ASSESSMENT OF CALTRANS 2070 CONTROLLER
IN MEETING HARDWARE REQUIREMENTS OF
ADVANCED TRAFFIC MANAGEMENT SYSTEMS

by

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SUMMARY

Traffic signals are a critical element in the transportation network in improving the safety and efficiency of traffic operations. The proper installation, operation, and maintenance of traffic signals can maximize the capacity of a network, while reducing vehicle stops, travel time, and fuel consumption. As traffic demands continue to increase, Advanced Traffic Management Systems (ATMS) are being used to better manage transportation facilities.

One element of ATMS includes advanced signal control systems, which acknowledge the effect and interrelationship of control between adjacent traffic signals. These advanced signal control systems collect data using a variety of monitoring equipment located throughout the network and transfer that data to a central processing computer. After the central computer processes the information, an optimal signal timing plan for each signal is developed and then transferred to traffic signal controllers, where the plans are implemented. If this process can occur nearly instantaneously, the signal control system would be able to respond in “real time” to varying demands in traffic.

One of the potential barriers to the successful implementation of ATMS include the communications and information processing limitations of existing traffic controllers. To insure that ATMS can become a reality, the California Department of Transportation (Caltrans) is developing specifications for a new Type 2070 controller to handle the high-end applications of ATMS. The objectives of this paper include: 1) reviewing existing signal controllers; 2) evaluating their abilities in satisfying the hardware demands of current and upcoming signal control strategies; 3) summarizing the Caltrans approach toward controller design; 4) identifying the advantages and disadvantages of that design; and 5) providing recommendations on how that design can be improved.

The approach of this paper was to review available literature pertaining to the design and applications of existing signal controllers. Literature pertaining to the Type 2070 controller was also reviewed. Signal controller manufacturers, software developers, transportation officials, and transportation researchers were contacted to discuss the progress of the Type 2070 controller development, as well as issues that must be considered before field implementation.

Existing signal controllers lack sufficient flexibility and computing power to accommodate the hardware requirements of ATMS. While controller standards exist to promote interchangeability between different manufacturers, such standards do not adequately address features such as system coordination and communications, features that are crucial to ATMS. As a result, different manufacturers include proprietary features that limit interchangeability, and thus the use of controller equipment to a variety of traffic control applications. Other controllers are designed to provide interchangeability and flexibility, but lack the communications and information processing capabilities to perform complex control strategies. While some controllers can be upgraded using custom hardware and software to perform specific applications, the absence of controller standardization ultimately leads to flexibility, cost, and quality control problems. To address these deficiencies, the Type 2070 controller features improved computing power and is designed to be flexible, while maintaining compatibility with existing controller hardware.
While the proposed design of the Type 2070 controller is significantly improved from existing controller equipment, it is difficult to make an accurate assessment of its ability to satisfy the hardware requirements of ATMS. The range of ATMS requirements remain unknown and the specifications of the Type 2070 controller are not yet finalized. As a result, the capabilities of the controller cannot be tested. However, measures can be taken to improve the ability in meeting future needs. Rather than maintaining compatibility with existing hardware, an evaluation should be performed to determine if the Type 2070 controller can be designed with more advanced technology that can better accommodate the demands of future traffic control systems that have not yet been conceived. Although implementation of such a measure would be expensive, and the provision of features may never to fully utilized, the Type 2070 controller would more likely be able to withstand the demand for improved hardware as technology develops.
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INTRODUCTION

Since their installation in Cleveland, Ohio in 1914 (1), traffic signals have become a critical element in improving the safety and efficiency of operations on the transportation network. The proper design, installation, operation, and maintenance of traffic signals can maximize system capacity while reducing vehicle stops, travel time, and fuel consumption. Traffic signals are also used to orderly control potentially conflicting and hazardous pedestrian and vehicular movements. As a result, traffic signals have been utilized in a variety of applications to coordinate and manage transportation systems.

However, current trends of increasing automobile ownership and usage will undoubtedly place heavy demands on transportation engineers and planners to maintain high levels of mobility. To accomplish this task, the transportation community is relying on Advanced Traffic Management Systems (ATMS). ATMS utilize state-of-the-art computer technology and the latest innovations in electronics and communications to: 1) collect real-time traffic data; 2) manage that data; 3) develop traffic control plans in response to current conditions; and 4) communicate those plans to control points within the transportation network.

For the successful implementation of ATMS, the design of traffic signal controllers must be able to integrate new and upcoming technologies with existing hardware at minimal cost and labor. The ability of traffic signal controllers to accommodate advances in technology could yield further improvements to traffic operations.

Objectives

This paper provides an evaluation of the ability of current traffic signal controllers in integrating new technologies to existing hardware. The objectives of this paper are to:

1. review the design of existing traffic signal controllers;
2. identify deficiencies of existing controllers in accommodating current and upcoming technologies;
3. discuss the current approach in the design of a next generation of controllers;
4. identify the advantages and disadvantages of the new design; and
5. provide recommendations on how that design can be improved to accommodate a broad range of applications.

Scope

While different manufacturers are featuring a variety of advanced traffic controllers (ATCs) with similar designs, the scope of this paper is limited to the design of an ATC as defined by the Caltrans Transportation Electrical Equipment Specifications for the Model 2070 ATMS Controller Unit of October 1994 (2). This paper is intended to provide an evaluation of existing traffic controllers and the Type 2070 controller design. The content of this paper is based on a review of available literature and discussions with transportation professionals.
Study Approach

A state-of-the-art literature review was conducted in order to establish background information on existing traffic controllers, traffic control strategies, upcoming ATMS applications, Type 2070 controller architecture, computer open architecture standards, and computer operating systems. The progress of development of the Type 2070 controller was revealed by contacting signal controller manufacturers, software developers, consultant firms, transportation researchers, and officials from transportation agencies. Through the contacts, a variety of issues regarding implementation of the Type 2070 controller were also revealed.

