down into four basic parts that coincide with the four major components of ATMS. The first one, traffic control architecture, is very important since it defines the degree of control and management that the agency

will have over traffic operations. The implementation and utilization of the other three components will be influenced by the type of traffic control architecture used. These three components: surveillance, data communications and user communications are sequential in nature and can be implemented in a sequential manner. This is advantageous since the experience gained from the installation of one component can be used on other systems throughout the metropolitan area and state.

Traffic Control Architecture

The architecture will have a direct influence on the performance, flexibility, and expandability of a traffic control system. The operating philosophy as well as the degree of centralized/decentralized control needs to be identified. The operating philosophy of the proposed ASATMS can be a hybrid of the four defined generational philosophies taking advantage of desirable features from selected philosophies. From the available five generations of operating philosophies, only the first three (i.e.: first, second, and 1.5) have been implemented and have proven track records. The verdict on the latter two generations is not known; the third generation philosophy has been implemented in a few locations on a test basis while the fourth generation's objectives are vague in nature and are still being defined. Furthermore, both third and fourth generation philosophies rely almost completely on real-time data collection, analysis,

and traffic control. The comprehensive real-time control concept is still in its infancy and its effectiveness and versatility in differing traffic applications is not clear. In the 1985 *Capacity Manual*, it is stated that traffic data sampling periods less than 15 minutes in length are statistically unstable in which data variation is difficult to predict (TRB, 1985). This observation by the *Capacity Manual* is generic in nature in that it would apply to free-flowing facilities such as highways and freeways. Arterial surface roadways could be more susceptible to this statistical instability since they are not free flowing facilities and are subject to traffic signals inducing platoons and gaps in the traffic stream.

The philosophy of the proposed ASATMS should utilize real time data collection and analysis, but should also be based on a historic traffic database. This operational concept would allow for the three modes of traffic operation (i.e.: traffic responsive, time of day, and manual) but would use historic traffic data as a base to analyze, generate, or modify timing strategies. The traffic volume database would be dynamic in nature and would be updated daily with traffic data collected from the system detectors. Traffic volumes, flow rates, speeds, directional splits can be collected for every portion of the network and for any time period. Certain time periods (i.e.: monday morning peak periods, thursday afternoon peak hour, saturday peak periods, etc.) can not only be retrieved from memory, but can be averaged over time to yield typical

peak periods for the designated times. For example, a typical monday morning peak period can be averaged from previously recorded monday morning peak periods. This "average" peak period can serve as a typical profile in which characteristic patterns can be identified. Signal timing plan thresholds can be originated or modified from these profiles. Hence, at the beginning of a designated day, a "forecasted" time of day plan is developed and downloaded to the local controllers and master units. The plan can also serve as a background cycle throughout the day. As the day progresses, field data will be collected and tested against the forecasted plan. If the test passes, timing plans will be changed and recorded. Over a course of time, an elaborate library of network profiles and associated timing scenarios will be available for use. Because the database is always being updated, the resulting forecasted timing plans will be accurate; numerous transitions between timing plans can be reduced to acceptable levels. Since this philosophy has answered some of the shortcomings found in the second generation, this new operational concept can be labeled the "2.5" generation.

The proposed ASATMS should consist of a centralized control system with distributed intelligence. Distributed intelligence eliminates vulnerability and total reliance on a central computing facility and reduces communication needs and costs. Local controllers are becoming more automated and more powerful in regards to accumulating, storing, analyzing, and transmitting field data; as low echelon automation increases,

these features will continue to improve in local controllers. Master controller units may still be used but can reduce the ASATMS's flexibility in dynamically rearranged signal groups. Master controlled closed-loop systems can be part of the ASATMS in locations where a principal arterial roadway exists but has no major parallel routes nor connecting cross streets.

The computer architecture at the upper echelon of the proposed ASATMS could take several shapes. For the benefit of compatibility, flexibility, and price, a PC based-local area network (LAN) should be used. First, all traffic controllers and master units are PC compatible and are designed specifically to interface with personal computers. Second, a LAN is very flexible and can be added onto with more PC's and file servers to increase size and computing power. Hence, as the traffic network expands, so will the LAN. Third, the cost of PC's and file servers are a mere fraction of the cost of main frame central computers. City, county, and state governments may not be able to afford the high initial cost of main frame computers and the potential upgrades and or replacements. A powerful LAN could be purchased at prices below \$20,000 and can be upgraded easily without complete replacement. In addition, the potential power of the personal computer cannot be underestimated. Later this year, the 586 microprocessor will become available making PC's faster and more powerful than their 486 counterparts. Before the turn of the century, an 886 or 986 microprocessor could be available; the computational speed and operating memory could be

remarkable and yet at affordable prices. Furthermore, advances in super-conductivity, virtual reality, and parallel processing could completely revolutionize the personal computer field within the next ten years. It may be one's advantage to consider PC's over main frame computers at this time. This does not imply that main frames should no longer be used in traffic control. A main frame can be used on traffic control systems but should be able to interface with a LAN.

