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16. Abstract

The purpose of this research is to develop a reliable analytical methodology to improve the overall design and operation of actuated controllers in coordinated systems and generate the parameters for coordinated arterial or network operations.

The report summarizes the state of the art in coordinated, actuated controller operations. The methodology developed in the study was successfully tested and demonstrated on two real-world arterial signal systems in Kingsville and Burleson, Texas. The results indicate that coordinated, actuated schemes operate much better than pretimed systems. In addition, coordinated, actuated operations can potentially postpone the "possibility of over-saturation." The report provides the recommended coordination strategies and operational guidelines for using actuated controllers on coordinated signal systems.

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COORDINATION OF ACTUATED CONTROLLERS ON TRAFFIC CONTROL SYSTEMS

by

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in Coordinated Traffic Control Systems

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Texas Department of Transportation
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Texas Transportation Institute
The Texas A&M University System
College Station, Texas 77843-3135

METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

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

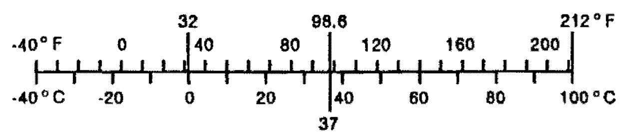
Note: Volumes greater than 1000 L shall be shown in m^3.

These factors conform to the requirement of FHWA Order 5190.1A

*SI is the symbol for the International System of Measurements

APPROXIMATE CONVERSIONS TO SI UNITS

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



IMPLEMENTATION

This report was sponsored by the Texas Department of Transportation under Research Study No. D-1255, "Efficient Utilization of Actuated Controllers in Coordinated Traffic Control Systems." The developed methodology will be available for analyzing signal timing at individual actuated intersections. The study will effectively assist users in selecting the proper controller/detector combinations and improving system detector locations. It will also aid users in optimizing actuated timing parameters in actuated control operation of arterial signal systems. Specifically, this research could help reduce intersection delay, fuel consumption and pollution while increasing capacity.

DISCLAIMER

The contents of this report reflect only the views of the authors, who are responsible for the opinions, findings, and conclusions presented herein. The contents do not necessarily reflect the official views or policies of the Texas Department of Transportation or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

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SUMMARY

The purpose of this research is to develop a reliable analytical methodology for improving the overall design and operation of actuated controllers in coordinated systems, and generate coordination parameters.

The state-of-the-art in the coordination of actuated controllers is summarized. The methodology developed in the study was successfully tested and demonstrated on two arterial signal systems in Kingsville and Burleson, Texas. The results proved that the coordinated, actuated schemes operate much better than pretimed systems in most volume cases. In addition, coordinated, actuated operations can potentially postpone the "possibility of over-saturation". The report provides the recommended coordination strategies and operational guidelines for using actuated controllers on coordinated signal systems.

CHAPTER 1. INTRODUCTION

Actuated traffic signals are designed to respond to random traffic variations through the placement of traffic detectors on one or more intersection approaches. Three (3) types of signal control systems are used by traffic engineers, namely pre-timed, semi-actuated, and fully-actuated. The performance of these systems depends on effective detector-controller combinations, respective operational requirements, and control strategies.

The increased use of actuated equipment in arterial signal systems has brought traffic engineering to near real-time control. However, there is still a lack of concrete methods for analyzing and optimizing actuated control systems. Most existing traffic engineering software is designed for the analysis of pretimed signal systems. On the other hand, traffic simulators, such as NETSIM and TEXAS, can analyze the effects of controller parameters, but are not capable of optimizing the signal settings directly.

With appropriate detector-controller configurations, actuated control can keep signals "green" for the preferred intersection approaches and provide flexible signal control to handle traffic fluctuations. By carefully implementing proper actuated designs, control systems can efficiently adjust phase green times and cycle lengths at signalized intersections for effective arterial coordination.

STUDY OBJECTIVES

As shown in **Figure 1-1 "Overall Study Flow,"** in order to accomplish the study, the Texas Transportation Institute **(TTI)** has formulated a systematic methodology to:

1. Assess the operational effectiveness of available traffic optimization/simulation models to analyze actuated signal control,
2. Extend the usage of actuation controllers with coordination for maximum arterial progression,
3. Develop a systematic analysis procedure to develop traffic signal timing plans under complicated operations, and
4. Devise system evaluation techniques to improve coordinated, actuated signal system operations.

DESIGN CONSIDERATIONS

Analysis tools, study evaluation procedures, and recommended control strategies have been devised in this study to provide a qualitative and quantitative assessment of the opreational performance of the coordinated actuated signal control.

HPR 2–18–91–1255 STUDY "EFFICIENT UTILIZATION OF ACTUATED CONTROLLERS IN COORDINATED TRAFFIC CONTROL SYSTEMS"

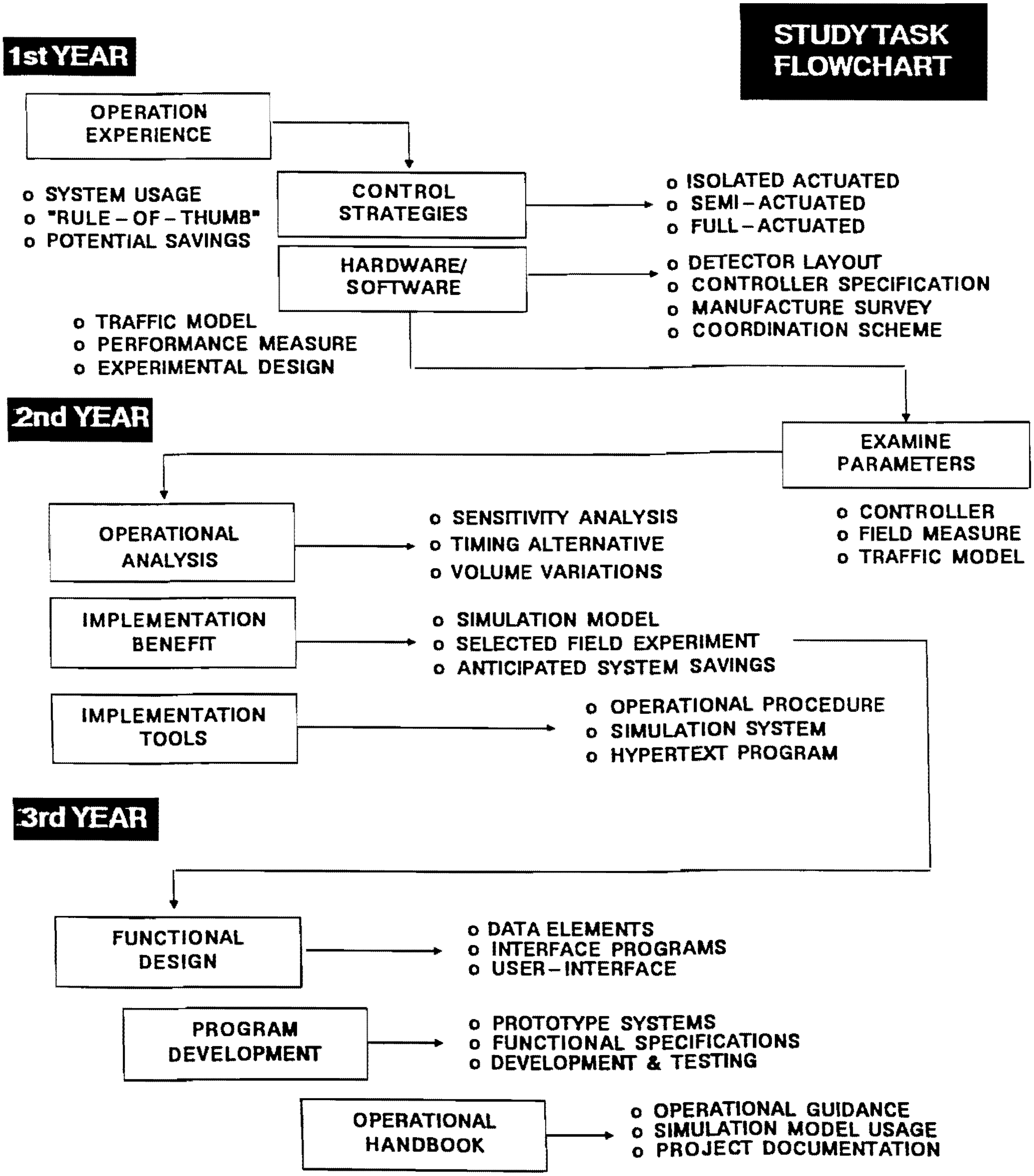


Figure 1-1 Overall Study Flow.

Available Analysis Tools

Optimization software is designed to provide deterministic results by considering random behavior macroscopically. Available software can simulate some aspects of actuated control. However, most software is limited to measuring traffic behavior and actuated control under coordination.

Coordination and Actuation

Pretimed coordination often performs very well under high volume conditions and predictable oversaturation. However, the capability to provide control flexibility and optimum performance under low volumes is somewhat restricted. Actuated controllers have the capability to fall back to pretimed operations, as well as to handle variable demands under different operating conditions. However, it is difficult for engineers to combine actuated control and signal coordination easily and provide satisfactory performance.

Analysis Procedure Development

Isolated pretimed and actuated signals have been studied by many researchers in the past. NCHRP Report No. 233 summarized several important variables under different conditions [Tarnoff, Parsonson 1981]. Recommended settings are given for different signal control at isolated intersections. Due to the similarity of the basic concepts, analysis techniques for pretimed coordination will be extended to analyze coordinated, actuated operations.

Improved Actuated Operation

Coordination improves traffic system performance by taking advantage of the progression opportunities available. Semi-actuation has been successfully used at isolated intersections and coordinated systems. Real time coordination depends on the system size and expected traffic behavior. When the signal control switches to a more responsive type, the need to provide more flexible control strategies becomes necessary.

CHAPTER 2. STUDY BACKGROUND

The use of actuation to control variable traffic demands dates back to the early 1930's. Many researchers have examined the relationships among actuated variables in the case of isolated intersections. The effects of the highly probabilistic behavior of actuated systems make the interpretation of the studies extremely difficult. Most studies are specific to certain geometric and phasing combinations. As indicated, a qualitative and quantitative evaluation of actuated signal control, especially under coordination, has not been conducted.

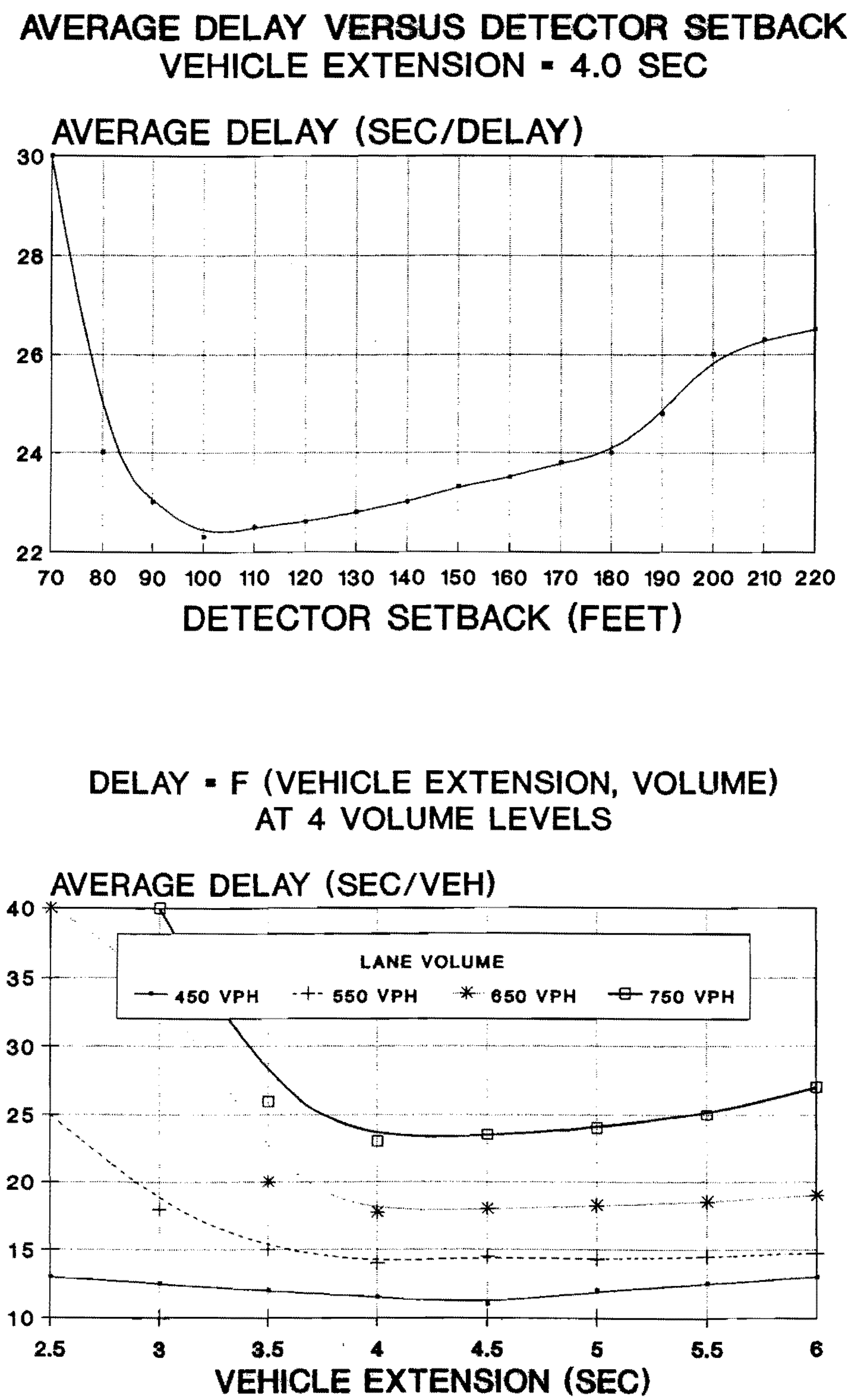
LITERATURE REVIEW

Lin and Percy examined the modeling of vehicle queuing for the interaction of presence mode detectors and discharging queue interactions based on observed headway data [Lin, Percy 1984]. These findings were later used to modify queuing models to provide optimal timing settings and detector lengths for full-actuated signals by Lin using RAPID, a simulation model. The study arrived at timings based on a peaking factor. The suggested maximum greens varied from an extra 10 seconds over the optimum pretimed split to 2.5 times the optimum pretimed split, for a peaking factor variation of 1.0 to 0.7. This result was a bit different from the values suggested by Kell and Fullerton, which was 1.25 to 1.5 times the optimum pretimed splits for maximum greens at isolated intersections [Kell, Fullerton 1982].

Tarnoff and Parsonson found that at low volumes the performance of full-actuated contollers is superior to pretimed controllers [1981]. At high volumes close to saturation, the researchers also indicated that full-actuated control tends to perform worse than pretimed signals. The conclusions indicate that shorter vehicle extensions close to 2.5 sec. are ideal. They also recommended a detector setback of 150 ft. as being ideal in the case of volume density controllers for approaches with traffic above 35 mph.

Bullen argues that a vehicle extension of 4.0 sec is ideal for single detector operations under passage or pulse mode, regardless of the detector location or approach speeds [Bullen 1990]. This conclusion contradicts previous results. However, the model **(EVIPAS)** used by Bullen considered variable queue discharge headways. This result may not be of importance in the case of large detector setbacks, due to the unlikelihood of queues reaching the detectors. Major modifications have been made to several traffic optimization programs to account for actuated operations. An interesting feature in TRANSYT-7F uses the Arterial Priority Option **(APO)** [Muscaluk, Parsonson 1988]. This provides the user with the option to give more priority to arterial direction, while providing a user-set degree of saturation to minor movements in order to control cross-street performance degradation acceptable levels.

From the above research, two important factors, vehicle extension and detector setback, can determine actuated, isolated intersecton performance as indicated in **Figure 2-1 "Effects of Vehicle Extension and Detector Setback."** Both NETSIM and TEXAS support these observations. Identifying optimum values



Reference: [Lin 1985, Bullen 1988].

Figure 2-1 Effects of Vehicle Extension and Detector Setback.

that can provide the best coordination is an important aspect which many previous researchers have not addressed. Theoretically, isolated control parameters are applicable to coordinated systems if progression and traffic randomness can be accounted for. Most field observations indicate that actuated system performance varies depending on site location and specific traffic characteristics. In isolated actuated control, performance depends on demand patterns and control settings. Under coordinated operation, factors such as force offs, minimum green, maximum green, and vehicle extension are more important.

COMPUTERIZED TRAFFIC MODELS

As indicated in **Figure 2-2 "Computerized Traffic Models,"** a number of computerized analysis tools are available in different emphasis areas [Ross 1977]. Four tools are available for analyzing coordinated and actuated operations, as given below.

PASSER II-90

PASSER II is a traffic signal optimization program developed by the Texas Transportation Institute. The model can simulate and optimize arterial signal operations under pretimed control. It assumes a macroscopic flow and provides timing plans for traffic engineers. PASSER II can optimize cycle lengths, phase sequences, splits and offsets. This model takes the information on whether a signal is pretimed or actuated only to adjust the delay estimation. This model, however, cannot handle grid-type network systems.

TRANSYT-7F

TRANSYT-7F is a traffic simulation and optimization program originally developed in England. Later, it was modified to suit American conditions. The current version of TRANSYT can simulate and optimize arterials and networks. The optimization minimizes systemwide delays and stops. The latest versions have added an option to indicate whether an approach is actuated or not. The results of evaluating actuation features will be discussed in detail later.

G.TRAF-NETSIM

G.TRAF-NETSIM is a microscopic simulation model developed by the Federal Highway Administration (FHWA). This model can simulate traffic control systems in detail. The latest version includes the preprocessor, simulator, and post-processor. The preprocessor provides input data editors, a database, and utilities. The simulator includes error checkers and simulation programs. Postprocessors can graphically display results and present the system on-screen. The model can handle isolated intersections and coordinated systems under uncontrolled, stop/yield controlled, pretimed and semi-actuated systems.

TEXAS Model

The TEXAS Model was developed by the University of Texas at Austin and the Texas Department of Transportation [Rioux, Lee 1977]. This microscopic simulation can simulate intersections and diamond interchanges under pretimed

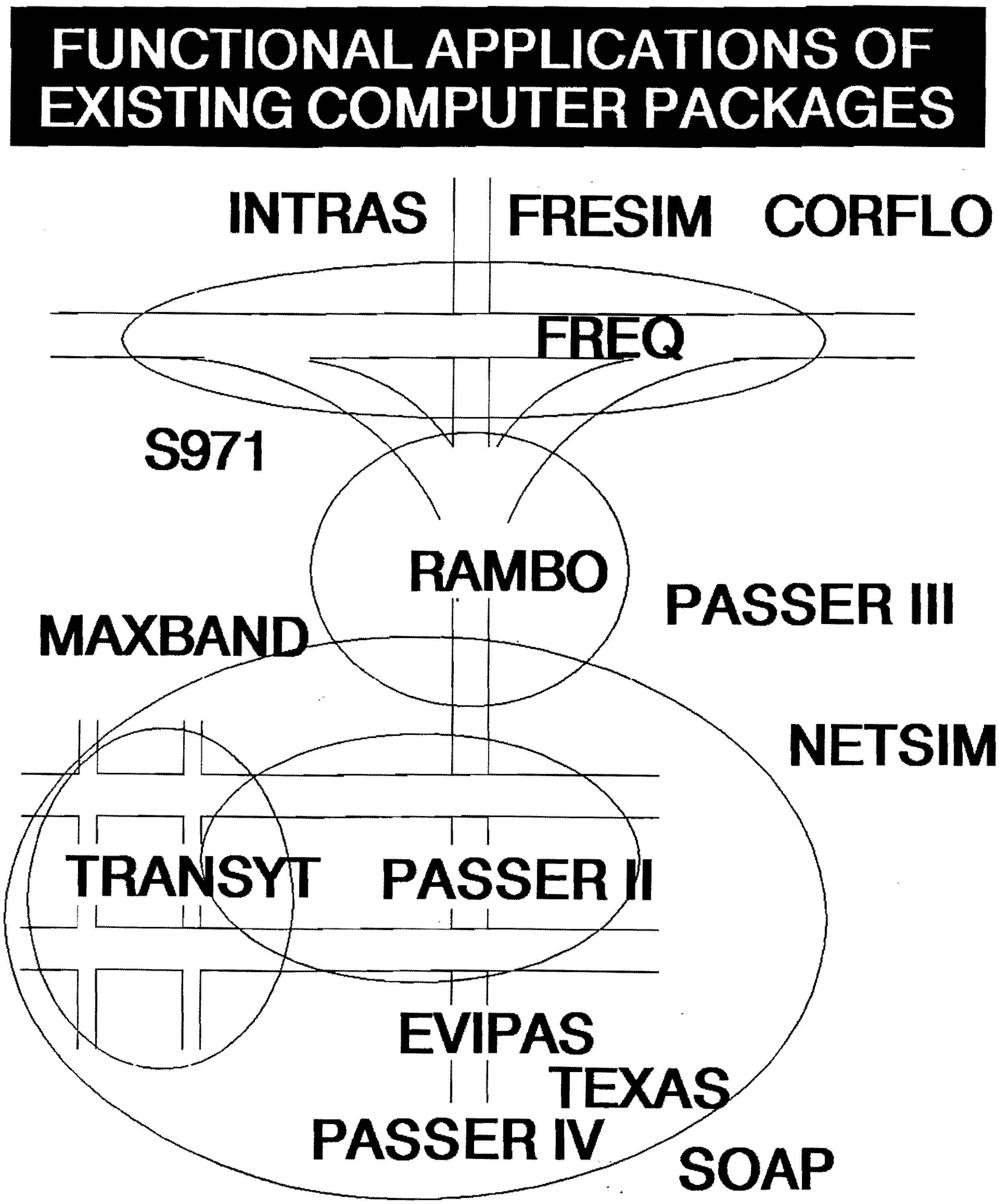


Figure 2-2 Computerized Traffic Models.

simulation can simulate intersections and diamond interchanges under pretimed and actuated control. The output produces the same level of details as the NETSIM model. The TEXAS model also has a postprocessor that can represent the traffic scenario graphically.

MODEL COMPARISONS

Most computer models have drawbacks. The optimization packages tend only to approximate control behavior, without an explicit way to examine factors such as vehicle extension detector setback. Furthermore, most simulation models cannot directly provide optimized signal timings.

Actuated Features

TRANSYT-7F takes input as to whether a signal is actuated or not. However, this information is used only to adjust the degree of saturation of relevant movements. Research results from actuated control operations indicate that performance depends highly on the setting of actuated variables. These variables are not explicitly built into the optimization algorithms to provide more accurate performance estimates.

Optimization Objectives

Most optimization algorithms are based on some default procedures or user selection criteria. The specific optimization objective, however, relies mainly on the specific field operational requirements. For example, the minimization of stops would be a primary objective on some arterial streets, where the minimization of emissions would be of higher importance at other locations.

Arterial Coordination

PASSER II-90 uses bandwidth maximization as the primary optimization objective and calculates in minimum arterial delay of vehicles travelling on the arterials. On the other hand, TRANSYT-7F tries to minimize the performance index, i.e. combined function of system delay and stops, as the optimization objective. Therefore, the major difference between the two models is the former model provides better performance on arterials, while the latter tries to improve the entire network without favoring a particular direction.

Aggregate MOE

Most traffic models consider delay, stops, travel times, and emissions as primary measures of traffic flow. However, it is often difficult to combine these factors into a single physical index, since most variables are interrelated. Aggregation of the related factors expressed in terms of real dollars is proposed as a more realistic optimization measure. This combined index should indicate the total cost of certain strategies to society, and will provide more practical sense than an arbitrary measurement.

CURRENT PRACTICE

Traffic signal design can contribute to the successful operation of both urban and rural traffic control systems. Proper settings of signal timing parameters increases the effective operation of actuated traffic signal systems. The actuated system responds to random traffic demand fluctuations through appropriate controller settings and suitable detector configurations. When designed and implemented properly, the actuated traffic signal system can efficiently and continuously adjust green splits and cycle lengths. Therefore, signal-timing plans can be modified according to instantaneous real-time traffic demands from vehicular detectors. However, the proficiency of actuated signal detector-controller systems depends on local traffic requirements and the signal control settings employed. The capabilities of actuated signal controller systems depend on specific detector-controller systems and their individual operational requirements as in **Figure 2-3 "Detector/Controller Combinations."**

Field observations indicate that the performance of coordinated and isolated systems also vary, depending on site conditions. Therefore, the study approach should also include field verification.

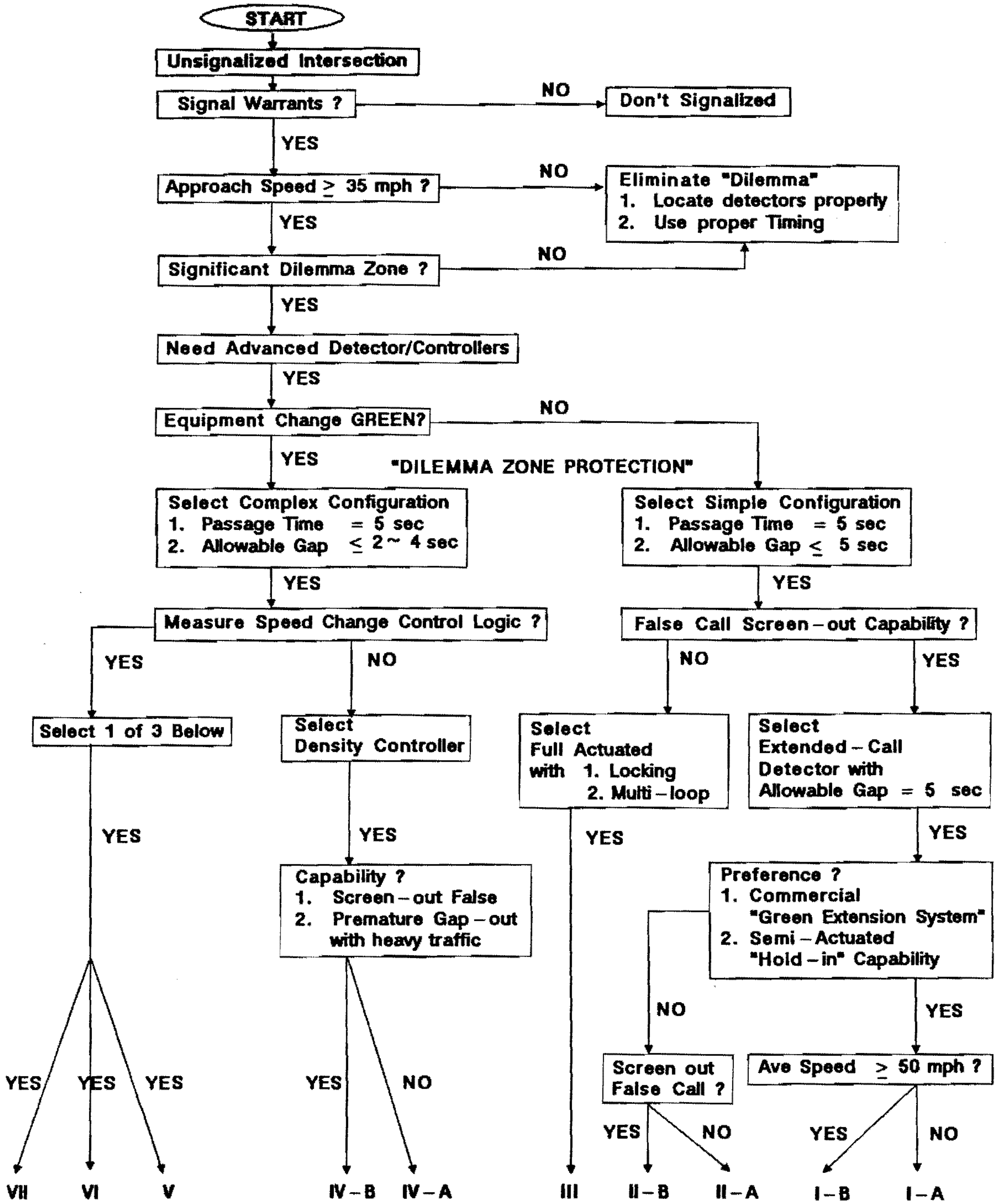
Aggregate MOE

Recently, air quality and fuel emissions have become a primary factor. Many engineers are applying techniques that consider emissions into signal system design. It is difficult to combine many of these factors into a single physical index, since some of the variables are highly interconnected. An aggregate of these factors in terms of monetary value is proposed as a more realistic optimization objective. As indicated in **Figure 2-4 "Development of S-Index,"** the proposed index would indicate the total cost of operation of any control strategy to society, and provide a more practical indication than an arbitrary sum of physical quantities.

Analytical Guidelines

A few analytical models have been developed to represent actuated signal operations. However, none are powerful enough to represent coordinated, actuated operation. Lin attempted to examine isolated actuated operation as a probability-based queue processor [Lin 1985]. This analytical model can calculate the probability of an approach gapping out at different volume levels. Similar methodology can be extended to account for the effect of multiphase control and queuing processes. It is doubtful, however, that the approach would account for the effects of coordination.

NCHRP Study The NCHRP Report 233 documents one of the most exhaustive efforts to identify ideal traffic control for a variety of conditions [Tarnoff, Parsonson 1981]. The study examined pretimed, semi-actuated and full-actuated control in detail for a wide matrix of volume and geometric combinations. A cursory examination of coordinated operations was also conducted, and possible techniques for evaluating coordinated signals were indicated. The selection criteria, as suggested by NCHRP report, is given in **Figure 2-5 "Traffic Control Criteria."**



Reference: [Chang 1989].

Figure 2-3 Detector/Controller Combinations.

