FREEWAY AND ARTERIAL INTEGRATED CONTROL SYSTEM

WA-RD 293.2

Final Report
May 1993

Washington State
Department of Transportation

Washington State Transportation Commission
Transit, Research, and Intermodal Planning (TRIP) Division
in cooperation with the U.S. Department of Transportation
Federal Highway Administration

TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO. WA-RD 293.2	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.
4. TITLE AND SUBTITLE FREEWAY AND ARTERIAL INTEGRATED CONTROL SYSTEM		5. REPORT DATE May 1993 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Mark E. Hallenbeck John Nisbet		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Washington State Transportation Center (TRAC) University of Washington, JD-10 University District Building; 1107 NE 45th Street, Suite 535 Seattle, Washington 98105-4631		10. WORK UNIT NO. 11. CONTRACT OR GRANT NO. GC8719, Task 8
12. SPONSORING AGENCY NAME AND ADDRESS Washington State Department of Transportation Transportation Building, MS 7370 Olympia, Washington 98504-7370		13. TYPE OF REPORT AND PERIOD COVERED Final Report 14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

This study was conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration.

16. ABSTRACT

A computer system was developed to integrate three pre-existing traffic control systems. These three systems were the traffic signal systems on SR-99 and SR-522 in northern King County and the freeway ramp metering system (FLOW system) on Interstate 5 north of the Seattle central business district. This project continued previous WSDOT research, described in the report "Arterial Control and Integration, Final Report," March 1990.

The integration system developed in this effort consisted of a single microcomputer that communicated with both the mini-computer that operated the FLOW system and the microcomputer through which an operator controlled both arterial signal networks. To minimize development efforts and costs and to demonstrate the potential for adding integration capabilities to traffic control systems, the integration system relied extensively on the control systems' existing capabilities.

Tests of the integration system produced mixed results. The basic system design was flexible and met the needs described in the earlier WSDOT report. The control system also showed that it can use the data collected by one control system to adjust the control strategy of another, independent system. Unfortunately, the integration system was not a complete success and therefore was not implemented by WSDOT. The integration system suffered from unreliable inter-computer communications. The communications difficulties were caused by "off-the-shelf" computer networking software that was not sufficiently fault tolerant for real-time control system applications. That is, the integration system experienced intermittent communications failures between the control system computers. These failures disrupted system operation, and that disruption could have significantly degraded traffic operations. A system operator was able to easily fix the communications failures, but the integration computer could not automatically handle them.

17. KEY WORDS Traffic Control Systems, Traffic Control Integration, ATMS, Advanced Traffic Control Management Systems	18. DISTRIBUTION STATEMENT No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22616

19. SECURITY CLASSIF. (of this report)	20. SECURITY CLASSIF. (of this page)	21. NO. OF PAGES	22. PRICE
None	None	35	

Final Report

Research Project GC8719 Task 08
Freewy/Arterial Integrated Control System

FREEWAY AND ARTERIAL INTEGRATED CONTROL SYSTEM

by

John Nisbet
Research Assistant

Mark Hallenbeck
Deputy Director, TRAC

Washington State Transportation Center (TRAC)
University of Washington, JD-10
University District Building
1107 NE 45th Street, Suite 535
Seattle, Washington 98105-4631

Washington State Department of Transportation
Technical Monitor
Les Jacobson
Traffic Manager, District 1

Prepared for

Washington State Transportation Commission
Department of Transportation
and in cooperation with
U.S. Department of Transportation
Federal Highway Administration

May 1993

DISCLAIMER

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

SUMMARY

This research project developed and tested a computer system that integrated three existing traffic control systems. These three systems were the traffic signal systems on SR-99 and SR-522 in northern King County, and the freeway ramp metering system on Interstate 5 north of the Seattle central business district (the FLOW system). This project continued work begun in previous WSDOT research, described in the report "Arterial Control and Integration, Final Report," 1990.

The integration system consists of a single microcomputer that communicates both with the minicomputer that operates the FLOW system and the microcomputers that serve as the operator's control computers for both arterial signal networks. To minimize development effort and costs and to demonstrate the potential for adding integration capabilities to existing traffic control systems, the researchers developed the integration system to rely extensively on the existing control systems' capabilities.

All data collection and signal control capabilities supplied by the integration system were previously possible with the existing traffic control systems. Instead of functionality, the integration system provides two important advances:

- the ability to use information external to the existing control system data collection process to assist in selecting traffic control plans, and
- the ability to automatically perform functions that originally required an operator's intervention

Tests of the integration system showed mixed results. The basic system design is flexible and adequately meets the varied needs described in the earlier WSDOT research report. The control system also showed that it is capable of using the data collected by one control system to adjust the control strategy of an independent control system. These two advances helped produce a positive reaction to the potential for integrating independent control systems in jurisdictions north of the Seattle metropolitan area.

Unfortunately, the integration system was not a complete success and is not being used by WSDOT. The integration system suffers from unreliable inter-computer communications. The communications difficulties are caused by "off-the-shelf" computer networking software that is not sufficiently fault tolerant for real-time control system applications. That is, the integration system experiences intermittent communications failures with the control system computers. These failures disrupt the operation of the system, and that disruption has the potential to significantly congest traffic. Although the communications failures can be easily fixed by a system operator, they can not be automatically handled by the integration computer.

Finally, while the system's evaluation showed benefits, those benefits do not warrant a staff position to monitor the system. Without this monitoring function, the integration system (as it currently operates) is not sufficiently reliable for use by WSDOT. Because WSDOT does not have (and does not otherwise need) a staff person to act as system operator, the integration system has not been implemented.

