Adaptive Traffic Signal System for Cupertino California

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ABSTRACT

The City of Cupertino, in California, operates a Naztec Streetwise advanced traffic management system (ATMS) for the arterials within the city. These arterials provide important connections to several freeways and major employment centers in Silicon Valley. The traffic patterns vary during the peaks, accommodating long distance commuters destined elsewhere in the Bay Area, commuters to local generators, and local colleges and schools. A new module is being developed to provide full adaptive traffic signal control system for the Streetwise ATMS, and a demonstration project will encompass several of the key arterials.

The objectives of the project are to: build on the existing ATMS and infrastructure as far as possible; provide a fully adaptive system capable of running totally unattended; provide facilities for operators to modify or override the adaptive system at any time; and provide the ability to accommodate both normal arterial traffic patterns and adjacent ramp metering impacts.

This paper will summarize the concept of operations, including the control philosophy and an overview of the algorithms, and the physical design modifications required to install the adaptive system. The paper will also report on the current status of development and testing.

INTRODUCTION

The City of Cupertino installed the Naztec Streetwise ATMS in 2000. A new control center was established in City Hall and all the City's signals are connected to the central system. In its basic form, the Streetwise ATMS uses fixed cycle length plans, selected by time of day (TOD).

Since this initial installation, the City funded development of a Generation 1.5 module, called "Optima", which allows for off-line optimization of the stored TOD plans. This current project involves the development of a fully adaptive traffic signal system control module for StreetWise ATMS.

Cupertino is typical of many US cities in having major intersecting arterials arranged generally on a grid system, with several freeways crossing these arterials. The signals on the arterials and the local streets are under the operation and maintenance of the City. However, the signals at the ramp intersections are under the jurisdictions of the Caltrans (California Department of Transportation). In the case of Cupertino, the City operates the controllers at the ramp intersections, but the timing is subject to the continued approval of Caltrans, which maintains the right to resume control at their discretion.

Background

During Spring 2000, the City installed and commissioned a new Traffic Operations Center (TOC) at City Hall and the Naztec Streetwise ATMS central control signal system. Since then, a new Generation 1.5 module ("Optima") has been developed and installed. This module allows off-line generation of new timing plans, based on updated traffic volume data collected by the local and system detectors. This improves the efficiency of the process used to update timing plans to account for changes in traffic patterns. It retains the traditional selection of stored coordination plans by TOD. The adaptive system will automatically generate signal-timing plans that are adapted to the current traffic conditions, in real time.

The development of an adaptive module is the logical next step after "Optima". It will provide for real-time signal timing plan preparation, in response to current traffic conditions.

An associated project, the Cupertino Ramp Meter Arterial Systems Interconnect Project, which is under separate development, will provide coordination of ramp metering on Caltrans ramps with the City's arterials signal system. This will run in parallel with the adaptive system, ensuring that both systems are initially compatible and eventually integrated into the one module.

Objectives of the Project

The purpose of this project is to design and implement an adaptive traffic control system that is fully integrated with the City's new ATMS operating the Streetwise ATMS software.

The objectives adopted for the adaptive system development are:

- Provide a module to calculate or select appropriate cycle length, phase split and offset for each coordinated intersection;
- Build on the existing Naztec StreetWise ATMS;
- Maintain consistency with the emerging National Transportation Communications ITS Protocol (NTCIP) standards for System Masters;
- Minimize the need for additional detection equipment;
- Avoid the need to install additional conduits, especially at intersections;
- Provide sufficient automation and self-calibration features so that staff will become more efficient, and not have an increased workload.
- Provide facilities for operators to modify or override the adaptive system at any time; and
- Provide the ability to accommodate both normal arterial traffic patterns and adjacent ramp metering impacts.

EXISTING ADAPTIVE SYSTEMS

Overview

A review was conducted of the existing adaptive traffic systems available with two aims:

- Determine the adaptive approach that best suits the needs of the City of Cupertino; and
- Determine whether any of the existing systems could be added to the existing Naztec's Streetwise ATMS.

