DIGITAL COMPUTER PROGRAMS
FOR THE RAMP METERING SYSTEM
ON THE GULF FREEWAY

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ABSTRACT

Ramp metering has proven to be an effective means of improving the operational efficiency of an over-crowded urban freeway. This report discusses the digital computer programs used to implement freeway ramp control on a section of the inbound Gulf Freeway in Houston, Texas. The operational characteristics of the supporting detection, transmission, and signal control subsystems are considered. The data acquisition, control, and system supervisor programs are executed in a priority assigned fashion that is based on the control philosophy and enabled by the architecture of the digital computer. The programming techniques used in evaluating the effectiveness of freeway ramp control are described.

The computer programs used for the Gulf Freeway ramp control can be applied to other urban freeway control systems where utilization of a central digital computer is employed as the basic process monitor and controller. However, modification to the programs may be needed to reflect the variations in individual systems.

Key Words: Ramp metering, digital computer, data acquistion subroutines, interrupt structure, real-time control system, analysis techniques.

DISCLAIMER

The opinions, findings, and conclusions expressed or implied in

this report are those of the research agency and not necessarily those

of the Texas Highway Department or the Federal Highway Administration.

SUMMARY

To broaden the application of real-time freeway operations, systems,
the Texas Transportation Institute, and the Texas Highway Department, in
cooperation with the U.S. Department of Transportation, began a research
project entitled "Freeway Control and Information Systems" in 1969. One
of the objectives in this project is to develop and test an automatic
freeway control system which will initiate and terminate ramp control as
traffic conditions warrant and be very responsive to freeway conditions
in the metering process. The basic objective of this report is to des-
cribe the computer programs that are used to monitor the traffic opera-
tion and regulate the entrance ramp demand.

To aid in developing a more comprehensive understanding of the com-
puter programs, descriptions of the operational characteristics of the
supporting hardware systems are provided. It is through the orderly op-
eration of the detection, transmission, and data acquisition hardware
subsystems that real-time traffic data are available for control deci-
sions. The traffic data are provided by the detection subsystem from
sensors in the roadway in the form of mechanical relay closures. The
transmission subsystem provides the communication link between the field
locations, where traffic detection occurs, and the interface units in
the Control Center. The interface units form sensor indications for the
digital computer as well as the backup analog controllers. Inputting
the sensor indications in a priority assigned fashion into the digital
computer is made possible by the data acquisition hardware of the machine.

The results of control decisions are issued by an output device of the digital computer into an interface unit. The control interface unit provides indications to the ramp signal controllers via the transmission subsystem. The signal control subsystem, composed of the ramp signal controllers and displays, enables control decisions to be displayed to the entrance ramp traffic. It is through the action of the supporting hardware subsystems that traffic responsive ramp control is possible.

The computer programs developed to monitor and control the freeway and ramp traffic operations execute within the priority assigned interrupt structure of the digital computer. The data acquisition programs provide real-time sensor information for interrogation by the ramp and system supervisor programs. The metering of ramp vehicles operates basically in a fixed rate mode with gap acceptance characteristics being utilized whenever possible. Freeway and ramp traffic operations are examined and evaluated each minute by the system supervisor program and, if necessary, adjustments to the ramp metering process are made. The interaction of the data acquisition, ramp, and system supervisor programs constitutes the real-time freeway ramp control programs.

In order to evaluate the performance of the controlled system, analysis programs were written to execute after each control period. The analyzed data presented results for evaluating the traffic operation of a total controlled system, subsystem, and each ramp, as well as the initiation and termination of the ramp metering control. From the evaluation, parameter changes in the ramp and system supervisor programs can be made.

IMPLEMENTATION STATEMENT

The digital computer programs developed and implemented for freeway ramp control on the Gulf Freeway can be used for other urban freeway control systems. However, modifications to the programs may be needed to compensate for variations in the hardware systems and control objectives.

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INTRODUCTION

In September, 1963, the Texas Transportation Institute was authorized to initiate studies in the area of freeway surveillance and control in order to increase the efficiency of existing urban freeways and to determine how to improve the level of service of future facilities. A research project sponsored by the Texas Highway Department and the then U.S. Bureau of Public Roads was formulated with the basic objective of developing criteria for the design and operation of automatic surveillance and control systems. The systems would permit the attainment of acceptable levels of service on heavily traveled urban freeways during peak periods of demand.