S-INDEX

To combine all the relevant performance measures, a monetary value is developed and proposed as a measure that can better reflect the total system operating cost to society. The S-Index can be used to compare systems and control strategies based on the fixed dollar value and more meaningful persuasion to the decision maker. The combined "S-Index", calculates the dollar value on total delay, stops, fuel consumption, and emissions of Carbon Monoxide (CO), Nitrogen Oxides (NOx), and Hydrocarbons (HC).

$$SI = Kt * TT + Ks * S + Kf * F + KCO * CO + KHC * HC + KNOx * NOx$$

where

- SI = S Index,
- Kt = Cost of vehicle and passenger time,
- Ks = Cost of a vehicle stop,
- Kf = Cost of fuel,
- KCO = Cost of CO emissions,
- KHC = Cost of HC emissions,
- KNOx= Cost of NOx emissions,
- TT = Total Travel Time,
- S = Number of stops,
- F = Quantity of fuel consumed,
- CO = Quantity of CO produced,
- HC = Quantity of HC produced, and
- NOx = Quantity of NOx produced.

Obtain these costs from various sources and keep data up-to-date. Calculate the index using acceptable dollar values as follows.

S Index = \$13.2*Total Time + \$0.03*Stops + \$1.1*Fuel Consumption + \$3050*HC + \$300*CO + \$2750*NOx

Estimate fuel consumption from the formulas in PASSER II and TRANSYT-7F.

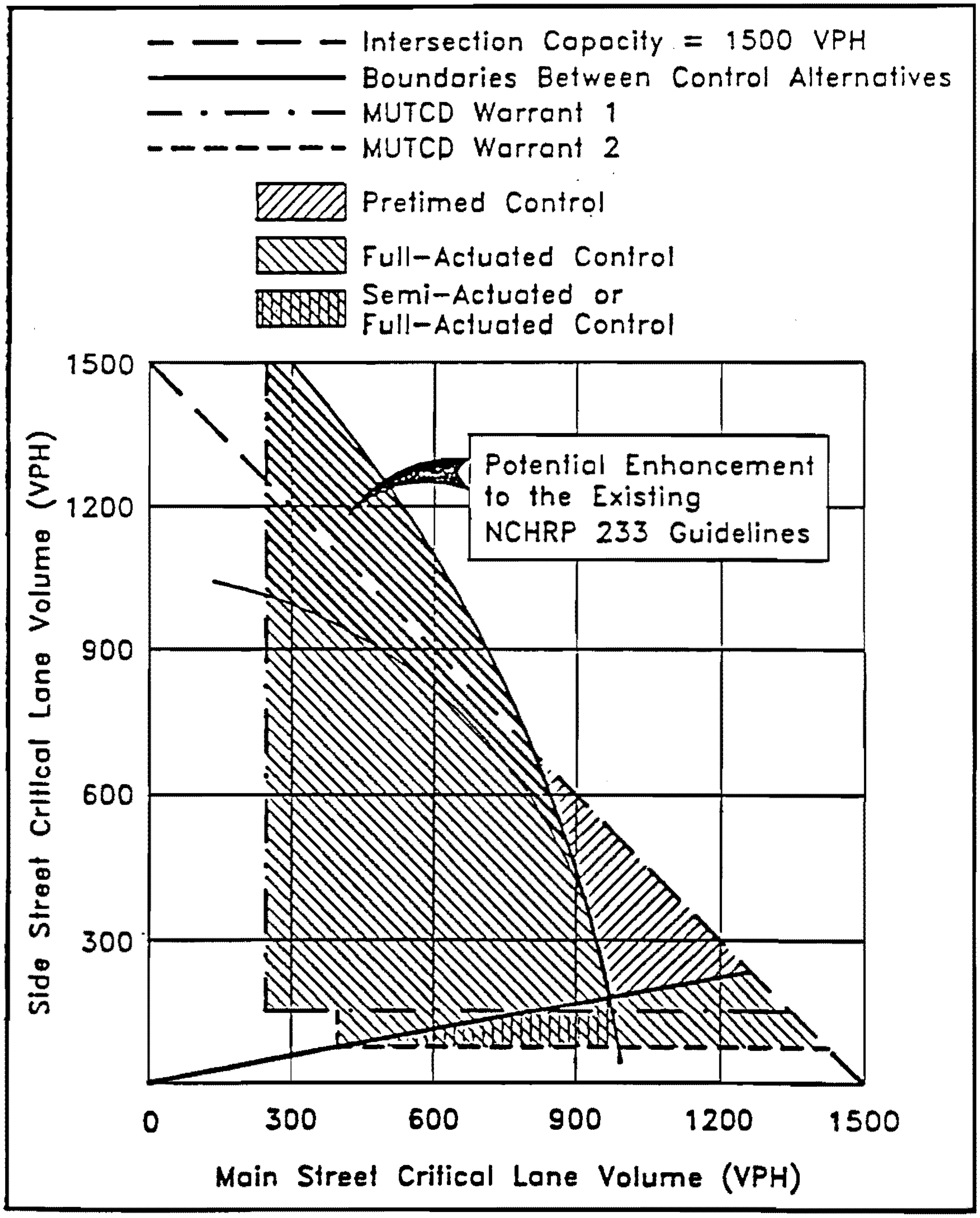
$$F = [0.075 - (1.5899*10-3) * v + (1.50655*10-5) * v**2 + 0.0122 * D + (6.14112 * 10-6) v**2 * S] * l * V$$

where

- F = Total amount of fuel consumed (gallons),
- v = Free speed (mph),
- D = Stopped delay (min/mile),
- S = Number of Stops (stops/mile),
- l = length of route (miles), and
- V = Average traffic volume along the route.

Estimate the amount of pollution generated by applying either the MOBILE 5.0, EMFAC7, Modified Winfrey Method, or newer versions.

Figure 2-4 Development of S-Index.



Reference: [NCHRP 233, 1981].

Figure 2-5 Traffic Control Criteria.

Advantages and Disadvantages

The current analytical models are inadequate to represent all the operating conditions, especially when larger coordinated actuated signal systems are used. However, simple analytical models can be used to evaluate less complicated operations. The operational advantage is that such analytical models can be easily used to arrive at possible trends of different traffic signal control parameters.

As shown in **Figure 2-6 "Analysis Methodology,"** this study is based on analytical models, simulation programs, and field observations. Simulation studies were conducted to identify optimal values for both isolated actuated and coordinated actuated control. Finally, the field experiments were conducted. The performance of each timing scheme was first evaluated through the G.TRAF-NETSIM simulation model, and then compared through field study.

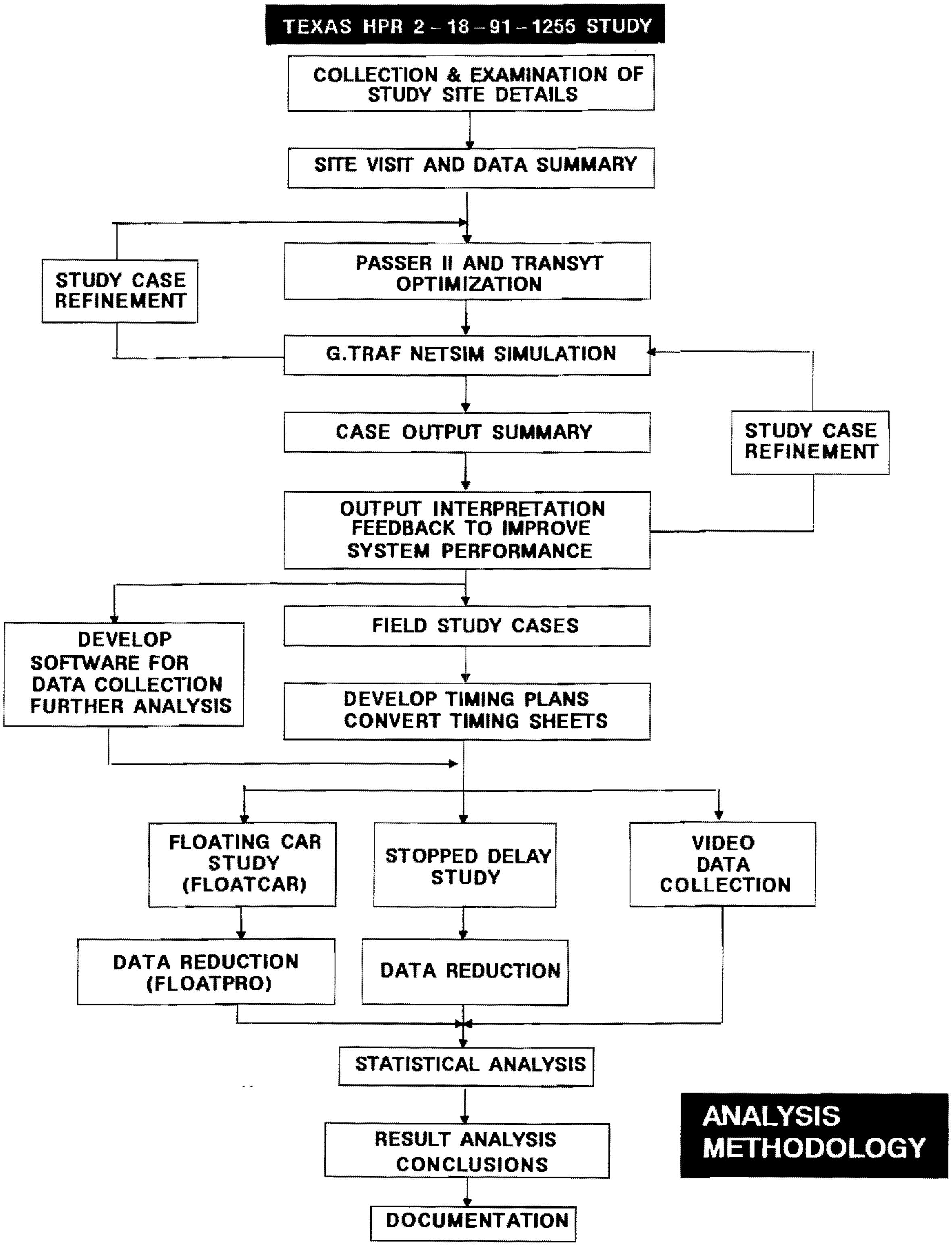


Figure 2-6 Analysis Methodology.

CHAPTER 3. FEASIBLE CONTROL STRATEGIES

As shown in **Figure 3-1 "Signal Control Comparisons,"** pretimed, semi-actuated, full-actuated, and volume-density controls involve a number of signal timing variables that have somewhat different field equipment and data processing requirements. The basic objectives for installing traffic actuated controllers or actuated control systems include:

1. Keeping a signal green if enough traffic demand exists on the intersection approach,
2. Keeping traffic volume from all directions moving through the controlled intersection in an efficient manner,
3. Avoiding catching stragglers or random arrival traffic between competitive or conflicting traffic demands,
4. Providing flexible traffic signal timing control in addition to the use of pre-timed, fixed-cycle operation strategies,
5. Taking advantage of the multi-phase traffic signal controller which provides safe and efficient urban traffic control maneuvers, and
6. Shortening the cycle lengths in a more responsive manner.

SIGNAL CONTROL TYPES

Traffic actuated equipment and adaptive control have become increasingly popular due to their fallback, pre-timed capability and increased flexibility during medium to low volume conditions. Arterials with actuated signals may achieve effective progression by terminating actuated phases early and giving extra time to the coordinated phases for additional progression opportunity. As shown in **Figure 3-2 "Signal Timing Design Considerations,"** these different signal controls use various sets of signal timing parameters to manage demand variations than do fixed-time controllers.

Effective signal control design is sometimes difficult to achieve. This design problem is often aggravated further by resource and institutional constraints imposed on an agency responsible for the acquisition, installation, operation, and maintenance of traffic signals. Signal control logic varies from one type to another. As shown in **Figure 3-3 "Comparisons of Pre-timed and Actuated Signal Control,"** performance characteristics of each signal control types can be affected by intersection geometrics, timing settings, signal phasing, detector configuration, and flow patterns.

The operation of efficient and effective traffic signals have become an art in traffic engineering. The work often includes selecting available traffic controllers, vehicle detectors, and different system configurations. Over the years, engineers have relied on practical experience to determine the detector locations and traffic controller settings which will provide improved traffic performance. However, inspection of the available literature shows that most research involves the location of detectors during design and installation of computerized signal systems. There has been limited research dealing with the effective use of traffic actuated controllers, particularly on the determination of coordinated signal timing settings.

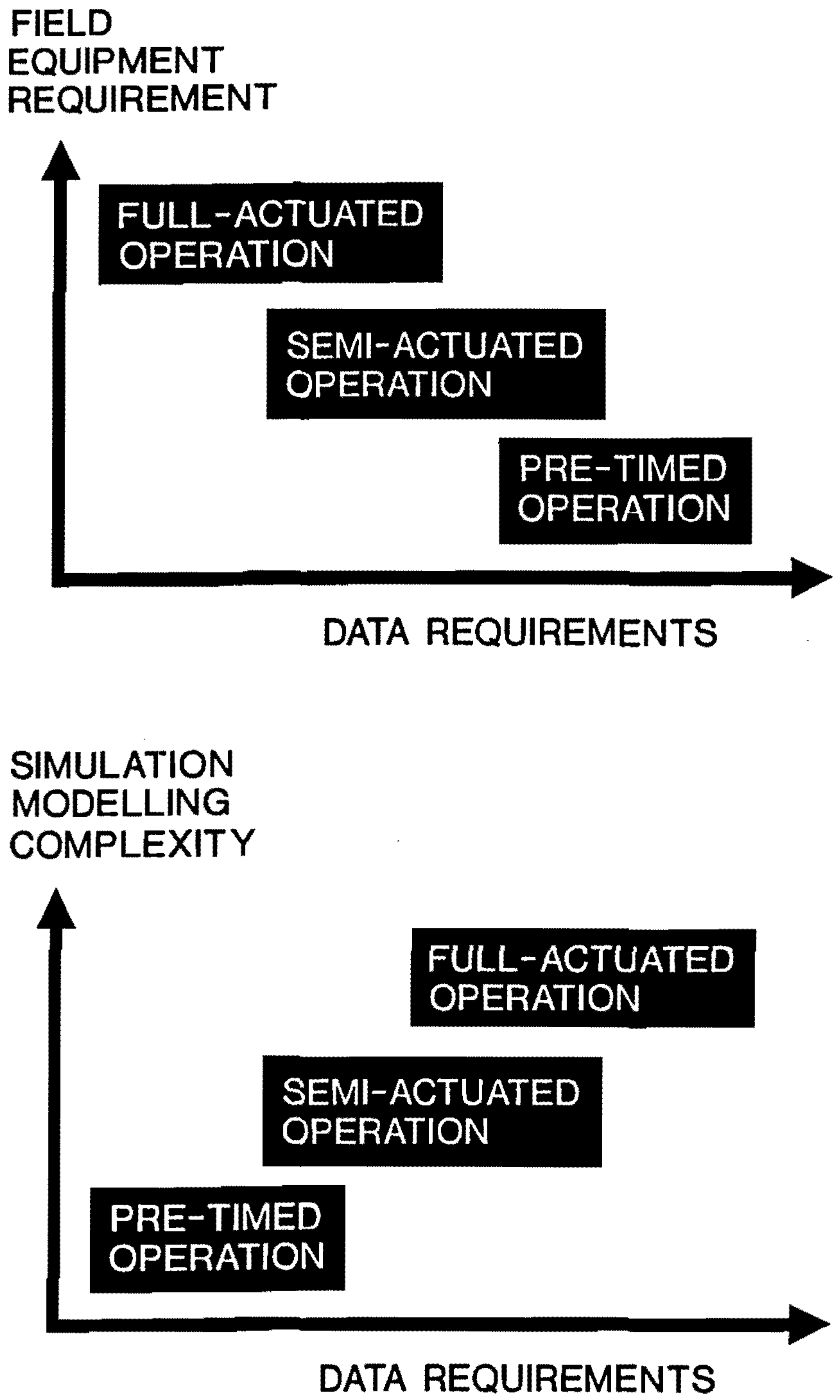


Figure 3-1 Signal Control Comparisons.

MAJOR SIGNAL TIMING DESIGN CONSIDERATION			
NO	CONTROL TYPE	TRAFFIC SIGNAL TIMING PARAMETER	
1	PRETIMED CONTROL	PHASING PLAN	PHASE SEQUENCE
		PRETIMED SETTING	CYCLE LENGTH
			GREEN INTERVAL
			CHANGE INTERVAL
		PEDESTRIAN	WALK AND DON'T WALK INTERVALS
2	SEMI-ACTUATED CONTROL	PHASING PLAN	PHASE SEQUENCE
		NON-ACTUATED	CYCLE LENGTH
			GREEN INTERVAL
			MINIMUM GREEN
		ACTUATED PHASE	MINIMUM GREEN
			VEHICLE INTERVAL
			MAXIMUM GREEN
		DETECTOR CONFIGURATION	DETECTOR TYPE
			DETECTOR SETBACK, LENGTH
			CALL DELAYS
			CALL EXTENSIONS
		CHANGE INTERVAL	YELLOW TIME
		PEDESTRIAN	WALK AND DON'T WALK INTERVALS
3	FULL-ACTUATED CONTROL	PHASING PLAN	PHASE SEQUENCE
		ACTUATED PHASE	MINIMUM GREEN
			VEHICLE INTERVAL
			MAXIMUM GREEN
		DETECTOR CONFIGURATION	DETECTOR SYSTEM DETECTOR TIMING
		CHANGE INTERVAL	YELLOW TIME
		PEDESTRIAN	WALK AND DON'T WALK INTERVALS
4	VOLUME-DENSITY CONTROL	PHASING PLAN	PHASE SEQUENCE
		ACTUATED PHASE	MINIMUM INITIAL
			MAXIMUM INITIAL
			ADDED GREEN PER ACTUATION
		DETECTOR TIMING	PASSAGE TIME
			MINIMUM GAP
			TIME BEFORE REDUCTION
			TIME TO REDUCE
		CHANGE INTERVAL	YELLOW TIME
		PEDESTRIAN	WALK AND DON'T WALK INTERVALS

Figure 3-2 Signal Timing Design Considerations.

COMPARISONS OF PRETIMED AND ACTUATED SIGNAL CONTROL			
NO	DESIGN CONSIDERATIONS	SIGNAL CONTROL TYPES	
		PRETIMED CONTROL	ACTUATED CONTROL
1	TRAFFIC VOLUME VARIATIONS	Not efficient under large volume variations.	Maximum efficiency at intersections with large volume fluctuations. Complex intersections with some sporadic movements can be efficiently controlled.
2	SIGNAL COORDINATION	Consistent starting time and interval duration facilitates coordination in arterial systems and grid systems.	Semi-actuated control can provide maximum efficiency at intersections where a minor street with sporadic traffic intersects with a major street.
3	ARTERIAL PROGRESSION	Precise timing relationships allow for operating closely spaced intersections efficiently and with a degree of speed control.	Maximum efficiency at intersections unfavorably located within progressive systems. A background cycle may be required to ensure coordination and progression.
3	SIGNAL CONTROL RESPONSIVENESS	Signal response may be poor, especially under low volumes.	Could provide continuous stop-and-go operation, even in periods of light traffic without causing unnecessary delay to traffic on the major street.
4	DETECTOR SYSTEM	Not dependent on proper operation of detectors. Not sensitive to driver behavior and work-zone situations.	Affected by failure of detectors.
5	PEDESTRIAN REQUIREMENT	More acceptable if pedestrian volumes are large and fairly consistent. Confusion with ped-push-buttons are avoided.	Preferable when pedestrian volumes or vehicle volumes are low and sporadic.
6	SYSTEM INSTALLATION COST	Equipment costs less.	Equipment is costly.
7	OPERATIONAL MAINTENANCE	Simpler to maintain.	Higher maintenance.

Figure 3-3 Comparisons of Pre-timed and Actuated Signal Control.

The operations of signal controller may be affected by the geometric conditions of the signalized intersection, signal timing settings, signal phasing plan, detector configurations, and traffic flow patterns. If designed and implemented properly, the arterial signal system can be made more traffic responsive to changing demands than systems equipped with only fixed-time controllers, especially during low and moderate traffic conditions.

SIGNAL COORDINATION

There are four major arterial system design considerations to implementing certain coordination schemes:

1. Operational benefits,
2. Design objectives,
3. Adverse effects, and
4. Special circumstances.

Operational Benefits

The major benefit of coordination is improvement in the level of service and performance of the system. Measuring the benefits of signal coordination in terms of a "penalty" function is common. This function is a weighted combination of stops, delay, and other relevant terms. The higher the value of the penalty function, the less the expected benefits are.

The design objective is to find an operational scheme to minimize the costs of operation and maintenance. Traffic engineers should use computerized signal optimization programs to produce timing plans, and then obtain a numeric function value to estimate the reduction in the penalty.

There are many operational benefits resulting from the appropriate arterial signal-coordination.

Better Speed characteristics The signal setting encourages certain speeds. Vehicles traveling much faster or slower than the system preferred speed range will be discouraged from maintaining their inefficient speeds. Proper signal time setting will lead to desired speeds.

Better Platooned Progression In a well-formed progression platoon, or a group of vehicles, the average time headway between vehicles is generally shorter than when the vehicles start from a stop. The decrease in headway leads to more efficient use of roadway facilities.

Better Queue Management On short blocks with heavy flows, it is important to stop as few vehicles as possible. If all vehicles have to stop, the queue that results may overflow the space available to store vehicles.

Environmental Considerations Keeping vehicles moving as smoothly as possible at efficient operating speeds will lead to lower fuel consumption and air pollution of the entire system.

Adverse Effects

On the other hand, the signal coordination and arterial progression may also have some adverse effects. These factors may limit the benefits of signal coordination that can be realistically achieved:

1. Inadequate roadway geometries,
2. Wide variability in traffic characteristics like operating speed, and turning volumes,
3. High system permeability, and
4. Heavy turn-out volumes.

Special Circumstances

Sometimes the entire system acts as two separate systems, one on each side of a heavily loaded intersection. Such signalized intersections, often called "critical intersections," cannot operate in tandem with the rest of the system. As shown in **Figure 3-4 "Critical Intersection,"** the critical intersection could be handled by building the progression around it, or simply by detaching it from the rest of network.

FEASIBLE CONTROL STRATEGIES

As shown in **Figure 3-5 "Feasible Control Strategies,"** there are four (4) types of feasible control strategies for operating coordinated traffic signal systems, depending on different system traffic loading conditions.

1. Pretimed Strategies,
2. Actuated Strategies,
3. v/c Ratio Strategies, and
4. Early Return Strategies.

Pre-Timed Strategy

Pretimed controllers have fixed splits and are generally developed with optimization algorithms using various data obtained from extensive traffic counts. This form of traffic control may be found acceptable for intersections, arterials, and networks with very minor volume variations, where the benefits of actuation do not justify the cost.

In general, pretimed systems can be operated efficiently using settings derived from optimization software available on the market. The optimization objectives under such operations are to maximize the progression opportunities, to keep a good bandwidth, and to provide priority to arterial movements. Such systems operate quite well when the volumes are predictable and predominant in the through direction.

The optimization of the pretimed traffic signal timing settings can be obtained from the recommended study approach as shown in **Figure 3-6 "Traffic Signal Timing Process."**

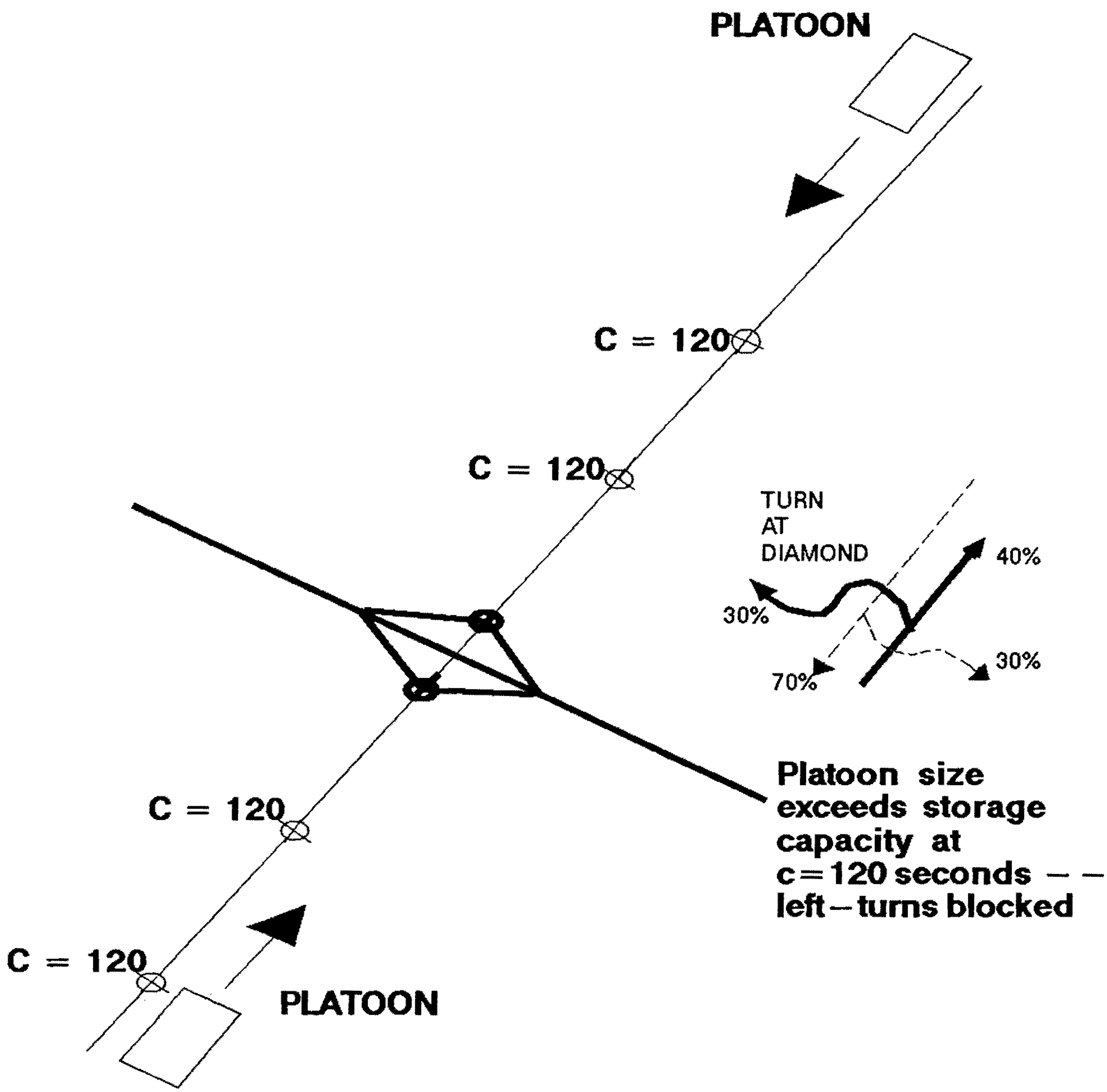


Figure 3-4 Critical Intersection.

RECOMMENDED COORDINATED, ACTUATED CONTROL STRATEGIESS					
OPERATING CONDITIONS			RECOMMENDED SYSTEM CONTROL STRATEGY	POTENTIAL IMPROVEMENTS	
NO	OPERATIONS	Crit.V/C		DELAY	STOPS
1	LIGHT TRAFFIC OPERATION	BELOW 0.4	USE FULL ACTUATED CONTROL	40%	35%
			NO COORDINATION NEEDED		
2	UNDER SATURATED OPERATION	0.5	USE EARLY RETURN WHENEVER POSSIBLE	20%	18%
			MINIMIZE STOPS AND DELAYS		
		0.6	ACTUATED OR WELL TIMED MULTI-DIAL, FIXED-TIME CONTROL	25%	20%
		0.7	KEEP CYCLE REASONABLY SHORT AND TRAFFIC MOVING	33%	11%
2	NEAR SATURATED OPERATION	0.8	USE SEMI-ACTUATED CONTROL	36%	50%
			OPTIMIZE SPLITS, OFFSETS		
			MINIMIZE STOP AND DELAY ON UNCONGESTED APPROACHES MINIMIZE QUEUES ON CONGESTED APPROACHES		
		0.9	USE EARLY RETURN WHENEVER POSSIBLE	25%	20%
			CONTROLLING CYCLE LENGTH FOR MAXIMUM EFFECTIVENESS		
2	OVER SATURATED OPERATION	1.0	USE V/C RATIO CONTROL	17%	15%
			MINIMIZE QUEUE ON CONGESTED APPROACHES		
		1.1	CONTROLLING APPROACH AND DEGREE OF SATURATION	12%	7%
		1.2	USE CRITICAL INTERSECTION CONTROL	10%	10%
			OPTIMIZE GREEN SPLITS		
			MINIMIZE QUEUE SIZE AVOID QUEUE BACKUP ON CRITICAL APPROACHES		
		1.3	USE ADVANCED DETECTION	5%	5%

Figure 3-5 Feasible Control Strategies.

RECOMMENDED TRAFFIC SIGNAL RETIMING PROCESS			
NO	STUDY STAGES	STEP	WORK TASKS
1	STUDY INVENTORY	1	Establish Data Base
		2	Code Traffic Data
2	BEFORE STUDY	3	Calibrate to Existing Conditions
		4	Evaluate Existing Operations
3	PROBLEM IDENTIFICATION	5	Select Critical Intersections
		6	Analyze "Critical" Intersections
4	LEFT TURN TREATMENT	7	Determine Left Turn Options
		8	Evaluate Existing Phase Protection
5	ARTERIAL PROGRESSION	9	Determine Phase Sequence Options
		10	Determine Optimal Progression
6	FINE-TUNE SYSTEM	11	Finalize Left Turn Sequences
		12	Fine-Tune System Design
		13	Implement, Operate, and Fine-Tune

Figure 3-6 Traffic Signal Timing Process.

Actuated Strategy

Four (4) types of actuated strategies can be implemented.

Semi-Actuated Control Semi-actuated control can be used at intersections where a major street with relatively uniform flow is crossed by a minor street having traffic with relatively low speed and high volume fluctuations. The major phase remains green indefinitely until vehicle detectors, located on the minor approaches, are actuated. Additional actuations during the side street green can extend the minor phase to its preset maximum green. The semi-actuated controller can be applied to provide more progression through green for better arterial coordination, thus efficiently combining the advantages of pretimed and actuated controllers.