INTRODUCTION

Traffic congestion is a growing concern in today's urban environment. Metropolitan areas face increasing demand on freeway and arterial networks already operating at or near their capacities. With resources for major capacity improvements declining, the focus of the traffic engineering profession is turning towards ways of managing congestion to ensure maximum efficiency from the existing road network.

A significant part of this management effort relies on computerized traffic control systems to control and smooth the flow of vehicles using both freeway and arterial systems. Unfortunately, traffic control systems often operate independently. Each traffic control system looks only at traffic volumes and conditions within its boundaries, rather than also considering the effects of nearby traffic volumes and conditions that may significantly affect how that control system will soon operate.

The result is that many of the benefits that can be obtained from coordinated traffic control systems are lost at the boundaries of neighboring control systems. In some instances, the problems that cross control system boundaries are so significant that they overwhelm the control capabilities of the traffic control system.

PROJECT OBJECTIVES

The principal objective of this work was to develop a system that could integrate the operation of existing traffic control systems at a low cost and within the constraints of existing hardware. The project was designed to show that a low cost system could integrate existing systems well enough to productively improve facility operation.

PROJECT BACKGROUND

Traffic congestion (or its effects) often crosses control system boundaries, as well as jurisdictional boundaries. For example, queues at a ramp meter can extend to adjacent arterial streets, causing congestion on the streets. In addition, traffic flowing through one control system often migrates to a neighboring system. For example, traffic using an arterial is not aware that the control system operating that arterial may change as the arterial moves through jurisdictions. In this example, data shared between two adjacent control systems could provide advantages in the selection of control system strategies.

These advantages have two basic forms. In the long term, simply sharing information can be beneficial. Most traffic control strategies are based on expected traffic movements, and knowledge of routine traffic movements on neighboring facilities can help traffic engineers create more effective control system plans.

In the short term, benefits can also be derived from the provision of real-time traffic information to neighboring systems. Such information is especially useful when significant changes in traffic volumes occur. Advance notice of these changes (for example, notifying a neighboring system that a large change in volume will soon occur as traffic passes from the current control system to the neighboring system) allows the neighboring system to change to an appropriate control strategy before the arrival of the expected traffic. This preparation can delay and even prevent breakdowns in traffic flow, producing significant savings for the traveling public.

In these cases, neighboring system traffic information can be useful to traffic control plan selection. For example, where parallel roadways exist, route diversion may take place when unusual traffic congestion occurs (such as that caused by an accident). Again, advance knowledge of traffic volume changes caused by the diverting vehicles will allow the system to implement appropriate control plans before traffic flow breaks down on the parallel facilities.

If information regarding incidents and the resulting or expected traffic conditions could be shared among neighboring facilities, control strategies for neighboring systems could be altered to accommodate these temporary increases in demand before that demand reached the diversion route.

TRAFFIC CONTROL SYSTEMS BACKGROUND

In many respects, the functionality required to share information between neighboring control systems already exists in modern traffic control systems. Despite their very different operational functions, both the arterial traffic signal and freeway ramp metering systems involved in this integration effort have similar sets of basic functions. This appears to be the case for most modern traffic control systems.

All modern traffic control systems perform some level of traffic performance data collection, along with either facility access control or provision of motorist information based on an analysis of the collected data. Furthermore, most of these systems include the capability to store traffic performance data for later use.

In addition to similarities in functional capabilities, most modern traffic control systems have similar system architecture. There are typically two, and in many cases three, levels of supervision or control for traffic control systems. In the three-level approach, the system architecture typically consists of an on-street, location specific level of control (local controller); an on-street, sub-system, supervisory level of control (on-street master controller); and an off-street, multi-system, supervisory level of control (system central computer). The two-level approach typically omits the on-street system level.

In the study's existing traffic control systems, the local controller contains most all timing parameters. The arterial masters are central communications hubs to which local controllers send data, and through which major changes in timing plans are initiated. The central computer is primarily used to provide an operator interface to the arterial master. This link allows the operator to override existing timing plans, change the data collection functions, and access and store for later analysis the data collected by the local controllers.

The functional and hardware similarities between different control systems allow an integration strategy to be developed (as in this project) that can be readily applied to the vast majority of traffic control systems used in the United States. While the control software of most of these systems would require minor changes, in many cases the technical problems for integration would be smaller than the non-technical problems.

USER CONSIDERATIONS

The WSDOT research report "Arterial Control and Integration, Final Report," March 1990, listed a number of concerns that traffic engineers interested in control system integration have expressed. The primary concerns of these engineers are cost (both the initial cost of the integration effort and the ongoing maintenance and operational costs) and control. Most agencies are interested in the benefits of integrated operations, but they must work within limited resources while retaining control of their facilities for political accountability.

For an integration system to be acceptable to operators of independent control systems, the integration system must be structured to provide the following features:

- the ability to communicate with existing, "off the shelf" traffic signal control systems without requiring substantial modifications to these systems,
- the ability to utilize features already available in existing signal systems, again without significant modifications to these existing systems, and
- the flexibility to allow users to define the data that their control systems will receive, including data content, format, source, and time increment.

Additional guidelines for integrating systems are presented in the Implementations section of this report.

PROCEDURES

This project consisted of the following six tasks:

- develop the evaluation framework,
- collect before data,
- develop the control algorithm (including software development),
- implement and adjust the algorithm,
- evaluate the system, and
- write the report.

As noted above, additional work relevant to this project was completed during previous WSDOT research. The earlier WSDOT work described the basic functional model on which the integration system developed in this project was based. Thus, the primary new intellectual work for this project, the design of the integration software and hardware system, took place in tasks 3 and 4.

This report documents the system that was designed for this project and the results of the implementation testing of that system.