After studies on several freeways in Texas, the Gulf Freeway in Houston was selected as the proving grounds for the research project. It was reasoned that the development of a system for traffic surveillance (accomplished mainly through closed circuit television) and control (accomplished through ramp metering) for this facility would furnish an excellent pilot study from which technology could be developed that would be applicable to freeway systems in other parts of the nation.

Two studies of ramp closures and ramp metering were made on the Gulf Freeway in the summer of 1964. Following the preliminary studies, work began on designing, installing, and evaluating automatic ramp metering equipment. In the summer of 1965, traffic signals were installed on eight inbound entrance ramps.

After evaluation of two automatic prototype controllers, an eight

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ramp analog control system was designed and installed in 1967. This
control system was replaced as the primary controller in 1968 by an
IBM Model 1800 digital computer. The analog system now serves as the
back-up control unit.

To broaden the application of real-time freeway operations systems,
the Texas Transportation Institute and the Texas Highway Department, in
cooperation with the U.S. Department of Transportation, began a research
project entitled "Freeway Control and Information Systems" in 1969.
This project is an outgrowth of the previous research on the Gulf Free-
way which culminated in an operational freeway ramp control system. One
of the objectives in this project is to develop and test an automatic
freeway control system for the inbound Gulf Freeway. The system pro-
vides ramp control which will initiate and terminate as traffic condi-
tions warrant and be very responsive to freeway conditions in the meter-
ing process.

The basic objective of this report is to describe the computer pro-
grams used to regulate the entrance ramp demand. The descriptions in-
clude:

1) the basic hardware systems,

2) the data acquisition, ramp control, and system supervisory
    programs, and

3) the evaluational techniques used by the ramp and system
    analysis programs.

This report, as well as the approach taken in programming the freeway
ramp metering process, will be useful in the design and implementation

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of other freeway ramp control systems where a central digital computer

is employed as the basic process monitor and controller.

BASIC HARDWARE SYSTEMS

The basic components used to implement ramp control on the Gulf
Freeway are:

1) sensors placed on the inbound freeway and ramp lanes to detect
    vehicles;

2) a multiconductor, twisted pair cable connecting sensors and
    signal controllers to the Control Center;

3) a digital computer used to monitor and control the freeway op-
    erations; and

4) the ramp signal controllers and displays which accept commands
    from the digital computer so that movement of traffic through
    the entrance ramp can be regulated.

These distinctive hardware components or subsystems are discussed in
greater detail in the following subsections.

Detection Subsystem

The detection subsystem consists of 107 inductive loop sensors and
their associated amplifiers installed on the inbound freeway lanes, en-
trance and exit ramps, and service road lanes. The locations of the sen-
sors were the result of freeway control objectives that were to be achieved;
namely:

1) to provide local merging control on each entrance ramp, and

2) to accomplish freeway control by locating congestion on the free-
    way lanes and attempting to reduce the effects of capacity reduc-
    tion through ramp control.

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An example of the relative positioning of sensors on a small subsection of freeway is shown in Figure 1.

The inductive loop consists of three coils of No. 14 gauge insulated wire placed in a saw cut in the roadway pavement. An amplifier unit, housed in a nearby cabinet, is connected to the leads of the closed loop, and an oscillatory circuit is 'tuned' to the existing electrical and environmental conditions. As a vehicle enters the loop's field of influence, a shift in the phase of the oscillatory circuit causes the contacts of a relay housed in the amplifier unit to close. The contact closure provides a means of detecting the presence of a vehicle by a remote controller or digital computer. Through the sensor actuations of the detection subsystem, the ramp metering and freeway system operations are monitored.

Transmission Subsystem

The transmission subsystem is a multiconductor cable buried along the freeway right-of-way. It connects the sensors and ramp signal controllers to interface units in the Control Center. The cable also provides the communication link for the closed circuit television surveillance system. The cable is connected at intervals along the freeway right-of-way to local sensor amplifiers and ramp signal controllers. At present, one wire per sensor and two wires per signal controller are used.