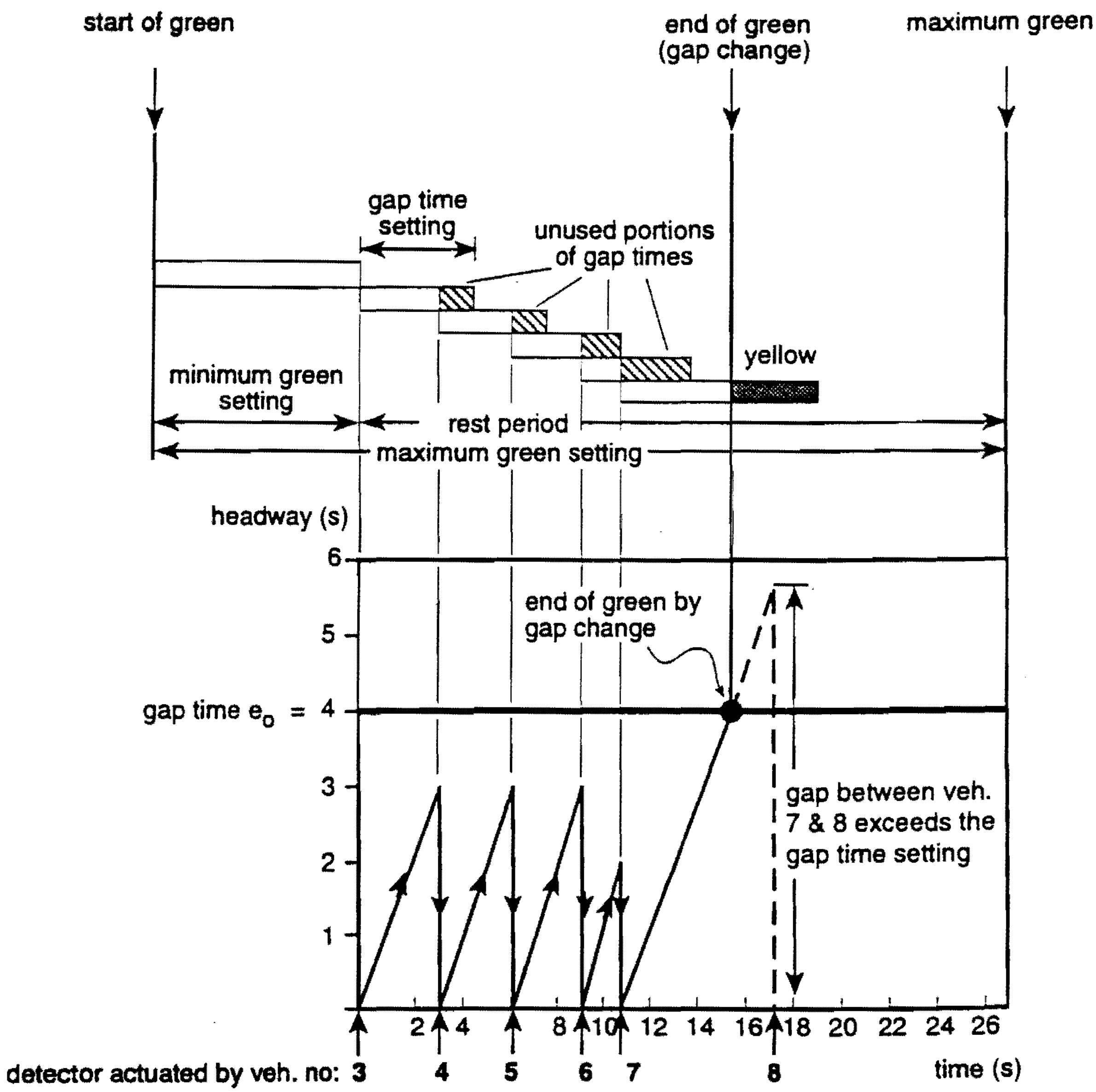
Full-Actuated Control Fully actuated controllers are often installed at intersections with relatively equal volume splits but varying or sporadic traffic distributions. Detectors are placed on all approaches to the intersections. Each phase has separate minimum green periods to provide queue dispersing time for standing vehicles. Phases can be kept on recall to give priority depending on the traffic demands on the other phases.

Volume-Density Control Volume-density controllers are designed for approaches with traffic speeds of 35 mph or higher. The detectors are placed on all approaches far in advance of the intersection so that the signal can react to the existing traffic conditions. Each phase has a certain minimum green interval and signal timing settings for the required number of actuations needed to increase the initial green to the maximum initial green. As shown in **Figure 3-7 "Gap Time Reduction,"** green time per actuation can be extended after satisfying minimum green requirements.

Closed-Loop System Control Closed-loop systems are another control scenario in which the operation of individual intersections is controlled, in part, by a central computer. The central computer usually operates in actuated mode and selects operations for each signal based on traffic mesures. There are other examples, such as the SCOOT, SCATS, and ATSAC systems.

Actuated controllers can be used to minimize stops and delay by being responsive to traffic variations. Such techniques can be effectively used to control widely varying volumes. The timing of actuated signal control systems involves many design elements, such as signal controller features, detector types, and detector locations. If traffic actuated signals are not properly timed, the resultant, unnecessary delay during actuated operations may offset the advantages of signal control equipment.

As shown in **Figure 3-8 "Coordinated Actuated Signal Timing Parameters,"** there are eight (8) elements needed for specifying the progression timing settings in addition to the basic parameters for the actuated controller-detector system. Since most signalized intersections also have to accomodate pedestrian crossing timing, the provided phase link must include both vehicle and pedestrian clearance time intervals. However, the proper timing of the actuated controller must be coordinated with signal control equipment specifications according to the user's requirements.



Reference [Akcelik 1993].

Figure 3-7 Gap Time Reduction.

COORDINATED ACTUATED SIGNAL CONTROLLER TIMING SETTINGS		
NO	ITEM	FUNCTIONAL DEFINITION
1	YIELD POINT	The earliest point at which the coordinated phase may end to give right of way to one or more of the opposing phases.
2	FORCE-OFF	Fixed points in the background cycle length used to terminate the duration of the actuated phases, guaranteeing a green window for the coordinated phase to provide for arterial progression.
3	GREEN SPLIT	A division of the cycle length allocated to each of the various phases. Can be expressed for arterial progression.
4	COORDINATION OFFSET	Time relationship expressed in seconds or percent of cycle length, determined by the difference between a defined interval portion of the coordinated phase green and a system reference point.
5	PHASE INTERVAL	A part of the signal cycle during which the signal indication does not change.
6	REFERENCE OFFSET	Point for which offset is calculated from the start of coordination phases 2 or 6 or, phases 4 or 8.
7	PHASE	The controller sees each phase as individual movements. Total of eight (8) possible phases can be destinated at each intersection for left turn and through movements, respectively. Concurrent phases are protected, non-conflicting phases that are timed together, such as "1 + 5" represents phase number 1 and number 5 running together at the same time.
8	PHASE REVERSAL	For an 8 phase dual ring controller, in some cases, phases 1 and 2 in ring 1 could be reversed. The existing 1+5 phase would become 2 + 5.

Figure 3-8 Coordinated Actuated Signal Timing Parameters.

Selecting the most suitable coordination cycle length is the first important decision in signal coordination, because all intersections in the progressive system generally must operate from the same background cycle length. Coordinated operations are often needed during certain control periods, such as the AM, PM, or OFF peak periods, to accommodate progressive flow. A full-actuated controller under coordinated control will normally be operated as a semi-actuated controller with coordinated offset settings and actuated/nonactuated phasings.

The signal timing design should avoid actions that may reduce the existing intersection signal capacity. Actions such as the undesirable usage of separate turn phases and inefficient allocation of available green times may create excessively long cycles that may cause overflow of left turn bays. Cycle lengths running longer than 100 seconds usually suggest an intersection capacity problem that should be improved by adding additional turn lanes, re-striping, and restricting parking activities. System operations can be evaluated through floating car and side-street stopped delay studies.

Early Return Strategy

If the timing generated by pre-timed optimization packages, especially PASSER II, is directly applied to an actuated system, the extra green time left over after those required for the side streets is wasted. This time, called "early return time," causes unused green time on the arterial outside the progression bandwidth. Offsets and splits could be devised to generate timings which can effectively make use of the "early return time."

This timing technique attempts to use all the green splits, as suggested by pretimed optimization, and the revised coordination offsets as derived from a reoptimization using anticipated green time on the non-coordinated phases as a constraint on the maximum green times. The anticipated green times, as suggested by TxDOT, is summarized in **Figure 3-9 "Early Return Strategy."**

This strategy recognizes that PASSER II is an excellent tool for setting up progression in a fixed time system. If the signal timing plans generated by PASSER II are directly applied to an actuated system, early return typically creates unused green time on the arterial outside the progression bandwidth. To compensate for the potential early return, another PASSER II should be made to adjust the minimum splits to anticipate the amount of actual green time.

V/C Ratio Strategy

If some movements have lighter traffic and some others have comparatively heavy movements, then appropriate movements can be selected for coordination. Options such as the Arterial Priority Option (APO) in TRANSYT-7F and bandwidth weighting factors available in the MAXBAND-86 and PASSER IV programs, can also provide extra priority to some selected links. In this way, anticipated operation would be possible by keeping a target v/c ratio for some of the non-main movements, and providing the main movements with the maximum possible green time. This method can also be achieved by changing signal control and measuring system performance in PASSER II through the iterative process illustrated in **Figure 3-10 "V/C System Strategy."**

EARLY RETURN STRATEGY

PASSER II is an excellent tool for setting up progression in a fixed time system. However, if the timing generated by PASSER II is directly applied to an actuated system, early return typically creates unused green time on the arterial outside the progression bandwidth. The following procedure outlines the process which tries to maximize the bandwidth by efficient use of the features of actuated equipment in a coordinated system.

1. **Target Cycle Length** Establish the target system cycle length. This will usually be the longest minimum delay cycle at any intersection in the system.

2. **Calculate Green Splits** Generate split times by using PASSER II and actual minimum split times desired. These split times are typically longer than the effective split in actuated systems due to the equipment's ability to give unused time of non-coordinated phases back to the arterial coordination. These splits can be thought of as the MAX times for this cycle.

3. **Adjust Minimum Splits** To compensate for early return, make another run using PASSER II adjusting the minimum splits to anticipate the actual green time by the following procedure.

   a. Calculate the **vehicles/cycle/lane** for every non-coordinated approach on a vehicle per cycle basis.
   b. Assign the **"anticipated green time"** for each movement on the following basis.

vehicles/cycle/lane	phase split time
1	9
2	11
3	13
4	15
5	17

4. **Develop Coordination Offsets** Use the offsets from the second PASSER II run to establish your progression offsets for the coordinated, actuated system.

   This "early return" procedure yields three benefits. First, it allows the user to take advantage of features of actuated equipment such as having a MAX green to handle the occasional burst of traffic. Second, it anticipates early return so that the extra green time occurs during the bandwidth, not 10 or 15 seconds prior to the arrival of the platoon. Third, by effectively utilizing the predictable green time created by early return, the green time can be used to widen the bandwidth while reducing the delay for the cross-street.

Figure 3-9 Early Return Strategy.

V/C CONTROL STRATEGY

This "V/C Control Strategy" design uses the existing PASSER II program to increase the coordinated phase(s) while shortening up the minor or non-coordinated phase(s) for efficient coordinated/actuated operations. The following study procedure outlines the study process that can increase the length of the arterial coordinated phases, while keeping a "target V/C ratio" for the non-coordinated phase.

1. **Check Critical Phase** The critical phases for both the arterial and cross street are those movements that have the highest volume-to-capacity ratios as calculated by PASSER II.

2. **V/C Calculation** The user should, at first, calculate the sum (S) of all the ratio of the volume-capacity ratio (Ri) between each phase and the maximum ratio from PASSER II output.

   S = SUM ((1 - Ri) x (PASSER II Phase Length - Lost Time per phase))

   This sum (S) represents the total amount of possible green time reduction combined from all non-coordinated critical phases while keeping the reasonable amount of green times at all other movements.

3. **Add Arterial Green** Add the possible reduction in the non-coordinated phases to the minimum phase time at the targeted coordinated phase, and code this arterial green time into PASSER II for the critical coordinated phases. To obtain the coordination signal solution, a new optimization run should be made.

4. **Check Minimum Time** The minor coordinated phase may be increased, if required, by reducing the conflicting left turn and giving this extra green time to the minor coordinated phase.

5. **Balance Cycle Length** If the minor coordinated phase for the arterial is shorter than the major critical coordinated phase, then a similar adjustment should be made by reducing conflicting left turn time by a desired amount and adding this reduction time to the through phase.

6. **Test Timing Interval** To accomodate the minor coordinated green, each of the reduced phases should be checked to see if the new volume-capacity ratio has exceeded the targeted v/c ratio.

   Although PASSER II was originally designed for progression analysis in a fixed time system, this analysis procedure allows the user to satisfy the requirements for the critical traffic phase(s) with some targeted v/c ratio, and effectively utilize the remaining green times for progressive movements.

Figure 3-10 V/C System Strategy.

CHAPTER 4. IMPORTANT DESIGN VARIABLES

Traffic signal design is important to successful urban traffic control system operations. Proper signal parameter settings are needed for effective actuated signal operations. The actuated system responds to random traffic demand fluctuations through controller settings and detector configuration combinations placed on one or more approaches to a signalized intersection. If implemented properly, the actuated traffic signal system can efficiently adjust green splits and cycle lengths continuously.

Therefore, signal-timing plans can be modified dynamically according to instantaneous real-time traffic measures. However, the proficiency of actuated signal detector-controller systems depends on local traffic requirements and the signal control equipment employed. The capabilities of actuated signal controller systems depend on specific detector-controller systems and their individual operational requirements.

STUDY CONSIDERATIONS

As illustrated in **Figure 4-1 "Signal System Design,"** the selection, design, and timing of modern traffic signals involves a step-by-step process. Several critical decisions must be determined during the design process:

1. The geometric layout of the intersection
   (i.e. lane movements, length of turning lanes, etc.),
2. The type of control to be used
   (i.e. pretimed, semi-actuated, full-actuated and volume-density),
3. The left-turn phasing of signal control
   (modern eight-phase dual-ring controller and four-phase, single-ring controller allow many combinations), and
4. The settings for each timing variable for each phase
   (up to eight variables per phase plus the clearance timings).

Operational Objectives

Operating conditions are to be evaluated first to examine the feasible signal control strategies. Operational effectiveness for both normal time-of-day operation and various control conditions, during isolated operation, coordinated operation, congested operation, and late night operation are to be separately considered.

Control Objectives A number of system control objectives are often considered in arterial traffic signal system timing design. System efficiency, including maximizing throughputs, minimizing delay, stops, travel time, and fuel consumption are often used. Operational safety to the pedestrian and vehicular traffic, and other considerations are often used due to the local land use patterns.

Arterial Operations The arterial signal system coordination plans will first be optimized to offer pre-timed progression settings and the time-space diagram. Traffic signal timing parameters, such as background cycle length, phase lengths, coordination offsets, and phase sequences, will be developed.

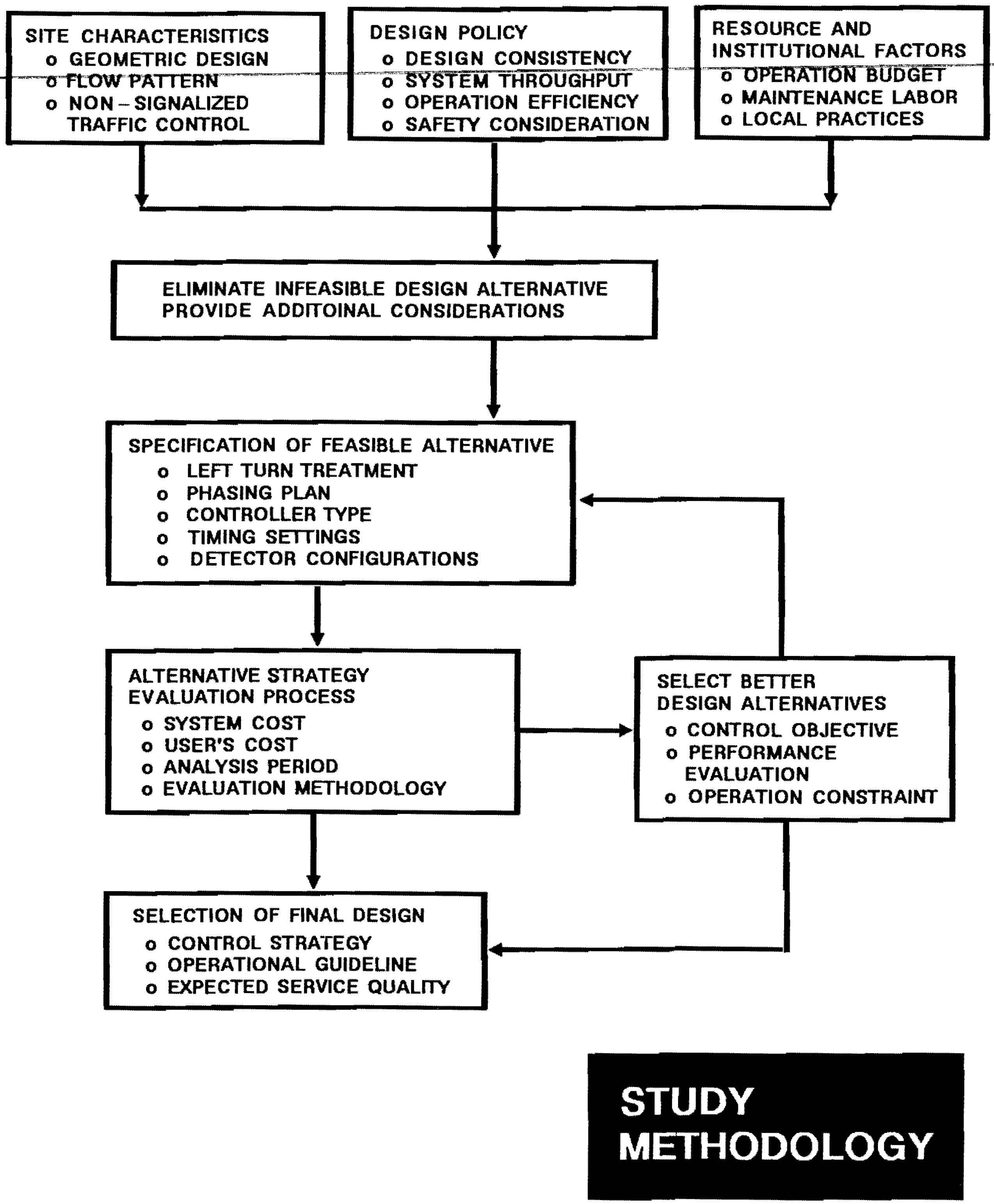


Figure 4-1 Signal System Design.

Then, actuated control features will be devised for one of the signal intersections in the system to provide the added considerations for improved operations with regard to pedestrian safety and left-turn operation efficiency.

Coordination Schemes Four (4) arterial coordination schemes will be examined to maintain the required system progression operations. These include the use of the permissive/protected left-turn treatments, yield, force-off, and phase omit functions to provide the coordination available through the use of NEMA and Type 170 controllers.

SYSTEM CONTROL FEATURES

To accommodate certain traffic management problems, it is very important to link available detector input functions and advanced actuated signal controllers for improved system operations. **Figure 4-2 "Recommended Arterial Design Features"** summarizes desirable system control design features for coordinated, actuated arterial systems.

Detector Features

A wide variety of vehicular detectors is currently available in the commercial market. However, the inductive loop detector is, by far, the most common form of detector in the United States. The inductive loop detector can provide both presence detection and passage detection functions. As shown in **Figure 4-3 "Loop Detector Applications,"** the configuration, size, and placement of the loop determines the detector functions.

Figure 4-4 "Recommended Detector Features" summarizes the recommended functions and features for different detector systems. If the lane is a right turn only (RTO) lane on the arterial, no detection needs to be provided. If the RTO lane is on the side street, and there is a possibility of undetected traffic, four 6'x6' loops at 9 ft spacing should be provided. The front two loops should be delayed by 10 seconds. The rear two loops should be delayed by 99 seconds.

On through lanes, if the speed limit is greater than 35 mph, advanced detection should be provided at roughly 4 seconds of travel time. If there is a possibility of an undetected vehicle and the phase is not on recall, a queue loop of 6'x40' should be provided. If there is a possibility of undetected traffic at night, then four 6'x6' loops should be used. However, if the speed limits are less than 35 mph, vehicle detection should first be employed, using two 6'x6' loops per 8' to 12' width.

If an approach with no left turn phase is placed on recall, a 6'x30' loop should be used on the left turn lanes. If the approach is not on recall, three 6'x 6' loops at 9' spacing are to be used. If there is a protective permissive left turn phasing, a 6'x30' followed by 25' space followed by 6'x25' loop should be used. The 6'x25' loop should be delayed by 10 second. If the left turn lane is for a true left turn phasing, a 6'x100' detector loop should be used.

RECOMMENDED COORDINATED ARTERIAL SIGNAL DESIGN FEATURES

1. Use coordinated, actuated operations whenever possible.
2. Use closed-loop system to ts2+ standards.
3. Provide all arterial coordinated actions, i.e., the yield point and force-offs, with automatically, internally calculated "easy programming" features.
4. Use coordinated phase extension on selected intersections.
5. Provide each through phase with pedestrian signal, pedestrian detector, and MUTCD pedestrian sign.
6. Use minimum driver expectancy green times on minor movements that are not coordinated.
7. Reduce minor movement, non-coordinated phases as desired to increase coordinated phases. Use the recommended procedure to modify PASSER II outputs.
8. Use permitted/protected left turns as much as practicable.
9. Use "smart detection" features on all detectors.
    a. Use "non-locking memory" for all minor/non-coordinated movements (memory off)
    b. Use "split detection" on approaches with significant right-turn volumes.
    c. Use "delayed calls" on permissive movements/or detector inhibit by phase status.
    d. Use "detector inhibit" on minor movements after green off (queue clearance).

Figure 4-2 Recommended Arterial Design Features.

LOCATION OF DETECTORS

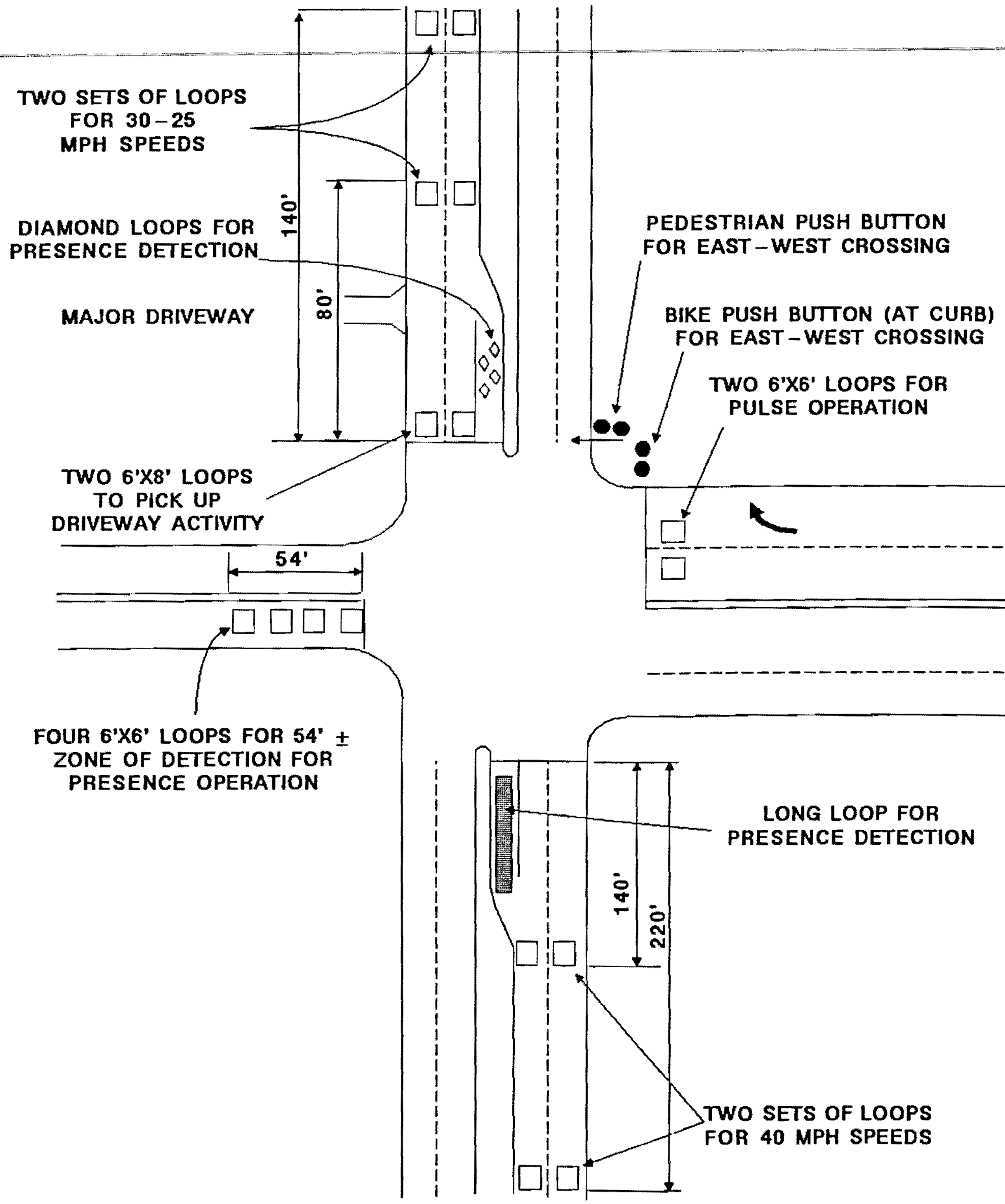


Figure 4-3 Loop Detector Applications.

DETECTOR SETTING FOR ACTUATED SIGNAL CONTROL SYSTEMS					
	DETECTOR TIMING SETTINGS				
DETECTOR TYPE	DELAY	MAXIMUM INITIAL	TIME BEFORE REDUCE	TIME TO REDUCE	MIN. GAP
6'x6' RTO - Front Queue Loops	10 sec.	-	-	-	-
6'x6' RTO - Rear Queue Loops	99 sec.	-	-	-	-
Advanced Detector(s) (with vehicle extension)	-	*2.0-3.5sec.	*5-15 sec.	*10-50sec.	*2.5-3.5sec
First Vehicle Detectors (through lane with no advance detection)	-	3.0 sec.	-	-	-
LTO (with protective permissive) Rear Detector (present) Front Detector(s) 6'x100' Detectors	 10 sec. - -	 2 sec. 2 sec. 0.2 sec.	 - - -	 - - -	 - - -

NOTE - 1. Right Turn Only Lanes (RTO) -

- o IF the arterial is placed on Recall, then no detection Required.
- o If there is a possibility of undetected traffic, provide 4-6'x6'loops at 9 feet spacing. The front two loops should be delayed by 10 secs. The rear two loops should be delayed as much as 99 sec.

2. Through Lanes -

- o If speed limit is =>35 mph, place advanced detection on roughly 4 seconds of travel time.
- o If there is a possibility of an undetected vehicle and the phase is not on recall, a queue loop of 6'x40' should be provided. However, If there is a possibility undetected traffic late at night ,4-6'x6' loops should be used.
- o If speed limit is < 35 mph, use first vehicle detection, 2-6'x6' per 8'-12' of lane width.

3. Left Turn Only Lanes (LTO) -

- o If non-phased (no Left Turn Phase) and the street is on recall, use 6'x30'. If not on recall, use 3-6'x6' at 6'spacing.
- o If there is the protective permissive Left Turn phasing, use 6'x30' followed by 25' space followed by 6'x25'. The 6'x25' loop should be delayed by 10 sec.
- o If there is true Left Turn phasing, use a 6'x100'.

Figure 4-4 Recommended Detector Features.

TYPE OF FEATURES

Three types of controller features will affect the arterial progression ~~of actuated signal controllers. These include traffic signal controller~~ settings related to the per unit, per ring, and per phase basis. **Figure 4-5 "Controller Features"** explains the corresponding actuated phase status for operating intersection signal control in non-actuated mode.

Per Unit

"Call to Nonactuated Mode" and "Walk Rest Modifier" are provided.

Call to Nonactuated Mode (two per unit) Two inputs are provided which, when activated will cause any phase(s) appropriately programmed to operate in the Nonactuated Mode. The two inputs are designated Call To Nonactuated Mode I and Call To Nonactuated Mode II. When both inputs are active, all phases programmed for Nonactuated Mode operate in the Nonactuated Mode. Only phases equipped for pedestrian service are used for Nonactuated Mode operation.

Walk Rest Modifier The input when true will modify nonactuated operation only. With this input active, nonactuated phase(s) will remain in timed-out Walk state (rest in Walk) in the absence of a serviceable conflicting call without regard to the Hold input status. With this input, nonactive, nonactuated phase(s) will not remain in the timed-out Walk state unless the Hold input is active. The controller unit will recycle the pedestrian movement when reaching State D in the absence of a serviceable conflicting call.

Per Ring

Force off and pedestrian recycle are provided on a "Per Ring" basis.

Force Off By applying this signal, the "Force Off" command provides the termination of Green timing or Walk Hold in the nonactuated mode of the active phase in the timing ring in which the termination of service is subject to presence of a serviceable conflicting call. The Force Off function is not effective during the timing of the Initial, Walk, or Pedestrian Clearance. The Force Off input is effective only when the input volume is sustained.

Pedestrian Recycle An input to control the recycling of pedestrian movements, this operation is dependent upon whether the phase is operating in the actuated or nonactuated mode as follows:

a. When the phase is operating in nonactuated mode: if the phase has reached State D, the Pedestrian Omit is not active and a serviceable conflicting call does not exist, then the pedestrian movement will be recycled to State B, when the Pedestrian Recall input is active.

b. When the phase is operating in actuated mode: if a serviceable pedestrian call exists on the phase and the Hold input is active, then the pedestrian movement will recycle when the Pedestrian Recycle input is active, regardless of whether a serviceable conflicting call exists.