DISCUSSION

SITE DESCRIPTION

The demonstration system combines the control functions of SR-522, SR-99, and I-5 in the northern end of King County (see Figure 1). The SR-99 arterial control system stretches from N.E. 155th Street to N.E. 205th Street (the Snohomish County line). The SR-522 signal system stretches from N.E. 165th Street to 80th Avenue N. Intersections both north and south of the study sections are also signalized, but they are controlled by agencies other than the WSDOT and operate on separate traffic signal control systems.

The three study facilities provide roughly parallel north/south movements although they serve somewhat different traffic sheds. Because they are parallel, the conditions on one of these facilities can influence the traffic conditions on the others. An analysis of traffic volume data collected at the onset of this project indicated a relationship between conditions on each of these three facilities. However, this interaction did not appear to be uniform and was difficult to quantify for SR-522.

The study indicated that conditions on the freeway affect arterial traffic conditions, but that conditions on the arterials have a less quantifiable impact on the freeway. No direct relationship between conditions on the two arterials was apparent.

EXISTING CONTROL SYSTEMS

As indicated earlier, each of the facilities included as part of the demonstration project has its own traffic control system. The two arterials use Type 170 traffic signal control hardware and run both time-of-day and traffic responsive, coordinated traffic signal plans. While both arterials use the same software and hardware, they are controlled from separate on-street masters and are not coordinated with each other. However, both arterial masters are accessed by the same central microcomputer for data uploading and traffic pattern downloading.

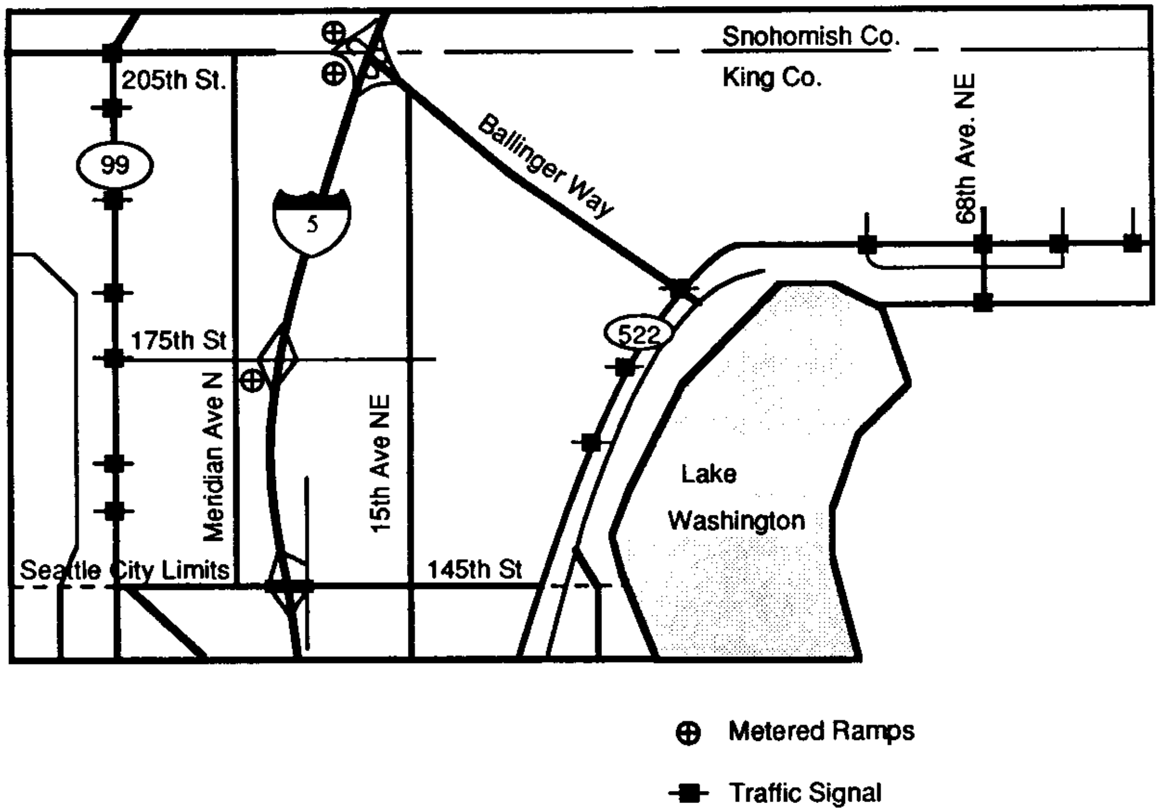

Figure 1. Demonstration System Facilities

The freeway control system consists of a centrally controlled ramp metering system that calculates metering rates in real time. The central computer for this system is located at the Traffic Systems Management Center (TSMC). (Since completion of the project, the central computer function has been moved to a new computer located in the new District 1 headquarters building.) To calculate metering rates, the TSMC computer monitors mainline and ramp loop detectors and computes whether sections of the freeway system are storing vehicles. If vehicle storage on the freeway is detected, an algorithm (the "bottleneck algorithm") reduces ramp volumes upstream from that point of congestion. Once congestion has cleared (vehicles are no longer being stored), metering rates are increased to allow additional traffic to enter the freeway.

The TSMC computer calculates metering rates and communicates them to Type 170 controllers in the field that control the ramp meters. Reductions and increases in metering rates are allocated between ramps on the basis of a weighting system WSDOT has developed. The weights applied to individual ramps are based on the operational characteristics of each ramp and the need to encourage motorists to use the ramps that create the smallest environmental and operational impacts.

Under some circumstances, the freeway control system operator can "drop" specific ramps out of the bottleneck calculation. When a ramp is dropped from the bottleneck algorithm, local freeway conditions at that ramp (determined from the mainline loops) are used to set the metering rate for that location. This rate is usually higher than that calculated by the bottleneck algorithm.