In the Control Center, the sensor actuations are shared by the digital computer and the backup analog control system. This is accomplished by utilizing special relay interface equipment between the control systems (analog vs. digital). Similarily, special interface equipment enables the

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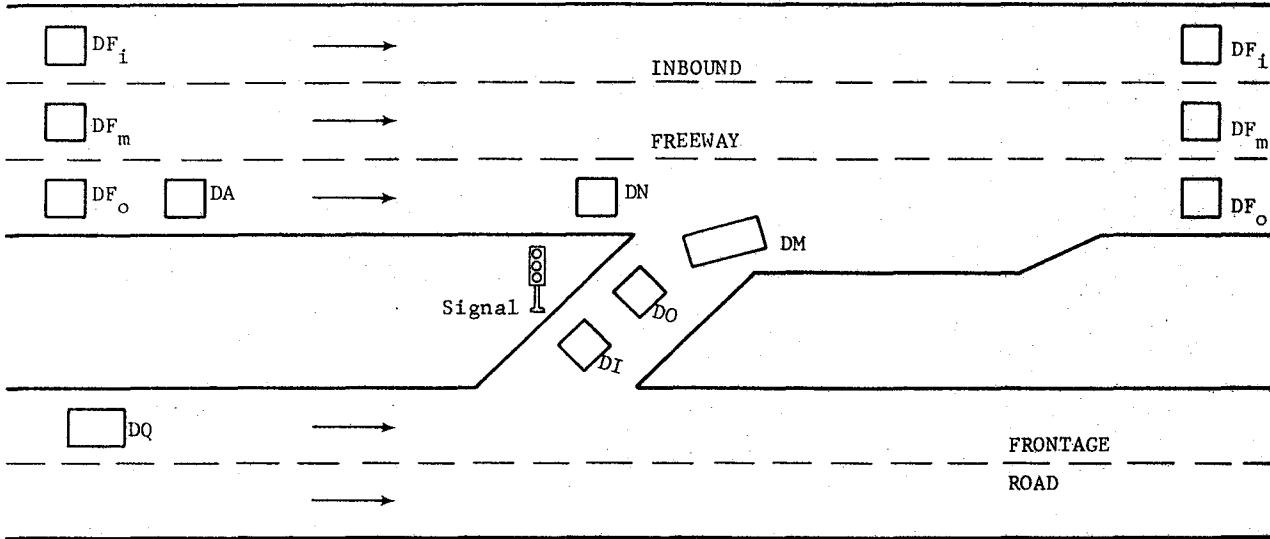
Sensors	Measured Information	Purpose
$DF_{i,m,o}$	speed, volume, occupancy	freeway operation
DA	speed, volume, occupancy	gap project & fwy. operation
DN	speed, volume, occupancy	operation of outside lane ramp merge
DM	occupancy	determine if vehicle in merge area
DO	volume	ramp volume count
DI	occupancy, volume	determine if vehicle is waiting for green signal
DQ	occupancy	determine if ramp queue exceeds a given length

Figure 1.   Relative positioning of sensors in a small subsection.

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backup analog controllers to be selected as the primary ramp controller.

Digital Computer Subsystem

The digital computer used for freeway ramp control is an IBM Model 1800. The computing system contains 24,576 words of core storage of sixteen usable bits of information per word. The basic machine cycle time is four microseconds. Input/Output (I/O) devices supported by the IBM 1800 digital computer include: (1) two mass storage disks, (2) a 150 line per minute printer, (3) a card read/punch, (4) a typewriter/keyboard, and (5) a small drum plotter. The I/O devices aid in the analysis of the freeway and ramp metering operations.

The IBM 1800 is a data acquisition and process control digital computer. As such, it operates as an event or interrupt driven computer. This mode of operation is accomplished by structuring the data acquisition or input devices of the computer into groups and levels. Each level is assigned an interrupt priority and may contain sixteen different input devices. An interrupt generated by an input device may be the result of an I/O operation or a process input from a sensor actuation within the freeway or ramp operation. A maximum of sixteen different sensors may be entered into each process input device. It is through the interrupting priorities of the input devices that those sensors, critical to the proper functioning of the freeway ramp merging operation, may be recognized.

Upon the recognition of an interrupt request, an interrupt servicing subroutine is executed. The functions performed by the servicing subroutine will reflect the role assigned to the interrupt, namely, a volume or speed update or a recalculation of an occupancy reading. If an interrupt

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request on a higher priority level is initiated during the execution of an interrupt servicing subroutine on a lower priority level, the execution of the lower level program is temporarily halted, and the higher level interrupt request is serviced. Service is returned to the initial request only after all higher interrupt level requests have been serviced. In this way, every interrupt request is obeyed immediately, provided no higher priority servicing is presently in execution.

Just as the digital computer utilizes special process input devices for the orderly recognition of the freeway and ramp sensor actuations, it also provides devices for controlling the process or ramp merging operation. These devices are program (or software) controlled. When commanded, the action of these output devices provides contact closures similar to the action of mechanical relays. Sixteen contact closures are included per output device. It is through the action of these output devices that orderly control of the ramp signal is accomplished.