The adaptive systems reviewed are:

- SPOT / UTOPIA – Urban Traffic Optimization by Integrated Automation
- OPAC – Optimization Policies for Adaptive Control
- RHODES – Real-Time Hierarchical Optimized Distributed and Effective System
- SCOOT – Split Cycle and Offset Optimization Tool
- SCATS – Sydney Coordinated Adaptive Traffic System
- ATCS - Adaptive Traffic Control System
- MOTION - Method for the Optimization of Traffic Signals in On-line controlled Networks
- ITACA (from Spain)

- RTACL (from University of Maryland)

All of these adaptive systems are operational and either deployed or being deployed at this time. Most, if not all, of these adaptive systems require a large infrastructure of detectors. Furthermore, adaptive systems based on peer-to-peer communication (e.g. RHODES) need a large communication infrastructure as well. Installation of such adaptive systems may cost up to $50,000 per intersection. Thus, financial and other constraints prevent most cities from investing in such adaptive systems.

Recognizing this fact, the Federal Highway Administration (FHWA) has recently funded a project to develop a scaled-down version of adaptive control to be known as ACS-Lite. ACS-Lite architecture calls for an adaptive system component that will use the emerging NTCIP objects for System Masters to provide the capability of updating timing plans every 15 minutes. Thus, ACS-Lite will allow retrofitting existing closed-loop systems. The first system prototype, scheduled for completion in 2003, will provide for cycle, split, and offset adjustments in real time. The second stage of this project will be coordination with National Electrical Manufacturers Association (NEMA) vendors to develop an implementable adaptive system.

Furthermore, there are several other adaptive algorithms that have been postulated for either stand-alone systems or as enhancements to other systems. Some were developed as part of FHWA’s RT-TRACS initiative. Examples include REALBAND, GASCAP, CARS, and ADAPT. Some have been tested in a simulation environment, but none have been built into an operational system. Although such algorithms may become available as workable adaptive systems in the future, they are not considered viable options for this project.

Existing Adaptive Split Operation

Streetwise ATMS has an element of adaptive control at the local controller level. Critical Intersection Control (CIC), currently implemented within the TS/2 traffic signal controller and first implemented in 1993 within the framework of NEMA’s TS/1 specification, provides an adaptive split feature selectable on a pattern-by-pattern basis. This feature manages the “slack time” by dynamically modifying the split times based on actuated operation.

Actuated phases that gap-out during coordination return “slack time” to the end of the coordinated phase. Actuated phases that max-out during coordination may also utilize the available “slack time” as needed. The controller performs cycle-by-cycle adjustments to the split values assigned to the active pattern. This feature is fully described in the Naztec StreetWise ATMS controller manual (Chapter 13 - Advanced Coordination). However, this feature becomes less sensitive as an intersection approaches saturation, and will be improved by the adaptive operation described below.

Analysis

None of the existing adaptive systems will successfully operate on the City’s existing field equipment. Most of these systems require either proprietary equipment or external interface and processing units. All would require central and local controller software to replace the existing Naztec central and local controller software. The operating concepts and selected features of several existing adaptive systems could be implemented within the software structure and system architecture of the StreetWise ATMS.

While the operational philosophies of the systems sponsored by FHWA are still experimental and are essentially unproven, several of the proprietary systems have been operating in excess of 20 years. They have operating philosophies that appear well suited to Cupertino's traffic conditions and arterials network.

The strength of the SCATS system is its method of calculating cycle length and phase splits based on measured degrees of saturation at the stop line in each critical lane. The SCOOT system uses system detectors to provide volume inputs to a model derived from TRANSYT, the most respected off-line signal timing analysis program for networks. The Los Angeles Department of Transportation (LADOT) adaptive system has features with strong similarities to the SCATS system. All three adaptive systems have been subjected to rigorous evaluation of their effectiveness. Both SCATS and SCOOT have been successfully implemented in both small and large cities in Europe, Asia and Australia.

Evaluation

The adaptive philosophy of SCATS is well-suited to the traffic conditions and road geometry of Cupertino, and is well-proven in a variety of circumstances. The phase split control has some similarities to the existing CIC features in the Naztec Streetwise ATMS. However, the NTCIP standards (1202 – Actuated Signal Control; 1210 – Field Management Stations; and 1211 – Control Groups) provide data constraints within which the adaptive system should be implemented. This will therefore form the basis of the Naztec adaptive control module.

PROPOSED ADAPTIVE OPERATION

Based on Existing Infrastructure

The proposed adaptive system will rely initially on the existing communications infrastructure in Cupertino. No additional communications equipment will be required. Existing communications protocols will be maintained, although some modifications will be made to accommodate the latest NTCIP standards.