Detection and Surveillance

The inductive loop should serve as a primary source of detection for the proposed ASATMS. This type of detector has wide spread use in Indianapolis area and throughout the state. The loop detector should be used on intersection approaches as well as for system detectors located between major intersections. Likewise, inductive loops should be installed on the Indianapolis freeway network and the connecting ramps; these applications should follow those on the proposed Borman freeway traffic management system. The uses for loop detectors should include signal timing control, ramp metering, and data collection. The loops can connect with the nearest signal controller to interface with the system.

The use of video image processing also should be considered for use in the Indianapolis ASATMS. Commercially known as AUTOSCOPE, this advanced video detection system should be used on freeway segments and ramp locations.

AUTOSCOPE can detect the same traffic parameters as any in-pavement detection device; its ability to have over 50 detection zones per camera make the AUTOSCOPE concept valuable in areas where numerous lanes are diverging and the placement of conventional loop detectors may prove to be disruptive to traffic operations. AUTOSCOPE could also be applied at signal locations adjacent to freeway ramps and certain ramp metering locations. The increased field of view of a high-mounted video camera may benefit in advance detection of vehicles entering or leaving the freeway. The use of AUTOSCOPE on intersection approaches could be performed but should be reserved for unique, non-standard intersections whose performance is crucial to desirable traffic performance.

Additional surveillance techniques should also be considered in the Indianapolis area. The use of the "Hoosier Helper" patrol vehicles could be a benefit to both the freeways and selected surface routes in Indianapolis. These patrol vehicles would perform similar tasks as they do on the Borman Expressway. Although the Indianapolis freeway network has greater degrees of redundancy than the Borman expressway corridor, the "Hoosier Helper" patrols would still be instrumental in the early detection and removal of incidents and accidents.

Other types of detection devices mentioned in this report such as magnetometers, and wayside aerial detectors utilizing infrared, radar, and ultrasonic technology should be investigated for potential use in the proposed system.

Data Communications

The communications network for the proposed ASATMS in Indianapolis should compliment the centralized control with distributed intelligence architecture. The primary source of data communication should be done with fiberoptics cable. This should be used especially on the primary or "trunk" communication lines leading from the TOC to field locations. The fiberoptics lines leaving the downtown TOC could follow major surface arterial roadways, use downtown Interstate freeways' right-of-ways, or a combination of the two. The use of the I-465 right-of-way could allow communication lines to total encircle the main Indianapolis network. The fiberoptics lines could "branch out" at every major intersection or interchange to reach surface arterial streets and corridors. It would be desirable to use fiberoptics at the lower levels of communication between intersections; twisted pair may be allowed to exist on a site specific basis.

The use of leased utility lines should not be considered for major use on the proposed ASATMS. Past experience has revealed traffic agencies' vulnerability to leasing agreements with utilities and inconsistent levels of quality. This does not imply that IDOT nor INDOT should not look into leasing agreements with utility companies. Agreements can be made for communications with signals or signal systems on the outer fringes of the network. It is essential, however, for the traffic agency to own and operate its primary communication lines to insure desirable and consistent levels of service.

Radio communications do have potential and should be investigated for future use. This is true in particular with spread spectrum communications which are currently being developed and tested for traffic operations. If proven to be effective, spread spectrum could rival the primary fiberoptic lines leading out from the downtown TOC. Spread spectrum technology could allow the TOC to interface with any traffic control location that is capable of having a transmitter/receiver antenna. If the TOC is located in the state office buildings (INDOT Headquarters), line-of-sight radio communications are possible provided that the broadcast tower is mounted atop the tall state buildings. Both spread spectrum and fiberoptics could be used jointly by segregating different data/command information to each mode of communication. Likewise, spread spectrum could easily be applied to the other IVHS components as they are introduced in the Indianapolis area.

User Communications

Motorist Information Systems (MIS) will most likely be the last ASATMS component implemented in the proposed system. A comprehensive MIS should be compatible to both surface arterial roadways and freeways. Hence, the freeway traffic management system should be installed before the MIS is complete.

Changeable Message Signs (CMS) should be considered as a primary role player MIS for both freeways and surface streets.

An in depth study must be performed to determine the locations of where CMS's should go. In general, CMS's are used to inform motorists of traffic situations ahead and potential alternative routes. Hence, a thorough investigation of each candidate corridor should be made to identify the relevant alternative routes. CMS's should be considered for use on surface arterial roadways on the approaches to freeway interchanges. CMS's positioned midway between intersections could be used to inform motorists on what the optimal speed is for desirable progression. Motorists can easily comply since most modern vehicle speedometers give a digital readout. CMS's should also be located on the approaches to intersections whose roadways connect to other freeway interchanges. Such an application can result in effective diversion/alternative route guidance. High traffic generators such as shopping centers and athletic stadiums could be equipped with CMS's to inform departing patrons on traffic conditions and where to get on selected arterials and freeways. Consideration should be given to exclusive CMS's as well as "partial" CMS's that would be affixed to a standard guide sign. Partial CMS's would compliment the main guide sign message; these types of CMS's have been used with successful results. Additional studies would need to be performed on what type of messages are to be used at these CMS locations.