The analog equipment, which controlled the ramp signals before the IBM 1800 digital computer was installed, serves as backup control units. Each ramp has an analog controller that uses a fixed rate control strategy. One of the five manually set metering rates is selected by each analog controller based on the freeway operation on or near the controlled ramp. However, the ramp control operation, accomplished by the separate analog controllers, does not provide for system control.

Control Signals Subsystem

Each entrance ramp is controlled with a standard three indication traffic signal. Indication selection either by the backup analog control-

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ler or digital computer enters an encoder in the Control Center which changes the selection to a two-part message as shown in Table 1. The output of the encoded signal message is transmitted via the transmission cable to a decoder at the entrance ramp controller. This device, in turn, changes the two-line logic into the proper state in order that the selected indication can be displayed at the signal head. It is through the regulation of the traffic signal that the desired metering of entrance ramp vehicles is achieved.

Summary

Monitoring of the freeway traffic operation, made possible by the orderly operation of the detection, transmission and data acquisition hardware subsystems, enables control decisions to be based on real-time data. The results of the decisions are used to influence and control the freeway traffic operation by changing the signal indications on the entrance ramps.

TABLE 1

ENCODE/DECODE CONTROL

Signal Indication	Line 1	Line 2
Dark	0	0
Red	0	1
Amber	1	0
Green	1	1

'0' - OFF
'1' - ON

REAL-TIME CONTROL PROGRAMS

The programs developed and implemented to control the operations of

the inbound Gulf Freeway are arranged into three general groups based on

their real-time execution priorities, as shown in Figure 2. The highest

priority group recognizes and arranges sensor data for interrogation by

the ramp control and system supervisor programs. Next in the execution

hierarchy, the ramp control program monitors and controls the operation

at the entrance ramps. Finally, the system supervisor program period-

ically performs data storage, evaluates freeway operations, and changes

control variables in the ramp control program. The first two program

sets are written in the IBM 1800 assembly language (or so-called machine

language) while the system supervisor program is written in Basic For-

tran IV. The vendor supplied systems programs enabling the IBM 1800

digital computer to function as a real-time data acquisition and process

control computer are not discussed in this report. A description of the

IBM Time Sharing System for the 1800 is available through the IBM Company.

Data Acquisition Subroutines

A series of subroutines constitute the data acquisition portion of

the real-time freeway ramp control program. Each subroutine functions as

an interrogation routine. The hardware structure of the IBM 1800 directs

the processing for each process input device to a unique routine. The ser-

vicing subroutine for the input device must determine which sensor inter-

rupted. The subroutine will perform one or more of the following functions:

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REAL-TIME DATA ACQUISITION AND PROGRESS CONTROL OPERATING SYSTEM

	EXECUTION PRIORITY	RESPONSE TIME
	0	REAL-TIME
	1	0.1 SECONDS
	2	1.0 MINUTES
	3	EACH CONTROL PERIOD

FREEWAY AND RAMP OPERATIONS

SENSOR ACTUATIONS

DATA ACQUISITION SUBPROGRAMS

DISPLAY

RAMP SIGNAL OPERATION

CONTROL COMMANDS

DATA

RAMP CONTROL PROGRAM

RAMP PARAMETERS

DATA

SYSTEM SUPERVISOR PROGRAM

SYSTEM PARAMETERS

DATA

RAMP AND SYSTEM ANALYSIS PROGRAMS

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Figure 2. Flow diagram of the real-time control programs.

1) record the time of day the sensor interrupted,

2) update a volume counter,

3) add to an occupancy counter,

4) recalculate a speed indicator, or

5) perform all or part of the preceding functions.

The functions performed by the data acquisition subroutines yield sensor indications and measurements required by the system supervisor and ramp control programs. As indicated in Figure 3, sensor actuations from the freeway mainlanes are used for computing volume, speed, and occupancy information. The ramp sensor actuations provide basic information for the monitoring of the ramp operation. The arrangement of the data acquisition subroutines, shown in Figure 3, is not ordered with respect to interrupting or execution hierarchy. In all cases, sensor actuations used in speed or occupancy calculations will be serviced on higher priority levels than those sensors used for volume or ramp indications. This is necessary since speed and occupancy calculations require more accurate time measurements.