In Cupertino, local controllers communicate directly with the central computer, and this arrangement will be maintained. In other StreetWise ATMS systems, field masters are employed to distribute some of the processing/communication functions. The system design accommodates this additional level.

The existing communications infrastructure places limitations on the amount of data that can be transmitted each second between the central master and the local controllers. In addition, the more processing that is undertaken at the central location the greater the impact of a communications failure. It is therefore desirable that as much of the second-by-second processing as possible take place in the local controllers.

No additional hardware modules will be required at either the local controllers or the central computer, other than additional detector sensor units on the arterials. The communications load will be managed to accommodate the bandwidth of the existing system. It is also recognized that full detection will not be available at all intersections.

Control Concepts

The proposed system has two control levels; strategic, and tactical. The *Strategic Level* establishes limits on the operation of control at each intersection. The *Tactical Level* control resides at the controller, and provides for cycle-by-cycle adjustments within limits set by the *Strategic Level*. These concepts are illustrated in Figure 1. Combined, both control levels will provide three main elements:

- Cycle length calculations for each critical intersection;
- Phase split calculation for each intersection; and
- Determination of offsets between adjacent intersections.

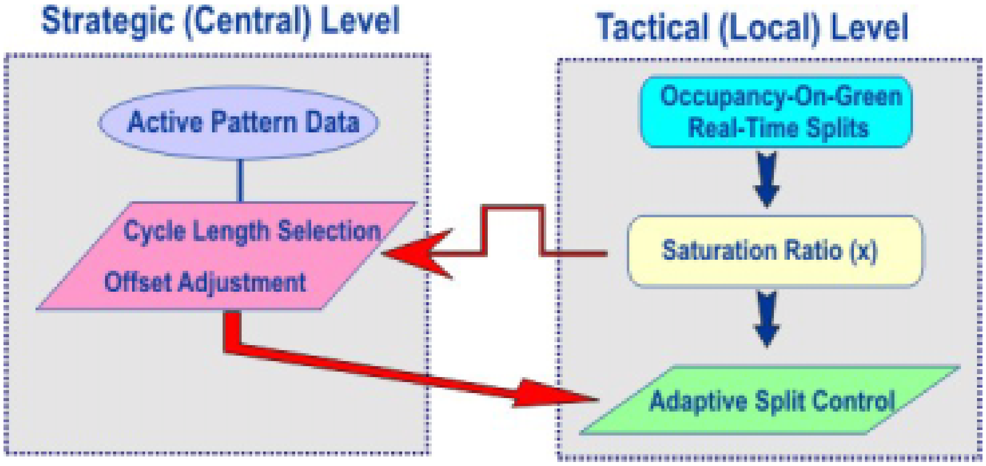

Figure 1 Strategic and Tactical Levels of Control.

By design, the Cupertino arterials network to be coordinated will be subdivided into small groups, and each group will have a maximum of one critical intersection. A group may be any number of intersections, but will always be composed of at least one intersection. One key function of the *Strategic Control* is to decide when to join two or more groups into one coordinated systems. The desired cycle lengths for individual groups will be used for this purpose. When two groups require similar cycle lengths, they could be joined to form one coordinated system for the next control period.

The desirable cycle length will be calculated for the critical intersection in a group. This will occur through a look-up table based on the minimum delay cycle length calculations by the local controllers. The phase split will then be calculated for the critical intersection. This will be done by the local controllers to achieve equal degrees of saturation (where detection is available) or look-up tables in the case of minor intersections with limited detection. For non-critical intersections within the group, the phase split will generally be determined by the minimum phase length requirements of the non-coordinated phases.

The other main function of the *Strategic Level* control is to select a common cycle length, matching phase sequence, and offsets for various groups and to pass these control constraints to individual controllers.

The controller will have the ability to fine tune splits and offsets on a cycle-by-cycle basis, and to determine desired cycle lengths. Controller software will be revised to provide this functionality. These concepts are described in the next section.

Detection Approach

Degree of Saturation

The key parameter for use in cycle length selection and phase split determination is degree of saturation (X value). This will be measured directly at the stop line by loop detectors. Two algorithms will be used to calculate X: one when individual lane detection is available, and one for situations in which one loop covers multiple lanes.