Of the different types of CMS's that are currently available, it is recommended that the agency conduct field

tests in order to determine what type should be chosen for the ASATMS/FTMS. Current research finds the fiberoptic and LED CMS's to be the most effective; INDOT may desire to intensify its investigation of these two types.

Other types of MIS should be considered for use in the long term. The use of radio and television mediums may be beneficial in informing the motoring public real-time conditions and long-term patterns. A traffic map of the arterial street network can be generated from real-time traffic data by the central LAN system. It can be color-coded to reveal conditions ranging from free-flowing to gridlock. This traffic map can be downloaded to various sources including cable television, the news media and high traffic generators (i.e.: downtown office buildings, shopping centers, stadiums, etc.). Traffic reporters could effectively relay this information periodically over Highway Advisory Radio (HAR) and private FM/AM radio broadcasts. Likewise, cable television could be equipped with a traffic version of the "Weather Channel", which could graphically give motorists real-time traffic reports as well as "forecasts" for the next hour or peak period. Long term construction project announcements and the resulting traffic detours could be effectively relayed to the public via cable television.

Estimated Costs and Benefits

An effective ATMS will improve roadway users' travel time and speed while reducing delay. This translates to a benefit of getting the public to their destinations faster and hence, increasing their work and personal productivity. The highway agency allocates the cost of the traffic control system; the initial installation costs can be high due to the applications of advanced technologies on a network-wide, macroscopic level. Following the initial construction, annual operating costs are incurred by the agency. Hence, the taxpaying motorist is the indirect but eventual purchaser and beneficiary of an ATMS. It is the highway agency's objective to assure that available resources are allocated efficiently to produce an effective traffic control system. In this section, costs and benefits that are most likely to be encountered by an advanced traffic control system will be covered.

Existing Traffic Control Systems

Benefit analyses are regularly performed on existing or recently installed traffic control systems. In particular, "before and after" studies are emphasized to evaluate changes in traffic control; these types of evaluations have been carried out since the development of first generation systems.

Because a traffic control system is made up of a series of signalized intersections, the total delay for the entire system takes precedent over the delays at individual intersections. One method in determining this type of

effectiveness is with what is called the floating car technique (Homburger and Kell, 1984). A test car is used by the traffic agency to collect data such as delay information from the roadway network. The test car "floats" or travels through the traffic stream passing as many vehicles that pass it. Another version of this technique is based on the selection of what is judged to be representative of the average speed of the subject roadway. This technique can be used to determine travel time, delay time, and average speed; before and after studies can be applied to signal improvements to see if favorable changes occurred (Aleman and Allen, 1990). Traditionally, the vehicle would be equipped with two stopwatches. One would be started at the beginning of each run and would record the arrival times at various control points along the route. The second stopwatch would be used to record the magnitude of stopped-time delays encountered at intersections or other locations along the route. The time, location, and cause of delay would be recorded on paper forms or voice recording equipment. Although mechanical tachographs have replaced the stopwatch method, they are subject to failure and are tedious to operate. Caltrans has developed an automated system that uses a lap-top personal computer onboard the test vehicle. The PC interfaces with the vehicle to acquire data on distance, speed as well as user defined events. The data can then be downloaded to an office PC to create summary tables and graphs on the performance of the traffic controlled roadway. The analysis and summary

reports can basically be generated instantaneously which, compared with manual or mechanical methods, can save over \$100,000 per year in floating car costs (Page and Palen, 1989).

Analysis techniques such as the floating car method are instrumental in determining the performance of a surface arterial roadway. Roadways can vary significantly in terms of the number of lanes, posted speed limits, the types of adjacent land use, and the number and spacing of intersections. Hence, surface arterial roadways possess differing attributes that make them unique to their neighboring counterparts. Because of this, no rigid test or analysis is available that can take into account the numerous variables. The floating car technique is basically immune to the individual characteristics because it records average travel time and delay. Furthermore, this technique is very useful in analyzing before and after changes in principle parameters like timing and phase plans.

Benefit analyses have been performed on all different generations and sizes of traffic control systems. Earlier in this report, the city of Evansville's centralized traffic control system was described. In addition, a before and after study was performed to determine the system's effectiveness (JHK, 1986). It was found that overall traffic delay had been reduced by 8% and the corresponding average speeds increased between 2 and 32 percent. It was also estimated that 2,887 person-hours/day and 1,782,270 gallons of fuel per year were

saved as a result of using the system. The combined savings in fuel and time was determined to be approximately \$5.5 million annually. When compared to the original installation cost (uniformly spread out over 10 years) of \$658,154 a Benefit to Cost ratio of 8.4 was achieved.