Organization of Report

The report is divided into five sections. The first section of the report summarizes the types of traffic signal controllers currently in use. The second section reviews the different network control strategies that are used to optimize the efficiency of the transportation network as a complete system. The third section evaluates the ability of existing controllers to accommodate the hardware requirements of existing network control systems. The purpose of this section is to identify the strengths and weaknesses of existing hardware in light of ATMS requirements and demonstrate the need for developing the Type 2070 controller. The fourth section of the report outlines the architecture of the Type 2070 controller and summarizes the advantages of disadvantages of its design. The final section provides a discussion of the range of ATMS applications, conclusions, and recommendations for an improved design.
EXISTING TRAFFIC SIGNAL CONTROLLER TECHNOLOGY

A traffic signal controller is an electrical mechanism mounted in a cabinet that establishes the signal timing plan, the sequence and durations that green, yellow, and red indications are displayed for various phases. Each phase controls a set of traffic movements. Two types of controllers are currently in use: pretimed and actuated.

Pretimed Controllers

With pretimed controllers, signal timing plans are predetermined using either simple manual strategies or computer optimization programs. Based on historical data, a set of off-line signal timing plans are developed for AM, Midday, PM, and off-peak hours. The manner which signal timing plans are implemented vary depending on the type of pretimed controller, electromechanical or solid-state.

Electromechanical Controllers

Electromechanical controllers were the first commercially available units for traffic control and remain in use in many U.S. cities (1). As shown in Figure 1, this type of controller is comprised of a dial driven by synchronous motors and a camshaft. The motor drives a dial through a set of gears. The size of the gear determines the cycle length (the amount of time to complete one complete sequence of phases). One complete revolution of the dial produces one cycle. The number of dials (one, two, or three) controls the number of different cycle lengths available. Keys fit into the dial and at the preset point cause a set of contacts to close and advance the camshaft. Separate cams on the camshaft control the displays (green, yellow, red, WALK, etc.) for a particular phase.

Solid-State Controllers

Solid-state pretimed controllers perform the same function as an electromechanical controller, but solid-state parts replace the synchronous motors, dials, keys, and camshafts (1). The signal timing plan is stored in random access memory (RAM) and can be changed via keyboard entry, thumbwheel switches, program pins, or dual-in-place switches. The software and data for performing controller operations are “burned onto” chips representing programmable read-only memory (PROM). A microprocessor processes the software and sends commands that control signal operations.

To ensure that a microprocessor-based controller is functioning properly, additional auxiliary equipment is required. Conflict monitors determine if the controller attempts to allocate right of way to conflicting movements. Other equipment or software adjustments are required to perform special functions (discussed in later sections).
Figure 1. Dial and Camshaft For Electromechanical Controller (1).
Actuated Controllers

The inherent weakness of pretimed controllers is its inability to vary a signal timing plan in response to varying levels of demand. An actuated controller is a solid-state, microprocessor-based controller that operates with variable vehicular and pedestrian timing and phasing intervals that are dependent on current traffic and pedestrian volumes. Vehicle demands are determined from information obtained by detectors installed in the pavement while pedestrians are detected with push buttons. There are currently two types of actuated controllers, one that is based on National Electrical Manufacturers Association (NEMA) standards, or the other on Type 170 standards.

NEMA Controller

Manufacturers of controller equipment have voluntarily agreed to conform hardware to standard mechanical and electrical connectors as specified by the NEMA TS1 standard (3). For example, the standard sets physical and functional specifications for input/output connections (see Appendix A). In spirit, the purpose of this standard is to provide interchangeability between controllers of different manufacturers that conform to the NEMA standard.

Type 170 Controller

The Type 170 standard was jointly developed by the California Department of Transportation (Caltrans) and the New York State Department of Transportation (NYSDOT) to set specifications for a uniform traffic control microcomputer. The Type 170 standard, like the NEMA TS1 standard, sets specifications for electrical connectors. However, the standard also sets specifications for the type of microprocessor, memory requirements, and read only memory (ROM) sizes (4). In addition, portable software standards are set through a specified program module--an insertable card with ROM that stores the traffic control program. This module could be inserted into any other Type 170 controller without modification.

Caltrans uses the Type 170 exclusively as its standard traffic controller. These units function as stored program, digital microcomputers to provide programmed logic for traffic control. Each unit is composed of a case and plug-in printed circuit board modules as shown in Figure 2. Basic modules include memory, central processing unit (CPU), input-output (I/O), panel control, PROM, modem, and power supply. The performance of the microcomputer is dependent on the selection of hardware and software. A modernization of the Type 170, called the Type 179, has been undertaken by NYSDOT (5). Although similar to the Type 170, the Type 179 features more computing power and a real-time operating system (4).
Figure 2. Type 170 Controller Unit Block Diagram (5).
NETWORK CONTROL STRATEGIES

The previous section reviewed the basic traffic signal controller hardware and the possible traffic control strategies for “isolated” signals. An “isolated” signal is one whose signal timing plan is independent of adjacent signals in the vicinity. This section reviews different control strategies that optimize the efficiency of the transportation network as a complete system.

Signal Coordination

A “coordinated” signal is one whose signal timing plan is designed to help optimize the efficiency of the transportation network by accounting for the timing of other signals. To assist in the development of optimized timing plans in coordinated systems, many agencies rely on computerized models, which are based either on progression-based or performance-index-based techniques.

Progression-based techniques maximize the “bandwidth” along an arterial (the amount of green time available for the continuous movement of vehicles). Such techniques are most appropriate for isolated arterials because they favor movement along an arterial at the expense of cross-street traffic, which could produce adverse effects at adjacent locations of the network. Two time-space diagrams, shown in Figure 3, describe the application of progression-based techniques along an arterial. The first diagram demonstrates a signal timing plan that treats both directions along the arterial equally, while the second describes a plan that favors only one direction (as might be done on an arterial with a predominant directional flow) (6). Because the application of progression-based techniques become more difficult as the complexity of traffic patterns and signal timing plans increase, many engineers use models such as PASSER and MAXBAND. These models determine the optimal cycle length, phase sequence, splits, and offsets at each intersection along the arterial to maximize the sum of the bandwidths in both directions (7). In addition, PASSER estimates measures of effectiveness (such as volume-to-capacity ratio, delays, stops, and fuel consumption) to evaluate each timing plan.