INTEGRATION SYSTEM DESIGN

The integration system design relies on the traffic data that can be electronically collected through the TSMC computer (volumes and occupancies) and the arterial system central computer (primarily volume data), and the inherent ability of these central computers to provide control instructions to their respective signals. The hardware and software portions of the integration system are described below.

Hardware Design

The hardware design for the system is shown in Figure 2. Data from the mainline loops and ramp meters are sent to the TSMC. In addition, four "data stations" (each comprising a set of loops and some electronics) send volume and occupancy data from the arterials to the TSMC computer. (Two stations have been installed on both SR-99 and SR-522.) These data are also passed from the TSMC computer to the project's integration microcomputer via the same RS-232 hardwire link used to transfer freeway data.

The TSMC computer aggregates volume and occupancy data from a designated set of mainline loops at 5-minute intervals and then transmits these data (also at 5-minute intervals) to the integration microcomputer. Table 1 shows the mainline data stations that are used for aggregation and data transmittal in the demonstration system.

The integration microcomputer also communicates with the central computer (microcomputer) for the two arterial systems. This communication is also done over RS-232 cable with a simple LAN connection.

The central arterial system computer transmits to the integration microcomputer volume information that has been collected by arterial "system detectors" and aggregated by the arterial system masters. The integration microcomputer combines this information with the data from the TSMC to compute traffic conditions on all three facilities. If traffic conditions are significantly different than expected on one facility, the integration microcomputer determines the appropriate control strategy for the other two facilities. These decisions are based on simple analyses of volume and lane occupancy data, which are described later in this report.

If the integration microcomputer determines that an alternative control plan should be implemented on one or more of the demonstration facilities, instructions to implement the new control plan are sent to the appropriate control computer via the same

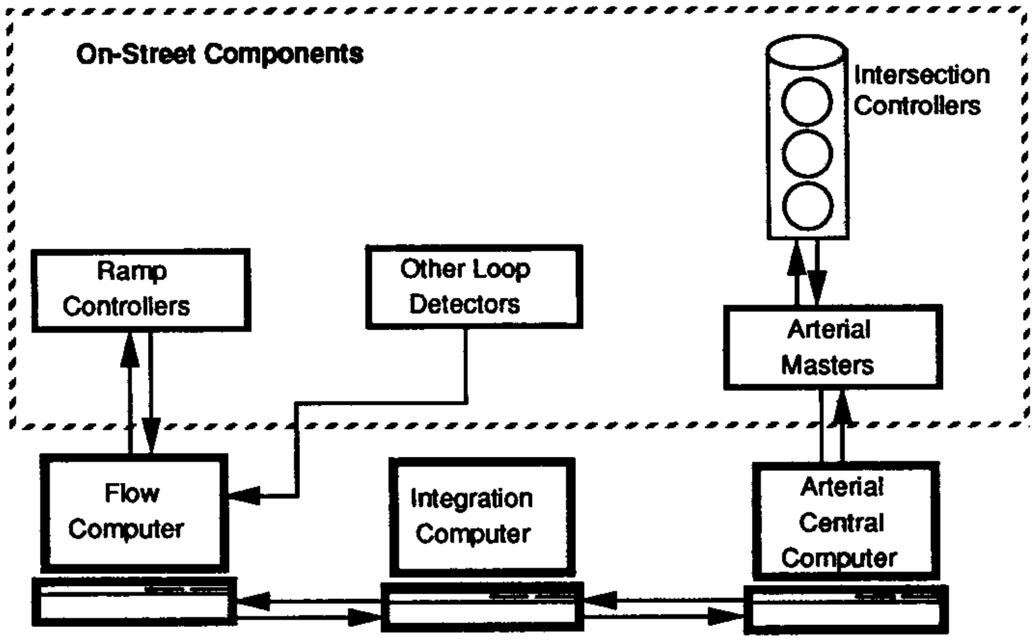

Figure 2. Integration System Hardware Configuration

Table 1. Freeway Data Stations Used by the System

Data Station ID	Cross Street	Direction of Travel	Mile Post	Number of Lanes
0	NE 110	NB	172.88	5
1	NE 120	NB	173.30	5
2	NE 130	NB	173.71	5
3	NE 137	NB	174.16	5
4	NE 145	NB	174.58	5
5	NE 155	NB	175.11	5
6	NE 162	NB	175.50	5
7	NE 175	NB	176.12	4
8	NE 185	NB	176.73	4
9	NE 195	NB	177.21	4
10	NE 205	NB	177.66	3
11	SE 220	NB	177.84	3
12	SE 230	NB	178.19	4
13	SE 250	SB	178.19	4
14	SE 230	SB	177.84	4
15	NE 205	SB	177.66	4
16	NE 195	SB	177.21	4
17	NE 185	SB	176.73	4
18	NE 175	SB	176.07	4
19	NE 162	SB	175.50	4
20	NE 155	SB	175.11	4
21	NE 145	SB	174.60	4
22	NE 137	SB	174.16	5
23	NE 130	SB	173.71	5
24	NE 120	SB	173.30	5
25	NE 100	SB	172.86	5

communications channels that carry the traffic data to the integration microcomputer. The control computers (TSMC or arterial central) respond to these messages from the integration computer and transmit control instructions to the field hardware that physically controls the signals. When these special control plans are no longer appropriate, the integration microcomputer instructs the control computers to reinstate "normal" control plans over the same communications structure.

Software Design

The software design for the integration system is simple. It is based on the idea that all the control functions available to the integrated system should already be present in the existing control systems. No significant new types of control strategies were devised within this demonstration.

The integrated system simply provides a means for extending the available control functions of the current systems to include data not now used by the central computer to select control plans. The existing central control hardware for both the freeway control system and the arterial control system provides the same commands that were available before the implementation of the integrated system, but these commands are now given without the need for human operators.