Similarly, benefit analyses have been performed on other centralized traffic control systems yielding comparable findings. Orlando, Florida has had 375 intersections under centralized control since the late 1980's. User benefits for the first 113 intersections were determined based on the floating car technique. The results are as follows:

- Reduced fuel consumption: 670,000 gallons/year
- Reduced travel time: -23%
- Reduced stops: -56%
- Reduced delay: -56%
- Increased speed: +42%

When the Orlando system expands to its proposed 375 locations, the savings in fuel are expected to triple (Aleman and Allen, 1990). Another centralized control system in Sioux City, Iowa was found to have annual savings of \$946,440 (Maze et al., 1990). With the initial cost of \$155,093, the amortized benefit/cost ratio was calculated to be over 55 to 1.

Closed-loop systems have also been subject to benefit analyses. Eleven closed-loop systems were installed in Hennepin County, Minnesota and were evaluated for traffic performance and user benefits (Westwood, 1990). The number of signals per closed-loop system ranged from four to fourteen with an average of six. Table 1 shows the before and after

results in traffic operations for six of the closed-loop systems. The changes in average speed, number of stops, average delay, and average travel time are not only favorable but considerable in some cases. It has been estimated that the closed loop systems in Hennepin County will benefit road users over a ten year analysis period 45.35 million dollars while costing approximately 1.73 million dollars. The resulting benefit/cost ratio is a desirable 26 to 1. Another analysis took place on a twenty mile long surface arterial north of Minneapolis (Gobeli and Boje, 1991). Twenty-five signals were controlled by three closed-loop systems. Efforts were made to coordinate the systems together by means of effective timing with traffic signal software. The before and after changes in arterial roadway performance were positive. Delay decreased by over 11% during the peak periods while the number of stops went down by over 28%. Likewise, travel time saw a decrease between 1.6 to 3.9 percent while the average travel speed increased during the peak hour from 1.6 to 4.1 percent. It was determined that approximately 104,500 delay-hours would be eliminated over the course of a year, as well as 14,150,000 stops, and 71,400 gallons of fuel. The annual dollar savings for the improvements was figured to be \$999,700 while the annual benefit/cost ratio was estimated to be 6.7 to 1. In other published analyses, nine closed-loop systems in Iowa were installed and evaluated for before and after benefits. The amortized benefit/cost ratio on these projects

Table 1 Hennepin County Closed-Loop System
Performance
(Westwood, 1990)

AVERAGE SPEED IN MILES PER HOUR DRIVING ROUTE IN BOTH DIRECTIONS				
ROUTE	SPEED			% CHANGE
	BEFORE	AFTER	CHANGE	
C.S.A.H. 17	26.4	28.8	2.4	9.2
C.S.A.H. 3A	21.9	27.2	5.3	24.1
C.S.A.H. 5	24.3	27.7	3.4	14.0
C.S.A.H. 53	23.7	27.8	4.1	17.4
C.S.A.H. 52N	26.9	27.8	.9	3.5
C.S.A.H. 52S	32.5	36.5	4.0	12.4
AVERAGES	25.9	29.3	3.4	13.0

AVERAGE NUMBER OF STOPS DRIVING ROUTE IN BOTH DIRECTIONS				
ROUTE	STOPS			% CHANGE
	BEFORE	AFTER	CHANGE	
C.S.A.H. 17	7.0	4.0	3.0	42.9
C.S.A.H. 3A	5.5	2.7	2.8	50.5
C.S.A.H. 5	5.4	2.3	3.1	56.8
C.S.A.H. 53	10.0	4.9	5.1	51.1
C.S.A.H. 52N	2.8	1.7	1.2	41.0
C.S.A.H. 52S	2.0	.3	1.7	83.5
TOTALS	32.7	15.9	16.8	51.3

AVERAGE DELAY IN SECONDS DRIVING ROUTE IN BOTH DIRECTIONS				
ROUTE	DELAY			% CHANGE
	BEFORE	AFTER	CHANGE	
C.S.A.H. 17	246	191	55	22.4
C.S.A.H. 3A	201	111	91	45.1
C.S.A.H. 5	113	40	73	64.8
C.S.A.H. 53	353	187	166	47.1
C.S.A.H. 52N	86	74	13	14.8
C.S.A.H. 52S	48	14	33	70.2
TOTALS	1048	616	432	41.2

AVERAGE TIME TO TRAVEL ROUTE DRIVING IN BOTH DIRECTIONS				
ROUTE	TRAVEL TIME			% CHANGE
	BEFORE	AFTER	CHANGE	
C.S.A.H. 17	655	600	55	8.4
C.S.A.H. 3A	466	376	91	19.5
C.S.A.H. 5	593	520	73	12.3
C.S.A.H. 53	1,046	880	166	15.9
C.S.A.H. 52N	372	359	13	3.4
C.S.A.H. 52S	314	281	34	10.7
TOTALS	3,446	3,015	432	12.5

did not go below 6 and went as high as 34 to 1 (Maze et al, 1990).