Performance-index-based techniques generate signal timing plans that minimize the performance index (PI) of operations, a weighted average of delays, stops, or fuel consumption in the transportation network (7). The TRANSYT model, which can be used for optimizing a single arterial, intersecting arterials, or a variety of network configurations, is an example of this approach. Using information on traffic volumes, system geometries, travel speeds, and signal timing data, the model simulates traffic flow on the system and estimates travel times, delays, number of stops, volume-to-capacity ratios, fuel consumption, and queue lengths. The model then optimizes the PI by selecting appropriate cycle lengths, splits, and offsets for the signal system. Some of the weaknesses of the TRANSYT model include its inability to optimize phase sequences, or model interactions between different signal subsystems.
Figure 3A. Time Space Diagram for Treating Both Directions Equally (6).

Figure 3B. Time-Space Diagram for Treating One Direction (6).
To implement the signal timing plans generated by computerized models, traffic signals can be coordinated using either time-based coordination or direct interconnection.

**Time-Based Coordination**

Time-based signal coordination is performed by using synchronized clocks, which may either be external units, or part of a Type 170 or NEMA controller. A library of signal timing plans generated off-line using historical data is input to the controller and each plan is designed to operate at a particular time of day. The use of synchronized clocks assures that coordinated signal timing plans will be implemented at all controllers simultaneously.

Some of the problems associated with time-based coordination include hardware limitations. Controller equipment may be incompatible, or the existing controller cabinets may be too small. It is often less expensive to replace the controllers with new units that have time-based coordination capabilities, rather than upgrading existing hardware. Another problem with time-based coordination is the absence of physical links or communication between controllers.

**Direct Interconnection**

Direct interconnection is used to physically link controllers so they can function as a system. The simplest form of interconnection is to provide a dedicated hardwire or cable to link each controller into a network. Signal controllers can be connected to transmit commands and data transmission using a variety of hardware: telephone lines, coaxial cable, fiber-optics cable, and radio communications. The ability of controllers to communicate within a network is one of the critical components to implementing more advanced control systems and strategies, as will be discussed in the following sections.

**Advanced Signal Control Systems (6)**

Advanced control systems have been developed for use with a variety of electronic signal equipment. Through different combinations of interconnection hardware, monitoring and display media, and detectors, these systems can better adjust signal timing plans to varying traffic patterns. The three advanced control systems discussed include: 1) central control systems; 2) arterial control systems; and 3) integrated control systems.

**Central Control Systems**

Today, there are approximately 60 central control systems in the United States, most of which are of the Urban Traffic Control System (UTCS) type. UTCS is a general purpose, hardware-independent software package developed and tested by the Federal Highway Administration. Private vendors also feature central control systems similar to UTCS. This type of control system uses a central computer to monitor and control the status of traffic signals second-by-second. Selection of signal timing plans, detection of hardware failure, unattended system operation, and signal preemption phasing functions can all be implemented through the central computer.
Arterial Control Systems

For coordination of controllers on small arterial systems, on-street master controllers are interconnected with other local controllers to provide for traffic responsive timing plan selection. A different approach is to use “closed loop” arterial control systems, which allow for coordination and monitoring of local controllers from a local office using a microcomputer.

Integrated Control Systems

Integrated control systems coordinate local street and arterial systems with freeway surveillance and control systems to improve traffic conditions on a corridor basis. One example of such a system is the Integrated Motorist Information System on Long Island, New York. This system controls surface street signals and freeway ramp metering signals. Other features include freeway incident detection and variable message sign control. Another example is in Toronto, where approximately 1,500 signals are coordinated with a freeway control system so that signal timing plans can vary depending on volume information from freeway ramps.

Advanced Signal Control Strategies (6)

With advanced control systems in place, more advanced signal control strategies can be used to match signal timings to traffic patterns. As the variability and complexity of traffic patterns increase, the ability of these systems and strategies to respond becomes increasingly important. As previously stated, the conventional approach to accommodating traffic is to develop time of day plans based on historical data. A variety of strategies that improve this approach are discussed in the following section. They include: 1) “first generation”; 2) “1.5 generation”; and 3) on-line strategies.

“First Generation” Strategies

In practice, three to five signal timing plans are developed based on historical data, even though this number represents only a fraction of the possible number of plans that could be implemented with existing equipment. For example, an electromechanical controller with three dials can operate up to nine plans, and up to 20 plans in time-based coordinated units. Up to 64 different plans can be used in UTCS systems. To better utilize the capabilities of existing equipment, a number of options are used to have been developed to improve responsiveness to traffic demand in systems capable only of conventional control:

1) Traffic Responsive Plan Selection - A variety of timing plans are developed and the best timing plan for a particular traffic pattern is selected based on volume and density data collected from detectors on the network.

2) Expert Systems / Artificial Intelligence - A system operator in a regional control center is assisted by an expert system in making decisions for overriding the current control strategy. Such changes include changing timing plans or providing priority to a particular traffic movement to relieve short-term congestion.
(3) Critical Intersection Control - Splits at critical intersections vary on a cycle-by-cycle basis to accommodate fluctuations in traffic demand. However, the cycle length at these intersections remain consistent with adjacent intersections to maintain signal coordination.

(4) Other Operating Strategies - A system operator decides, based on surveillance data, to operate signals in one or more subsystems in either pretimed, semi-actuated, or fully actuated mode.