To function, the integration system uses congestion information collected by one traffic control system to identify when demand for the alternative facilities is likely to change. When these expected changes are large enough to warrant a change in the "normal" peak hour traffic control strategy, the integrated control program selects and implements the appropriate traffic control strategy for each facility.

Once traffic conditions have returned to "normal," either as a result of incident clearance or the end of the peak traffic period, control of the facilities returns to the conventional control processes for each road (i.e., the arterials return to their usual time-of-day operation, and the freeway ramp meters return to their normal operating plan for that time of day). These same tasks were already accomplished manually by a system operator before the development of the integration system; the new system simply automates those steps.

Because changing between control plans on arterials can increase traffic congestion during the transition process, the "special control strategy" was designed to be used only when the expected traffic improvements due to the new control strategy would exceed the disruption caused by the transition. The alternative control strategies were designed to be employed at most once per peak period, and were not implemented at all on most days.

The integrated system design assumed that more than one "special" control plan would be required for each demonstration facility. This means that the integration microcomputer must not only communicate to the correct control computer (see above), but each message that is transmitted must identify the facility that will implement the change and the control strategy to be implemented. Requiring system identification information also allows the integration system to be expanded, as long as the hardware can handle the communication requirements of additional traffic control systems.

Arterial Control Plans Implemented By The Integration System

To remain consistent with the design philosophy, the only control commands that the integration system could send were commands that were normally transmitted by the arterial central computer. Therefore, the project team designed the arterial central computer to request the implementation of a new timing plan that would match the expected traffic levels. (Manual implementation of timing plans is a standard arterial central computer function for most closed-loop traffic signal control systems.)

The plans requested by the integration system are specifically designed for abnormal flows. The plans tested in this project are optimized for traffic volumes much higher than "normal," although plans could also be developed for lower than normal traffic volume levels. These higher traffic volumes require a different "optimum" signal plan, with alternative cycle lengths and in some cases different phase splits.

To calculate these plans, the researchers analyzed data collected during the early stages of the project to determine the magnitude of the traffic demand changes on the arterials when significant "events" occurred on the freeway. New timing plans were developed for the traffic expected under these conditions. These special patterns are stored within the signal control library of each of the signal controllers. Sufficient space exists on the Type 170 hardware to store these special patterns. Consequently, when the integration microcomputer identifies a "significant disruption" on the freeway and determines that demand for the arterial will change significantly, it requests the implementation of a timing plan designed to optimize traffic flows under those expected conditions.

To change signal plans, the integration microcomputer informs the arterial central computer that the "normal" timing plan for a particular arterial system should be overridden and that a specific timing plan (already in the signal system library) should be implemented instead. This function can already be performed manually from most central signal control computers. The difference is that the commands to make this change come from a computer, rather than from human input at a keyboard.

<u>Freeway Control Plans Implemented By The Integration System</u>

In the case of the TSMC computer, the existing control process is the "bottleneck" algorithm. Like most control systems, the TSMC ramp control process could already be manually modified by the TSMC system operators. The primary means for changing the control functions are to modify control parameters within the bottleneck algorithm or to remove a ramp from the algorithm.

For the integrated system, analysis showed that most of the traffic impacts that resulted from congestion on the demonstration's arterials occurred at one or two specific freeway ramps, although the size of those impacts varied and was difficult to accurately predict. Therefore, the integration control strategy for the freeway is to increase metering rates at those interchanges (to prevent and/or relieve arterial congestion) without significantly degrading freeway performance. To accomplish these goals, the selected integrated control strategy causes the TSMC computer to remove specified ramps from the bottleneck algorithm. (Again, this process simply automates a task that could already be done manually.)

Via the communication link discussed above, the integration microcomputer relays a message to the TSMC computer indicating that a specific ramp should be removed from the bottleneck algorithm. The TSMC computer "reads" this message and modifies the control parameters before sending revised metering instructions to the field controllers. The bottleneck algorithm accounts for "dropped" ramps by redistributing to other ramps any ramp volume reductions that would have been allocated to the ramps "deleted" from the bottleneck algorithm. These procedures are already part of the existing system and do not require extensive new capabilities within the existing control system.

Once conditions on the arterial have returned to normal, the integration computer sends a message to the TSMC computer indicating that the selected ramp meter can be returned to the bottleneck algorithm.

PROGRAM FLOW WITHIN THE INTEGRATION SYSTEM SOFTWARE

The integration program, written in the "C" programming language, has three basic functions. These are to

- receive and store detector data from each control system,
- perform calculations and comparisons using these detector data to determine the need for control parameter modifications for any of the control systems, and
- transmit control parameter commands to the respective control systems.

These three tasks, although performed separately from a programming standpoint, are clearly interdependent. To provide the ability to perform these tasks, the required sequence of events had to be defined. The following section describes this event sequence.

Sequence of Program Events

The program sequence of events takes the form of a continuous loop, or cycle, that is repeated at a consistent, predetermined interval. The duration of each cycle is determined by the length of the desired data collection time slices. The primary events that occur each integration program cycle (every 5 minutes) and the sequence of these events are as follows:

1. upload the data,
2. scroll the data,
3. process the control plans, and
4. transmit the control modification request.

For the purposes of this demonstration project, the time slice increment, and thus, the duration of the event cycle, was 5 minutes.

The justification for the 5-minute time slices consisted of two factors. The first of these factors was the need to provide as short a response time as possible in detecting severe congestion on any of the three test facilities. The second was the need to ensure that the data time slice interval was long enough to filter out short but intense fluctuations in traffic that might occur under normal conditions. In the case of the freeway system, a relatively short interval (1 minute) meets both of these criteria. However, for the two arterial systems, a longer interval was required because of the fluctuations in arterial conditions that result from platooning.