The ideal situation is to have individual loops in each lane of an approach at the stop line. In this case, the X value will be calculated as:

$$X = [green - (unused\_green)] \div (available\_green)$$

This will accurately calculate the ratio of efficiently used green to available phase green. The unused green is the space time greater than or less than the saturation space time. Thus unused green will be zero at saturation flow, positive if the movement is unsaturated, and negative if it is oversaturated.

When a loop covers more than one lane, the degree of saturation can be estimated by measuring the time at the end of green after the initial queue has discharged. This is detected by sensing the gap time, and finding the point when the gap time exceeds the saturation space time. In this case, the calculation is:

$$X \approx [g_s \div (r_p + g_s)] \times (c / g)$$

Where:

$g_s =$ length of green at saturation flow

$r_p =$ length of red during which queue is growing

$c =$ cycle length

$g =$ length of green for the phase

For some calculations, such as direction of offset, volume is required, rather than degree of saturation. Two approaches will be available for determining movement volume: direct measurement or estimation from degree of saturation.

Direct measurement will be available by using detectors that output both presence and actual count. This will provide the most accurate counts. However, a very good estimate of volume can be derived from the measured degree of saturation and lane saturation flow, using:

$$Vol = X \times greentime \times \text{ (}\textit{vehicles per second at saturation flow}\text{)}$$

Detection Zone

In order to measure degree of saturation, loops at the stop line will need to be sized to provide a monotonic relationship between time space and speed. This will require a loop array 16 feet long. The derivation of this as the appropriate length for this purpose is well documented, and summarized below.

In simple terms, the time space between vehicles is relatively independent of the size of following vehicles, but directly related to the speed of a vehicle. Within the range of non-congested speeds encountered at traffic signals, a loop array of 16 feet length will give a reasonable estimate of the speed of traffic, and an accurate count. It therefore provides the raw data for the degree of saturation and volume calculations. The relationships are illustrated in Figure 2.

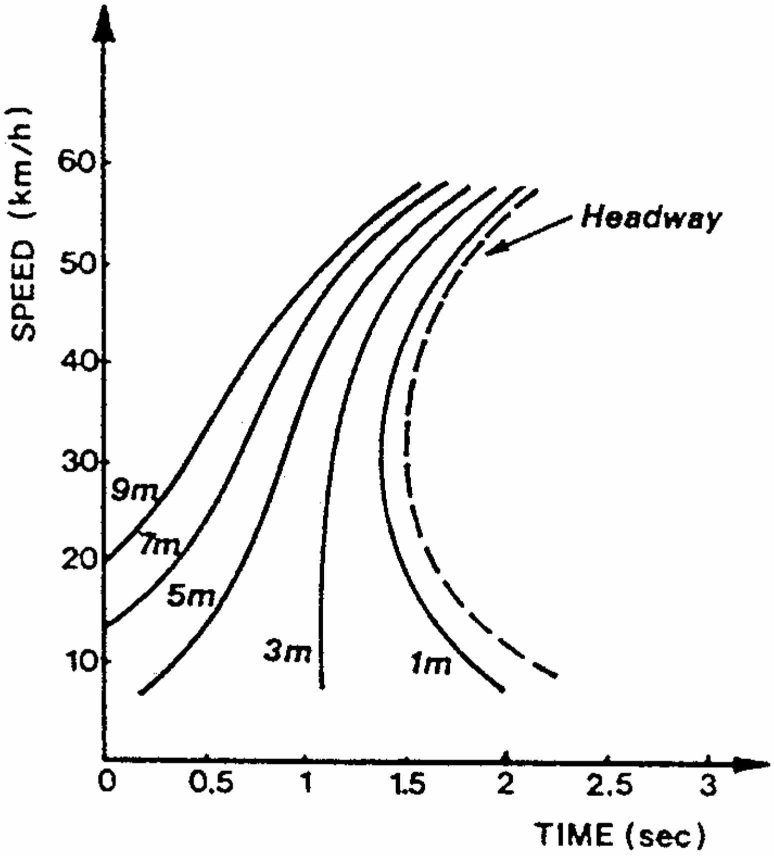

Figure 2 Basic Detection Relationships

This relationship is well document in Sims and Dobinson (1979) and Fehon and Moore (1982).

Cycle Length Selection

The relationship between critical cycle length and minimum delay cycle length during actuated and pre-timed control is shown in Figure 3. The *Critical Cycle Length* is typically 15% less than the *Minimum Delay Cycle Length*.