“1.5 Generation” Strategies

The “1.5 generation” control strategies continue to use fixed-time plans developed off-line. However, system detectors estimate approach volumes to traffic signals that are used to develop new timing plans (generally using the TRANSYT model). Measures of effectiveness from the implementation of the new plan is compared with those of the plan already in operation. Based on such evaluation, an operator decides whether to implement the new plan. The advantage of this strategy is that changes in traffic patterns, as a result of growth and development, can be easily accommodated by minor changes to the timing plan. An evaluation by the operator ensures that the new plans are acceptable. However, major changes to timing plans still require field evaluation and verification.

On-Line Strategies

Signal control strategies using fixed-time plans remain somewhat inflexible to variable traffic flows or incidents that create short-term disruption of traffic flow. However, on-line or “real-time” strategies can detect variations in traffic patterns and respond as they happen to improve traffic operations significantly. Three such strategies, ATSAC, SCATS, and SCOOT, are discussed:

(1) Automated Traffic Surveillance And Control (ATSAC) - The Los Angeles Automated Traffic Surveillance And Control (ATSAC) system utilizes an enhanced UTCS package to provide a flexible traffic management tool. Traffic data is provided to the Control Center using loop detectors and closed circuit television. Since 1984, the ATSAC system has expanded from 118 intersections to 1,200 in 1993. By 1998, a total of 4,000 signalized intersections are scheduled to be within the ATSAC system.

When significant changes to traffic flow occur, the system utilizes four traffic control strategies to determine the appropriate signal timing plan. First, new timing plans are developed based on traffic volumes obtained from the loop detectors. The plans are then fine-tuned based on observation of traffic conditions using either traffic data or visual observation through closed circuit television. The second strategy involves the use of critical intersection control strategies. The third strategy utilizes a computer algorithm that matches surveillance data with the data used to create the available timing plans to select the most appropriate plan. The fourth strategy attempts temporary manual override of automated timing plans during nonrecurring traffic conditions.
(2) Sydney Coordinated Adaptive Traffic System (SCATS) (8)- The Sydney Coordinated Adaptive Traffic System utilizes several features of UTCS, where signal plans are selected based upon traffic conditions and adjusted based on traffic conditions at critical intersections. The area of control is broken down into regions or subsystems, and critical intersections control coordination within subsystems. As traffic demands vary, subsystems coordinate with each other.

The degree of saturation, the ratio of effectively utilized green time to the total available green time, is the most important parameter used in SCATS. The effectively utilized green time is the total time a detector located at the stop line is being occupied. Using the degree of saturation and traffic volume data, a regional computer determines the phase split plan that equalizes the degree of saturation for all approaches at critical intersections, the internal offset plan, and cycle length plan for the subsystem.

(3) Split Cycle Offset Optimization Technique (SCOOT) (8)- The Split Cycle Offset Optimization Technique was developed jointly by the Transport and Road Research Laboratory and a consortium of U.K. companies from the private sector. Developed as a coordinated, fully responsive traffic control strategy, SCOOT automatically reacts to changes in traffic flow by using an on-line TRANSYT type optimization process.

Vehicle detectors located at the upstream end of an approach link to a signalized intersection are used to generate cyclic flow profiles (arrival flow patterns). Using these flow profiles, SCOOT performs a TRANSYT analysis develop cycle length, phase split, and offsets plans. As vehicle detectors continually measure traffic flow data, the system continually updates the timing plan.
EXISTING HARDWARE EVALUATION

The aforementioned advanced control systems place requirements of existing traffic controllers to process large amounts of information. These systems require controllers to receive data from a variety of detection methods including loop detectors and video imaging. Depending on the complexity of the system, the data may be processed locally to select a signal timing plan from an available library, or may be transmitted back to a central location. After developing a timing plan at a central location, it is transmitted back to appropriate control points within the transportation network.

No matter how complex the system, its effectiveness is dependent upon the ability of the traffic controller to receive, process, transmit, and respond to data collected from different monitoring systems. Therefore, existing traffic controllers should be evaluated to assess their capabilities in accommodating these systems. From the strengths and weaknesses of existing hardware drawn from this evaluation, their ability to accommodate the requirements of ATMS can also be inferred.

Accommodating Advanced Control Systems

In the evaluation of existing traffic controllers to accommodate advanced control systems, four criteria were used: 1) method of interconnection; 2) communications capabilities; 3) controller flexibility in a variety of control applications; and 4) cost of supplemental hardware, if available, to enhance controller capabilities. Each type of controller (electromechanical, solid-state, NEMA, and Type 170) was subjectively evaluated with the four criteria using a scoring system defined by Table 1. The scores from the evaluation of the four criteria for each controller were then summed, and shown in Table 2.

Table 1. Scoring System For Controller Evaluation.

<table>
<thead>
<tr>
<th>Evaluation</th>
<th>Equivalent Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poor</td>
<td>0</td>
</tr>
<tr>
<td>Fair</td>
<td>0.5</td>
</tr>
<tr>
<td>Good</td>
<td>1</td>
</tr>
</tbody>
</table>

Advantages/Disadvantages of Pretimed Controllers

Through the test of time, pretimed controllers have proven to be a reliable method of traffic control. However, the demands of advanced control systems simply cannot be accommodated by the outdated technology of pretimed controllers. With pretimed controllers, interconnection and communication is limited to hard-wiring, where a single master controller sends coordination pulses to different controllers (9). Selection of optimal timing plans are limited to pre-programmed time-of-day and day-of-week plans.
Table 2. Results of Evaluation of Existing Controllers in Accommodating Advanced Control Systems.