Centralized control systems with distributed intelligence have also been investigated for user benefits. In Lexington, Kentucky 250 intersections with 170 type controllers were connected to a central computer. The benefit estimates for the system, which was installed in the mid-1980's, indicated that the annual delay and fuel savings will be more than 2.5 million, which repays for the initial construction cost every year (Sampson, 1988). In Los Angeles, the first phases of the Automated Surveillance and Control (ATSAC) system were installed in 1984. The hierarchy of this system includes a very fast supervisory computer networked with consoles and area computers, which in turn, interface with type 170 signal controllers. An evaluation concluded that once ATSAC was completely installed, total stops would be reduced by 35%, intersection delay by 20%, travel time by 13%, fuel consumption by 12.5%, and air emissions by 10% (Rowe, 1987). The benefit/cost ratio was estimated to be 9.8 to 1 resulting in the system paying for itself within the first nine months of operation.

The above mentioned analyses reveal that advanced traffic control systems do provide benefits to roadway users. These benefits, measured in terms of travel time, delay, speed, and number of stops, may not be conspicuously noticed by an individual motorist on a single trip. However, it is the cumulative effective that these benefits have on the

entire traveling public in which noticable and favorable changes are observed. Some of the mentioned traffic improvements were significant in magnitude yeilding perecentage improvements well into the double digits. This may not necessarily be the exclusive work of the newly installed traffic control system. The existing traffic progression on a given surface roadway maybe so poor that even a time-based coordiated system could yeild benefits. This is not to say that advance traffic control systems are not needed. The ablility to upload field data and download timing commands make an advance traffic control system flexible to changes in traffic. Also, the little effort required to make and download changes to the system is infinitesimal when compared to the cumulative traffic improvements that will result. This is one reason why benefit to cost ratios are so favorable.

Analysis of an ASATMS in Indianapolis

A benefit and cost analysis of the proposed ASATMS for the Indianapolis metropolitan area will be performed. AASHTO has developed methods in determining the cost effectiveness of individual signalized intersections based on stopping and idling costs (AASHTO, 1977). However, it should be noted that this economic procedure, found in the AASHTO manual commonly known as the "Red Book", was developed in the mid-1970's and may not reflect current traffic control methodology. The red book's procedures were based on the methodologies found in the

1965 *Highway Capacity Manual*. The latest edition of the *Highway Capacity Manual*, which came out in 1985, contains considerable changes in traffic signal capacity analysis (TRB, 1985). Moreover, advanced traffic control systems cannot be directly evaluated as per the red book procedures since the AASHTO methodology did not have traffic control systems in mind. This discussion is not meant to discredit the AASHTO red book but to point out that its methodology towards intersection delay costs are over 15 years old and may not reflect current operating conditions. Hence, preliminary benefits to roadway users will be determined by methodology based on current consulting practice (JHK, 1986). In addition, the initial and annual costs of the ASATMS will be estimated. These estimates will reflect the ASATMS components proposed in the previous section.

Preliminary User Benefits

To attempt in making this analysis accurate, data provided by the city of Indianapolis was used whenever possible. It has been mentioned earlier that a travel demand forecast was developed for Indianapolis with the projection year being 2005 (IDMD, 1986). In this forecast model, a traffic assignment on the Indianapolis roadway network was generated. Table 2 summarizes the free-flow vehicle-hours, congested vehicle-hours, and delay hours resulting from the traffic assignment. The first row in Table 2 displays the summary of traffic delay for the entire roadway network for

the year 2005. The second row focuses on delay encountered on surface arterial roadways in 2005. In the third row, the delay values for the surface arterials are extrapolated

Table 2 Indianapolis Surface Arterial
Delay Summary

	Free-Flow Vehicle Hours	Congested Vehicle Hours	Delay Hours
2005 Network Traffic Assignment	789,024	1,003,672	214,648
Arterial Roadways (2005)	464,725	617,043	152,318
Arterial Roadways (1995)	394,957	524,408	129,451
Pre-ASATMS Arterial Roadways (75%)	296,218	393,306	97,088

to the analysis year 1995 using an annual rate of 1.64 percent that is consistent with the annual vehicle-miles of demand growth rate for the Indianapolis area (IDMD, 1991). It is assumed for this analysis that the ASATMS will be installed and fully operational by the year 1995. The last row adjusts the delay to assume that approximately 75 percent of all surface arterials will be part of the ASATMS. Hence, it can be seen at the bottom of Table 2 that the surface arterial roadway delay prior to the installation of a ASATMS is 97,088 hours per day.

Based on previous traffic control systems, it is assumed that the proposed ASATMS will produce a reduction in delay. The issue is what percentage reduction should be selected. The previous section discussed many different traffic control systems, and a wide range of delay reduction percentages were disclosed. Some reductions in delay were as little as 8 percent such as in the Evansville system while other delay reductions were as high as 56 percent as in the Orlando system. At any rate, the reported delay reduction percentages were significant and generally went into the double-digit. For the initial analysis, a conservative delay reduction of 5 percent is chosen since it is lower than the delay reductions reported. Furthermore, this delay reduction percentage, in light of the other reductions reported, can be considered as a conservative and low reduction rate for a network experiencing congestion. By applying this 5 percent reduction to the pre-ASATMS delay in Table 2, the revised delay becomes 92,234 hours per day. In other words, ASATMS saves 4,854 vehicle-hours per day.