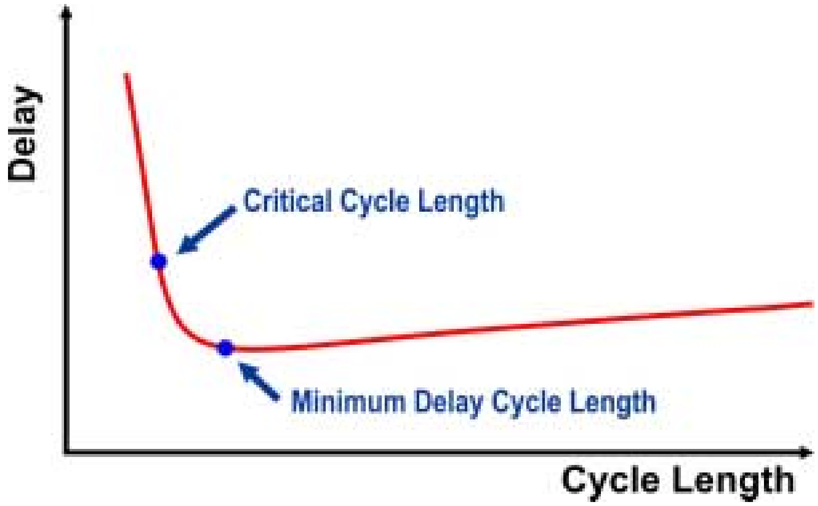

Figure 3 Cycle Length Selection and Dynamic Group Assignment

Cycle length will be calculated in several steps.

- First, the minimum acceptable cycle length will be calculated for each intersection that has suitable detection.
- Second, within each signal group, the intersection with the highest minimum acceptable cycle length will be identified. This will be set as the desirable cycle length for the group during the next cycle.
- Third, the desirable cycle length of all currently linked groups will be compared, and the highest selected as the minimum acceptable cycle length for all intersections in the linked groups for the next cycle. Acceptable cycle length is illustrated in Figure 4.

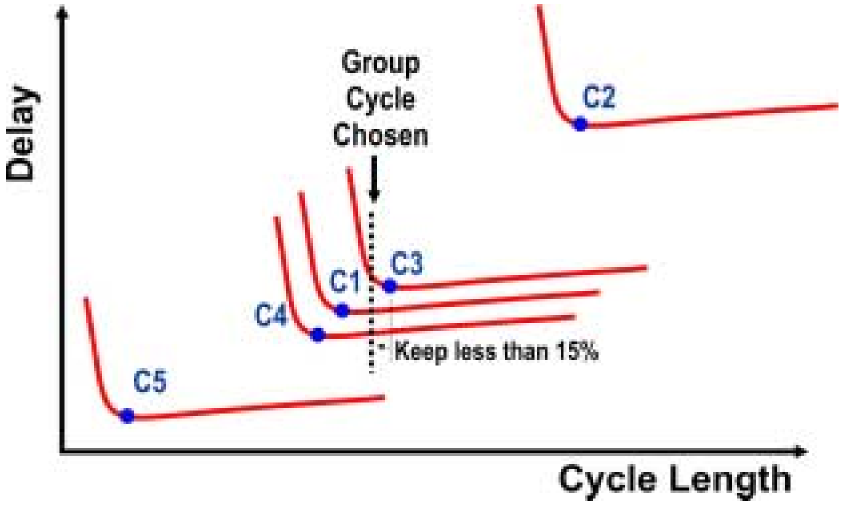

Figure 4 Constraints on System Cycle Length

In real time, the cycle length will not be allowed to fluctuate wildly, but will have some inertia built in. The cycle length algorithm will be of a form that calculates how much to move the cycle length from its current value, based on the how much the measured degree of saturation varies from the degree of saturation that matches the current cycle length.

A change in cycle length will be implemented in operator-defined steps (in the range of three to six seconds) to minimize the potential disruption from repeated small adjustments.

Several additional cycle length parameters will be applied to cycle length selection, so that different philosophies may be implemented during peak and off-peak times, and to account for “natural” cycle lengths based on street geometry and mid-block speeds. In the mid range of traffic conditions, the cycle length will generally increase or decrease as a linear function of degree of saturation. At high degrees of saturation, when it is often desirable to maximize the throughput on the coordinated streets, increases in cycle length will be added to the coordinated phases. At lower degrees of saturation, the optimum bandwidth is often determined by the critical intersection spacing and signal phasing, and two different low cycle length parameters will be available:

- Absolute lowest coordinated cycle length for a group; and
- Minimum cycle length accommodating all phases and pedestrian clearance times, and accounting for minimum required bandwidth.