<table>
<thead>
<tr>
<th>Control System</th>
<th>Electro-mechanical</th>
<th>Solid-State</th>
<th>NEMA</th>
<th>Type 170</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arterial Control System</td>
<td>1.0</td>
<td>1.5</td>
<td>4.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Integrated Control System</td>
<td>0.5</td>
<td>0.5</td>
<td>2.0</td>
<td>3.0</td>
</tr>
<tr>
<td>“First Generation” Control Systems</td>
<td>0.5</td>
<td>0.5</td>
<td>2.0</td>
<td>2.5</td>
</tr>
<tr>
<td>“1.5 Generation” Control Systems</td>
<td>0.0</td>
<td>0.0</td>
<td>1.5</td>
<td>2.0</td>
</tr>
<tr>
<td>On-Line Control Systems</td>
<td>0.0</td>
<td>0.0</td>
<td>1.0</td>
<td>1.5</td>
</tr>
</tbody>
</table>

While additional hardware can be installed to improve the responsiveness of pretimed controllers to fluctuations in traffic conditions, such systems are often limited by the number of detectors that can be used, the number of intersections that can be coordinated, and the absence of communication between all of the controllers in the system. The application of such systems are also generally limited to arterial control.

Advantages/Disadvantages of NEMA Controllers

Several NEMA manufacturers feature controllers that adequately address the interconnection and communications requirements of some advanced control systems. Some manufacturers feature complete “closed loop” systems that are used to fully coordinate arterials, while providing the system monitoring capabilities of central control systems. Other advantages of NEMA controllers include tested vendor software as well as generally reduced costs for basic signal control systems.

As previously stated, the NEMA TS1 standard is intended to promote interchangeability between controllers of different manufacturers. Such compatibility is maintained if the software configuration is disregarded and the unit is controlling an isolated intersection. However, the TS1 standard does not adequately address features such as system coordination, time-based control, preemption, uniform code flash, communications, or diagnostics (10). While manufacturers have integrated these features into their controllers, they have done so using an undefined fourth connector (“D” connector) in addition to the three defined by the specifications. The pin-out (functions of each pin) of the “D” connector varies between manufacturers and may also vary with the same manufacturer, depending on the specific controller application (11).

The result of such nonuniformity is that any traffic control system requiring more advanced features must utilize controllers from a single vendor. The absence of standardization also requires that users and maintenance personnel must be trained for each specific system. NEMA controllers are also designed to control signalized intersections, which limits its flexibility to perform other control applications such as ramp metering. Such limitations of the NEMA controller become readily
apparent as the type of control system extends beyond the sophistication of arterial control. As the sophistication of the control system increases, the more likely the control system is to expand to coordination with control systems under the jurisdiction of other agencies. Therefore, the application of the NEMA controller to advanced control systems can be successful, in terms of interconnection, only if all agencies are using hardware from the same vendor. A successful implementation of these advanced control systems is also dependent on the available hardware and software capabilities of the controller, or the features of supplemental hardware, which are also limited by the products available from the vendor. If such equipment or features are available, they would likely be purchased at high costs because manufacturers would literally place a monopoly on the system’s success.

The NEMA TS2 standard, published in 1992, addresses the need for new traffic control capabilities (11). This system utilizes serial I/O architecture to provide modularity and expandability for load switches and detectors. More modern microprocessors support higher communication baud rates. However, the proprietary limitations of the NEMA controller continue to exist with the TS2 standard. The inflexibility of the NEMA controller to adapt to special applications, such as ramp metering, also limits its ability to integrate into a network control system.

Advantages/Disadvantages of Type 170 Controllers

Unlike the NEMA controller, the Type 170 controller provides interchangeability and flexibility through the specification of hardware. Designed as a traffic control microcomputer, the Type 170 controller has been used in a wide variety of applications including signalized intersection control, ramp metering, and sprinkler control.

However, the limitations of the Type 170 controller are the result of outdated technology. In a study conducted by Caltrans in 1989 to determine the current and future requirements of traffic control equipment in accommodating ATMS applications, several key deficiencies of the Type 170 controller were identified (5). The results of the survey are summarized in Table 3. Many of the deficiencies listed in Table 3 are the result of the eight bit microprocessor’s (Motorola 6800) speed

### Table 3. Type 170 Controller Deficiencies Identified by Caltrans Survey (5).

<table>
<thead>
<tr>
<th>• Communications</th>
<th>• Display</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Input / Output</td>
<td>• Keypad</td>
</tr>
<tr>
<td>• Software Development Tools</td>
<td>• Multi-tasking Capability</td>
</tr>
<tr>
<td>• No Standard Bus</td>
<td>• Quality Control</td>
</tr>
<tr>
<td>• No Operating System</td>
<td>• Noise Filtering</td>
</tr>
<tr>
<td>• Low-level Programming Language</td>
<td>• Availability</td>
</tr>
<tr>
<td>• Memory Size</td>
<td>• Interrupt System</td>
</tr>
</tbody>
</table>
and inability to perform multi-tasking. Multi-tasking is the utilization of microprocessor time (perhaps 20 milliseconds) by different application programs (12). The short durations of microprocessor utilization create the illusion that programs are running concurrently. The limitations of the microprocessor ultimately limit the communications and I/O capabilities of the controller, making evolving specifications like the National Traffic Control / ITS Communication Protocol (NTCIP) beyond its capabilities (11).

Software limitations of the Type 170 controller are associated with the absence of any standard operating system (10). An operating system is a body of software that provides functions to application software to allocate and manage the hardware resources of the controller. The absence of a standard operating system results in application software written in low-level programming languages that must be compiled using cross compilers. While the software for Type 170 controllers is capable, it is difficult to configure. Therefore, minor changes to software for site-specific applications are often ignored, causing less efficient operation because changes can be too difficult or expensive to implement and maintain.

The application of the Type 170 controller to advanced traffic control systems is limited by the hardware and software deficiencies described above. While the Type 170 controller is sufficiently flexible to perform a variety of applications, like the NEMA controller, implementation for increasingly sophisticated traffic control systems would require supplemental hardware. While the availability of supplemental hardware, due to the absence of proprietary features on the controller, is likely to be improved, a degree of liability of hardware and software is shifted from the proprietor to the public agency.