Studies have shown that the traffic flow for the typical 104 weekend days per year are approximately equal to the traffic flow of 80 typical weekdays. Therefore, the number of effective days in one year are as follows:

$$\begin{aligned} (52 \text{ weeks}) \times (2 \text{ weekends/week}) &= 104 \text{ weekend days} \\ (365 \text{ days}) - (104 \text{ weekend days}) &= 261 \text{ days} \\ (261 \text{ days}) + (80 \text{ days}) &= 341 \text{ days} \end{aligned}$$

Hence, based on 341 days per year:

$$(4,854 \text{ veh-hrs/day}) \times (341 \text{ days/yr}) = 1,655,214 \text{ veh-hrs/yr}$$

Therefore, in one year of operation, the proposed ASATMS will save Indianapolis roadway users 1,655,214 veh-hrs/yr.

It was reported in the travel simulation study that daily fuel consumption on the surface arterial roadways for the years 1980 and 2005 were 525,650 and 729,138 gallons, respectively (IDMD, 1986). By straight-line interpolation, the 1995 consumption rate would be 647,750 gallons per day. When considering that 75% of the arterial roadways would be involved in ASATMS, the 1995 consumption rate is proportionally reduced to 485,812 gallons per day. By dividing this consumption rate by the 393,305 congested vehicle hours for the ASATMS network (from Table 2), one gets an average vehicle consumption rate of 1.24 gallons per hour. By applying this rate to the annual savings in vehicle-hours, the fuel saved in one year would be:

$$(1,655,214 \text{ veh-hrs/yr}) \times (1.24 \text{ gal/hr}) = 2,052,465 \text{ gal/yr}$$

Assuming the average fuel price is \$1.40 per gallon, the fuel costs saved would be:

$$(2,052,465 \text{ gal/yr}) \times (\$1.40/\text{gal}) = \$2,873,451/\text{year}$$

Therefore, users of the ASATMS surface arterial roadways would save \$2,873,451 per year in reduced fuel costs.

To determine time savings that the proposed ASATMS would produce, a vehicle occupancy rate of 1.2 is assumed. The

actual rate in the Indianapolis area in 1980 was 1.14 (IDMD, 1991). On an individual basis, the time savings is:

$$(1,655,214 \text{ veh-hr/yr}) \times (1.2 \text{ per/veh}) = 1,986,257 \text{ per-hr/yr}$$

Given a personal value of time of \$4.45/hour, the savings are:

$$(1,986,257 \text{ per-hr/yr}) \times (\$4.45/\text{hr}) = \$8,838,844/\text{yr}$$

Therefore, when one considers the reduction of both fuel and time as a result of the ASATMS, the motoring public of Indianapolis may save approximately:

$$\$2,873,451 \text{ (fuel)} + \$8,838,844 \text{ (time)} = \$11,712,295/\text{yr.}$$

The reduction in carbon monoxide, hydrocarbon, and nitrous oxides can also be estimated. Table 3 shows the pollutant emission summary for ASATMS arterial roadways in 1995. The first column displays emission values that were interpolated from emission data from the travel simulation model study between the years 1980 and 2005. The second column has reduced emission values to reflect that 68% of all emissions come from surface arterials (IDMD, 1986) combined with the 75% surface arterial participation in the ASATMS. The third column represents the 5% assumed reduction in emissions corresponding to the 5% reduction in delay. Hence, the total annual emission

Table 3 Emission Reduction Summary

Pollutant	1995 Network Emissions (lb/day)	1995 ASATMS Emissions (lb/day)	ASATMS Emission Reductions (tons/yr)
CO	941,224	479,976	4,092
HC	82,324	41,976	358
NOx	92,894	47,376	404

reduction that the proposed ASATMS is the sum of the three pollutant values or 4,854 tons per year.

In summary, if the ASATMS is installed over 75 percent of the surface arterial network by the year 1995 and a overall delay reduction of 5 percent is experienced, the following estimated benefits are possible:

- Reduced delay: 1,655,214 veh-hrs/yr
- Reduced fuel consumption: 2,052,465 gal/yr
- Reduced fuel and time costs: \$11,712,295/yr
- Reduced pollutants: 4854 tons/year

Preliminary Costs

Preliminary installation and operating costs of the proposed ASATMS will now be estimated. It should be noted that detailed cost estimates are not possible until final designs for each element are completed. Cost analysis comparisons between centralized, decentralized, and centralized with distributed intelligence would not be accurate at this level. All systems share many similar

components making cost differences difficult. Also, no information exists at the time of this preliminary analysis on detailed cost comparisons between the three types of operating systems. Likewise, cost comparisons between different types of detection and communication systems at a macroscopic level may not yield accurate results for comparison since the actual design of the ASATMS has not been done.