Phase Split Determination

Phase split will be determined to equalize the degree of saturation on critical approaches (“equisat solution”). The algorithm will calculate the projected degree of saturation for each possible split plan, and the plan with the lowest maximum degree of saturation will be selected. The incremental change from existing split to next cycle split will be limited, to smooth the transitions and prevent oscillation.

The equisat solution will be applied at the critical intersection within each group, and other intersections that have full detection. For other intersections, the split will be determined from pre-set plans that can be implemented by time of day. In many cases, the side street walk and clearance times exceed the green time required for traffic, and at these intersections, the side street split will generally be set as a percentage of cycle length, subject to absolute phase minima.

Offset Selection

Within a set of linked groups, the offsets between intersections will generally be determined through a look-up procedure, following NTCIP 1210, based on relative volumes for each possible offset direction. These will be referenced to the cycle generator reference point for each intersection.

Some inertia will be built into the system, to prevent oscillation between offset directions. Minor changes in offset will be permissible from cycle to cycle, to accommodate the real-time cycle length variations.

Group Linking

All cycle length and split plan calculations are carried out at the critical intersection, and set for a group. This sets coordination for the group. Groups can be linked to achieve a longer length of coordination. Linked groups all have the same cycle length. Linking and unlinking will be controlled by choosing the optimal desirable cycle length and volume along the coordinated route.

Decision to Link

If the desirable cycle length of two adjacent groups is within an operator determined threshold, they will be forced to adopt the same cycle length. If one of these groups is already linked to another group, the linked tree will be examined one link at a time, starting at the group with the controlling cycle length.

If the traffic volume between adjacent groups traveling in one direction along the coordinated arterial exceeds a threshold determined from the available bandwidth or maximum queue storage, then they will also be forced to adopt the same cycle length.

Decision to Unlink

Once groups become linked, they will remain linked until the differences in desirable cycle lengths exceed a threshold value, and the traffic volume between adjacent groups falls below appropriate thresholds.

Some hysteresis will be built into these thresholds to prevent oscillation.

PROGRAM ARCHITECTURE

StreetWise ATMS distributes control of the system between the TOC, traffic signal masters (if present) and the local secondary controllers assigned to the system. Distributed control systems make efficient use of system communications and provide time base coordination as a fallback response when sections of the system fail. The StreetWise ATMS distributed level of control is illustrated in Figure 5.

The StreetWise ATMS manual control mode provides the highest level of control within the system and overrides all other control modes in the system. When the system manual control mode is in standby (SBY), all control is determined by the system TOD schedule. The central system either assumes control by TOD, traffic responsive operation, adaptive control or moves to SBY passing control of all or part of the system to the field controllers.

When the central system is in SBY, all control decisions are passed to any field masters present in the system and to the secondary controllers. Field masters determine the mode of operation of the secondary controllers defined in the closed-loop system. The master time-of-day schedule supervises the operation of the secondary controllers defined in the closed loop system just as the system time-of-day schedule supervises the field devices. Master controllers may also operate in standby and as a communication “hub” between the central system and secondary controllers assigned to the closed loop system. Traffic responsive operation under master and central control can be configured to select TOD patterns from the secondary controller schedules as a default under low volume and occupancy (V+O) conditions. Traffic responsive can be configured to switch to a special traffic responsive pattern at high V+O conditions to respond to incidents.

The lowest level of control is the system clock and the time-of-day schedule within each local controller. The system clock provides the synchronization required for coordination. Even if system communication is lost, the secondary controller can stay in coordination with the system for weeks at a time until brought back into operation.

Data Flow Diagram

The overall concept of the adaptive logic is illustrated in Figure 6. This will provide the basis for the detailed program design, which is the next phase of the project.

CURRENT STATUS AND FUTURE WORK

At the time of writing, the adaptive control module is almost ready for alpha testing. The plans and specifications for modifications to the detection at the critical intersections have been completed and approved. Field testing will commence in the Fall of 2003.