Accommodating ATMS

Successful implementation of ATMS requires the integration of sophisticated electronics and communications networks into the transportation system. As these technologies are utilized, the functions of traffic controllers can extend beyond their traditional role of intersection signal control to a broad range of applications. Some of the functions envisioned for ATCs are listed in Table 4 (13). Using the same criteria and scoring system described in previous sections, the ability of existing hardware to perform such applications was also evaluated. The results of that evaluation are also shown in Table 4.

The limitations of existing controllers in accommodating the hardware requirements of traffic control systems currently in use become even more apparent when applied to developing ATMS technologies. Existing controllers were never designed with adequate computing power or communications capabilities to handle the requirements of such high-end applications. Only the Type 170 controller has the flexibility to perform a limited number of these applications, but only with supplementary hardware and with limited results. Aside from the availability and liability issues of supplementary hardware discussed in earlier sections, other issues such as hardware reliability, expertise of personnel, and the absence of controller standardization further discourage the use of existing hardware in ATMS.
Table 4. Results of Evaluation of Existing Controllers in Accommodating Envisioned Functions of ATCs.

<table>
<thead>
<tr>
<th>Envisioned ATC Function (13)</th>
<th>Type of Controller</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Electro-mechanical</td>
</tr>
<tr>
<td>Freeway surveillance and control</td>
<td>0.0</td>
</tr>
<tr>
<td>Weigh-in motion</td>
<td>0.0</td>
</tr>
<tr>
<td>Variable message signs</td>
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<tr>
<td>Adaptive signal system control</td>
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<tr>
<td>Incident management</td>
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<tr>
<td>Highway advisory radio</td>
<td>0.0</td>
</tr>
<tr>
<td>Emergency response systems</td>
<td>0.0</td>
</tr>
<tr>
<td>Pavement moisture sensing</td>
<td>0.0</td>
</tr>
<tr>
<td>Irrigation monitoring</td>
<td>0.0</td>
</tr>
<tr>
<td>Automatic vehicle identification</td>
<td>0.0</td>
</tr>
<tr>
<td>Air pollution monitoring</td>
<td>0.0</td>
</tr>
<tr>
<td>Noise monitoring</td>
<td>0.0</td>
</tr>
<tr>
<td>Traffic flow monitoring</td>
<td>0.0</td>
</tr>
<tr>
<td>In-vehicle signing</td>
<td>0.0</td>
</tr>
<tr>
<td>Dynamic route guidance</td>
<td>0.0</td>
</tr>
<tr>
<td>Inter-agency coordination</td>
<td>0.0</td>
</tr>
<tr>
<td>Electronic toll and traffic management</td>
<td>0.0</td>
</tr>
<tr>
<td>Storm water monitoring</td>
<td>0.0</td>
</tr>
<tr>
<td>Water consumption monitoring</td>
<td>0.0</td>
</tr>
<tr>
<td>Bicycle/pedestrian MAYDAY system</td>
<td>0.0</td>
</tr>
</tbody>
</table>
CALTRANS TYPE 2070 CONTROLLER

The Type 2070 controller is intended to satisfy the needs of high end applications such as advanced traffic management systems, where greater performance or flexibility in terms of communications interfaces and protocols are required (14). Because the controller is intended for high end applications, the Type 2070 serves to supplement, rather than replace, the Type 170. Therefore, the Type 2070 must maintain physical and electrical compatibility with the existing Type 170 cabinet systems. The unit must fit within the standard rack space occupied by the Type 170, power and communication connections must be compatible, and as a minimum, satisfy the environmental and electrical interface specifications of the Type 170.

Recognizing the future requirements of traffic management systems, the Type 2070 controller is designed to be flexible. However, a controller designed to satisfy all possible applications would not likely be cost-effective (5). For example, it would be costly to design features to be included in all controllers, but only utilized in a small number of applications. Therefore, the purpose of the Type 2070 controller is to facilitate 90 percent of likely applications.

System Architecture (14)

The system architecture of the Type 2070 controller is intended to be modular to maximize interchangeability of modules between manufacturers, and thus promote competitive bidding. Modular system architecture maximizes the serviceability of the unit and reduces spare module inventories. The system architecture, shown in Figures 4 and 5, features six basic modules in the controller architecture: 1) central processing unit (CPU); 2) field input/output module; 3) system communications module; 4) power supply module; 5) front panel module; and 6) chassis and backplane; all of which are discussed in the following sections.

Central Processing Unit (CPU)

The central processing unit (CPU) of the Type 2070 controller, shown in Figure 6, is intended to be a fully specified, 3U VMEbus (VMEbus will be discussed in later sections) single board computer that provides the main processing capabilities of the controller, execute application programs, and carry out communication and control of other the other modules. All of the controller modules connect to the CPU. The front panel, field input/output, and system communications modules interface with the CPU through a minimum of seven serial connections. Serial connections between modules provide for simplified interfaces while reducing costs, isolation of functionality for modularization, and simplified hardware and qualification tests.

The microprocessor for the CPU is selected from the Motorola 68000 family of processors. The compatibility of the 68000 family with the 6800 family (used in Type 170 controllers) ensures that existing software programs can be utilized. Another factor on the selection of the 68000 processors included the multi-vendor availability of CPU and support chips. Rather than specifying
Figure 4. Proposed Type 2070 System Architecture (14).
Figure 5. Type 2070 Inter-Module Interface Diagram (14).
Figure 6. Central Processing Unit Architecture (14).
the processor chip, a Motorola CPU32 instruction set capable of operating at a minimum clock rate of 16 MHZ was specified. By specifying only the instruction set, all future hardware designs can use the most advantageous chip (of the 68000 family) for the specific application.

Field I/O Module

The field I/O module consists of a Motorola 68HC11 processor, and includes all software (programmed in EEPROM) and hardware to provide a separate subassembly that performs all interconnection functions between external field equipment and control cabinet equipment. This module also contains all the hardware necessary for physical and electrical compatibility with the Type 170 I/O module, including the 44 inputs and 56 outputs of the TSCES (Traffic System Controller Equipment Specification) C1 connector used in the Type 170. Functional enhancements include an additional connector capable of up to 64 inputs and outputs.