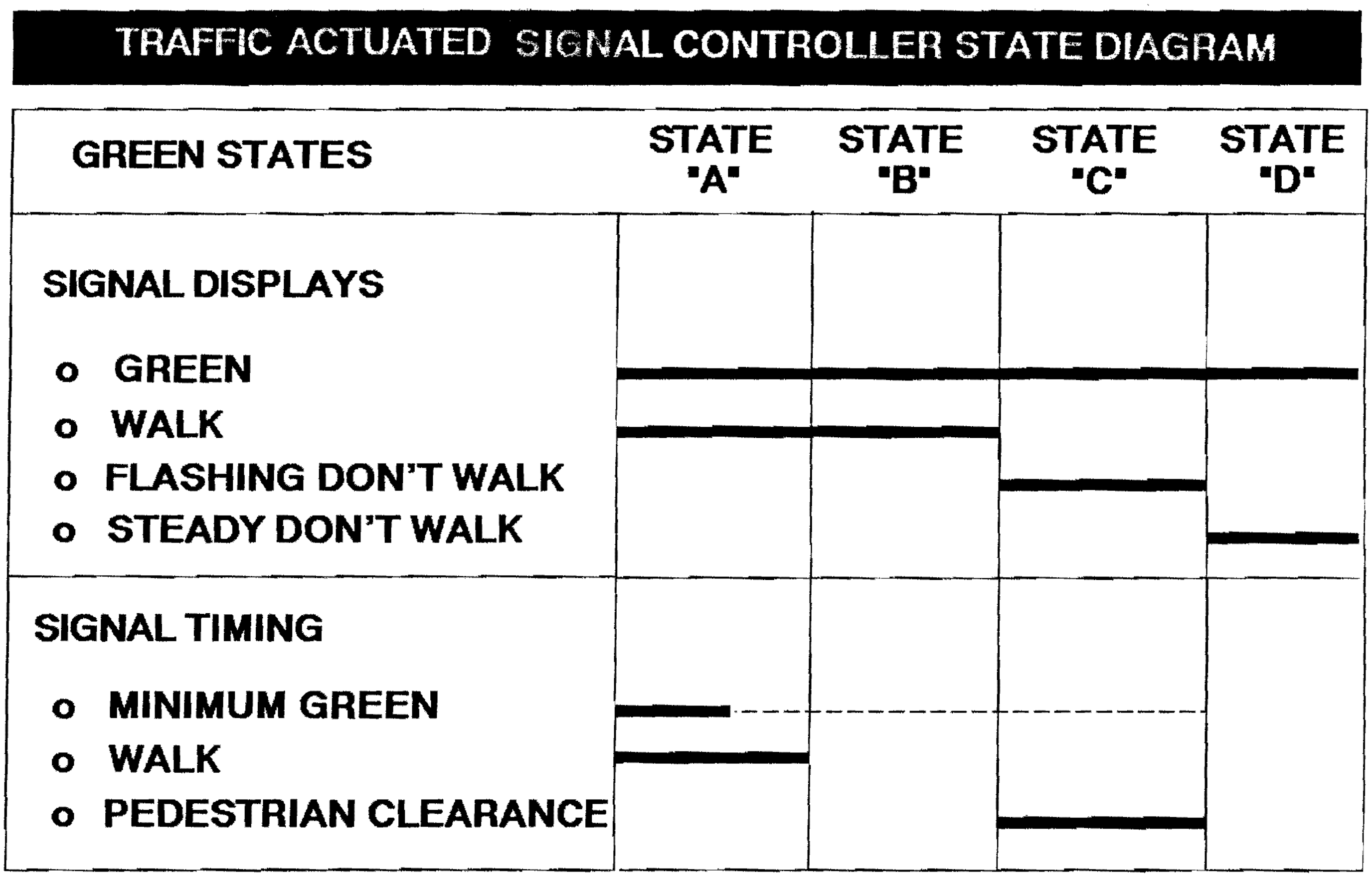


Figure 4-5 Controller Features.

Per Phase

"Per Phase" operations include "Hold" and "Phase State."

Hold An input command that retains the existing right-of-way and has different controller unit responses depending upon the current state in either the vehicle-actuated or nonactuated mode.

a. For a nonactuated phase, Hold maintains the controller unit in the timed-out Walk period with Green and Walk indications displayed. With the Walk interval timed-out, dropping Hold will cause the controller unit to advance into the Pedestrian Clearance interval.

b. For an actuated phase, Hold keeps a normal phase from advancing into its vehicle change interval and recycling off pedestrian service unless Pedestrian Recycle is on and a serviceable pedestrian call exists on the phase. The rest state for the phase is Green for traffic and Don't Walk for pedestrians.

Turning Hold off allows the phase to advance into the Green Dwell/Select state when all Green periods are timed out. The controller can recycle to Walk if there is no conflicting demand for service and a pedestrian call exists for the phase. However, any conflicting service call would cause control to advance into the Vehicle Change interval and not re-cycle to a Walk on the phase until the conflicting demands have been served.

Phase States The operational status of an active phase is defined by one of several sequential positions during phase selection. The status is defined by the state indicator of the timing and the code of the output bit status. The phases are classified as being actuated or nonactuated. Coordinated phases are called nonactuated.

1. Active phase is in the Green interval operating in actuated mode.

   Code 0 - Minimum Timing in the Initial, Walk, or Pedestrian Clearance portions of the Green interval.
   Code 1 - Extension Timing in the Green interval following the completion of the minimum timings.
   Code 2 - Maximum Green Timing following extension, under a Hold.
   Code 3 - Green Rest is a dwell period when not timing in another green state.

2. The active phase is in the Green interval and operating in the nonactuated mode.

   Code 0 - Walk Timing in the Green interval (nonactuated State A).
   Code 1 - Walk Hold is the state after Walk timing ends under Hold (nonactuated State B).
   Code 2 - Pedestrian Clearance Timing in the remaining portion of Minimum Green is timing (nonactuated State C).
   Code 3 - Green Rest is a dwell when the timing of Pedestrian and Minimum Green intervals are complete (nonactuated State D).

3. The active phase is not in its Green interval.

Code 4 - Yellow Change of the phase is timing.
Code 5 - Red Clearance of the phase is timing.
Code 6 - Red Rest is a dwell when timing is complete and a Red indication is displayed.
Code 7 - Undefined.

<u>Intersection Timing Parameters</u>

The study team has surveyed several NEMA and Type 170 signal controller manufacturers. As shown in **Figure 4-6 "Comparisons of Controller Features,"** it is important to understand feasible progression coordination schemes and operational guidelines for different signal controllers. The key points and optimum values recommended for the proper actuated controller variables and parameter settings applicable to current system design methodology are summarized in **Figure 4-7 "Recommended Actuated Controller Timing Settings"** for use in the field.

<u>Minimum Initial</u> A four second minimum initial has been found to work well when stop bar detection is present. When only advance detection is provided, a ten second minimum may be more desirable with the combination of variable initial timing parameters.

<u>Added Initial Per Actuation</u> The amount of time to add per actuation depends upon the loop configuration. If only one lane is detected on a phase or if multiple lanes are counted separately, a 2.2 second added initial per actuation is acceptable. If multiple lanes are counted with one loop, or one controller input, a shorter extension is recommended to compensate traffic dispersion among various lanes. A 1.5 second added initial per actuation may be an appropriate time.

<u>Maximum Initial</u> The maximum initial has historically been set to the length of the detector setback divided by 10 plus startup time. Startup time should be between two and four seconds. No study results were obtained that contradict this recommendation.

<u>Vehicle Extension</u> With adjustments for the resolution problems of the simulation models, a vehicle extension of roughly 2.5 to 3.0 seconds appears to be optimal for the recommended detector configuration. Gap reduction does not appear to be justifiable except to provide a longer extension during queue discharge. Further research may provide some insight into this area.

<u>Maximum Green</u> Under coordination, maximum green is seldom reached due to the existence of a force off. When max-out is likely, roughly 180% of the optimal pretimed setting can be used for a peaking factor of 0.85. 10 seconds longer than optimal pretimed timing can be used for a peaking factor of 1.0.

<u>Memory Lock</u> To prevent vehicles being trapped downstream of the detection, the memory lock should be set on any approach which has advance detection without stop bar detection.

COORDINATION FEATURES AMONG DIFFERENT SIGNAL CONTROLLERS						
CONTROLLER FEATURE	DIFFERENT SIGNAL CONTROLLERS					
	TEXAS SPECS	NAZTEC 900	ECONOLITE ASC-8000	EAGLE EPAC	W4IKS 170	LACO-1 170
NEMA CONTROLLER	V	V	V	V		
TYPE 170 CONTROLLER					V	V
MANUAL CONTROL OF COORDINATION FEATURES	NOT NEEDED (1)	HOPEFUL	HOPEFUL	EXTERNAL UNIT NEEDED (2)	LIKELY	DEFINITELY
FORCE-OFF	AUTOMATIC	PRIMARY FORCE-OFF	YIELD + COORD. + FORCE-OFF SPLIT EXT	N/A	FORCE-OFF	FORCE-OFF
HOLD FUNCTION	AUTOMATIC	APPLY HOLD	YIELD	N/A	SPLIT	HOLD
PED-OMIT FUNCTION	AUTOMATIC	PED-OMIT	EXTERNAL UNIT NEEDED	N/A	OPPOSITE OF PED-PERMISSIV E	PEDESTRIA N RESTRICT
PHASE-OMIT	AUTOMATIC	PHASE OMIT	PHASE SPLIT = 0	N/A	N/A	SPECIAL PROGRAM VERSION
VEHICLE RECALL PER RING	AUTOMATIC	EXTERNAL UNIT NEEDED	VEHICLE RECALL	N/A	MIN. RECALL	HOLD W/ CALL

NOTE -

1. TEXAS SPECIFICATIONS ONLY REQUIRE THAT THE CONTROLLER BE ABLE TO RUN UNDER COORDINATION WITH GIVEN SPLIT AND OFFSET INFORMATION. MANUAL CONTROL OF THE COORDINATION FEATURES IS NOT REQUIRED.

2. NEMA SPECIFICATIONS REQUIRE THE INPUT PINS FOR SPECIFYING THE COORDINATION OF THE RING FORCE-OFF, PHASE HOLD, AND PHASE OMIT. ALL NEMA CONTROLLERS PROVIDE SOME CONTROL OVER THESE COORDINATION FEATURES IF AN EXTERNAL UNIT IS INSTALLED.

Figure 4-6. Comparisons of Controller Features.

RECOMMENDED ACTUATED CONTROLLER PARAMETER SETTINGS					
SIGNAL TIMING PARAMETER	TRAFFIC MOVEMENTS				
	ARTERIAL STREET		SIDE STREET		ALL
	MAJOR INTERSECTION	MINOR INTERSECTION	MAJOR INTERSECTION	MINOR INTERSECTION	LEFT TURN
MINIMUM INITIAL	4	10	4	4	4
ADDED INIT / ACTUATION	-	2.2	-	-	-
MAXIMUM INITIAL	-	25	-	-	-
MAXIMUM QUEUE	25	-	25	-	-
INITIAL					
VEHICLE EXTENSION	A	A	A	3.0	1.1
MAXIMUM GREEN	60	60	60	30	25
YELLOW CHANGE	4	4	4	3	3
RED CLEARANCE	0	0	0	0	0
RED REVERT	1	1	1	1	1
RED LOCK	NO	NO	NO	NO	NO
YELLOW LOCK	NO	YES	YES	NO	NO
DOUBLE ENTRY	NO	NO	NO	YES	NO
LAST VEH. PASSAGE	NO	NO	NO	NO	NO
VEH. (MIN) RECALL	YES	YES	NO	NO	NO
RED REST	NO	NO	NO	NO	YES

NOTE - 1. "A" - INDICATES 2.5 SECONDS SHOULD BE USED UNLESS OTHERWISE INDICATED.
2. "-" - INDICATES NOT APPLICABLE.

Figure 4-7 Recommended Actuated Controller Timing Setting.

Last Vehicle Passage With the recommended detector setback and vehicle extension, last vehicle passage should not be set.

Vehicle (Minimum) Recall Vehicle recall is typically placed on the artery to guarantee the return of green. This practice appears to be appropriate for signal timing.

Red Rest If the vehicle recall is not used, which may be desirable at a major-to-major signalized intersection, red rest should be set for all minor phases, such as in the left turn phases. This will prevent operational resting in a phase with little traffic demand.

Detector Setback If possible, the detection should be designed at roughly four (4) seconds upstream of the signalized intersection. For a 35 mph approach, this design would place detection at roughly 200 to 225 feet. The detectors should operate in presence mode to detect vehicles for longer intervals if they are in queue discharge and moving slowly. If existing advance detection is not located at the optimal distance, the vehicle extension does not appear to change. However, intersection performance will not be as high.

Arterial Coordination Schemes

Coordination schemes are dependent on intersection signal timing parameters, background cycle length, and coordination offsets. Important timing parameters include the splits provided for each approach, and the corresponding phase sequences. The system would be run based on a repetitive fashion, which would be related to a background cycle length. The sum of all phases at each intersection would equal this background cycle length or an integral multiple of it. Each of these intersection cycles would be offset in time such that the vehicles leaving an intersection are processed at the next approach without having to stop. Proper timing and offsets would thus provide adequate progression opportunities to the traffic through the system.

Advanced Management Features

Assuming the detection system can identify congested approaches, arterial platoons, and delayed controller actuation, three (3) advanced traffic management problems could be addressed.

1. "Near Saturated" intersection operations,
2. "Early Return" to main street green, and
3. "Late Arrival" of progression platoon.

The proper linkages are made by adjusting coordination force-off schemes, phase sequences, and ring reversal for coordinated, traffic responsive operations. Most manual timing adjustments and operational sensitivity evaluations can be made from the existing PASSER II-90 model.

Force-off Schemes Three (3) types of "Force-Off" schemes can be used to shorten/extend coordination phases and enhance system progression without having to overrun any coordinated phases. Possible "Force-Offs" include:

1. "Fixed Force-Offs" - takes "next phase" to accommodate any coordinated green extension.
2. "Floating Force-Offs" - takes "last phase" to accomodate any coordinated green extension.
3. "Proportional Force-Offs" - takes some green time proportionally from each of the subsequent phases to accomodate any coordinated green extension.

Phase Sequence Under the conventional signal controller "Barrier Concept", the proper per-scheduled phase sequence, which defines relationships between Main Street (2+6) and Cross Street (4+8), must be carefully maintained while improving coordination through "Fixed/Floating Force-Offs" schemes.

1. Fixed Force-Offs. (2+6) -\-> (4+8)
2. Floating Force-Offs. (4+8) -\-> (2+6)
3. Proportional Force-Offs. Phase sequence doesn't matter.

As a result, putting the Main Street and Cross Street coordination phases together, with main leading-cross lagging or main lagging-cross leading would be preferred to support both Fixed and Floating Force-Off options.

Offset Adjustments Certain offset adjustments are possible to advance offsets to provide traffic responsive operations for accommodating early/late arriving platoons/queues and maintaining two-way progression:

1. Use "Ring Reverse" features to call other sequence, and
2. Change "Barrier Offsets" based on detector status.

DESIGN CONSIDERATIONS

A methodology is provided to quantify actuated signal systems performance measures. As shown in **Figure 4-8 "Overall Coordination Criteria,"** design considerations, study site description, and performance measures are developed. In this way, all geometric factors, signal phasing, detector design, and actuated settings can be properly evaluated.

To provide a qualitative and quantitative assessment of coordinated, actuated signal control, both available analysis tools and systematic study evaluation procedures are provided.

Available Analysis Tools

Optimization software is designed to provide deterministic results by considering random behavior macroscopically. Available software can simulate some aspects of actuated control. However, most software is limited in its assessment of traffic behavior and actuated control under coordination. The use of a simulation model is necessary for evaluation.

Traffic signal system analysis software packages are classified as either macroscopic or microscopic. "Macroscopic models" use mathematical expressions to analyze traffic flow over urban streets to determine a system's measures of effectiveness: delay, queue, and fuel consumption. These models can carry out

ARTERIAL PROGRESSION COORDINATION CRITERIA			
NO	IMPLEMENTATION GUIDELINE	ATTRIBUTE MEASURES	
1	HIGH PERCENTAGE OF THRU TRAFFIC ON OUTBOUND LINK OF INTERSECTION **(THRU TRAFFIC)**	1. STATE HIGHWAY WITHOUT BYPASS	
		2. ARTERIAL STREET	
		3. LEVEL OF SERVICE EVALUATION THRESHOLD	A >= 90%
			B >= 80%
			C >= 70%
			D >= 60%
			E <= 60
2	HIGH PERCENTAGE OF THRU TRUCKS TRAFFIC VOLUME **(TRUCK TRAFFIC)**	1. TRUCK EQUIVALENT FACTOR	Lv=30, E=30/15=2.0
			Lv=42, E=39/15=2.6
			Lv=48, E=48/15=3.2
3	UNIFORMLY SPACED SIGNALS THAT PROMOTE PROGRESSION AT DESIRED PROGRESSION SPEED **(GOOD ARTERIAL GEOMETRY)**	1. PASSER II PROGRESSION EFFICIENCY	"E" >= 25%
		2. LEVEL OF SERVICE EVALUATION THRESHOLD	A >= 35%
			B >= 25%
			C >= 15%
			D >= 5%
			E <= 5%
4	ARTERIAL THRU VOLUMES AT MANAGEABLE LEVELS DURING PEAK HOUR PROGRESSION OPERATION **(ACHIEVEABLE PROGRESSION)**	1. TRAFFIC VOLUME	1. 200-450 pcphpl
		2. VOLUME-TO-CAPACITY RATIO	2. 0.4 <= v/c <= 0.9 (200) (450) c = 500 pcphpl
5	SIGNIFICANT UNI-DIRECTIONAL OR BI-DIRECTIONAL TRAFFIC PATTERN NEAR MAJOR ACTIVITY CENTERS **(DIRECTIONAL PATTERN)**	1. AREA LOCATION	DOWNTOWN CBD
			SUBURBAN ARTERIAL
		2. ACTIVITY CENTER	FACTORY ENTRANCE
			SHOPPING CENTER
			WORKPLACE
6	OTHER FACTORS (TO BE ADDED)		

Figure 4-8 Overall Coordination Criteria.

optimization or simulation activities. Optimization permits a search for the signal timing plan which results in the best optimimization objective value, while simulation uses predetermined signal settings to assess system performance. "Microscopic computer models" simulate individual vehicle movements through the street system and update their status in small time increments. Most of the traffic models, however, can only carry out limited simulation analyses.

Each evaluation tool offers distinct advantages and disadvantages with some models yielding more realistic results for certain applications. Therefore, the limitations of each model must be considered so that the model will yield realistic results for the conditions being modelled.

Coordination and Actuation

Pretimed control often performs very well during coordination under high volume conditions and predictable oversaturation. However, the capability of pretimed control provides control flexibility and optimum performance under low volumes is minimal. Actuated controllers have the capability to fall back to pretimed operations, and provide the leeway needed to handle variable traffic demand under different operating conditions. However, it is difficult for engineers to combine actuated control and signal coordination easily for satisfactory performance.

Analysis Procedure Development

Detailed studies on isolated pretimed and actuated signals have been conducted by several researchers. NCHRP Report No. 233 provides a detailed examination of the sensitivity of several variables under different conditions [Tarnoff, Parsonson 1981]. Guidelines are recommended regarding the type of signal control at isolated intersections. MUTCD warrants also provide the needed decision-making guidelines [MUTCD 1985]. Because of the similarity of the basic concepts, existing analysis techniques for pretimed coordinated systems will be extended to analyze coordinated, actuated operations.

Improved Actuated Operation

Coordination can improve traffic system performance by taking advantage of available progression opportunities. Semi-actuation is being successfully used at isolated intersections and coordinated systems. Real-time coordination depends on system size and expected traffic behavior. When the signal control switches to a more responsive type, the need to allow more flexible control becomes important.

CHAPTER 5. OPERATIONAL EVALUATION

This chapter illustrates a real-world operational evaluation comparing existing uncoordinated full-actuated, pretimed, and other arterial coordinated signal timing alternatives that can take advantage of the coordinated, actuated controller features.

EVALUATION CONSIDERATION

An analysis of the operational evaluation will yield realistic and practical system strategy comparisons.

Simulation Study

Signal timing analysis software has been increasingly used to improve the design and operation of coordinated arterial signal systems. Most existing tools, however, use optimization algorithms based on default settings or user-selectable criteria. The relative importance of the various measures of effectiveness and quantitative magnitude is, however, very location sensitive. Stop minimization may be a primary objective suitable at some locations, whereas emission minimization may be of higher importance at other locations. Therefore, the selection of performance measures as indicators is important.

For instance, the engineering methods for achieving system coordination, as commonly used in PASSER II and TRANSYT, are quite different. PASSER II-90 is designed for the maximization of progression bandwidths to explicitly achieve low delay and stops in the arterial direction. TRANSYT-7F minimizes the performance index, which is a combination of system delay and stop measures, as the basic system optimization objective.

Field Study

The measurements of effectiveness considered for arterial system measure should include delay, stops, fuel consumption, emissions, etc. The number of stops is an important measure of system effectiveness. Emissions are becoming an increasingly important factor, and traffic engineers are starting to apply techniques to consider pollution in signal system design. Factors, such as operational safety, ease of operation, and operating speed are important for determining proper control strategy. In addition, quantifying the effects of such qualitative factors could be difficult.

However, the system-wide delay measure should also be considered from an economic perspective. In particular, the performance of different control strategies with respect to user controllable factors should be integrated. An evaluation of operational sensitivity with respect to these control variables should be examined.

ANALYSIS APPROACH

As shown in **Figure 5-1 "Study Analysis Approach,"** after the initial sets of coordinated signal timings were obtained from the TxDOT Corpus Christi District and the Fort Worth District, series of coordinated timing plans were

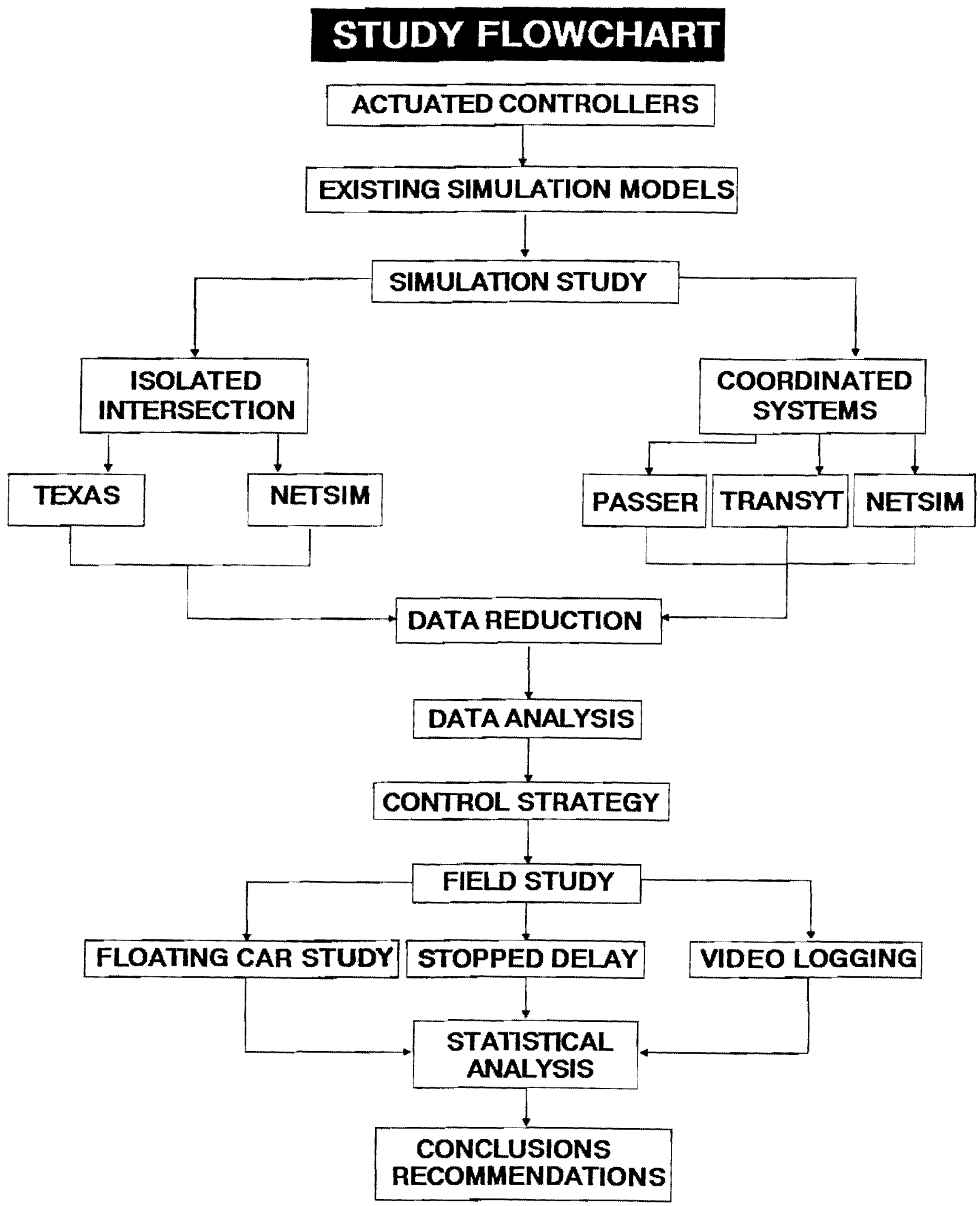


Figure 5-1 Study Analysis Approach.

developed. Simulation studies were conducted to identify the optimal values under both isolated actuated and coordinated actuated control. The performance of each timing scheme was first evaluated through the simulation model. The field experiments were conducted. Finally, the results were compared against the field study.

Simulation Analysis

The study procedure for analyzing an actuated coordinated system is similar to that of a pretimed system. The major differences are the additional considerations and the required variables to account for the necessary translation. Therefore, some analysis steps commonly used in pretimed systems must be modified for coordinated actuated systems.

Pretimed analysis requires data collection, tabulation, and an understanding of existing operations. The adjustment features in the actuated system can adapt to traffic conditions dynamically to accommodate variations that would otherwise result in inefficient pretimed operations. Pretimed analysis will provide the user with the information required to achieve good coordination. The field study procedure described below summarizes the needed data reduction, data processing, and value translation to achieve reasonable actuated system parameters. Iteration with traffic software such as PASSER II, TRANSYT, NETSIM and TEXAS, can be used to assist the analysis.

Field Study

To improve any given coordinated actuated arterial signal system, field study analyses must incorporate the following study steps:

1. Basic Data Collection The first step is the data collection and data reduction from the existing system. This is similar to the analysis of an actuated system as in the 1985 Highway Capacity Manual. Additional data may be collected to estimate emissions. Data should also be selected from the field at time intervals with representative volume conditions for the user.

2. Control Strategy Selection The decision on the type of control is provided by the implementation guidelines. For example, selection depends on volume conditions and site specific requirements. Low side street volumes suggest semi-actuated control. Low volumes with large signal spacing indicate full-actuated control, within certain limits. Phasing selection could be decided initially, and refined later depending on control requirements. Leading Lefts would be preferred in locations with fewer left turns, with most arrivals in progression bands.

3. Pretimed Analysis and Control Requirements This stage includes a close examination of the system to address the possibility of tweaking the system parameters with different control settings. Guidelines and Handbooks should adequately aid the engineer in identifying possible parameters. The pretimed analysis result would provide a comparison between actuated and pretimed systems.

The detector positions could be arrived at using the optimum parameters mentioned in the guidelines.

The location and dimension of physical devices, such as detectors, should be as suggested in this report. Detector operations should be made clear through site-specific guidelines. Determining controller settings is important in actuated control. Adequate information should be provided for each variable to identify the best possible setting.

4. Conversion of Pretimed Setting into Actuated Settings Pretimed Optimization usually provides the user with the most frequent maximums required. The force-offs in a coordinated system would be ideally suited for serving the approach as soon as the largest possible demand is detected without sacrificing other approaches. Thus, the best settings for the force-offs would be the pretimed splits provided by the pretimed analysis. Other variables could be easily derived from graphs indicating ideal vehicle extensions and detector setback for a similar configuration.

5. Signal Timing Implementation The implementation of the timing plan would not be complete without the description of how it is to be made in the field. A set of instructions should be developed to indicate how to incorporate these timings into the controller, with special attention being given to the combination of variables that the user must provide for efficient progression operation.

MEASUREMENTS OF EFFECTIVENESS

Actuated controllers have already proven their potential to handle the stochastic demand variations at each intersection. Arterials can also benefit from the extra time provided by the actuated phases that terminate early and give extra time to other phases, such as in arterial directions. This can further improve arterial progression along main street approaches.

A number of performance measures were examined to see the operational sensitivity of control treatments under various conditions. The simulation study provides operational sensitivity measurements and offers other quantitative measurements that may be expected from field data collection study. Several different elements are being evaluated to quantify the system results. These measures of effectiveness are listed below:

Saturation Ratio To represent various volume loadings, volume-to-capacity or saturation ratios can be used to represent typical operations and loading conditions throughout different times-of-day.

Progression Efficiency The progression efficiency is defined as the ratio of the available progression bandwidth to the cycle length, expressed as a percentage. A progression efficiency of 30% to 40% is considered good. Anything beyond these limits may be acceptable only if the arterial directions have unequal priority.

Delay **Stop delay** is the difference between the time a vehicle takes to clear a system and the time it would have done so if it had travelled without stopping. **Stopped time delay** is the time the vehicle spends stopped at the intersection. **Approach delay** is the sum of time lost in acceleration, deceleration, and stopped delay. **Time-in-queue delay** is the time spent in queue over the time taken to clear the intersection.

Delay is a disutility measure, expressed in seconds or hours lost on a per vehicle basis. An appropriate measurement technique should be arrived at depending on ease of measurement, unambiguity, data-collection crew size, and length of intersection approach to be observed. Generally, the higher the value of the delay measurement, the worse the performance of the system.