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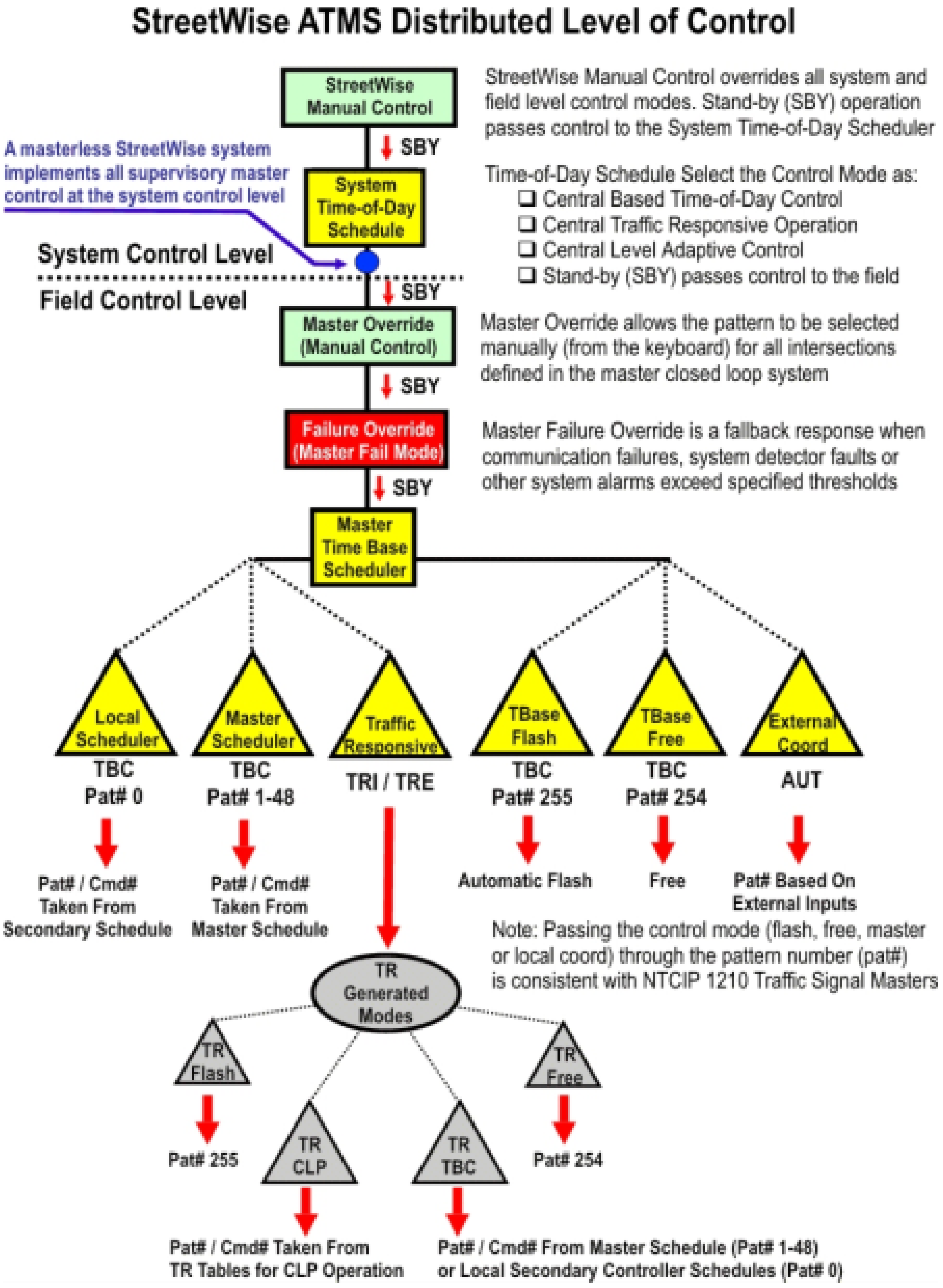

StreetWise ATMS Distributed Level of Control

StreetWise Manual Control overrides all system and field level control modes. Stand-by (SBY) operation passes control to the System Time-of-Day Scheduler

Time-of-Day Schedule Select the Control Mode as:

- ☐ Central Based Time-of-Day Control
- ☐ Central Traffic Responsive Operation
- ☐ Central Level Adaptive Control
- ☐ Stand-by (SBY) passes control to the field

Master Override allows the pattern to be selected manually (from the keyboard) for all intersections defined in the master closed loop system