System Communications Module

The system communications module consists of a 3U VMEbus card that contains all the necessary hardware and communications software to interface with remote higher level control systems, lower level controllers, or controlled external field equipment. Four external communication ports will be available on two separate slots. One of the ports will have the functionality and compatibility of a TSCES Model 400 modem, currently used in the Type 170 controller. The other three ports will link through an auxiliary communication module to extended backplane ports to make standard interfaces available beyond the chassis.

Front Panel Module

The front panel module, shown in Figure 7, features: 1) an industrial standard, backlit liquid crystal display capable of displaying four lines of forty characters each; 2) a numeric and separate cursor control keypad; and 3) a serial interface to facilitate connection with an external computer. The front panel module improves the user friendliness of the Type 2070 controller. Rather than specifying precise architecture, only functional and mechanical standards are specified to allow manufacturers to develop the module in the most effective manner.

Power Supply Module

The power supply module provides all of the Type 2070 controller’s electrical power requirements by converting AC power to DC voltages. Filtering and voltage requirements assure safe and reliable operation of controller modules. This module is a replaceable plug-in unit for ease of maintenance.
Figure 7. Front Panel Module (14).
The term VME stands for Versa Module Eurocard and refers to an open computer architecture developed by Motorola, Mostek, and Signetics corporations. VMEbus refers to a standardized platform from which data is transferred along specified paths. VMEbus modules are cards conforming to a mechanical standard based on the Eurocard format. There are two VMEbus module sizes: single and double height modules (sometimes referred to as 3U and 6U boards respectively). The single height board (shown in Figure 8) can generate or accept up to 24-bit addresses and 16-bit data transfers while a double height board (shown in Figure 9) can perform up to 64-bit address or transfers.

VMEbus modules are interconnected by a backplane (shown in Figure 10), which can support between two and twenty-one bus modules. The type of backplane limits the type of VMEbus modules that can be used. The type of backplane and the number of modules that can be interconnected is limited by the size of the chassis.

As previously stated, all of the Type 2070 controller modules connect to the CPU, which consists of one 3U VMEbus module. The chassis of the Type 2070 controller must fit into the standard rack space occupied by the Type 170. This constraint limits the size of the backplane to providing four 3U VME slots, one of which is utilized by the CPU (14). The remaining three slots facilitate the expansion of the Type 2070 controller to perform future traffic management strategies with provision of additional VMEbus modules.

**Advantages of Type 2070 Controller**

Aside from the flexibility, downward compatibility, and improved computing power of the Type 2070 controller, there are other advantages that make its design advantageous to ATMS applications. These advantages are discussed in the following subsections.

**VMEbus (15)**

The use of VME open architecture standards provides the Type 2070 controller with the flexibility to enhance its capabilities to perform future ATMS control strategies through the use of additional VMEbus modules. VMEbus can accommodate real-time applications in its ability to transfer data using a master-slave architecture. VMEbus modules called masters transfer data to modules called slaves. Because many modules can reside on the bus it is called a multi-processing bus. Before a master transfers data, it must first acquire the bus using a central arbiter, which determines which masters receives access to the bus. All bus activity takes place on four subbusses shown in Figure 11. VMEbus is asynchronous, which means that no clocks are used to coordinate data transfers. Data is passed between modules using interlocked handshaking signals. The result is a high data transfer rate, an essential element in real-time applications where the traffic controller must coordinate between concurrently running strategies and respond nearly instantaneously to conditions on the transportation network.
Figure 8. Single Height 3U VMEbus Module (16).
Photo courtesy of Matrix Corporation

Figure 9. Double Height 6U VMEbus Module (16).
Photo courtesy of Matrix Corporation

Figure 10. Sub-rack with 20 Slot Combination J1/J2 Backplane (16).
Photo courtesy of Matrix Corporation
Figure 11. VMEbus Functional Block Diagram (15).
Compliance With Industry Standards

Unlike the use of customized hardware in traffic controllers, the use of VME takes the advantage of existing electronics industry standards. The use of standardized equipment ensures orderly hardware and software changes using reliable devices that have been lab or field-hardened (5). The devices used would also comply with industry accepted communications protocols, which becomes more important as the variety of hardware to be integrated with ATMS increases. Another advantage of using VME is that no proprietary rights are assigned to the architecture, which allows independent vendors to build compatible products without royalty fees or licensing. As such, a large number of vendors exist who can competitively bid to supply hardware, thus reducing start-up and maintenance costs.

Software Development Tools

An operating system is a body of software that provides functions to application software to allocate and manage the hardware resources of the controller. Because the Type 2070 controller is designed for use in real-time applications, the software needed must be supported by a run-time environment that is oriented to such applications (12). If a standard operating system is specified, it is possible to share software between different projects and applications, provided that the software is sufficiently robust. Based on the familiarity of Caltrans personnel, the OS-9 real-time operating system is specified (1). OS-9 provides multi-tasking and the capabilities of being configured for specific hardware designs, such as I/O drivers, network file systems, and communications packages.

The capabilities of the Type 2070 controller are bound by the limitations of its hardware and the imagination of the user to develop application software for ATMS. To encourage the development of improved application software, and thus the advancement of ATMS, the high-level C programming language is specified. The popularity and familiarity of this programming language encourages third-party software development and allows easier customization of software by the user.

User Friendliness

The modular design of the Type 2070 controller promotes the ease of maintenance. Rather than replacing an entire controller or a group of components, a single module could simply be disconnected and replaced. The modular design also facilitates better system diagnostics. Other elements of user friendliness include the improved display and keypad, which allows the technician or engineer to better set or monitor controller operation.