Stops If a vehicle travels below a certain predefined speed it can be considered to have stopped. In some cases, a lock-wheel situation only is considered to be a stop. This disutility measure, expressed in number of times the vehicle entered a bound range of speeds, is considered to be the number of stops incurred.

Fuel Consumption and Emissions The fuel consumed by the vehicle traveling through the system is a common disutility measure. The corresponding air quality measures, expressed in nitrogen dioxide (NOx), hydrocarbons (HC) and carbon monoxide (CO), is another important disutility factor. With the recently passed environmental protection laws, many traffic control related decisions are dependant heavily upon those measures.

Combined Measures

Other system throughput efficiency measures, such as total volumes and travel speeds, are examined in the exercises in the project. System disutility functions, such as delay, stops, and saturation ratios are also investigated. Other field measurable operational parameters, such as cycle length, green utilization, and other combined indicators were also examined.

S-Index For the evaluation of the different traffic control strategies, the S-Index was proposed. This index is the total cost to society for the operation of a traffic signal system. This includes a dollar value on the total time, stops, fuel consumption and emissions of Carbon Monoxide, Nitrogen Oxides, and Hydrocarbons.

The S-Index is a combination of factors used in the comparisons of the Valley Boulevard Coordinated System study. This index can be easily understood by policy makers, since it gives a good picture of the financial implications of adopting a particular control strategy. The index is, however, variable with location, time and implementation priorities. The same combinations of constants should be used in examining any one system. It is easy to estimate the values for the calculation of this index in the field. This index is generally dominated by the delay factor, and hence in some of the comparisons, decisions were made purely on the basis of the delay values.

An estimate of the S-Index can be easily obtained for the artery from the appropriate field data. The recommended method of obtaining this data is the floating car arterial travel time study. The data should be recorded with the total travel time between each signal, stopped delay at each signal, total number of stops, and all stops and other travel interference.

All data that is significantly affected by external factors should be disregarded. In addition to the above data, traffic volume counts should also be performed along the study route. To calculate the S-Index, the cost of the various items can be obtained from various sources and should be kept up to date. The total travel time experienced by all drivers can be estimated from the average travel time experienced by the floating car multiplied by the average total volume recorded travelling the street. The total number of vehicle stops can be recorded in a similar manner.

EVALUATION TECHNIQUE

The following assessment of operational sensitivity will be obtained from both computer simulation and limited field observations.

Analysis Methodology

Simulation studies are generally time intensive and require detailed and accurate input data to arrive at an accurate output estimate. Simulation models are not capable of accurately replicating many of the field situations, and hence approximate approaches may need to be devised. However, simulation studies have the advantage of being performed repeatedly to identify variable sensitivities, and to provide a testing ground for examinations without affecting the real world system.

Field studies, on the other hand, are laborious, time intensive and expensive. They may not be easy to replicate and may not provide an accurate benchmark for comparison. In most traffic studies, including this project, field studies are considered as a verification and validation stage.

Simulation Model

Computer software packages for traffic signal system modeling can generally be classified as either macroscopic or microscopic models. Macroscopic computer models use mathematical expressions to analyze traffic flow over urban streets to determine a system's measures of effectiveness, such as delay, queue, and fuel consumption. These models can carry out either optimization or simulation activities. The optimization option permits a search for the signal timing plan which results in the lowest vehicular delay, while simulation uses predetermined signal settings to assess system performance.

Microscopic computer models simulate individual vehicle movements through the street system and update their status in small time increments. These traffic models, however, can only carry out limited simulation analyses. Each evaluation tool offers distinct advantages and some models yield more realistic results for certain applications. Therefore, the limitations of each model must be considered so that the model will yield realistic results for each set of conditions.

FIELD STUDY

As illustrated in **Figure 5-2 "Field Data Collection,"** the recommended method of obtaining this data is the **floating car study** combined with the **spot intersection delay study**. These field studies are described in the 1985 HCM, and should include data collection on:

- Total travel time between each signal,
- Stopped delay at each signal,
- Total number of stops, and
- Reasons for all stops and other travel interference.

All data significantly affected by external factors should be disregarded. In addition, traffic volume counts should also be performed along the study route and major cross streets. The major study, as performed in Kingsville, Texas, includes the floating car studies and side street delay studies.

Stopped Delay Study

Stopped delay studies were conducted on the cross streets at Lott by recording the queue at 15 second intervals, the total volume on the approach and the total number of vehicles that were required to stop. **Figure 5-3 "Stop Delay Data Collection Form"** shows the data collection format used.

Video Study

Field study data was also recorded using a video camera installed in a van for a visual record and later assessment of the performance of the various systems. Three of the intersections were also recorded using a stationary video camera. This video record was also used to estimate the average cycle length of the signals operating under full-actuation.

Floating Car Study

Figure 5-4 "Travel Time Data Collection Form" shows the usual format for floating car studies. In the exercise a car was driven up and down the street, and the travel time between each intersection, the stop time at each intersection and the total stops were recorded. All attempts were made for the floating car to match the prevailing travel speed of the traffic stream. The floating car studies provide a good indication of the progression provided by the system. Progression is important if there is heavy through traffic on the street, or if there are high priority vehicles that travel the street. To achieve an optimum solution, one must weigh the relative benefits of stops, delays, fuel consumption, etc., as well as the importance of the artery to the side street. In this study it was assumed that side street traffic is equal in importance to arterial traffic.

During the field studies, three signal timing control scenarios were tested per day. The time periods were the Noon Peak (11:00 a.m. to 1:00 p.m.), Evening Peak or "PM-1" (4:00 p.m. to 5:00 p.m.), and Evening Peak or "PM-2" (5:00 p.m. to 6:00 p.m.).

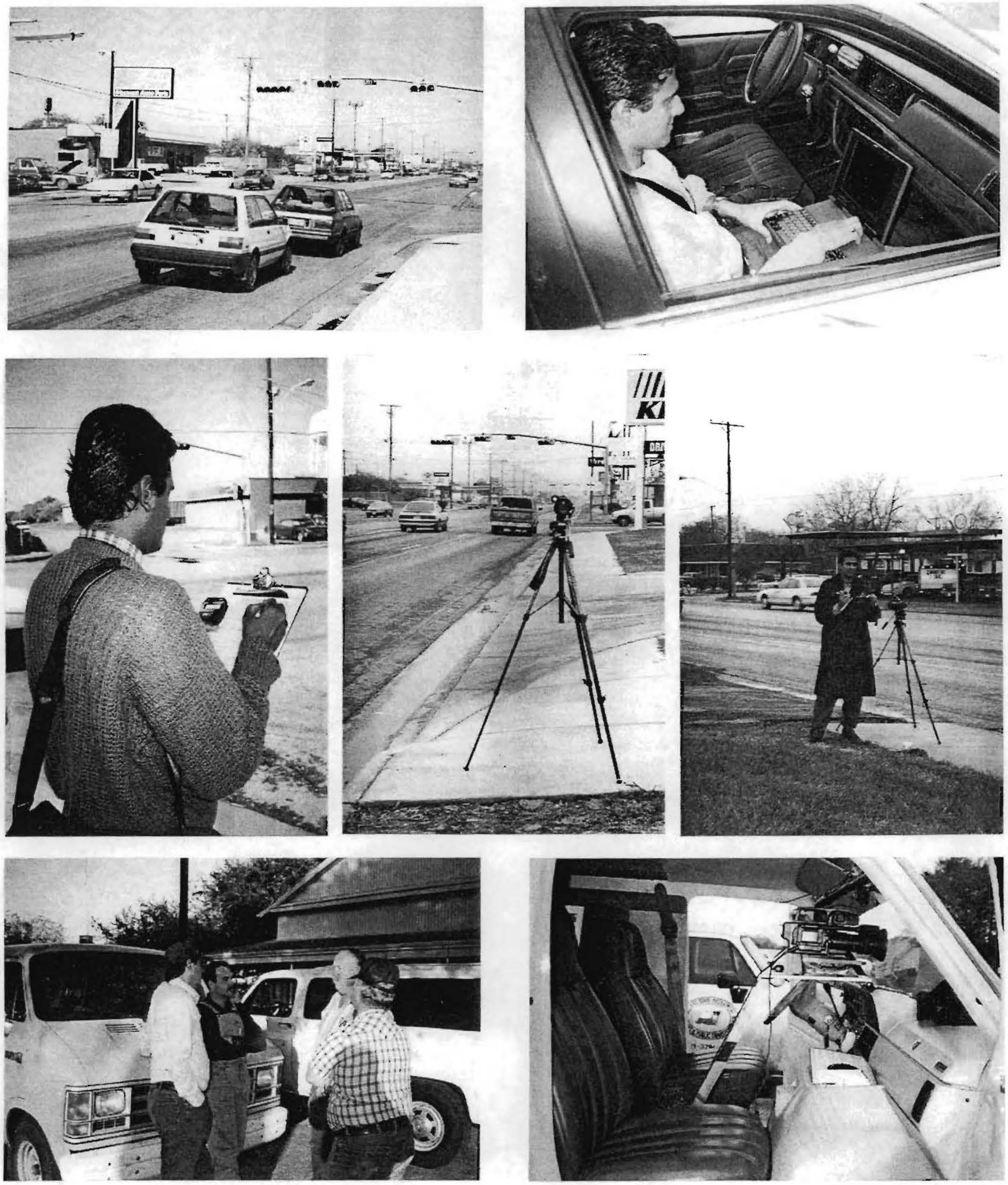


Figure 5-2 Field Data Collection.

INTERSECTION STOP DELAY STUDY

STUDY: ___________ LOCATION: _______________ PAGE:____ OF ____
DATE: ___/___/___ TIME: AM__OFF1__OFF2__PMOBSERVER: ______
7-9 10-12 1-3 4-6

NO	TIME PERIOD (HR:MIN)	NUMBER OF VEHICLES STOPPED IN APPROACH AT TIME				APPROACH TOTAL	
		+ 0 SEC	+ 15 SEC	+ 30 SEC	+ 45 SEC	NO. STOP	NO. PASS
1							
2							
3							
4							
5							
6							
7							
8							
9							
10							
11							
12							
13							
14							
15							
TOTAL							
1							
2							
3							
4							
5							
6							
7							
8							
9							
10							
11							
12							
13							
14							
15							
TOTAL							

SUMMARY OF STOPPED DELAY STUDY

TOTAL DELAY	=	TOTAL NUMBER QUEUED VEHICLES * 15 SEC	=	
AVERAGE DELAY	=	TOTAL DELAY / APPROACH VOLUME	=	
% STOPPED	=	NUMBER QUEUED / APPROACH VOLUME	=	

Figure 5-3 Stop Delay Data Collection Form.

TRAVEL TIME FIELD DATA COLLECTION WORKSHEET

Arterial________________________ Date________________________

Driver____________ Recorder____________ Direction________________________

SIGNAL LOCATION	Distance (Mile) (Feet)	RUN NO.___ TIME_____ CUM/TT (SEC)		STOP TIME (SEC)	RUN NO.___ TIME_____ CUM/TT (SEC)		STOP TIME (SEC)	RUN NO.___ TIME_____ CUM/TT (SEC)		STOP TIME (SEC)

Note - Coding for small squares in CUM/TT columns:

S - Signal (lower box)
LT - Left Turn (upper box)
P - Pedestrian (upper box)
PK - Parking (upper box)
4W - 4-Way Stop (upper box)

Figure 5-4 Travel Time Data Collection Form.

Study Tools

Two programs, FLOATCAR and FLOATPRO, were developed to facilitate field-data collection, reduction and analysis, as illustrated in **Appendix B and Appendix C.** The use of the two programs greatly reduced the time and tediousness involved in the data collection effort. They also drastically reduced the data reduction and analysis time requirement, while ensuring data reliability. The programs performed well during the data collection effort, and are therefore recommended for data reduction and analysis.

FLOATCAR is a user-friendly menu-driven program that eases floating car field data entry. This program can be used in any IBM Compatible PC or Laptop. The data collected using the FLOATCAR program can be processed using the FLOATPRO program to get tabulated floating-car study data values.

The output from the FLOATPRO program consists of a comma-separated file tabulating the details of the run, the travel times recorded at each intersection, and the total stopped delays during the different runs. The average values for a set of runs in different directions are provided. The output file stores these values, which can be used for immediate processing.

KINGSVILLE STUDY

The first demonstration site is located at Kingsville, Texas, located 50 miles south of Corpus Christi. Kingsville has a population of 27,000. The signal system consists of two main arterials, route US-77 (North - South) and route SH-141 (East - West). These routes carry a majority of the traffic among the primary city generators. The two streets form a T-system as shown in **Figure 5-5 "Kingsville Study Site."**

There are 12 moderately spaced intersections in the entire system. Seven of these intersections are located along US-77, four are located along the SH-141, one of which is at the intersection of SH-141 and US-77, and two intersections are located off the two main routes. One intersection on US-77 is five-legged, and all the other intersections are standard four-leg design. Two-way left turn lanes are provided on both of the major routes for mid-block turners and all signals are full-actuated. The peak hour falls during the evening hours, and the traffic volumes are well below capacity. The speed limit for the section relevant to the study is 35mph, except for a short length at the northern end where the speed limit is 40 mph. The Kingsville system runs full-actuated, without any coordination. Recently, the signals have been brought under the control of a closed loop system, manufactured by Econolite. This state-of-the-art system provided the opportunity to control, observe and investigate the system from a central location.

Study Procedure

Field studies require great manpower and financial resources. Hence a set of simulation studies was first undertaken to understand the system and to identify the scenarios that needed to be considered. Fourteen scenarios were considered for the first screening. After examining the results, a total of seven (7) control strategies were examined in the field experiments conducted

KINGSVILLE, TEXAS

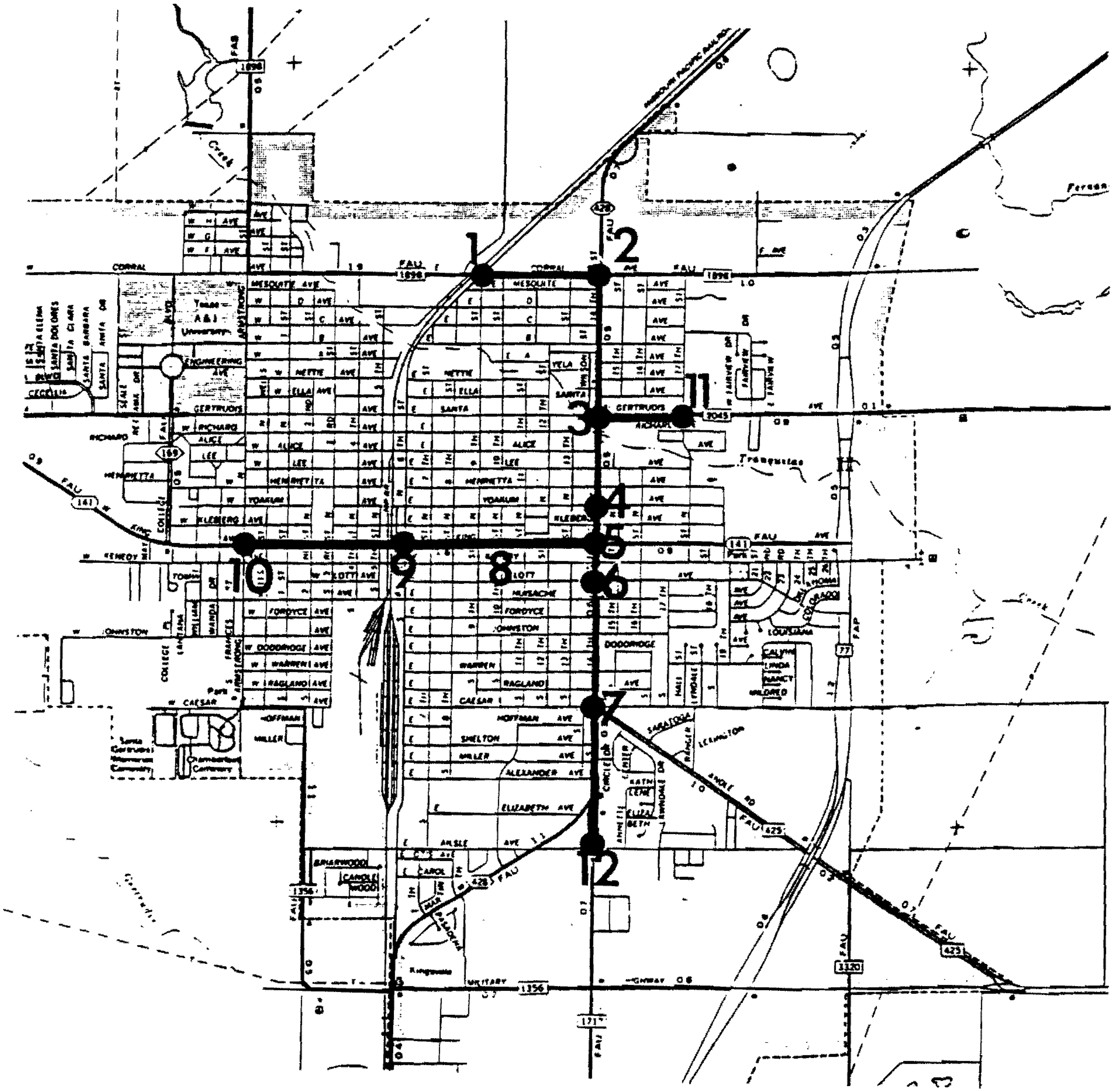


Figure 5-5 Kingsville Study Site.

on 12/08/92 (Tuesday) and 12/10/92 (Thursday):

CASE 1. Full-Traffic Actuated running free (Currently used by TxDOT),
CASE 2. Semi-Traffic Actuated coordinated with a 100 sec cycle length,
CASE 3. Full-Traffic Actuated running free (Currently used by TxDOT) at evening,
CASE 4. Three intersections (King, Lott and Ceaser) operating Semi-Actuated with a 55 sec cycle with the rest of 4 signals operating free,
CASE 5. Semi-Traffic Actuated coordinated with a 70 sec cycle length,
CASE 6. Pretimed coordinated with a 70 sec cycle length,
CASE 7. Semi-Traffic Actuated coordinated with a 55 sec cycle length,
CASE 8. Semi-Traffic Actuated coordinated with a 55 sec cycle length, and
CASE 9. Semi-Traffic Actuated coordinated with a 80 sec cycle length (TxDOT modified timing).

Cases 1, 4 and 7 were conducted during the NOON peak period. The rest were conducted during the PM peak period. These strategies can be classified into four groups based on different analysis methodologies.

<u>TxDOT PASSER Based Semi-Actuated Timing Scheme</u> Timing Case 2 and Case 9 were obtained through the PASSER II-90 analysis by the TxDOT Corpus Christi District Office. These runs were made to improve overall arterial progression. The original run produced a 100 second cycle length. However, after modifications were made to the data set to account for actuated control, the program produced an 80 second cycle length with the early return strategy.

<u>PASSER-TRANSYT Based Pretimed and Semi-Actuated Timing Scheme</u> To further improve the PASSER II timing, the study has analyzed the Kingsville system using the TRANSYT-7F program. A 70 second cycle length was obtained. These were used in Timing Cases 5 and 6.

<u>Minimum Delay Cycle Length Based Timing Scheme</u> The examination of PASSER II-90 output indicated that the minimum delay cycle length at a number of intersections was in the range of 55 seconds. This led to the conclusion that the actuated controllers provided superior operation if they were coordinated with a 55 second cycle length. Such a system was designed with TRANSYT and tested as Timing Case 7 and Case 8.

<u>V/C Ratio Based Timing Scheme</u> The intersection volume-to-capacity-ratios ranged from 15 to 60%. It was suspected that the fixed coordinated cycle lengths could not compete against full-actuated control at intersections operating below 40%. Thus, a new timing scheme was produced that concentrated on coordinating signals operating above 40% volume to capacity. In this solution, intersections at King, Lott and Caesar along 14th Street were coordinated. Although Lott Avenue operates below the specified v/c level, it is included due to its location between two intersections that operate at much higher v/c ratios. This resulted in Timing Case 4.

<u>Approximation Method</u>

The previous examination of the system using NETSIM was based upon the overall system delay. Travel-times obtained from the floating car studies primarily reflect the status of the arterial only. An approximate method to calculate the overall system delay from the floating car data was proposed by the researchers to obtain a value that could be compared with the previous simulation results.

FLOATPRO is designed to give the absolute and average stopped delay during each floating car run as an output. The average stopped delay combined in both directions gives an approximation of the total delay experienced by a single vehicle on the arterial street. This is the same as the non-weighted sum of the delay-per-vehicle values at each of the arterial approaches. The manual stop delay counts conducted at Lott Avenue provided an estimate of the average delay experienced by a side-street vehicle approaching the system. The arterial stop delay and the side-street stop delay values were combined to compare with the values obtained from the NETSIM model as follows:

Total System Delay/Vehicle = 1.35 * Total Arterial Delay + 5 * Side Street Delay at Lott

Study Result

As shown in **Figure 5-6 "Simulated and Field Observations,"** the closeness of the trends is remarkable and strongly indicates the veracity of the simulation results. NETSIM delays in the figure are that of the PM peak period. Therefore, it can be confidently stated that the results previously obtained from the NETSIM simulation model are very accurate. This implies that the NETSIM model is a very accurate representation of pretimed and actuated signal operations.

The results of the experiments with NETSIM showed that actuated control improved the performance of the system when compared to pretimed control. A total of five coordinated timing schemes were tried on the system and all performed inferior to the full-actuated uncoordinated system due to the characteristics of the arterial system. In addition, there is significant improvement, based on the number of stops, when semi-actuated control is used rather than full-actuated or pretimed control. However, there are no significant delay reductions among all semi-actuated operations but the early return strategy tends to provide lower stops. The evaluation indicates that the potential system performance saving is very significant as compared to existing pre-timed operations, as shown in **Figure 5-7 "Potential System Improvements."**

BURLESON STUDY

The location of this study is along a 2.32 mile section of SH174 in Burleson, Texas. The SH174 study area extends from Hillary at the east end of Burleson to FM731 South to the west. Eight major signalized intersections are located along the section with intermediate distances ranging from 607 ft to 3076 ft. As shown in **Figure 5-8 "Buleson Study Site,"** the system consists of intersections SH174 with FM731 (North and South), Summer Crest, Newton, Ellison, Renfro, Lorna, and Hillery. At many of these intersections, frontage roads running parallel to SH174 have resulted in complicated side street

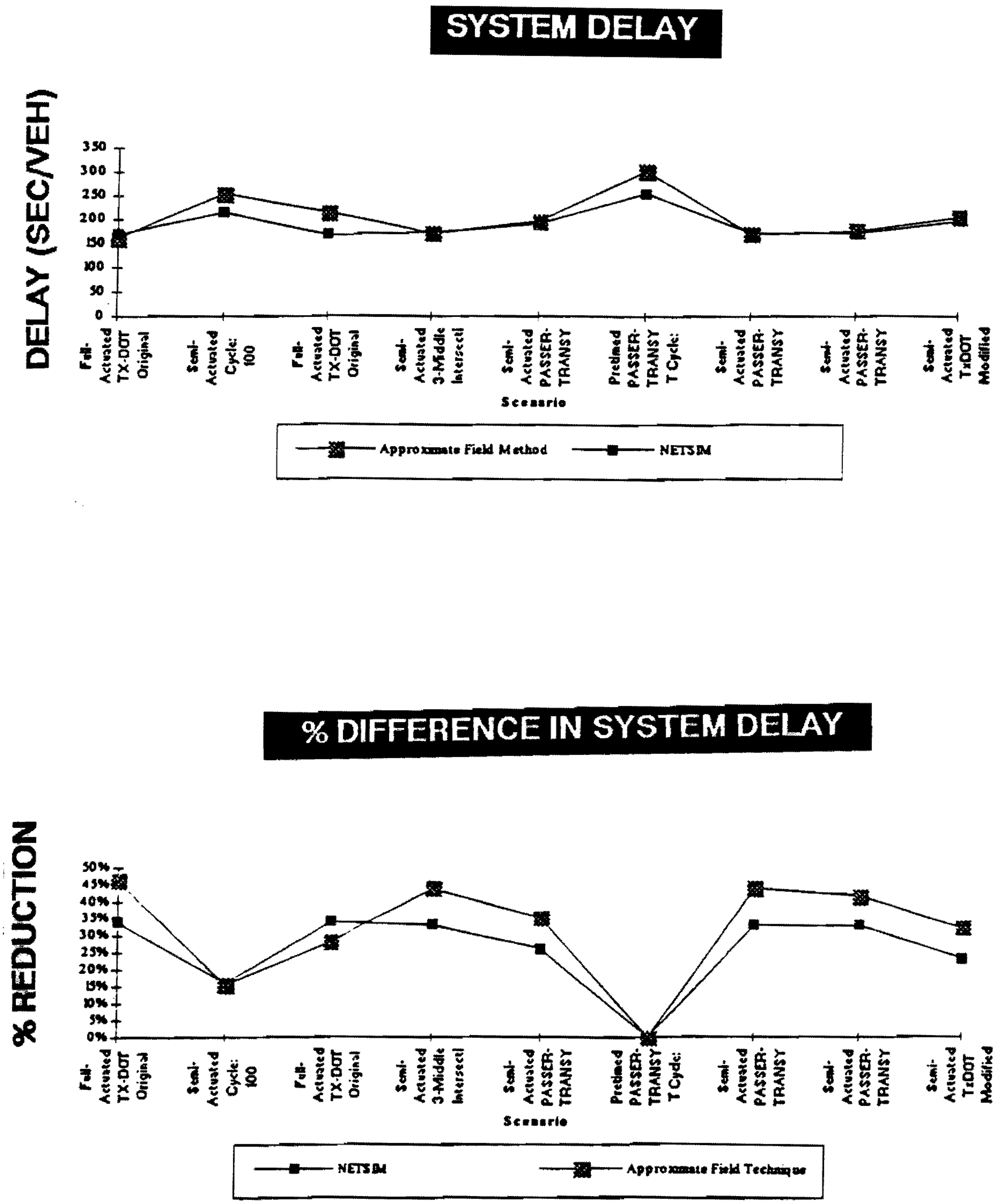
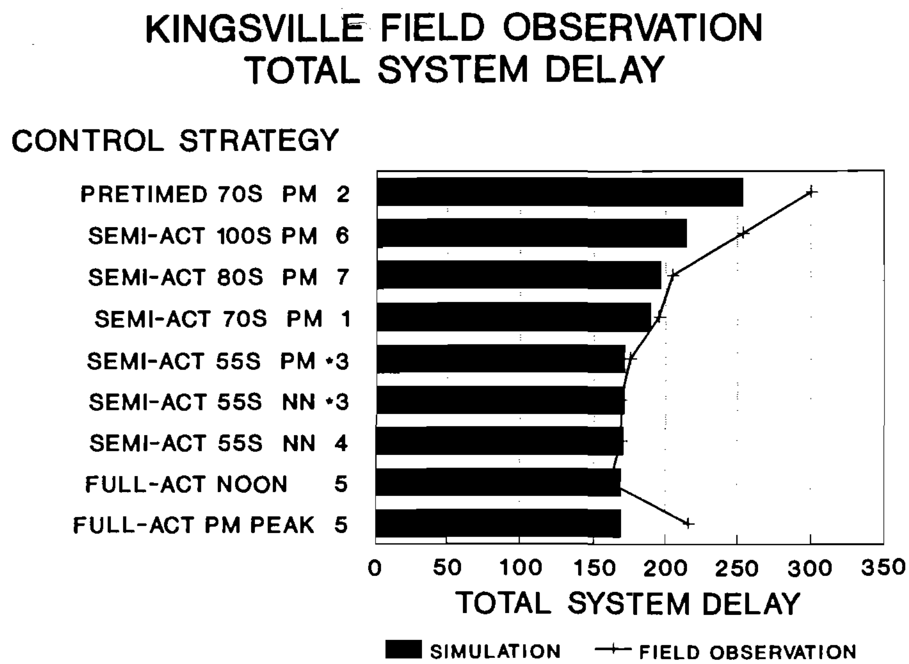


Figure 5-6 Simulated and Field Observations.



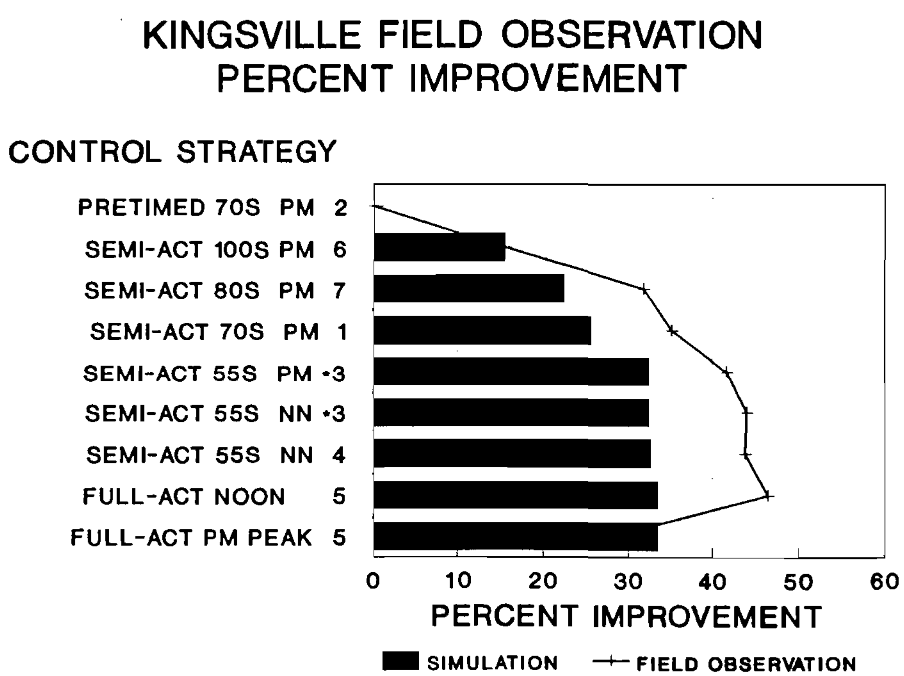


Figure 5-7 Potential System Improvements.