Integration Control System "Event" Algorithm

Three basic traffic condition parameters, or comparisons, are available for determining whether to implement specific integration system control plans (i.e., to determine when an "event" has taken place). Each of these comparisons utilize individual data station volume and/or occupancy data, or in the case of the arterials, volume and occupancy data from individual signal system detectors. As a result, six types of comparisons can be made–three using volume data, and three using occupancy data.

A. Single Period Station Volume or Occupancy Comparison. This parameter identifies an individual data station or arterial signal detector and assigns a threshold value to it. When the threshold value is exceeded, the condition is met.

B. Station Volume or Occupancy Change Over Time. This parameter identifies an individual data station or arterial signal system detector and compares the data for the current period with those of a past period (5 or 10 minutes previously). In setting up this condition, the operator identifies the station location, the differential threshold, and the previous period against which the data will be compared. If the difference between the two periods' data is greater than the threshold value, the condition is considered met.

C. Single Period Station to Station Volume or Occupancy Differential. This parameter compares the difference between the data of two data stations or arterial signal system detectors identified by the operator. In setting up this condition the operator identifies the first and second station locations and the data differential threshold.

Once a condition that requires a response has been detected by the integration system, the integration program transmits a specific control string (provided by the operator when the control parameters are defined) to the designated control system. The operator may specify, as an additional prerequisite, that a required number of consecutive periods of that condition must be met before the control string is transmitted. This allows the operator to develop a greater level of confidence that congestion is really occurring and that the observed value is not just a temporary reduction in traffic performance.

The system operator may also require that more than one traffic parameter condition exist before a command string is transmitted. When multiple conditions are defined for a single command string, all of the defined conditions must be met before that string may be transmitted. In addition, these conditions can apply to one or more traffic control systems. This allows conditions on one facility to affect one or more integrated systems without having the same impact on all of the connected systems.

In establishing an integration system control plan the operator may specify that one or more sets of these conditions trigger the implementation of a single control string. In addition, the operator may define multiple command strings (each with a corresponding but different set of traffic conditions) for each control system.

To maintain these alternative control strings and conditions, each system control plan (or string) is identified by a plan number (1 through X). More than one system control plan can be defined for a particular facility. When conditions for more than one plan on a single facility have been met, the plan whose conditions are met in the earliest period take priority over the other plans and remain in effect.

If the conditions defined for more than one plan on a single facility are met during the same period, the plan with the lowest plan identification number takes priority and is implemented (assuming no other plans for that facility are already in effect). This prioritization scheme was adopted to allow different traffic flow conditions to result in changes on the parallel facilities, while local agency control was still maintained over the relative importance of those conditions. The researchers adopted the operating philosophy that once a timing plan was implemented, that plan should remain effective until the conditions that warranted its selection had been alleviated. Because more than one plan could conceivably be applicable at any one time, the prioritization scheme was adopted to ensure an orderly selection between competing plans. The priority of these plans can be changed by having a system operator change the plan identification numbers within the integration microcomputer. These changes must be done off-line.

EVALUATION RESULTS

The research team evaluated the impacts of the demonstration integration system. The evaluation involved determining the operational improvements that could be realized from integrating the three control systems in the study area. To do that, the arterials' performance under non-integrated operations was compared with their performance under integrated control conditions.

The preferred evaluation method is to measure physical changes in traffic performance that result from the changes in the traffic control system. However, because the integration system was not allowed to operate "by itself" (because of the unreliable network communications described earlier), insufficient data were available to adequately measure the impacts of the changes caused by the traffic control plans the system selected. Therefore, the evaluation was performed with a computer simulation to model the roadway system under different traffic control alternatives.

The program chosen for the evaluation effort was the Traffic Network Study Tool, more commonly known as TRANSYT. The evaluation effort concentrated on SR-99 because it had the most well defined interaction with the freeway system.

Volume estimates used in the analysis were obtained from the data collected by the integration system. Estimates of diversion volumes were more difficult to obtain. The arterials operate under saturated conditions during most peak periods; thus, increased demand for these roads does not result in increased traffic volume during the peak periods (no increase in volumes is possible under saturated conditions). Estimates made from the data indicated that demand for SR-99 during peak periods may increase from 5 to 15 percent under extreme incident conditions.

The results of the simulation runs conducted for this evaluation are shown in Tables 2 and 3 below.

Table 2 - SR 99 AM Peak Simulation Comparisons

Condition	Cycle Length (Sec)	Total Delay (V-Hr)	Ave. Delay (Sec/Veh)	Fuel Cons. (Gallons)	Total Cost ($$)
1. Normal Conditions	160	271	47.3	498	1731
2. Incident Cond. w/o Modification	160	911	135.0	1036	3082
3. Incident Cond. w/ Modification	180	810	120.4	933	2787

Table 3 - SR 99 PM Peak Simulation Comparisons

Condition	Cycle Length (Sec)	Total Delay (V-Hr)	Ave. Delay (Sec/Veh)	Fuel Cons. (Gallons)	Total Cost ($$)
1. Normal Conditions	150	376	50.1	690	2408
2. Incident Cond. w/o Modification	150	1253	147.5	1399	4137
3. Incident Cond. w/ Modification	180	1060	125.0	1240	3742

Discussion of Simulation Results

The results displayed in Tables 2 and 3 indicate that, under these conditions, a significant increase in system performance could be attained with the ability to detect and respond to extreme or unusual traffic conditions. With this ability, average vehicle delay under incident conditions would be reduced by 10 to 15 percent, which would result in a fuel savings of approximately the same range. The final result would be a reduction in user operating costs of approximately 10 percent.