Traffic Operations Center

-Room Preparation	\$500,000
-Central Processing Units (1 file server and 5 PC's forming a LAN)	\$30,000
-Software (Proprietor developed and in-house modified)	\$120,000

Traffic Control Devices (Field)

-New Signal Controllers (Assume 400 new units at \$10,000/unit)	\$4,000,000
-Traffic Signal Modification and Replacement (Assume 200 intersections at \$2,000/int.)	\$400,000

Detection and Surveillance

-System Loop Detectors (Assume 2,000 applications at \$500/loop)	\$1,000,000
-AUTOSCOPE -- Video Image Detection (Assume 25 locations at \$42,000/location)	\$1,050,000

Motorist Information Systems

-Changeable Message Signs (LED) (Assume 25 surface arterial locations at \$250,000/location)	\$6,250,000
-Color-Coded Traffic Network Map (Initial Development)	\$500,000

Communications

-Utilize Existing Conduit (Re-cable as needed)	\$500,000
-New Conduit Installation (200 miles at \$14.50/ft.)	\$15,312,000
-New Fiberoptic Installation	\$5,280,000

Initial Installation Cost \$34,942,000

Annual Operating Costs

-Basic Operations (Includes staffing and "Traffic Channel" hook up to cable television)	\$3,500,000
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If one were to assume a annual interest rate of 8% and a design life of 10 years, the equivalent uniform annual cost of the initial construction cost is \$5,207,406. This, coupled with the annual operating costs of \$3,500,000 results in the effective annual cost of the ASATMS being \$8,707,406. When considering the annual benefits of the proposed ASATMS of \$11,712,295, the benefit to cost ratio becomes 1.35 to 1.

The above analysis reveals that the ASATMS project is cost effective. Although the B/C ratio calculated is lower than the ones reported from other signal systems, it was acknowledged that the actual B/C ratios in those projects actually surpassed the initial B/C ratio by as much as threefold (JHK, 1986). Also, the assumed delay in this analysis was conservatively low when compared with other systems. The potential for delay reductions to be greater

than 5 percent are strong, making the annual savings and B/C ratio even more favorable. Table 4 shows a summary of different delay reductions and how it effects the cost effectiveness of the ASATMS. The user benefits are varied while the initial and annual costs of the system remain the same.

Table 4 Summary of Different Delay Reductions
Given a Constant
Installation and Operation Cost

	5 % Delay Reduction	10 % Delay Reduction	15 % Delay Reduction	Break Even Delay Reduction
Daily Veh-Hrs Saved	4,854	9,708	14,562	3,609
Annual Fuel Cost Saved (Dollars)	2,873,451	5,746,903	8,620,354	2,136,243
Annual Time Cost Saved (Dollars)	8,838,844	17,677,686	26,516,528	6,571,163
Annual User Cost Saved (Dollars)	11,712,295	23,424,589	35,136,882	8,707,406
Benefit to Cost Ratio	1.35	2.69	4.04	1.00

As it can be seen, as the delay reductions increase, so do the user benefits. At a 15 percent delay reduction, a B/C ratio of 4.04 is achieved. In light of the previously

reported B/C ratios from other traffic control systems, this calculated B/C ratio is quite low. This would indicate that this benefit analysis is quite conservative and user benefits could actually be higher once the ASATMS is installed. Also the break even analysis where the B/C ratio is set at 1.0 revealed that 3,609 vehicle-hours would be saved per day. This relates to a delay reduction of 3.72 percent. Similar to the B/C ratios, this break even delay reduction is quite low when compared with reported delay reductions from other systems.

Similarly, the annual equivalent cost of the ASATMS can be varied with respect to a set user benefit. Suppose the ASATMS only controls 50 percent of the surface arterial network. By adjusting the initial installation costs appropriately, it is estimated that the initial construction cost would be approximately \$21 million. Given a ten year service life and a 8% interest rate, the equivalent annual cost of the installation of the ASATMS would be \$3,129,630. Coupled with an approximate annual operating cost of approximately \$2.1 million, the effective annual cost of the system would be \$5,229,630. When compared with the 5% delay reduction benefit of \$11,712,295, the resulting B/C is 2.24 to 1. To break even given an annual user benefit of \$11,712,295, the initial installation cost would most likely exceed \$47 million. This amount takes into consideration the 10 year service life, the 8% interest rate, and the annual operating cost being approximately 10 percent of the initial

installation cost. It is difficult to compare different installation/operation costs to a fixed benefit since the cost of the system is so dependent on its design. The design, of course, cannot be accurately determined from a macroscopic standpoint. However, the delay reduction of 5% is very low when compared with other systems mentioned in this study.

CHAPTER 8 CONCLUSIONS AND RECOMMENDATIONS

The objective of this report has been to identify feasible technologies and management strategies for a surface arterial roadway network in the Indianapolis area. This report has attempted to present feasible technologies but also directions that INDOT may take in regards to ATMS. Additional work is needed to accurately plan and design the traffic control system which will effectively meet the needs of the Indianapolis area. INDOT and other relevant agencies must work together in order to deciding on what should be done to develop a traffic control system. This section of the report attempts to identify direction and additional steps required for ASATMS implementation.

The following is a list of recommended tasks that INDOT should pursue for the development of an ASATMS. These tasks, spread out over the short, intermediate and long terms, are essential to the orderly development of an ASATMS and FTMS in the Indianapolis area.