STUDY SITE DESCRIPTION

SH 174, BURLESON, TEXAS.

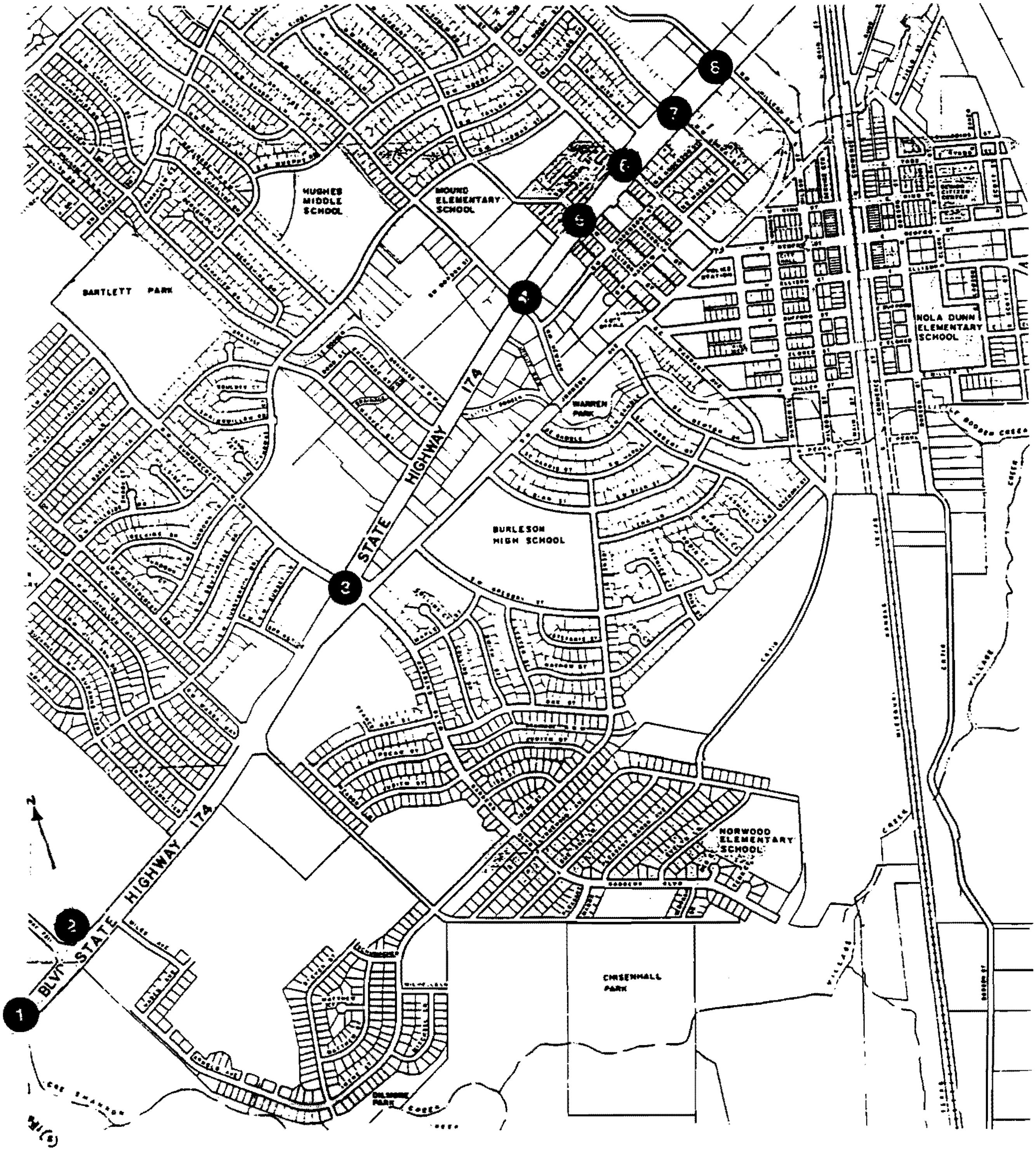


Figure 5-8 Burleson Study Site.

geometrics and detector layouts. Examination of the system details indicated features that are atypical for the arterials being considered.

After careful consideration by TxDOT and Fort Worth District officials (**Figure 5-9 "Field Study Discussion"**), the field control experiments were restricted to the arterial section between Newton to Hillery. Only this specific arterial section was evaluated in the field study, even though the entire system was analyzed in the simulation studies.

Control Strategy

Six timing schemes were tested on SH174. After careful evaluation of the system, the following control schemes were examined during 05/15/93 (Tuesday) through 05/16/93 (Wednesday):

Case 1. 110 second cycle Pretimed,
Case 2. 110 second cycle Semi-Actuated,
Case 3. 85 second cycle Semi-Actuated,
Case 4. 110 second coordinated timing, existing operation,
Case 5. 110 second cycle Semi-Actuated, Early return strategy (TTI), and
Case 6. 110 second cycle Semi-Actuated, Early return strategy (TxDOT).

Data Processing

The floating car data collected using the FLOATCAR program was manually examined to detect any errors in data entry. The comments entered during data collection were incorporated into the data file. The data were further processed using FLOATPRO to summarize the information and provide the travel times and stopped delay values into a form that could easily be analyzed.

The data output from the FLOATPRO program is formatted for direct import to spreadsheets. Microsoft Excel was used for data processing, recognizing its capability to conduct statistical tests on the data. The output data was defined as a database, and suitable information was extracted from the database block. Processing was made into a macro, which almost completely automated the analysis.

These tests were conducted at a 5% level of significance for the north-south direction, the south-north direction, and for both directions.

Early Return Strategy

One signal timing plan, the TxDOT early-return plan, was further refined using PASSER II after observing operations during the first day. This early return strategy is developed by using the following modification as obtained from the normal PASSER II progression analysis.

1. Increase East-West arterial volumes to 2,000 vph to increase arterial priority.
2. Aggregate left turn volumes in some side streets to reflect realistic lane use conditions.

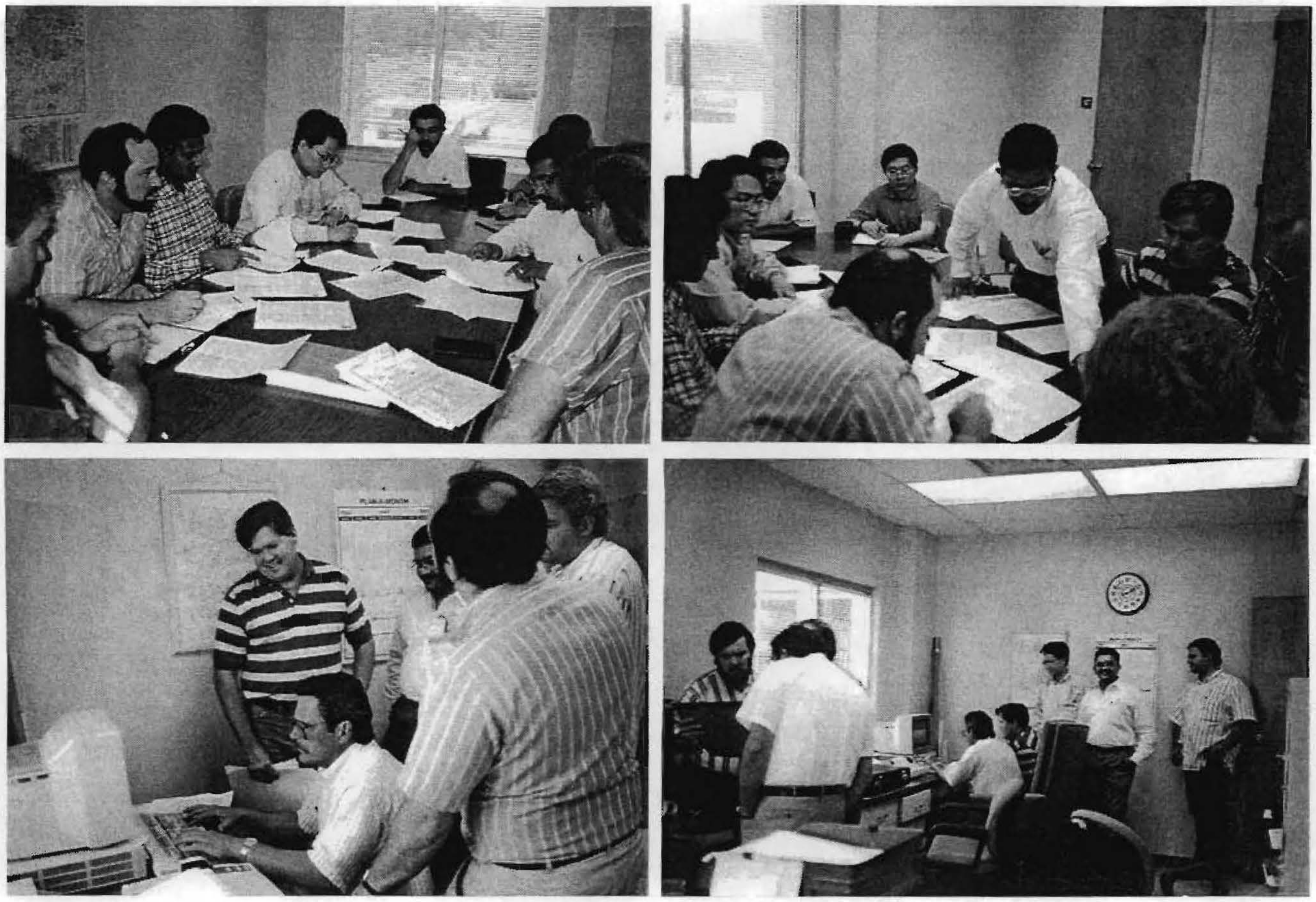


Figure 5-9 Field Study Discussion.

3. Convert some of side street traffic to left-turners to take advantage of the phasing arrangement.
4. Change some side street phasing to lead-lag phasing.

Study Results

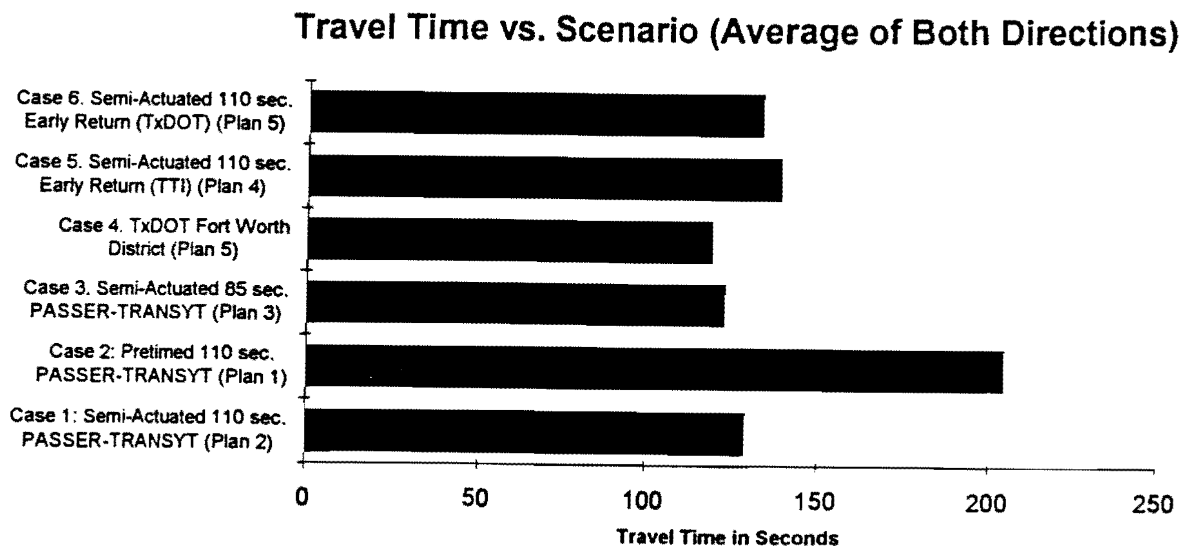
Figure 5-10 "Travel Time Summary" represents the travel times (combined for both directions) and percentage decreases in these measurements as compared to the pretimed base-case for each scenario. The number of stops (combined for both directions) and the percentage decrease compared to the pretimed base-case for each scenario is illustrated in **Figure 5-11 "Arterial Stop Summary."**

The overall conclusions of the study can be summarized as follows:

1. The semi-actuated strategies performed better than pretimed control in high volume conditions;
2. Strategies, based on optimized pretimed PASSER-TRANSYT timings, resulted in very good performance in semi-actuated operations;
3. Early-return strategies tend to redistribute the delay and stops within the system, and hence may push back oversaturation; and
4. The systemwide operational performance is not greatly improved by the early-return control strategy. However, the arterial peak directional traffic was clearly improved.

The statistical results suggest that semi-actuated coordinated schemes operate much better than pretimed systems. The semi-actuated timing schemes based on pretimed optimized timings tend to produce very good performance. These coordination schemes also tend to perform as well as, or better than the early-return strategies, when the side street and arterial delay are considered. This control strategy also performed well with respect to stops.

The lower cycle length strategy performed reasonably well in the low volume period. However, this control strategy was somewhat affected by the signal malfunction in the westbound direction at the intersection of Newton and SH 174 for 20 minutes on 05/19/93. That is, the 85 second strategy was found to be not significantly better than the 110 second cycle strategy. The early-return strategy performed reasonably well, and could redistribute delays from the critical bottlenecks in arterial signal system. This may be very important in pushing back the onset of oversaturation. The applicability of the recommended signal timing analysis methodology, as developed, was proven during high volume conditions.



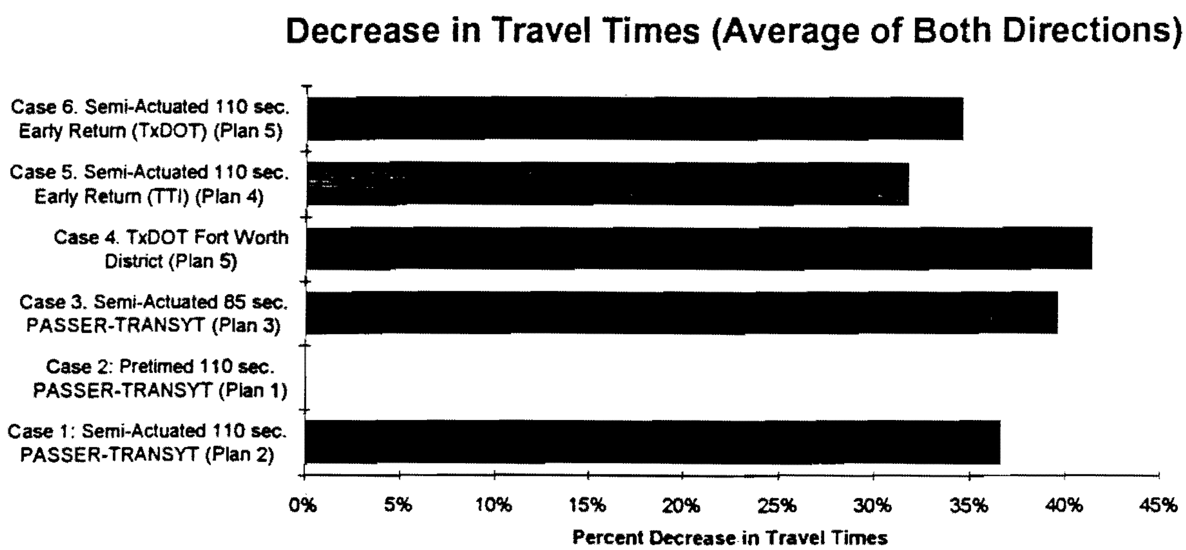
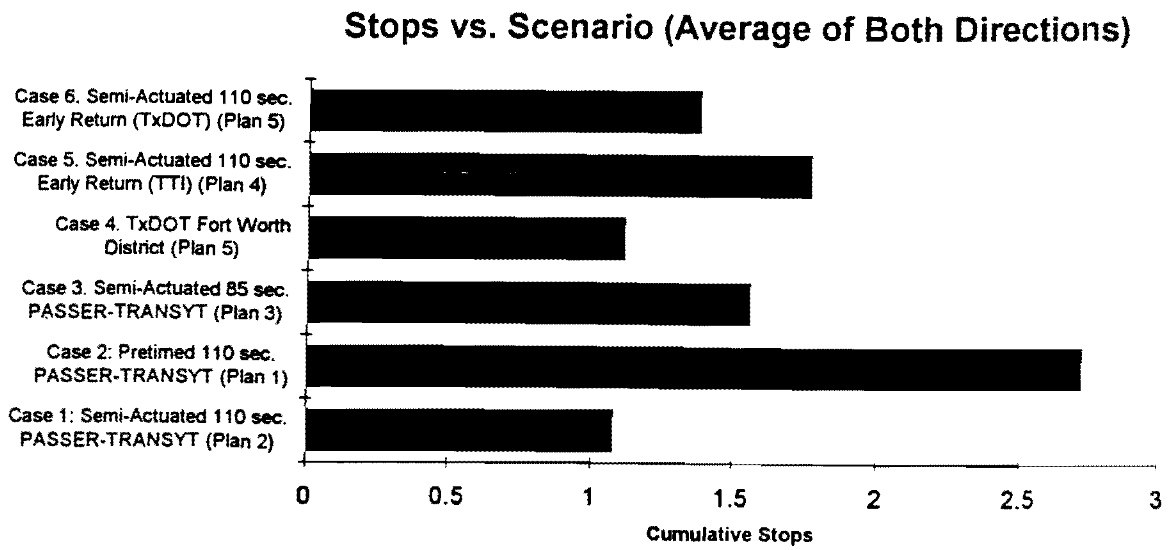


Figure 5-10 Travel Time Summary.



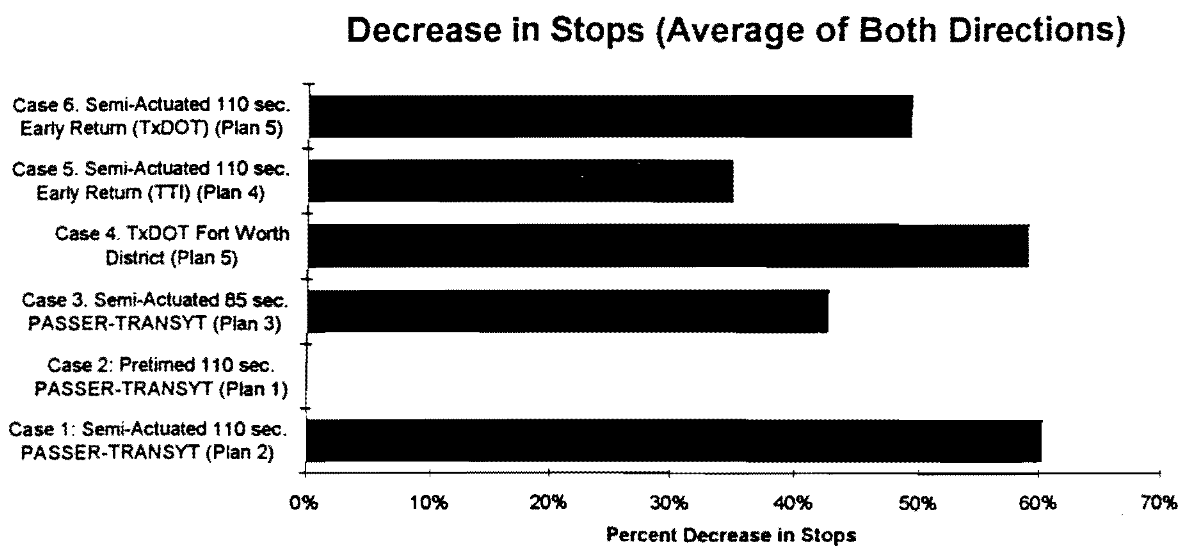


Figure 5-11 Arterial Stop Summary.

CHAPTER 6. IMPLEMENTATION GUIDELINES

Efficient arterial traffic signal operations relies on the proper combination of controller and detector configurations that meet user's requirements. As shown in **Figure 6-1 "System Design Considerations,"** the following design parameters should be evaluated:

1. Site Characteristics,
2. Resource and Institutional Constraints,
3. Alternative Signal Design, and
4. System Evaluation.

In addition, the following operational issues must also be considered in the overall signal system design process:

1. Intersection signalization type,
2. Signal warrant,
3. Approach speed,
4. Significance of dilemma zone protection,
5. Necessity for advanced detector/controller system,
6. Vehicle gap allowance,
7. Screening out of false calls and premature gap-outs, and
8. User preference of a particular system.

CONTROL SYSTEM FEATURES

There are a number of solutions to the objective of improving signal operations in Kingsville and Burleson, Texas. Many control strategies, as summarized earlier, are also applicable to other sites and could be adapted as a standard design procedure. The recommended features are summarized in **Figure 6-2 "Actuated Controller and Detector Settings"** and are explained below.

DETECTOR SYSTEM

The detector installation location does not have a significant impact on travel delay, as long as the detector installation and signal timing design can reasonably accommodate driver behavior. For example, a detector design with 60-100 feet or 100-200 feet detector setback will be adequate for presence and passage detectors, respectively.

A traffic signal designed and set to minimize delay for peak hours will be close to optimum for off-peak hours. Among the timing parameters, the minimum phase green, maximum phase green and vehicle intervals have the most profound effect on intersection operational efficiency, especially during medium and high traffic conditions. Intersection performance can be greatly improved by lowering the overall average cycle lengths. By maintaining maximum flexibility in split adjustment and gap-out, the signal can be responsive to directional traffic, thereby keeping the overall cycle length short.

As shown in **Figure 6-3 "Vehicle Extension Evaluation,"** a low minimum green-time setting for the non-actuated green phase will better serve traffic

A. Site Characteristics
   1. Geometric Design
      - o number of approaches
      - o number of lanes on each approach
      - o existence of turning bays
      - o physical dimensions
   2. Flow Pattern
      - o temporal and special (lane) distribution of traffic volume
      - o pedestrian volume and characteristics
      - o directional movements
      - o vehicle approach speed
      - o vehicle mixture
      - o arrival headway distribution
      - o saturation flow
   3. Traffic Control other than Signalization
      - o channelization plan
      - o right-turn-on-red policy
      - o parking policy

B. Resources and Institutional Constraints
   1. Operating budget and maintenance budget
   2. Skilled labor for maintaining control equipment
   3. Local standards and design practices

C. Alternative Signal Designs
   1. Controller Type
      - o by logic - pretimed, semi-actuated, full-actuated, volume-density
      - o by hardware - electromechanical, solid state, microprocessor
      - o by specification - NEMA, Type 170
   2. Phasing Plan
      - o treatment of left turns
      - o treatment of pedestrian flows
      - o sequential (signal-ring controller) or concurrent phasing (dual-ring controller)
      - o number of phases and overlaps
   3. Detector Configuration
      - o type - passage, presence, with or without special features, such as, call-delay and call-extension
      - o size of presence detector
      - o number and location
      - o delay or extension settings for detectors with special features
   4. Timing Settings
      - o vehicle change interval
      - o pedestrian phase intervals
      - o green intervals of pretimed signal
      - o settings for traffic-actuated signals - initial interval, extension interval, maximum green, minimum green, added initial per actuation, time to reduce, time before reduction, maximum gap, minimum gap, etc.

D. Evaluation
   1. Costs of Acquisition, Installation, Operating, and Maintenance
   2. User Costs - delay, stops, fuel consumption, and accident
   3. Analysis Period - peak hour, off-peak hour, day, year
   4. Decision Rules and Evaluation Methodology

Figure 6-1 System Design Considerations.

RECOMMENDED ACTUATED CONTROLLER AND DETECTOR SETTINGS				
NO	ACTUATED CONTROL	ADVANCED FEATURES	AVAILABLE SYSTEM FEATURES	
			OPERATING CONDITIONS	RECOMMENDED SETTINGS
1	DETECTION SYSTEM	ADVANCED DETECTION	SPEED $\geq$ 35 MPH	210 FEET BEFORE STOP BAR
		LEFT TURN DETECTION	PERMITTED LEFT TURN PHASE	6' X 25' DETECTOR AT STOP BAR. QUEUE DETECTOR 6' X 25' DETECTOR AT 60' UPSTREAM OF THE STOP BAR WITH 5 SECOND TIME DELAY
			PROTECTED LEFT TURN PHASE	
		SIDE STREET DETECTION	IF RIGHT TURN DETECTION REQUIRED	MULTIPLE SHORT LOOPS. FRONT 25' TIME DELAYED.
2	CONTROLLER SYSTEM	MINIMUM GREEN	STOP BAR PRESENCE DETECTION	4.0 SECONDS
			NO STOP BAR DETECTION	10.0 SECONDS
		VEHICLE EXTENSION	WITH RECOMMENDED DETECTOR SETBACK UNDER CONFIGURATION	2.5 SECONDS
		TURN DELAY	LEFT TURN POCKET	5.0 SECONDS DELAY
			RIGHT TURN DETECTION REQUIRED	1ST 25 FT. 10 SECONDS DELAY
		PEDESTRIAN PROTECTION	1 CALL PER 5 CYCLE AND PED BUTTONS	NO PED PROTECTION
			36' OR HIGHER WIDTH CROSS WALK	PROVIDE PROTECTION
			PED RECALL	5.0 SECOND WALK
			PED ACTUATION	7.0 SECOND WALK
		COORDINATION GUIDELINES	ARTERIAL THROUGH PERCENTAGE $\geq$ 70%	COORDINATED, ACTUATED OPERATION
			VOLUME $\geq$ 35% OF CAPACITY	COORDINATED, ACTUATED OPERATION
			CYCLE LENGTH $\leq$ 150 TIMES V/C	COORDINATED, ACTUATED OPERATION
			PROGRESSION EFFICIENCY $\geq$ 0.13	COORDINATED, ACTUATED OPERATION

Figure 6-2 Actuated Controller and Detector Settings.

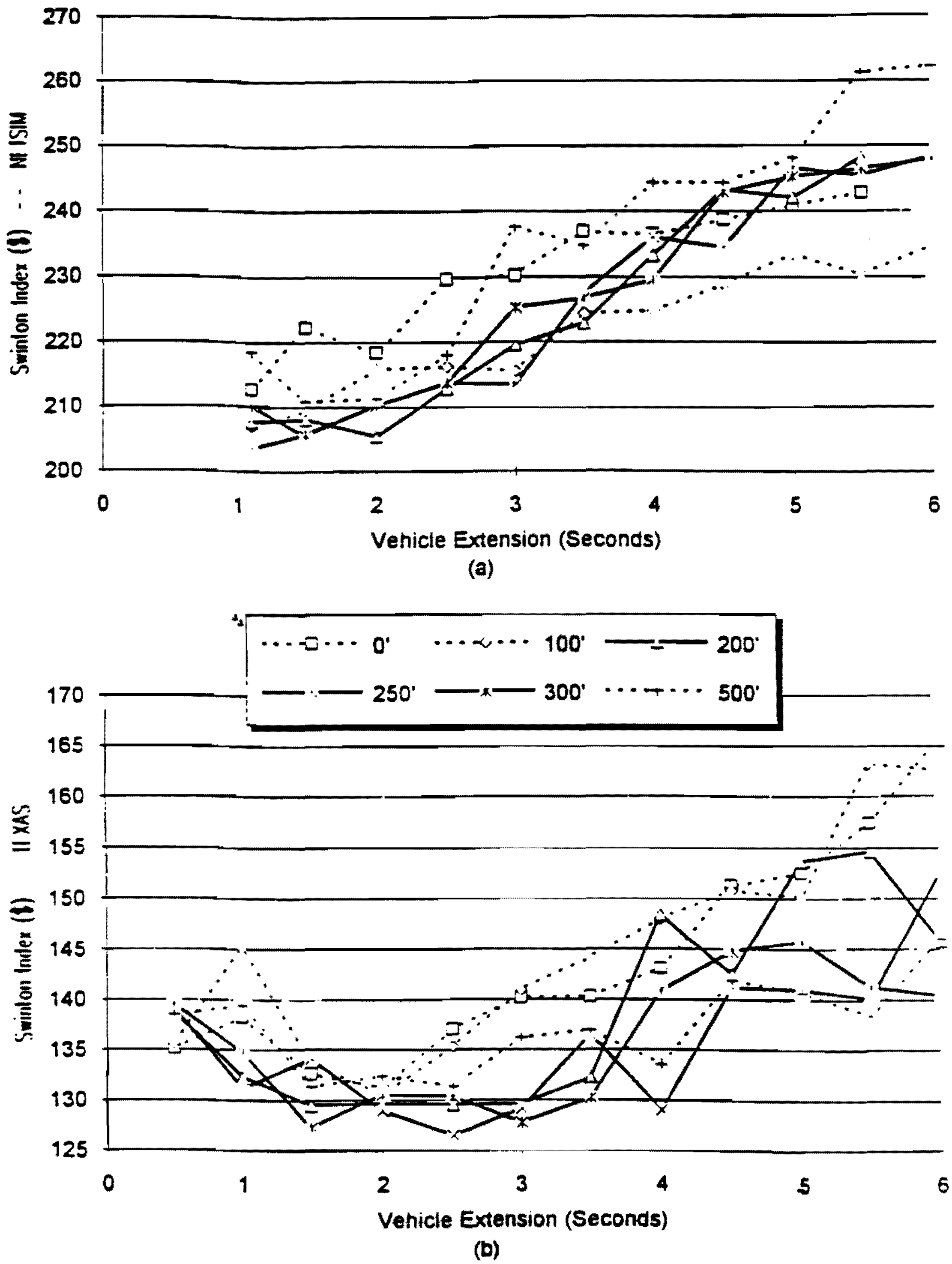


Figure 6-3 Vehicle Extension Evaluation.

demands in light traffic. In medium traffic, vehicle extension that can accomodate truck traffic and still provide efficient operation is critical. In heavy traffic, force off time will dominate the actuated signal as it converts to fixed-time operation. However, field experimentation with other settings to achieve delay minimization and maximum timing flexibility is essential to achieve optimum vehicle actuated control.