Assuming similar results could be attained on SR 522, with an estimated freeway incident rate of approximately two per month at a duration of 1 hour per incident, and an average fuel cost of $1.30 per gallon, the annual savings in fuel consumption for both arterials combined would be approximately $16,000 per year. The time savings would be approximately 14,000 vehicle hours per year, or, at an assumed vehicle occupancy rate of 1.2, nearly 18,000 person hours per year.

(The estimate of two incidents per month is derived from the selection of a triggering value of 35 to 40 percent lane occupancy. If this threshold value was lowered, more signal timing changes would be observed during a month. However, these smaller incidents would likely produce smaller route diversions, and would therefore result in smaller savings. A triggering value of 30 percent lane occupancy would result in approximately ten "triggering events" in both the AM and PM each month.)

While the cost savings estimated above are modest, they provide an excellent benefit/cost ratio for a low cost system (around $150,000), such as that developed in this test.

Sensitivity of Results

Additional simulation runs were conducted to determine the sensitivity of these results to the assumptions of volume changes caused by triggering incidents. The model was rerun with a range of volume adjustments. The results of the simulations both with and without the integration timing modifications were then compared and are displayed in Tables 4 and 5.

Table 4 - Traffic Demand Sensitivity Summary - AM

Vol. Increase (Mainline / Side street)	Ave. Delay w / out Mod. (Sec./Veh.)	Ave. Delay with Mod. (Sec./Veh.)	Delay Reduction (%)
10% / 3%	62.3	55.0	12
20% / 6%	88.1	72.9	17
30% / 10%	135.0	120.4	11
40% / 13%	188.9	143.1	24
50% / 16%	249.1	196.6	21

Table 5 - Traffic Demand Sensitivity Summary - PM

Vol. Increase (Mainline / Side street)	Ave. Delay w / out Mod. (Sec./Veh.)	Ave. Delay with Mod. (Sec./Veh.)	Delay Reduction (%)
10% / 3%	72.7	62.7	14
20% / 6%	106.0	82.4	22
30% / 10%	147.5	125.0	15
40% / 13%	191.0	163	15
50% / 16%	237.8	208.7	12

In conducting this analysis, the relationship between mainline volume adjustments and side street volume adjustments remained constant (a ratio of 3 to 1).

The results indicated that similar benefits would be attained under various degrees of demand adjustments. However, this analysis assumed that different signal control plans would be implemented for each separate condition. This would require that either

- accurate field measurements of actual diversions be taken and control plans be selected accordingly, or
- a single incident control plan be used but only implemented when a large enough incident took place to ensure that the anticipated diversion did occur.

This second condition provided the basis of the control plan modification for this project.

IMPLEMENTATION

To implement the integration system described in the previous sections, first the timing plans to be implemented by the integration system had to be developed, and then the control parameters (triggering algorithms) that were to indicate when those plans should be implemented had to be calibrated.

To do this, the integration system was connected to the arterial central computer and the TSMC computer and placed in its data collection mode. Arterial and freeway volume and occupancy data were then collected for several months (as the control algorithm portions of the integration program were written and tested) to provide a database for timing plan development and system calibration.

For the demonstration phase of this project, the project team and WSDOT District 1 operations staff decided that the system would initially be designed to change "normal" control system operation only when "major" traffic problems occurred. With the idea that the integration control plans should respond only to extreme congestion, the objective in establishing control plan parameters was to define thresholds that would clearly indicate abnormally severe conditions.

Lane occupancy is the measure WSDOT uses to define traffic conditions on its FLOW system congestion map. These parameter values were also selected to measure "extreme" congestion in the integrated system. To prevent congestion at a single point from indicating "extreme" congestion, the triggering algorithms also include the distance, or length, of the congested section in the control parameters by requiring that the congestion parameter threshold be surpassed simultaneously for two adjacent data stations. Thus each triggering algorithm involves two data stations. The occupancy threshold must be met at both stations for the plan to be implemented.

The stations of each plan overlap. For example, triggering algorithm 2 involves I-5 southbound stations located at N. 145th St. and N. 155th St., and triggering algorithm

3 concerns the same N. 155th St. station and also the N. 162nd St. station. In all, 18 stations are involved in 16 triggering algorithms.

INTEGRATION SYSTEM IMPLEMENTATION LIMITATIONS

To implement the system, the project team worked with BiTrans Corporation (the firm that wrote the software that operates the two arterial networks) to define the communications protocols and techniques required to perform the inter-computer communications tasks described earlier in this report. As part of this work, several alternative techniques were explored for connecting the integration computer to the arterial central computer.

Because the communication between these two components consists of writing to and reading from designated data files, the capabilities of a conventional, microcomputer based local area network (LAN) were expected to suffice. Two LAN technologies were selected, but both proved to be unreliable.

The initial solution was simple disk sharing software called Desklink. This software allows two computers, hooked together via RS-232 cabling, to share one hard disk. Unfortunately, the Desklink software was not designed to give two computers access to one file simultaneously. More importantly, the Desklink software did not support automated file locking (in which the software program prevents one computer from accessing a file while another computer is using that file). As a result, difficulties arose when both the arterial central and integration computers simultaneously tried to access the same data file. When this occurred, an error message was sent to the second computer (whichever computer requested access to the file last). This message suspended the program running on that computer and required an operator response (a keystroke) to reactivate the program.

By itself, the error message did not cause either the arterial central or the integration computer software to "bomb." However, the functioning of both programs was interrupted until a key was pressed, and during that time, the integration system ceased functioning. Because the system was not monitored by a WSDOT staff person, this message could remain unobserved for several hours (and often several days.)

The next solution was to employ a more complete LAN software system, rather than using the disk sharing software. BiTrans selected LANTastic network software, and the project team tested it.