Short Term

The following are tasks that can be performed almost immediately. These tasks will help in defining goals and objectives for the Indianapolis ASATMS.

-An advisory committee should be designated for the exclusive purpose of planning and implementing the ASATMS in the Indianapolis area. The committee should be made up from relevant transportation agencies, academia, and consultants. Short and long term goals should be formulated by this committee that would insure proper implementation of the ASATMS. The advisory committee should be represented by and have effective relations with all applicable agencies making the committee multi-jurisdictional.

-Regional arterial corridors need to be identified. These corridors may contain both freeway and surface arterial facilities that run parallel. Also, more than one principal arterial roadway can be represented. Major connecting roadway facilities should be identified in these corridors. The width of these corridors will be subject to the degree of available parallel routes. The formulation of these corridors should be based on similar traffic patterns (i.e.: volumes, directional splits, similar origins/destinations, etc.,). Alternative diversion and reliever routes should be identified within these corridors for the freeway and principal arterial system. Potential regional corridors are:

North Side Corridor

- Meridian St.
- College Ave.

Northeast Side Corridor

- Keystone Ave.
- Allisonville Rd.
- Fall Creek Rd.

South Side Corridor

- US 31
- I-65
- SR 431
- Meridian St.
- Bluff Rd.

East Side Corridor

- US 40
- Michigan St.
- New York St.

Far East Side Corridor

- I-465
- Shadeland Ave.
- Post Rd.
- Emerson Ave.
- Pendleton Pike

Far North Side Corridor

- I-465
- 86st St./82nd St.

-A degree of management in the proposed traffic control system needs to be addressed. Management issues such as network inventory, facility status, operations, surveillance, freeway integration, and multi-jurisdictional interaction need to be identified. The advisory committee must decide in the early stages to what degree these management issues should play in the ASATMS.

-A location of a traffic operations center (TOC) should be determined. The location could be in downtown at INDOT headquarters in the state office building or could be on the outskirts of town. The location of INDOT's headquarters is preferable since the tall government center can be used for a line-of-sight microwave or spread spectrum transmitting tower.

-A data communications line network should be formulated. The network plan should be influenced by the location of the regional corridors. Based on the location of the regional corridors, a network should be developed which shows the primary and secondary communication lines. An inventory of existing interconnect cable and utility lines which could be leased should be produced. Also, a policy on the hierarchy of modes of communication should be drafted. By recognizing the distance from the TOC to the traffic control location, hierarchical communication modes such as fiberoptics, microwave, twisted pair wire, and leased lines can be utilized to yield an effective data communications network.

-One regional corridor should be selected for the initial application of the ASATMS. The corridor should be represented by many elements (i.e.: major parallel routes, freeway entrance/exit ramps, major cross streets, diversion/alternative routes, etc.). This pilot installation should be investigated for possible changes and revisions in the ASATMS design. The regional corridor application would produce immediate results as

compared to waiting until the entire ASATMS was installed.

-A freeway traffic management system should be planned for the Indianapolis freeways. This FTMS should compliment and be consistent with the system being installed on the Borman Expressway. Integration between the freeway and surface arterial systems should be emphasized. The TOC for the freeway system should be the same facility for the ASATMS.

Intermediate Term

These tasks could be performed after the initial development and installation a ASATMS in at least one regional corridor.

-A study should be undertaken to determine what type of CMS technology should be employed on the freeway and surface arterial network. Exclusive CMS applications as well as the "partial" CMS/guide sign applications should be included in the study.

-A study should be made regarding the messages and the locations where CMS's are to be installed on the freeway and surface arterial network. This comprehensive study should include all of the regional corridors since CMS messages will most likely effect more than one corridor.

-Efforts should be made to develop color-coded traffic network maps of the Indianapolis ASATMS. The maps should enable the viewing of real-time traffic conditions and eventually display forecasts of traffic conditions for next day peak periods. Different formats should be investigated including travel time, speed, flow rate or volume. The maps should also be used to display current and pending construction projects with the associated lane closures. Once developed, the traffic map could be sent via cable to the media sources for traffic reporting.

Long Term

The following tasks should be used to insure the successful implementation and operation of the ASATMS for the long term.

- The ASATMS should eventually interconnect all traffic signals in the Indianapolis metropolitan area. Some signal locations made not warrant being part of a progressive corridor but should still be part of the traffic control network for monitoring and data collection purposes.

- The database in the TOC should be used to its full potential creating and updating an elaborate library of timing plans and scenarios that will assist the ASATMS in responding to a variety of situations.

- The freeway traffic management system adopted for the Indianapolis freeway network should be compatible with that used on the Borman Expressway in northwest Indiana. In addition, single point urban interchanges should be strongly considered for use for proposed interchanges or when existing interchanges are reconstructed.

- The effectiveness and availability of spread spectrum radio communications should be monitored for potential use in Indiana traffic projects.

- If the other components of IVHS are being considered for use in Indiana, integration with the ASATMS should be strived for.

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