Proper detector placement is critical for efficient and safe signal operation. There are four primary types of detectors:

1. Advance loops,
2. Left turn detection,
3. Stop bar detection, and
4. Side street detection.

Advance Detection

Advance loops should be used on progressed arterial approaches and high speed (greater than 35 mph) approaches. Simulations conducted as a part of this research project failed to indicate any significant affect on delay due to detector placement. However, there are important safety factors to consider. Detection should be placed far enough in advance to minimize dilemma zone problems. Studies have indicated that drivers' maximum safe deceleration rates for signals is typically 10 ft/sec^2. This corresponds to a distance of 132 ft for deceleration. Assuming a 1.25 second reaction time, the total distance required for driver reaction and deceleration is 196 ft. To provide additional protection for a range of driver aggressiveness, detectors should be placed so that the vehicle extension covers either side of this distance evenly. For example, with a 2.5 second vehicle extension, the detector should be placed at roughly 260 ft so that protection is provided until the vehicle is 132 ft from the intersection.

Left Turn Detection

Left turn detection for protected only phasing should be provided by a long loop located at the stop bar. The detector must be located at the stop bar to distinguish left turns from through traffic. A long loop is desired to prevent gap-out when a vehicle is rapidly approaching to make a left turn.

Protected and permissive left turn phasing requirements are quite different. It is undesirable to leave an arterial through phase only to serve a left turning vehicle that can safely wait and make a permissive turn. Furthermore, delay can be minimized by skipping the protected left turn phase in the absence of heavy demand. If there is little opposing traffic, left turners will be able to make a permissive turn. If there is heavy opposing traffic, the increased delay to the through traffic will be significant if left turn protection is provided. This may even result in over-saturating the through move. The left turn can always be made as a sneaking movement at the end of the through phase.

A dual detector design is suggested to maximize the potential of protected and permissive operation. Stop bar detector (6x25') should be located in the left turn pocket and wired to the through phase. This will prevent the arterial green from gapping out when there is permissive left turn demand; a condition was noticed in the field on numerous occasions. A second detector (6X25′) should be placed in the left turn pocket at roughly 60′ upstream of the stop bar and wired to the protected left turn phase. This detector will place a call to the protected phase when sufficient demand (i.e. four vehicles) exists for protected operation.

Since almost all of the left turn traffic will pass over this detector, even when there is no queue, it should be placed on time delay (5 seconds) to prevent false calls. Finally, if so desired, the front detection could also be wired to the protected phase with a long time delay, about one cycle length. This would prevent excessive delays to a driver who wants to wait for a protected arrow. Although this would not be recommended for high volume locations it may be necessary at the locations with low traffic volume and conservative drivers.

Stop Bar Detection

Stop bar detection on the artery can be provided to guarantee queue departure. If such detection is provided the minimum green on the phase can be reduced to minimal values (i.e., 4 seconds). However, this detection should supplement, not replace, to advance detection on arteries and high speed approaches. If stop bar detection is not provided, a ten second minimum green with variable initial is recommended.

Side Street Detection

Stop bar detection for the minor side streets should be designed to allow for right turn screening. Thus the right most lane should be equipped with multiple short loops to prevent multiple cars from being detected by a single loop. The front 25 feet of the lane should be delayed to prevent unnecessary side street calls created by right turners. The rear loop(s) should be time delayed so as to be effectively disconnected during the red, to prevent a moving queue from placing a call.

CONTROLLER SETTINGS

The recommended timing settings, including basic timing parameters, interval setting, and density features, should be used as summarized earlier.

Basic Timing Parameters

Minimum Green A minimum green of four seconds if stop bar detection is used and ten seconds with variable initial if only advance detection is used.

Vehicle Extension The vehicle extension of 2.5 seconds is used as indicated in the previous section.

Time Delay Time delay should be sufficient to prevent calls from right-turn-on-reds on a protected and permissive left turn pocket.

Pedestrian Protection Pedestrian protection is not necessary when pedestrian demand is known to be minimal (i.e., 1 call every 5 cycles) and pedestrian actuation is provided. Pedestrian actuation is recommended for all crossings of 36 ft or greater. If pedestrian recall is used, a 4 second walk should be sufficient for light demand. If actuation is provided, a walk of 7 seconds is recommended.

Advanced Timing Parameters

Minimum Initial A four (4) second minimum initial has been found to work well when stop bar detection is present. When only advance detection is provided, a 10 second minimum may be more desirable with the combination of variable initial timing parameters.

Added Initial/Actuation The amount of time to add per actuation depends on the loop configuration. If only one lane is detected on a phase or if multiple lanes are counted separately, a 2.2 second added initial per actuation has been found to be acceptable. If multiple lanes are counted with one loop, or one controller input, a shorter extension is recommended to compensate for the dispersion of traffic among the various lanes. A 1.5 second added initial per actuation would be appropriate in this case.

Maximum Initial The maximum initial has historically been set to the length of the detector setback divided by 10 plus startup time. Startup time should be between 2 and 4 seconds. No results were obtained from this project to contradict this recommendation.

Gap Reduction With adjustments for the resolution problems of the simulation models, a vehicle extension of roughly 2.5 to 3.0 seconds appears to be optimal for the recommended detector configuration. Gap reduction does not appear to be justifiable for any use except to provide a longer extension during queue discharge. Further research in this area may be needed.

Maximum Green Under coordination, maximum green is seldom reached due to the existence of a force off. However, when max-out is likely, the values suggested by Lin appear to be reasonable [Lin 1985]. These are roughly 180% of the optimal pretimed setting for a peaking factor of 0.85 and roughly 10 seconds longer than optimal pretimed for a peaking factor of 1.0.

Yellow Lock To prevent vehicles being trapped downstream of the detectors, yellow lock should be set on any approach that has advance detection without stop bar detection.

Last Vehicle Passage With the recommended detector setback and vehicle extension, last vehicle passage is not required and should not be set.

Vehicle (Minimum) Recall Vehicle recall is typically placed on the artery to guarantee the return of green. This practice appears to be appropriate.

Red Rest If vehicle recall is not used, which may be desirable at a major-major intersection, red rest should be set for all minor phases, such as left turn phases. This will prevent resting in a phase with little demand.

Detector Setback If possible, detection should be designated at roughly four seconds upstream of the intersection. For a 35 mph approach speed this design would place detection at roughly 200 to 225 feet. Detectors should operate in presence mode to detect vehicles for longer intervals if they are in queue discharge and moving slowly. If existing advance detection is not located at the optimal distance, the optimal vehicle extension does not appear to change. However, the performance of the signal will not be as great.

Coordination Setting

The control objective is to improve progression and make use of all progression opportunities. As illustrated in the examination of both Kingsville and Burleson signal systems, the following conditions seem to be beneficial for the use of coordinated, actuated signal systems:

1. The arterial through percentage at the intersection is at least 70% of the overall traffic,
2. The traffic volume is at least 35% of the capacity at most intersections in the arterial system,
3. The cycle length of the coordinated operation is less than or equal to 150 times the v/c ratio, and
4. Progression efficiency that can be achieved is at least 0.13.

Offset Optimization

The assumption to date has been that TRANSYT provides the best offset for coordination. However, the early return in actuated systems creates additional progression opportunities. Although all designs have not been investigated yet, the solution now appears to be to optimize offsets while adjusting the values of side street splits to reflect this. Actual splits in the controller may penetrate into the progression band, but due to early return it will seldom affect the bandwidth. The exact adjusted splits are unknown, but are expected to be roughly 80 percent of the split value.

Soft Coordination

Soft coordination may be beneficial at intersections that do not meet the above criteria but still have distinguishable platoons of traffic. The concept is to simply apply a hold to the arterial through phase during periods when platoons of traffic are expected to arrive. However, other phases are not forced off to provide a guaranteed green. This design should minimize long delays on the arterials due to the arterial gapping out just before the platoon arrives.

Pedestrian Settings

The minimum pedestrian phase time required depends on the width of the arterial street, the length of the detector on the minor street, vehicle length, average approach speed, and minimum phase time for driver expectancy. The requirements on the pedestrian phase time can be calculated from the expected values of green times for the actuated phase controlling the minor streets. Three control strategies are available depending on different vehicular and pedestrian traffic. Strategy I and Strategy II consider semiactuated operation, whereas Strategy III regarded basic pretimed operation. Strategy I uses traffic actuated control with pedestrian actuated push buttons. Therefore, the minimum green time required for pedestrians is provided only when push buttons are actuated. Strategy II contains traffic actuated control with no pedestrian actuated push buttons. Therefore, a minimum green time required for pedestrians has always to be provided for the minor street phase. In each strategy, a combination of the probabilities of vehicle and pedestrian arrivals were used to calculate the expected values of green times over a range of different combinations of vehicular and pedestrian volumes.

As shown in **Figure 6-4 "Average Phase Durations for Pedestrian and Vehicular Volume,"** Strategy I is more effective than Strategy II when vehicular volumes are low (approximately less than 500 vph). In this range, the minimum green time provided on the minor street is very high, to provide safety for pedestrians crossing the major street in the absence of pedestrian push buttons. The difference in the expected values predicted by Strategies I and II is higher when pedestrian volumes are low, and decreases as pedestrian volumes increase. Strategy I, using actuated control with pedestrian actuated push buttons, is more efficient than Strategy II, when the pedestrian volumes are low. However, with higher pedestrian volumes, the performance of Strategy I tends to merge with that of Strategy III.

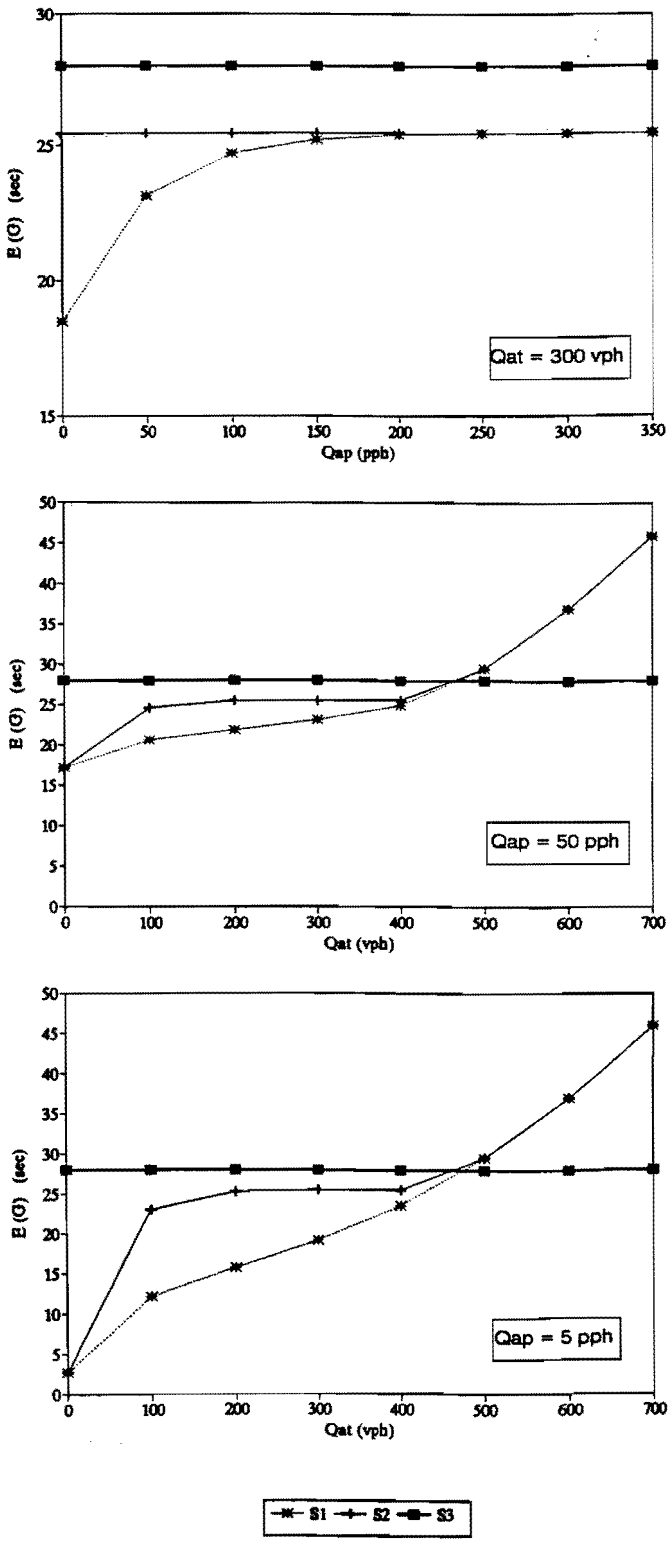
RECOMMENDED STUDY PROCEDURE

Traffic growth creates the immediate need for effective signal control that can be adapted to traffic demand variations. Actuated signals are effective in managing isolated intersections, and are more responsive than fixed-time controllers. Arterial progression systems with some actuated controllers are becoming increasingly popular. Traffic engineers must develop signal coordination plans for arterials having actuated signals.

However, there are no operational models readily available for optimizing control parameters explicitly for isolated or coordinated actuated operations. This section describes a feasible analysis approach that can be used to develop optimal signal timing plans through the manual approximation of timing parameters to allow coordination timing analysis using the PASSER II-90. It illustrates how to apply Yield-Point and Force-Off features to determine coordination offsets and phase sequences.

PASSER II can determine the background cycle length and offsets, or yield points, for arterial progression. However, the green splits calculated by the model are based on the average durations of phase green times for each phase movement. These green splits should be based on the heaviest input volumes and signal capacities at each intersection. The basic optimized settings should be converted into the specific settings that can be implemented on the actuated controller.

Field measurements and estimates are needed to describe traffic conditions during average phasing and interval durations. All other data should be recorded from controller signal timing charts so the model can



LEGEND: E(G) - Estimated Green Time.
Qap - Pedestrian Arrival Volume.
Qat - Vehicular Arrival Volume.

Figure 6-4 Average Phase Durations for Pedestrian and Vehicular Volume.

simulate existing operating conditions before the correct signal timing settings are implemented in the field.

Input Data Requirement

The basic input data required to analyze actuated signals is the same information necessary to set actuated controller settings. These signal input parameters include the number of phases, phase sequences, interval durations, background cycle lengths, fixed interval durations, variable interval durations, minimum phase intervals, and coordinated offsets.

Number and Phase Sequences Because of varying traffic demands, different signal phasing sequences are often offered. However, the average signal phasing pattern can be considered as fixed for each short-time interval or certain control period. The needed data should be collected or estimated for the multiphase signals which are capable of providing lead/lag operation and phase-skipping functions as illustrated in **Figure 6-5 "Left Turn Analysis."**

Some actuated controllers can use the "phase skip" feature to skip particular phases entirely and transfer all the green time to other movements. On the other hand, for two-phase semi-actuated controllers, or controllers with fixed phasing patterns, the input timing data should be obtained from the existing controller signal timing charts. The average varying conditions of traffic flow and the amount of pedestrian traffic associated with each signal phase movement should also be recorded.

Interval Durations The average interval durations of the green times per phase interval should be determined for each control period. Consequently, the average green times can usually be obtained through field observation. However, estimation of the existing actuated signal timing settings is also necessary for each specified signal timing interval.

The synchronized signal phase is usually not actuated and should have a minimum guaranteed green time. Other actuated phases may vary on each cycle between Minimum-Green and Maximum-Green. Extension of green time beyond minimum green usually depends on the arrival rate and magnitude of Vehicle-Extension. The green time for each actuated phase is terminated at the Force-Off point. Actuated controllers may have additional settings depending on the type of controller, e.g., variable initial green and reduction of extension interval for volume-density controllers.

Background Cycle Length The common cycle length, or background cycle length, is required to provide the necessary signal coordination in the arterial progression operations. The applicable hours of coordinated operation should be reviewed carefully so that the exact background cycle lengths and coordination requirements can be determined.

Fixed Interval Durations The pertinent controller timing settings, such as interval duration, should be recorded at each signalized intersection. These signal timing settings may include clearance intervals, (i.e., yellow and all-red periods) minimum initial green, vehicle extension, and maximum green times. Additional traffic signal settings, such as the platoon carry-over and

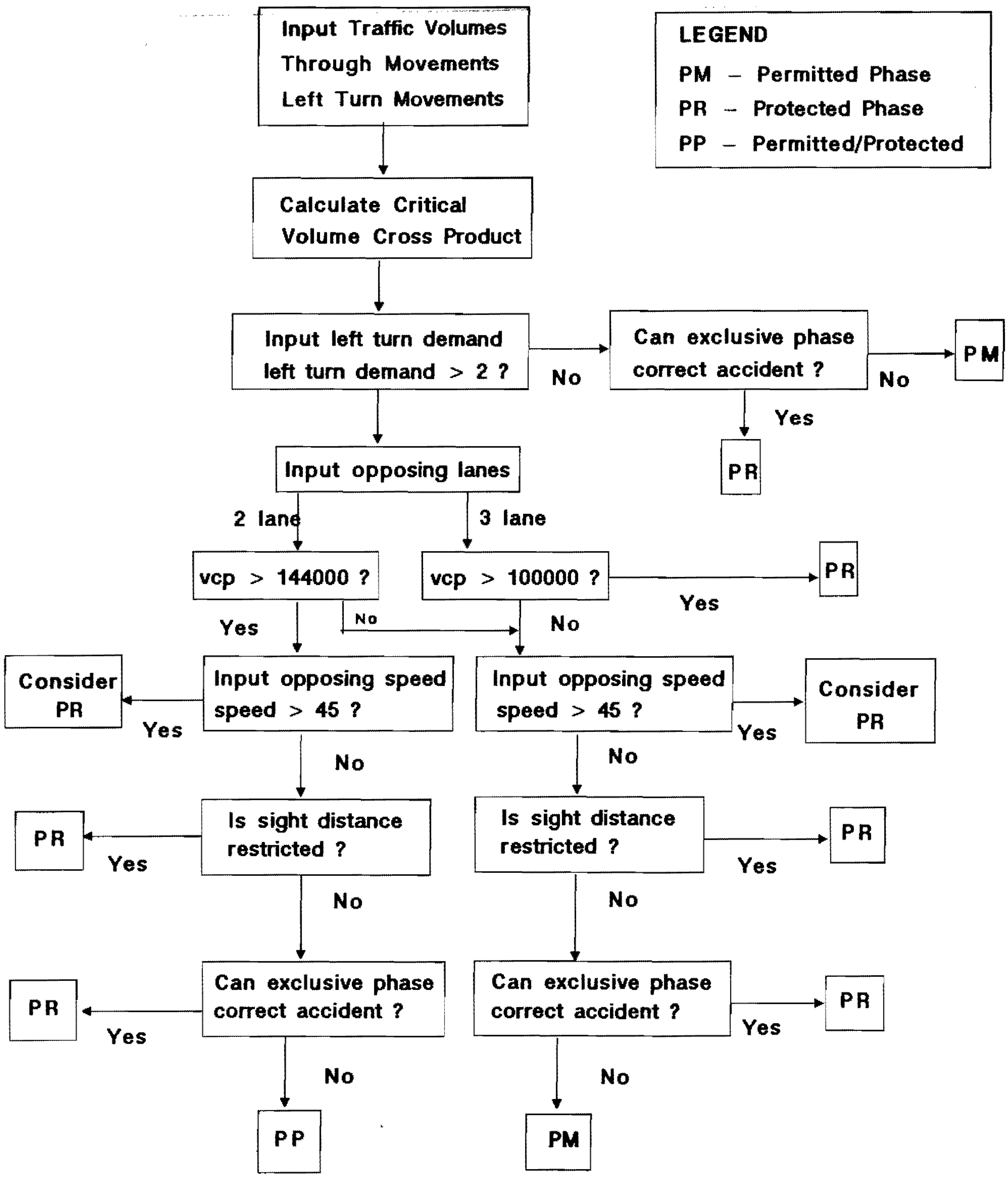


Figure 6-5 Left Turn Analysis.

recall switch settings, may also be necessary. The signal timing parameters should be considered in timing design depending on specific controllers.

Minimum Phase Durations The minimum green time or minimum phase duration should be determined for each phase interval, recorded and expressed in seconds. It is also necessary to record whether or not it is in the protected or permitted left turn movement phase.

Offsets or Yield-Points The coordinated offsets, or Yield-Points, for the synchronized signal phase and phase interval, should be recorded. The Force-offs for each traffic signal phase interval should be recorded. The required data for analyzing actuated controllers should include phase number, phase sequences, interval durations, background cycle lengths, fixed interval durations, variable interval durations, minimum phase intervals, and coordinated offsets. At the same time, signal timing analyses produced by the model represent an "equivalent" pre-timed plan for average traffic conditions during that particular control period.

Program Application

When the user completes the overall data collection or field estimation of the average green times, the input data for the PASSER II program analysis should be prepared as follows.

1. First, determine the "average variable interval durations" for each signal phase. This can be done using the measured actual green of the fixed intervals from the controller settings or estimated phase lengths from experience. For example, if the average split from the signal timing data is 12 seconds, and the clearances are 5 seconds, then the variable interval is 7 seconds.

2. Second, calculate the "Yield-Points" or "Recommended Local Offsets" for the synchronous phase, based on the existing coordination offsets and the estimated average green times. Record the time intervals and settings as illustrated in **Figure 6-6 "Coordination Offset."**

3. Calculate the "minimum phase lengths" in seconds, from the maximum of both vehicular and pedestrian clearance. The vehicular clearance phase should be equal to the minimum assured green for vehicles plus clearance intervals. The interval for pedestrian clearance is equal to the minimum time required for pedestrian crossing plus clearance intervals.

   If the signal operation, on the average, is not influenced by pedestrians, then this value can be ignored. Minimum green times should be coded into PASSER II-90 as equal to the minimum phase lengths for vehicle movements and the minimum pedestrian times ignored. If minimum green times are higher at intersections with high pedestrian activity, minimum phase length should be coded to satisfy minimum pedestrian requirements.

PRETIMED SPLITS AND PHASES AT INTERSECTION

10(1)	4	23(2)	4	7(3)	3	27(4)	4
10(5)	4	23(6)	4	15(7)	4	18(8)	4

FORCE – OFF SETTINGS DERIVED FROM PRETIMED ANALYSIS

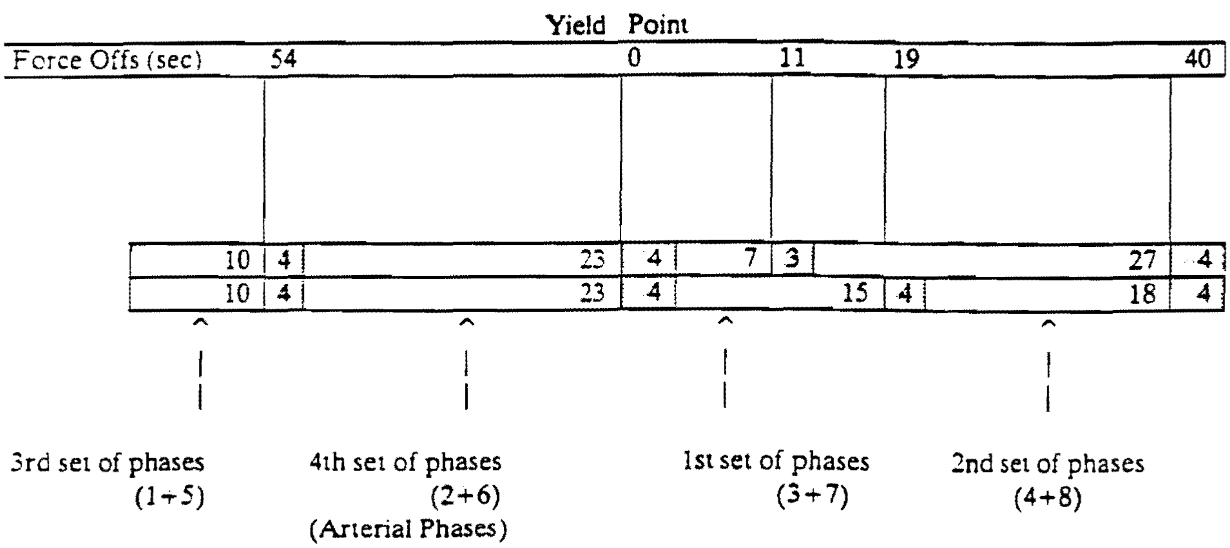


Figure 6-6 Coordination Offset.

4. A "system evaluation" must be performed to develop the coordination timing plans and the overall system performance should be evaluated through simulation evaluation and field study.

   The existing background cycle length should be coded as the system cycle length into the PASSER II-90 model. After this is done, the system should be simulated and the results analyzed. The evaluation results are summarized on the example data reduction sheet shown in **Figure 6-7 "Estimated Signal System Improvements."**

5. A field evaluation should be conducted with minor adjustments to green splits as necessary, since the estimated degrees of saturation may be slightly higher than the assumed 85% for side streets. Otherwise, the main street may become oversaturated due to the lack of available green times to favor arterial progression.

6. For practical operation of the coordinated, actuated signal systems, control strategies and experience may be diverse by location. This study recommends the use of semi-actuated control implemented through time-of-day control based on arterial progression needs during peak-hour operations. The timings should be based on pretimed operation. All intersections may be operated in isolated actuated mode for light traffic and late night operations.

SUMMARY OF ESTIMATED TRAFFIC SIGNAL SYSTEM IMPROVEMENTS							
SYSTEM PERFORMANCE MEASURES		VEHICULAR STOPS (STOPS)		TOTAL SYSTEM DELAY (VEH-HRS)		FUEL CONSUMPTION (GALLONS)	
		BEFORE	AFTER	BEFORE	AFTER	BEFORE	AFTER
HOURLY VALUES	AM						
	PM						
	OFF						
DIFFERENCES	AM						
	PM						
	OFF						
HRS/DAY	AM						
	PM						
	OFF						
DAILY TOTALS	AM						
	PM						
	OFF						
	TOTAL						
UNIT VALUES							
ANNUAL COST SAVINGS							

TOTAL ANNUAL COST SAVINGS: ____________________

BTU'S REDUCED: ____________________

SYSTEM B/C RATIO: ____________________

Figure 6-7 Estimated Signal System Improvements.

CHAPTER 7. CONCLUSIONS AND RECOMMENDATIONS

As major urban centers continue to experience growth in travel demands, budgetary constraints require more efficient use of existing highway facilities. Congestion levels are predicted to increase over time for many urban areas throughout the country. Actuated signals can be effective in managing both isolated intersections and coordinated arterial systems during undersaturated conditions, demand variations, and near saturation conditions. There is a large body of knowledge and experience available, including excellent computer programs, to assist pretimed control.

Many urban areas in Texas suffer from periodic traffic congestion. A serious operational problem occurs when a major arterial signal system cannot effectively move traffic due to long queues along arterials. Effective signal control and management strategies can be devised to minimize congestion using actuated controllers already in the field. The purpose of this research was to develop a reliable analytical methodology to improve the overall design and operation of actuated controllers, determine the best way to utilize the added flexibility of actuated control in a coordinated system, and generate the parameters for coordinated arterial or network progression operations.

The results proved that the coordinated, actuated schemes operate much better than pretimed systems in most cases. In addition, coordinated, actuated operations can potentially postpone the "possibility of over-saturation". The report summarizes recommended coordination strategies and guidelines for using actuated controllers on coordinated signal systems. An evaluation of various congestion management schemes, such as adding unused green time to main streets, measuring congestion control, and testing other queue detection/control strategies on existing arterials is needed. These study results will maximize all available resources for effective signal operations.

CONCLUSIONS

The applicability of the study methodology, as developed in this research, has proven the following points:

1. The statistical results suggest that the semi-actuated coordinated schemes operate much better than pretimed systems. Semi-actuated schemes based on pretimed optimized timings perform very well. This strategy also performed very well with respect to stops.

2. Both the v/c ratio and early-return strategy performed very well, and had the effect of redistributing delays away from critical points. This may be very important in pushing back the onset of oversaturation.

3. Among all the decision considerations, selecting the most suitable cycle length is the most important decision in signal coordination. All intersections in the progressive system generally should be coordinated from the same background cycle. Coordinated operations are often needed during certain periods, such as the AM, PM, or NOON peaks, to accomodate progressive flow.

4. A full-actuated controller under coordinated control will, in effect, be operated as a semi-actuated controller with coordinated offset settings and actuated/nonactuated phasings. However, even though this method becomes increasingly ineffective, the coordination can postpone and minimize time goes beyond the point of saturation.

5. The field study exercises proved the validity of the simulation results. The Kingsville System is typical of many U.S. cities with low to medium traffic volumes. The second exercise was conducted at a high volume urban arterial near Fort Worth, and similar results were obtained. This proves that the methodology identified through simulation is valid and is recommended for field practice.

The advantages of using actuation and arterial coordination were clear. The field experiments served to verify the earlier findings from simulation studies and in real-life operational environments.

RECOMMENDATIONS

Significant operational improvements can be made when semi-actuated coordinated timing is used, compared to full-actuation or pretimed coordinated timing. Among the semi-actuated cases, no significant differences were observed. However, it was observed that longer cycle lengths caused higher overall system delays. A number of strategies are available to improve high-speed urban arterials through the use of coordinated actuated signals on typical Texas arterial street systems. Many of these solutions are also applicable to other sites around the country.

Operational effectiveness depends on the design and implementation of detector configurations and settings, controller timing, and coordination settings. The methodology developed can be adapted as a standard design procedure for providing system adaptivity using existing equipment with the recommended values for signal timing parameters and detector settings as proposed in this study, the coordinated actuated operations can potentially postpone the "possibility of over-saturation" on many state highways.

This study further recommends the evaluation of potential queue-based management strategies that have been suggested for over-saturated operations. As illustrated in **Figure 7-1 "Research Problem Statement,"** the proposed study will develop near-saturation, over-saturation, and transition control strategies. These control strategies will allow signal systems to react to anticipated volume surges, manage queues better, and recover quickly from congestion. Specifically, it will identify how to implement strategies to adjust coordination settings, such as using early return, late arrival, and platoon identification schemes. The proposed study may also take advantage of system monitoring and fine-tuning capabilities now available on many closed-loop traffic signal control systems.