The problems that occurred were similar to the file sharing difficulties described above. The program errors differed, but the end result was similar: an interruption in the integration system until an operator responded.

Program interruptions under the LANTastic system are less frequent than under the Desklink system, but the interruption still required operator input to resume system operations, and the system interruption suspended all integration system operations, including data collection and the implementation of control plan modifications.

When the integration system was not operating, the three control systems continued to operate in the mode under which they were last set, with unfortunate consequences for the arterial system. On the arterial system, if a "special" timing plan was implemented by the integration computer, that plan would continue to operate until the integration computer sent a command indicating that the arterial system should resume normal operations. If the integration computer became inoperative while a special timing plan was effective, that plan would continue to operate indefinitely, even when it was totally inappropriate. (For example, an AM peak period timing plan might continue to operate in the PM peak, providing progression in the wrong direction.)

This result was so undesirable that the system was never fully implemented.

EXPANDING THE INTEGRATION SYSTEM

The integration system built for this demonstration project was designed to work with the specific WSDOT control systems described earlier. However, the system design also provides for expansion if other jurisdictions want to add their traffic control systems to the integrated control structure. To expand the system to other traffic control systems requires the followings:

- provision of communication capabilities to and from those systems,
- development of control codes to be sent by the integration system to the new control system, and
- revisions (if needed) to the central computer program of the new traffic control system to allow it to transmit traffic data to the integration system, recognize the control codes sent by the integration system, and automatically implement the plans identified by those codes.

To help other traffic control systems work in a more coordinated fashion, the project team has developed a draft standard that would allow these functions to be built into the central programming portion of conventional, "closed loop" traffic control devices. This draft document is included in the appendices of the technical report for this project. Also included in the appendices is a draft purchasing specification that can be used by jurisdictions that buy new traffic control systems or system software so that they can include these functions in their new systems.

In addition to adding the above functionality, the operator of the new traffic control system must work with the operator of the integrated system (in this case, WSDOT) to define the conditions under which the integration system should send control codes to the new traffic control system. The operator must also determine the new traffic control plans under the identified conditions. WSDOT must determine whether conditions on the newly integrated facility warrant changed control plans on WSDOT facilities. If this is the case, WSDOT must also determine how to identify those conditions and the necessary changes in the existing WSDOT control plans.

When the conditions under which to implement new control plans are selected, the parameters that are available from the existing control systems must be considered. The integration system does not include traffic performance monitoring capabilities of its own. Instead, it relies on the data collection functions that exist within the individual control systems. Thus, the parameters used to identify "special" conditions must be currently available within the existing control systems, or additional funds must be provided to add new data collection capabilities to the existing systems.

For the demonstration system, the FLOW system already provided volume and occupancy data for use in detecting congestion, but triggering algorithms do not have to be confined to these parameters. Because most arterial systems do not have vehicle detectors in locations that provide volume and lane occupancy data similar to freeway data, other types of data may be examined for use within triggering algorithms. For traffic signal systems these parameters might include the continued presence of vehicles over a queue detector, or the inability of the existing signal timing plan to clear all vehicles attempting to make a specific movement during one or more signal cycles. The triggering algorithm might even be based on the implementation of specific timing plans in neighboring jurisdictions.

INTEGRATION SYSTEM HARDWARE

The selection of computer hardware is dependent on the capabilities required of the integration system. Factors that affect this determination include

- the number of users (i.e., separate control systems that are connected),
- the desired data collection interval (which controls how often each system must be contacted),
- the number of data that will be collected and stored, and
- the number of control algorithms that may be effective at any one time.

As discussed earlier in this report, a problem in implementing this project's integration system was the communications limitations of the hardware and software used. In implementing a system of this nature on a broader scope, the communications aspect may very well determine the selection of the computer hardware.

USER ACCESS

If this integration system had been developed to integrate the operation of traffic control systems that were under the direction of several agencies, user access to the system certainly would have been an issue.

The location of the integration component and how each user would have access are issues that would certainly have been raised. Most likely, some type of local area network (LAN) on dedicated communication circuits would have been the appropriate method for providing these communications links.

ADDITIONAL CONSIDERATIONS

Additional factors that play a role in defining the structure and operation of the integration system when multiple agencies are involved include the following:

- a lead agency for development of the system,
- an agency to take ultimate responsibility for the operation of the system,
- the capabilities of each agency's control system,
- the practicality of providing the necessary modifications to these systems,
- the availability of expertise required to define and develop the system, and
- the availability of funding for alternative system designs.

These issues and others will all determine the shape that the final integration system takes.

IS AN INTEGRATED SYSTEM NEEDED?

The determination to integrate the operation of independent traffic control systems can represent a major change in operating philosophy for many agencies. Before embarking on an effort to integrate its control system, each agency should ask fundamental questions about the need for, and benefits from, integrating the operation of its traffic control systems with those of its surrounding neighbors. Important questions to answer include the following.

- Is a system of this nature necessary?
- Does traffic on one system affect the other system?
- What benefits can be derived from an integration system?

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

The main conclusion from this study is that the framework for the low cost integration system developed for this project is sound. The level of benefit associated with a system of this cost and complexity appears to be reasonable, especially given the ability to use the system at different levels of participation (data collection, semi-automated integrated control, fully integrated control).

At the same time, the decision to not fully implement the integration system was correct, given the reliability problems associated with the selected computer network.

RECOMMENDATIONS

The project team recommends that WSDOT continue efforts to integrate control systems, with an emphasis on low cost, high flexibility integration systems that require limited or no ongoing "care and feeding" from the participating local jurisdictions.

To accomplish this, the team that designs the computer system will need a very strong background in fault tolerant, real-time computer networking systems, as the key to the integration system will be the ability to communicate reliably with the various participating control systems.