The freeway data measurements are calculated according to the interrogation logic illustrated in Figures 4,5, and 6. The resultant data, grouped into common data arrays, are stored and then used by the system supervisor program for periodic operational evaluation. In some cases, a sensor may provide additional sensor information. For example, a primary speed or occupancy sensor may also be used to update volume data. Also, a sensor may provide information for freeway measurements as well as the ramp control program such as the freeway DA sensor.
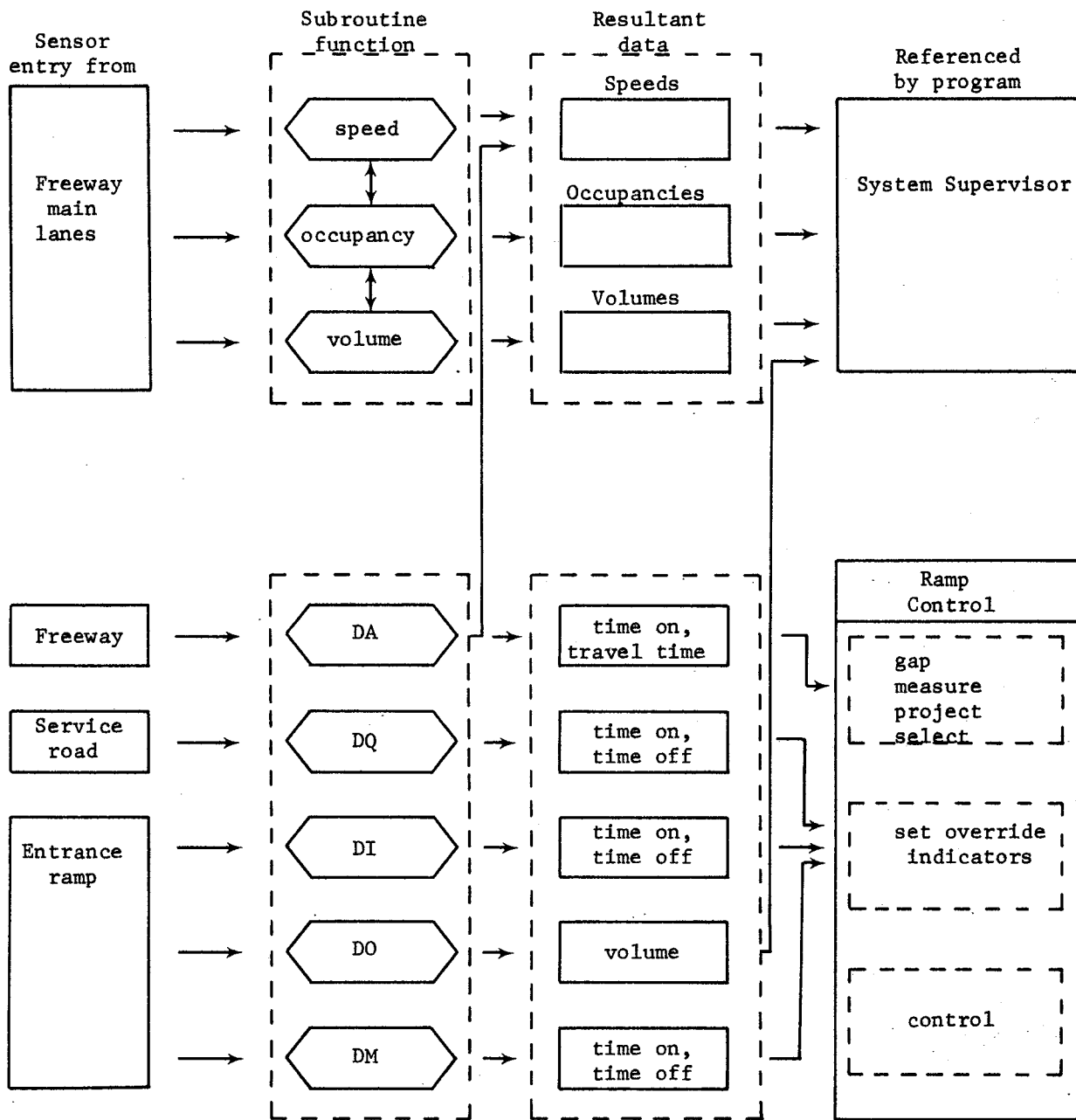