Master Failure Override is a fallback response when communication failures, system detector faults or other system alarms exceed specified thresholds

A masterless StreetWise system implements all supervisory master control at the system control level

Note: Passing the control mode (flash, free, master or local coord) through the pattern number (pat#) is consistent with NTCIP 1210 Traffic Signal Masters

Figure 5 StreetWise ATMS Distributed Level of Control

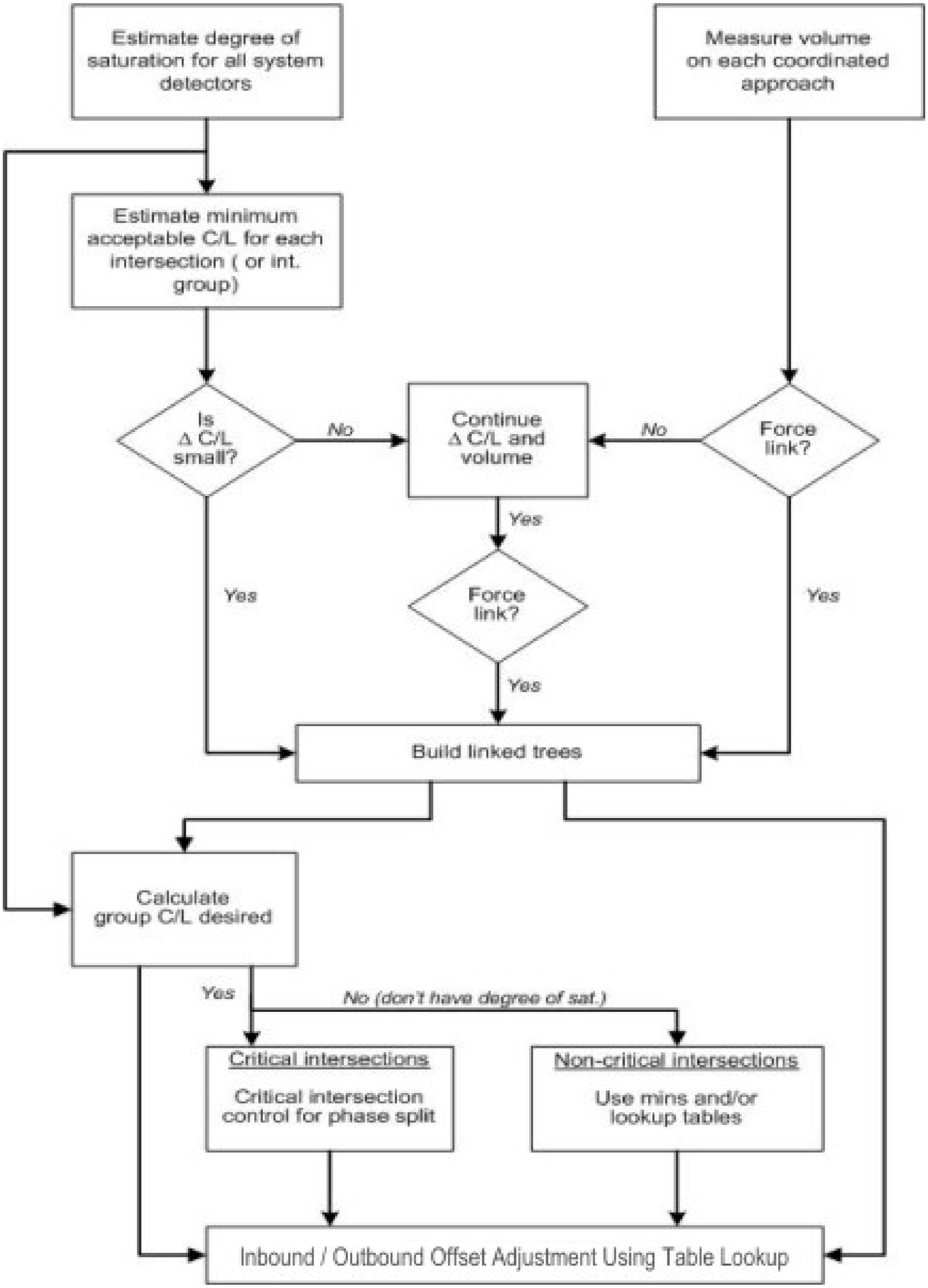

Figure 6 Overview Concept of the Adaptive Logic