FIRST-STAGE

RESEARCH PROBLEM STATEMENT

For D-10R USE ONLY		
Area No.	Program Year	Statement Number

I. PROBLEM TITLE:
Strategies for Coordinated, Actuated Control During Over-saturation

II. PROBLEM STATEMENT:
Many urban areas in Texas suffer from periodic traffic congestion. A serious operational problem occurs when a major arterial signal system can not effectively move more traffic due to long queues along the arterials. Effective signal control and management strategies can be devised to minimize congestion using many actuated controller(s) already in the field. Evaluation of various congestion management schemes, such as adding unused green time(s) to main streets, measuring congestion control, and testing other queue detection/control strategies, on real-world arterials are eminently needed.

III. PROPOSED RESEARCH:
As has been successfully demonstrated in SPR 2-18-91-1255 study, coordinated actuated operations can potentially postpone the "possibility of over-saturation" on many state highways. This study proposes to continue the current SPR 1255 momentum and committee enthusiasm to "jump-start" the evaluation of potential queue-based management strategies that have been recommended for over-saturation operations using the basic study evaluation methodologies developed jointly by TxDOT and TTI.

This study will develop "near-saturation," "over-saturation," and "transition" control strategies. These control strategies will allow signal systems to react to the anticipated volume surges, manage queues better, and recover quickly from congestion and back to normal operations. Specifically, it will provide: (1) **Strategy Development.** The study will identify how to implement control strategies to adjust coordination signal settings, such as using early return, late arrival, and platoon identification schemes, by effectively manipulating the existing and desiging new detection/controller features for congested arterials. (2) **Strategy Evaluation.** Control Strategies, using real-world data from urban Districts, will be analyzed through traffic simulation models, on a cycle-by-cycle evaluation basis. (3) **Strategy Validation.** The study will validate the system operational performance and document findings through field observations. The field study will also take advantage of system monitoring and fine-tuning capabilities now available on closed-loop systems.

IV. POTENTIAL IMPLEMENTATION AND BENEFIT TO THE DEPARTMENT:
Many urban areas are currently improving signal control through improved arterial coordination and traffic-actuated control. The results from this study will further maximize all available resources for effective signal operations.

V. SUBMITTED BY:

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Revised 6/3/91

Figure 7-1 Research Problem Statement.

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APPENDIX A. GLOSSARY

Actuation The operation of any type of detector. Operation implies the use of any output from a detector to the controller.

Advanced Actuated Controller An actuated controller that can count vehicles beyond the first. It generally has variable initial interval actuation.

Auxiliary Equipment Seperate devices used to add supplementary features to a controller assembly.

Basic Actuated Controller One that cannot count vehicles beyond the first. It does not have a variable initial interval.

Call A registration of a demand for right of way traffic.

Carry-Over Output The ability of a detector to continue its output for a predetermined length of time following an actuation.

Controller (1) A device which controls the sequence and duration of indications displayed by traffic signals, (2) Under computer supervision a device which switches the signal circuits according to the computer's instructions.

Controller Unit The part of the traffic controller assembly which performs the basic timing and logic functions.

Coordination The establishment of a definite timing relationship between adjacent traffic signals.

Cycle Length The time required for one complete sequence of signal indications.

Delay Time lost by vehicles due to traffic friction or control devices.

Delayed Call Detector A detector that does not issue an output until the detection zone has been occupied for a period of time that has been set into the appropriate detector unit.

Delayed Output The ability of a detector to delay its output for a predetermined length of time following an actuation.

Density A measure of the number of vehicles per unit length of roadway.

Density Controller Actuated controller that has timing adjustments for the selection of the allowable gap independent of the passage time. A volume-density controller and a modified density controller are each a type of density controller.

Design Speed The speed used as typical by the designer of the detector/controller scheme, under free traffic flow conditions.

Detection Zone The area of the road within which a vehicle will be detected by a vehicle detector.

Detector A device for indicating the presence or passage of vehicles and pedestrians.

Detector Failures The occurrence of detector malfunctions including non-operation, chattering, or other intermittent erroneous counting.

Dilemma Zone Protection Any method attempted to control the end of green interval so that the vehicle will be avoided in the dilemma zone when the signal turns yellow.

Dilemma Zone A distance of time interval related to the onset of the yellow interval. That portion of the roadway within which a driver is indecisive regarding stopping prior to the stopline or proceeding into or through the intersection. It is sometimes expressed as the increment of time corresonding to the dilemma zone distance.

Dummy Interval A redundant interval in the cam-switching mechanism to allow the total number of intervals in the cycle to correspond integrally with the total number of intervals on the cam-switch mechanism.

Emergency Vehicle Preemption The transfer of the normal control of signals to a special control mode for emergency vehicles.

Extended Call Detector A detector with carryover output. It holds or keeps the call of a vehicle for a preset time interval. It can be set to time before the vehicle enters the detection area or after the vehicle leaves the detection area or after the vehicle leaves the detection area.

Force-Off Command A system command which forces the termination of a phase of a traffic signal.

Gap Reduction A feature whereby the unit extension or allowed time spacing between successive vehicle actuations on the phase displaying the green in the extensible portion of the interval is reduced.

Gap-Out Termination of arterial green due to maximum number of vehicle actuations so green may be served to a competing phase.

Hold A command that retains the existing right-of-way. A command to the controller which causes it to retain the existing right-of-way.

Interval The part or parts of the signal cycle during which signal indications do not change.

Last Car Passage A selectable feature of a density controller which, upon gap-out, will cause the green to complete the timing of the passage time. The last vehicle to have been detected will therefore retain the green until it reaches the stopline. This avoids dilemma zone problems.

Locking Detection Memory A selectable feature of the circuit design for a controller phase whereby the call of the vehicle arriving on the red or yellow is held by the controller after the vehicle leaves the detection area until it has been satisfied by the display of a green interval to that phase.

Loop Detector A device capable of sensing a change in inductance of a loop sensor embedded in the roadway caused by the passage or presence of a vehicle over the loop.

Loop Occupancy Controller A detector or controller design using long detection loops (normally 30 ft or longer), and detector units operated in non-locking mode. A loop occupancy controller may, but not necessarily, be designed to rest in all red in the absence of any traffic demand.

Main Street Green Data sent from the intersection controller to the computer indicating that the controller is displaying a green signal to the main traffic phase.

Maximum Green The maximum green after the opposing actuation, which may start in the initial portion, after which the phase would be terminated.

Measurement of Effectiveness (MOE's) Indices of performance effectiveness of the system in improving traffic flow. Common bases of comparison include congestion, density, lane occupancy, stops, delay, and queue length.

Non-Locking Detection Memory A selectable feature of the circuit design for a controller phase whereby the call of a vehicle arriving on red (or yellow) is forgotten or dropped by the controller as soon as the vehicle leaves the detection area.

Occupancy The precentage of roadway occupied by vehicles at an instant in time. In general use, it is a measurement based upon the ratio of vehicle presence time (as indicated by a presence detector) over a fixed period of total time.

Offset The time difference or interval in seconds between the start of the green indication at one intersection as related to the start of the green interval at another intersection or from a system time base.

Passage Mode Detector mode in which an output is given as long as a vehicle remains in the field of influence. Also called Presence Mode.

Passage Period The time allowed for a vehicle to travel at a selected speed from the detector to the nearest point of conflicting traffic.

Pattern A unique set of traffic parameters (cycle, split, and offset) associated with each signalized intersection within a predefined group of intersections (a section or a subzone).

Phase The part of the cycle allocated to any traffic movements or to any combinations of traffic movements simultaneously receiving the right-of-way during one or more intervals.

Phase Overlap Refers to a phase which operates concurrently with one or more other phases.

Phase Sequence The order in which a controller cycles through all phases.

Preemption The term used when the normal signal sequence at an intersection is interrupted and/or altered in deference to a special situation such as the passage of a train, bridge opening, or granting the right-of-way to an emergency vehicle.

Presence Detection The ability of a vehicle detector to sense that a vehicle has appeared in this field whether moving or stopped.

Presence Loop Detector An induction loop detector which is capable of detecting the presence of a standing or moving vehicle in any portion of the effective loop area.

Presence Mode Detector mode in which an output is given as long as a vehicle remains in the field of influence. Also called Passage Mode.

Pulse Mode Detector mode in which a short output is given when detection occurs.

Real Time Control The processing of information of data in a sufficiently rapid manner so that the results of the processing are available in time to influence the process being monitored or controlled.

Recall An operational mode for an actuated intersection controller in which a phase, either vehicle or pedestrian, is displayed every cycle whether demand exists or not. Usually used during a temporary or emergency situation.

Red Rest A controller designed to rest in all red in the absence of any traffic demand.

Skip Phasing The ability of a controller to omit a phase from its cycle of operation in the absence of demand or as directed by a master control.

Slave A local control device whose interval timing and sequence of operation is controlled by a submaster in a distributed system.

Split A percentage of cycle length allocated to each of the various phases in a signal sequence.

Stops The number of times vehicles stop in the system.

Time Headway The time seperation between vehicles approaching an intersection, measured from the front of a vehicle to the front of the next vehicle.

Time-of-Day Patterns Signal timing plans selected according to the time of day.

Traffic Detector A device by which vehicles, street cars, trolley buses, or pedestrians are enabled to register their presence with a traffic actuated controller.

Traffic Responsive System A system in which a master controller specifies the cycle and offset based on real-time demands of traffic as sensed by vehicle detectors.

Variabale Initial Interval A controller design feature which adjusts the duration of initial interval for the number of vehicles in the queue.

Volume Density Controller An advanced actuated controller which, in its two phase model, has three gap-reduction factors, namely, Time Waiting, Cars Waiting, and Density.

Yield The action of allowing a semi-actuated controller, or an actuated controller operating in the semi-actuated mode, to terminate the main street phase to begin satisfying existing cross-street demand.

APPENDIX B. FLOATCAR USER'S MANUAL.

FLOATCAR is a user-friendly, menu-driven program designed to help traffic personnel conduct floating car studies efficiently and conveniently. This program can be used on any IBM compatible PC or laptop computer. The program can be used to collect travel time data using the test vehicle method. The data collection program is equally applicable while using either the "floating car" or the "average speed" driving strategy.

The FLOATCAR program can record a variety of information required for a full-fledged speed and delay study. Using this program helps users to record a large amount of required information with minimum effort and ensures data reliability at the same time. The data collected with FLOATCAR can be processed using the FLOATPRO program, described later in detail, to obtain travel time study data values in a format that can be directly taken into a spreadsheet for further statistical analysis.

OPERATIONAL PROCEDURE

To invoke FLOATCAR, the user must type:

FLOATCAR <Site Input Data Filename> <Output Filename>

The site input data file contains the following information stored on separate lines:

1. Name of the arterial (e.g., US 77),
2. The primary direction of run (e.g., NS),
   *Please note that the entry is given as NS, SN, EW, or WE for the primary directions. Either NS and SN or EW and WE are expected for a system, and hence depending on this value the program may allow modifications only between the relevant pair.
3. The number of intersections (e.g., 7), and
4. The intersection names (e.g., 1. FM1985).
   *Please enter one per per line, and should be the same in number as indicated in the third entry. It is recommended that the streets are given following the sequential number of the intersection for easy identification during data collection and analysis.

The direction of run can be modified later, if required, during program execution. However, changes are allowed only between the appropriate pair of directions. Comments may be incorporated into the data file by typing a "/" followed by any text. Any character beyond "/" is ignored by the program.

A minimum of one cross street or key point is required for the successful FLOATCAR execution. Two key points, "Starting Point" and "Ending Point", are always added by the program representing two arbitrary points on the two ends of the system. These are not given an ordinal number, so the user can assume that the 1st intersection in the system is the intersection to be given the number 1. Also, these points are interchanged when the direction of the run is reversed.

Start Program

To begin data collection, invoke the program from the command prompt by typing in the following statement (for example):

> > FLOATCAR KING.DAT KINGDATA

KING.DAT contains the site details, and KINGDATA is the output file into which the program will record all the information. It may be noted that the program always appends data to output file. The program does not overwrite existing file content but will always add the new output to the output file. This helps the user to continually collect data of several sessions into one file. However, the user will be warned by the program that the output will be appended to the existing file, if the file already exists. If the user opts not to append, another filename will be requested by the program.

If the program is unable to open any of the input or output files, a suitable error message is provided to the user. If there were no errors, the program requests the following information:

- A description of the run,
- The direction of the run, and
- The weather conditions.

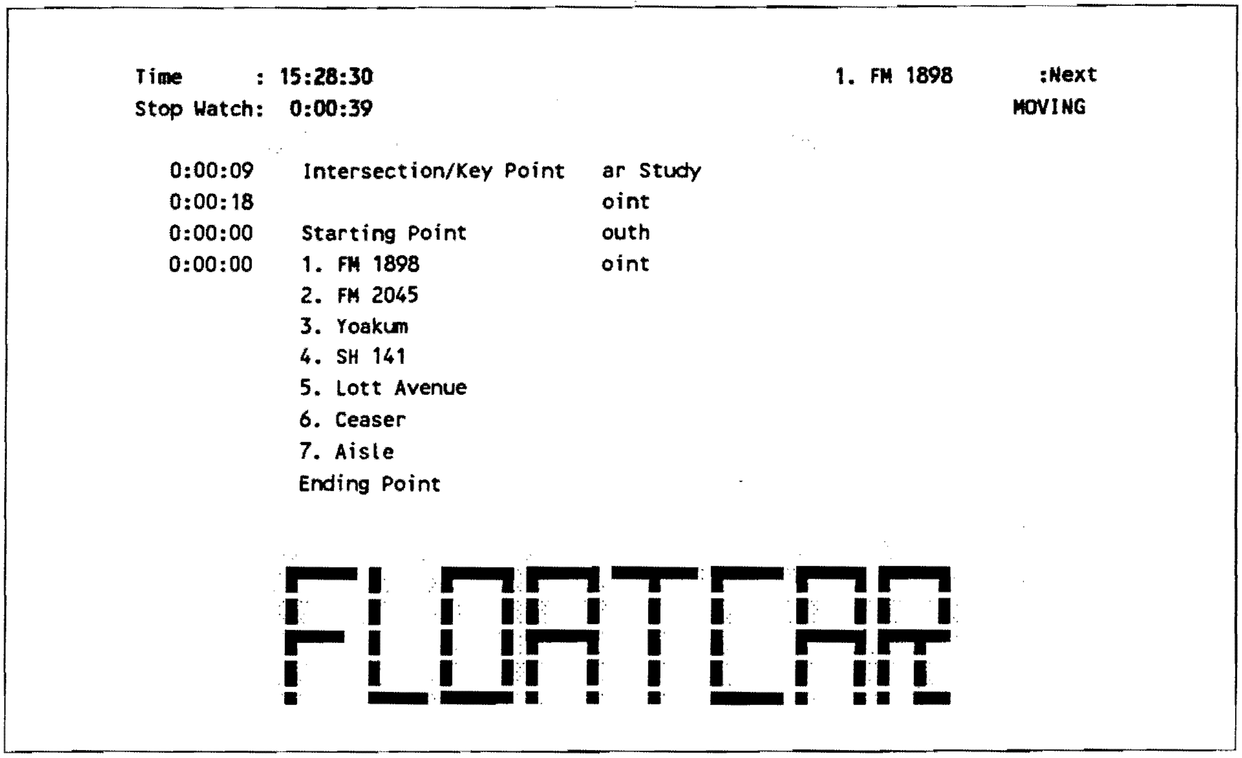
Data Entry

After the user selects from the relevant menu items, the program switches into "data entry mode." The screen display will show the current time and the stop watch time, next intersection name, and status of the car.

As shown in **Figure B-1 "FLOATCAR Program,"** a pop-up menu prompts the user for data entry. The following options are available to the user at all times:

C - Write Comments to Output File,
I - Record Crossing an Intersection/Key Point,
G - Record Go after a previous Stop,
S - Record Stop at any Point,
R - Reset Current Intersection,
U - Record Undo for the Last Step,
M - Enter Mileage,
B - Backup Data,
H - Shell to DOS, and
Q - Quit.

The function of each of the keys is briefly mentioned on the display. The user can use the cursor keys to move to the required selection and accept the selection by pressing the "Enter" key. The user is provided an audible signal, either in single or multiple beeps, whenever an important selection is made. The selections made by the user are recorded onto the output file and echoed to the display window above the pop-up menu for user feedback. All records made to the file and echoed to the display are given along with the time and the stop watch count at the instant the key is pressed.



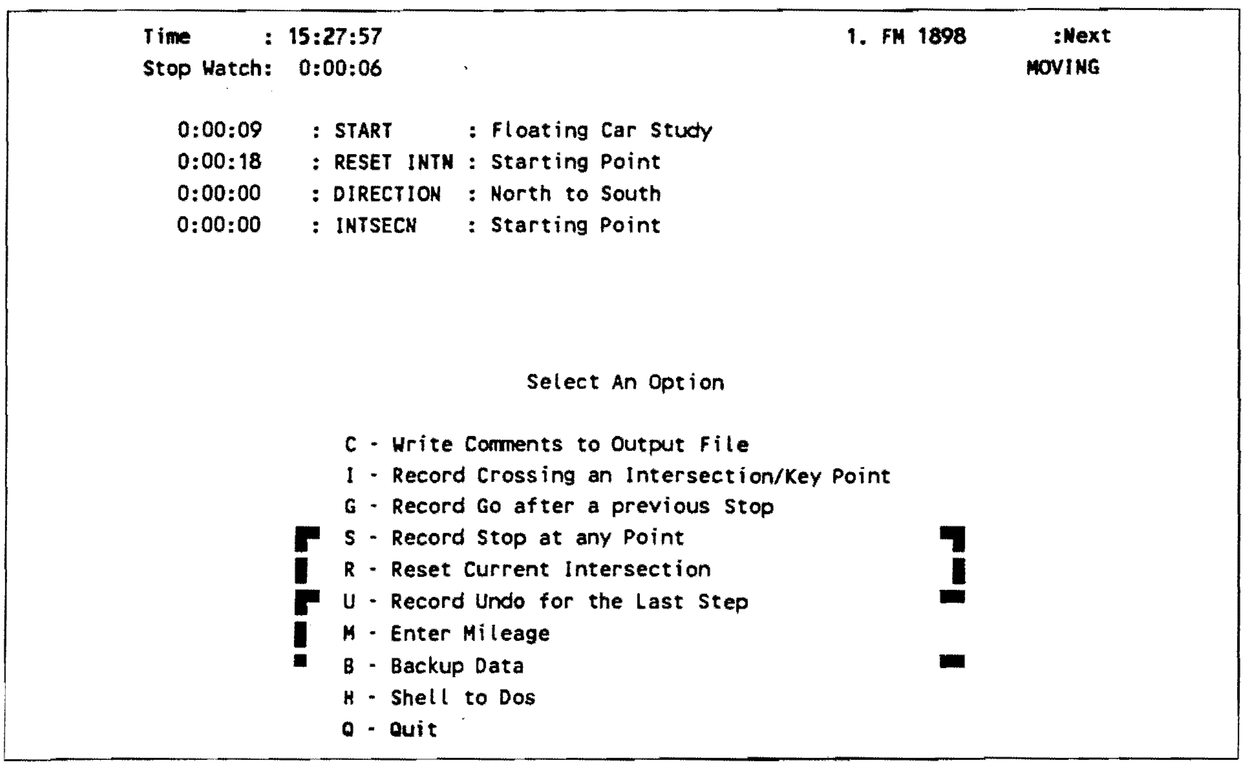


Figure B-1. FLOATCAR Program.

KEYBOARD COMMANDS

The actions assigned to the keys are as follows.

C-Write Comments to Output File

This option allows the user to enter a short comment, which could be used later during data processing.

I-Record Crossing an Intersection/Key Point

This option is selected when the test vehicle passes a key point or intersection, or the starting or end points. The key points must have already been mentioned in the site data input file. After all key points in one direction have been recorded, the program asks the user if another run in the other direction is required. If the user indicates yes, the program automatically swaps the street names and changes the direction of the run. If the key point is the starting point, the stop watch is reset to zero, signifying the initiation of a new run. The next key point of interest is displayed on the top-right corner of the display.

S-Record Stop at any Point

This option is selected whenever the test vehicle completely stops. The status of the car changes to "STOPPED", and the entry is recorded onto the file and echoed on the display. If the stop was indicated by mistake, pressing U (Undo Last) immediately changes the status of the car to "MOVING". After the vehicle is stopped, the program will accept only the following options:

- B - Create a backup file,
- U - Undo the last step,
- M - Enter the mileage, and
- R - Reset Intersection.

If any other option is selected, an error is indicated. Pressing the "Escape" key clears the error. Once the car is stopped the selection bar goes to the "G-Record Go after a previous Stop" option. The stop and go entries are recorded beside the name of the next expected intersection. The logic is that stops at a signal are usually made before crossing the intersection.

G-Record Go after a Previous Stop

After the user records a stop, the car must be restarted to resume normal data entry options. The status at the top-right will be restored to MOVING.

R-Reset Current Intersection

If the user registers an intersection by mistake, the error can be immediately corrected by selecting this option. A pop-up menu is provided for the user to select the correct current intersection.

U-Record Undo for the Last Step

It should be noted that the "UNDO LAST" registered by the option does not undo the last action made by the user, but is an indication to the user of the program to later remove the unnecessarily recorded lines, before further post-processing. However, if the last action was recording a Stop, the situation is restored by the program.

M-Enter Mileage

This allows the user to enter the mileage of the car at different locations, which gives a good record of the distances between intersections. The post-processor does not use this information.

B-Backup Data

This option is to be invoked if there is a need for backing up data onto a backup file. Disk operations are power intensive, hence backups should be made only when necessary. The FLOATPRO program may not accept incomplete outputs, and hence the backup files should be edited to remove incomplete runs if the original file is lost for some reason. It is always a good idea to make sure that batteries in laptop computers are fully charged for the period of data collection.

H-Shell to DOS

This option is provided to allow the user to shell out to the DOS for any file operation. The user may type EXIT to return to FLOATCAR.

Q-Quit

This option allows the user to exit the FLOATCAR program. The user is prompted to confirm the request. The program prompts the user for a run in the other direction once the test vehicle has reached the end of a run. It automatically records the direction, and intersections in the opposite direction. The program also provides helpful warning and error messages in the case of invalid user actions.

After data collection, the data can be edited (if required) to account for any mistakes made by the user during data entry. However, the user should take care not to change the data file format drastically. The FLOATCAR output is then provided to the FLOATPRO program. The output from the FLOATPRO post-processor program consists of a comma-separated file tabulating the details of the run, the travel times recorded at each intersection, and the total stopped delays during the different runs. The average values for a set of runs in different directions are also provided. The output file provides values for immediate spreadsheet processing.

These computer programs are highly recommended for frequent floating-car study where a high degree of data accuracy is needed to compare different control strategies. The use of these data collection and process programs can reduce the data reduction and analysis significantly.

APPENDIX C. FLOATPRO USER'S MANUAL

FLOATPRO is designed to process travel time collected by the FLOATCAR program. This program takes the site input data file and the FLOATCAR output file as input and generates condensed travel time data in a convenient format for further analysis using spreadsheets. The FLOATPRO output is in a comma-separated format and can be directly imported to most spreadsheet packages.

START PROGRAM

The syntax for invoking the FLOATPRO program is as follows:

FLOATPRO <Site Input File> <FLOATCAR Output File> <Output File>

The site input data file contains the same information provided to FLOATCAR. FLOATPRO ignores any comments and any UNDO LAST statements, (Except when UNDO LAST is encountered immediately after a STOP, in which case the car should be restarted again). Hence it is recommended that, if need be, the user manually edit the file to remove possible incorrect entries. FLOATPRO has extensive error checking capabilities, but any information entered as a comment or an UNDO may need to be corrected by the user.

DATA DESCRIPTION

The header of each output file contains the following information for the program internal record keeping usage:

- The description of the session,
- The name of the main arterial,
- The date and time of the session, and
- The weather during the session.

This information is followed by the tabulated values indicated below:

1. The cumulative travel time during each run from the starting point recorded at each key point and the overall cumulative travel time,

2. The stopped delay (not cumulative) encountered in the last segment (between the prior intersection and the indicated intersection) and the overall cumulative arterial stopped delay, and

3. The number of stops (not cumulative) experienced by the vehicle in the last segment (between the prior intersection and the indicated intersection) and the overall number of stops encountered by the test vehicle.

These values are provided for both directions separately. The values for each direction are followed by a summary of information for that session. The summary section contains the average of the measured values for a session in each direction and the total number of runs made in that direction. These values may be useful if each session was completely devoted to some specific case scenario.

DATA CHECKING

The program expects the FLOATCAR input file in the line format used by FLOATCAR. Therefore, any editing of the FLOATCAR output file should be done without altering the basic format of the file. The FLOATCAR output file is tab separated and neatly formatted and should present no problem for the user while editing. It is recommended that the entire line containing the incorrect information be deleted if the user had entered any incorrect entry using data collection.

If there is any problem in the file operation, the user is notified through error messages. If FLOATPRO detects any errors in the FLOATCAR data, further processing is suspended and the user is notified of the error, along with the data file line number where the error was detected. The user should be able to detect the error and correct it very easily by examining the line or the adjacent lines in the file.

As shown in **Figure C-1 "FLOATPRO Input File"**, each data line from the FLOATCAR program contains four (4) sections:

1. Time of entry,
2. Stopwatch reading at time of entry,
3. A token specifying the type of entry, and
4. A description of the entry, e.g., mileage, intersection name, comments.

These four sections are parsed by the FLOATPRO program while processing. If there are any errors while parsing, FLOATPRO gives an "Invalid Format in Input File" error. If the token specified in the line is unknown, an "Invalid Token" error is reported. The error messages provided by FLOATPRO can be easily understood.

If the program finds a sequence of entries that are not possible in a FLOATCAR session, an error of a form similar to "Found token FINISH while stopped" is generated. This implies that such a sequence of tokens is unlikely in a correct FLOATCAR session, and errors might have crept into the input data file during editing. A close examination of the input file should show the problem. This error is generally caused by incorrect editing of the input file, and the problem can be detected by comparing the input file with the original copy of the FLOATCAR output file. It is a good idea to keep an unaltered backup of FLOATCAR data for error checking. Incorrect data may also result in division by zero for some runs. This is trapped by the FLOATPRO program and an error message "Incorrect Entries. May result in Zero Division" is generated. The relevant run that results in this problem should be deleted before further processing.

DATA PROCESSING

FLOATPRO can handle a maximum of 40 intersections or key reference points, and 100 up and down runs per session. It can handle multiple sessions, for example, the same case scenario in different periods of the year. No limit has been set on the number of sessions that can be handled; however, the

```
******************************************************************************
*                              FLOATING CAR STUDY                            *
******************************************************************************
```

Description :STRATEGY-5. FULL-ACTUATED UNCOORDINATED - ORIGINAL TIMING - TXDOT
Date and Local Time :Tue Dec 08 10:58:39 1992
Weather :Cloudy Weather
Route :US 77

Time	Stop Watch	Status	Location
10:58:41.63	0:00:03	START	Floating Car Study
10:58:52.34	0:00:14	COMMENT	Cloudy Weather
10:59:12.23	0:00:34	COMMENT	Start from Signal Warning Sign - North

NEXT SET

Time	Stop Watch	Status	Location
11:00:30.72	0:00:00	DIRECTION	North to South
11:00:30.72	0:00:00	INTSECN	Starting Point
11:00:44.94	0:00:14	INTSECN	1. FM 1898
11:01:36.96	0:01:06	INTSECN	2. FM 2045
11:02:16.01	0:01:46	INTSECN	3. Yoakum
11:02:35.84	0:02:05	STOP	4. SH 141
11:02:54.95	0:02:24	GO	4. SH 141
11:03:02.20	0:02:32	INTSECN	4. SH 141
11:03:21.97	0:02:51	STOP	5. Lott Avenue
11:03:23.95	0:02:53	GO	5. Lott Avenue
11:03:29.66	0:02:59	INTSECN	5. Lott Avenue
11:04:24.37	0:03:54	STOP	6. Ceaser
11:04:39.31	0:04:09	GO	6. Ceaser
11:04:42.66	0:04:12	INTSECN	6. Ceaser
11:05:40.93	0:05:10	STOP	7. Aisle
11:05:42.91	0:05:12	GO	7. Aisle
11:05:45.82	0:05:15	INTSECN	7. Aisle
11:05:58.51	0:05:28	FINISH	End of Run
11:07:30.46	0:01:18	COMMENT	School Sign as Ending Point

Figure C-1 FLOATPRO Output File.

number of runs per session should not exceed 100. These limits should not create any problems under normal circumstances.

Since the FLOATPRO program can handle multiple sessions, it is recommended that the FLOATCAR output files obtained from a complete travel time study be combined into one file for processing. For example, if a set of files obtained during the 6 sessions over a period of three days are 1AM1.DAT, 2PM1.DAT, 3AM2.DAT, 4PM2.DAT, 5AM3.DAT, and 6PM3.DAT, these files can be combined into one file using the command:

```
COPY *.DAT ALL.CAR
```

It should be noted that the second argument of the copy command should not be included in the mask provided for the first argument. For example, if the second argument was named as ALL.DAT, this would result in an error "Content of destination lost before copy."

DATA OUTPUT

The final output obtained from FLOATPRO can be imported to any spreadsheet program that accepts the comma separated format. For example, in Quattro Pro, the command to load comma separated files is Tools|Import|Comma Delimited|<file name>. If Microsoft Excel for Windows is used, the file can be loaded by mentioning the option "Comma separated" under the Open dialog box. <u>If the comma separated option is not used, the lines would be treated as lines of text, which would prevent numerical analysis.</u>

The FLOATPRO output is designed so that the spreadsheet database facilities can be used to extract the necessary information from the output. For this purpose the output contains the lines Database Block, Criteria Block, and Extract Block. Usually spreadsheets require that each column of blocks of data be named. To prevent the user from having to type in a name for each column, the letters A through L are provided. When the different blocks are marked, the user may include the line of these letters as the first lines of the blocks.

The user may give some typical text from the data lines of interest in the criterion's range, to facilitate extracting only data in which the analyst is interested. Using the database facilities in spreadsheets is easy, and beginners are encouraged to refer to the on-line help facilities provided by almost all spreadsheet packages for further information.