Disadvantages of Type 2070 Controller

The advantages of the Type 2070 controller promote the development of ATMS. However, there are also disadvantages that must be considered before field implementation. These disadvantages are discussed in the following subsections.
Hardware and Software Costs

The cost of the Type 2070 controller can potentially place a barrier to its implementation. Estimated costs for a basic Type 2070 controller range from $3,500 to $5,000 each (13). A standard eight phase NEMA controller costs $2,000 to $2,500 each. Software development costs could also be high. However, it should be noted that the issues of hardware and software costs become unclear when the capabilities of the controller are considered. While the initial cost of the controller may be higher, the absence of supplementary hardware could potentially offset this difference. The development of robust application software could reduce the costs of developing customized software for one of a kind applications.

Cost-Effectiveness

The implementation of ATMS requires the use of more advanced control hardware such as the Type 2070 controller. However, the integration of control systems may require the installation of the Type 2070 controller at various locations where more advanced control systems are not required. Such implementation would reduce the cost-effectiveness of ATMS. Unfortunately, the benefits yielded from ATMS and the costs of implementation cannot be accurately determined, making an evaluation of the cost-effectiveness of the Type 2070 controller uncertain.

User Familiarity

The integration of new hardware into existing control systems places demands on manufacturers, engineers, and technicians to become familiar with the new technology. A lack of user familiarity introduces the costs of personnel retraining—costs that must be considered in the implementation of ATMS. As personnel become more familiar with the Type 2070 controller, improved technologies can be integrated to the hardware. However, until such familiarity is achieved, it is unlikely that ATMS achieve its full potential.
CONCLUSION

Advanced Traffic Management Systems place heavy demands on hardware to supply large amounts of data and communicate information in an expedient manner. However, it is clear that the limitations of existing traffic controller equipment can potentially halt the implementation of such systems. While existing equipment can be upgraded to accommodate specific applications, this measure does not facilitate standardization nor provides a cost effective solution. The development of a standardized advanced traffic controller is critical the implementation of ATMS at minimal costs.

It is difficult to assess the ability of the Type 2070 controller in accommodating ATMS applications. The full capabilities of the controller and the requirements of ATMS are uncertain. However, what this study has identified is that the flexibility of the architecture and careful planning of the controller specifications can result in hardware that satisfies such high-end application requirements. However, until the controllers conforming to the yet-to-be-finalized Type 2070 specifications are in the field and the requirements of ATMS are better defined, it is not possible to determine if ATMS can become a reality.
RECOMMENDATIONS

A. The specification of hardware must account for functional requirements of a wider range of ATMS technologies.

The envisioned applications of ATCs listed in Table 4 that apply to traffic management and control are designed to vary control strategies based on changing demands in traffic or communicate information to vehicle operators. While these goals can improve the efficiency of the transportation network, they do take full advantage of available ATMS technologies in optimizing the use of transportation facilities because the human element of traffic operations is not eliminated. For example, the reaction and information processing rates of vehicle operators place lower limits on the number of vehicles that can operate on a facility. Another example of how human limitations reduce system efficiency is the start-up and clearance lost times experienced at signalized intersections. A more efficient transportation network would utilize the technologies of ATMS, such as automatic vehicle guidance, to eliminate the elements of human interaction. ATMS technologies can also be used to improve the effectiveness of Transportation Demand Management (TDM) strategies such as congestion pricing.

The integration of these technologies will ultimately place demands on hardware for improved information processing and communications. Therefore, the specification of hardware should be such to better accommodate these demands. One of the functional requirements of the Type 2070 controller is to maintain compatibility with the Type 170 controller. However, an evaluation of the hardware specifications (such as the size of the chassis, type of backplane, and type of module) should be made to determine their effectiveness at accommodating all proposed ATMS technologies. Such an analysis would determine whether it is more cost effective to remain compatible with existing technologies, or to require vastly improved hardware that can accommodate a broader range of applications that may be more cost effective in the long-run.

B. Jurisdiction issues must be resolved before the implementation of Type 2070 controllers in multi-jurisdiction applications.

The open architecture of the Type 2070 controller provides the ability of single unit in managing traffic at multiple locations (for example: freeway ramps, interchanges, and local streets). The extension of control to multiple locations under different jurisdictions raises maintenance, funding, and liability issues that must be resolved before implementation.
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REFERENCES


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# APPENDIX A

## Input-Output Connector Pin Terminations for NEMA Controller

### A, B, and C Connectors (3)

<table>
<thead>
<tr>
<th>PIN</th>
<th>Function</th>
<th>PIN</th>
<th>Function</th>
<th>PIN</th>
<th>Function</th>
<th>PIN</th>
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<td>A</td>
<td>RESERVED</td>
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<td>A</td>
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<td>A</td>
<td>CODED STATUS BIT A (2)*</td>
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<td></td>
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<tr>
<td>B</td>
<td>+ 24 VOLT DC EXTERNAL</td>
<td>B</td>
<td>SPARE 1</td>
<td>B</td>
<td>SPARE 1</td>
<td>B</td>
<td>CODED STATUS BIT B (2)*</td>
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<td>VOLTAGE MONITOR</td>
<td>C</td>
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<td>C</td>
<td>02 PHASE NEXT</td>
<td>C</td>
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<td>D</td>
<td>02 GREEN DRIVER</td>
<td>D</td>
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<td>D</td>
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</tr>
<tr>
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<td>E</td>
<td>03 YELLOW DRIVER</td>
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</tr>
<tr>
<td>F</td>
<td>01 RED DRIVER</td>
<td>F</td>
<td>04 RED DRIVER</td>
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<td>F</td>
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<td>02 DON'T WALK DRIVER</td>
<td>G</td>
<td>04 CLEAR DRIVER</td>
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<td>04 CLEAR DRIVER</td>
<td>G</td>
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<td>H</td>
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<td>J</td>
<td>04 CHECK</td>
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<td>05 PED CALL DET</td>
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<td>05 PED CALL DET</td>
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<tr>
<td>N</td>
<td>STOP TIMING (1)*</td>
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* Numbers in parentheses ( ) refer to Ring Number (1) or (2).