Figure 3. Data arrangement from data acquisition subroutines.
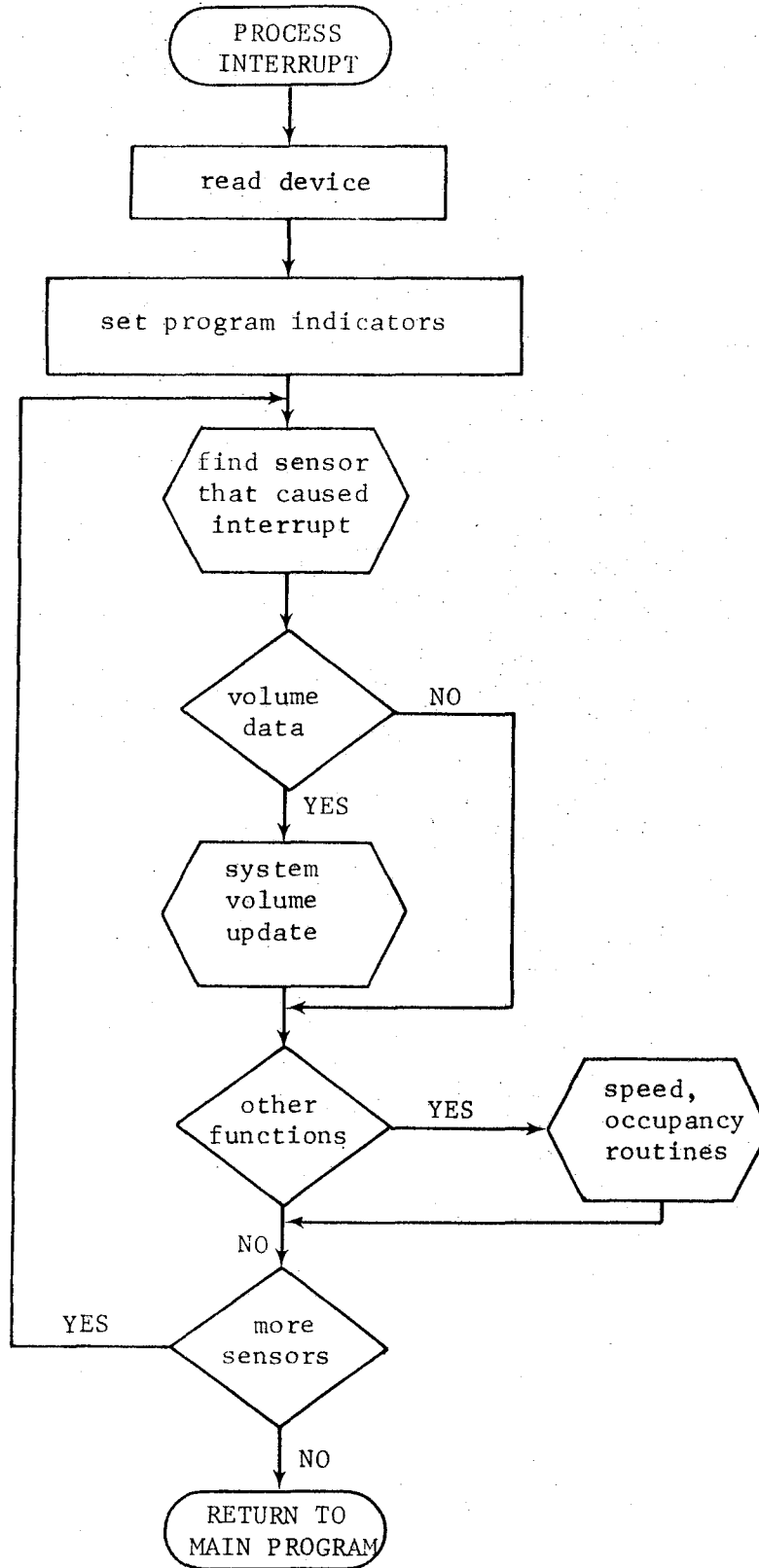
Figure 4. Data acquisition - Freeway volume

PROCESS
INTERRUPT

read device

set program indicators

find sensor
that caused
interrupt

sensor
just on

YES

save time of day
sensor on

NO

ΔT = time of day sensor off − time of day sensor on

ΔT
out of
limits

YES

NO

indiv. speed = $\dfrac{\text{loop distance}}{\Delta T}$

av. speed = old av. speed + .3 (indiv. speed −old av. spd)

other
functions

YES

volume,
occupancy
routines

NO

more
sensors

YES

NO

RETURN TO
MAIN PROGRAM

Figure 5. Data acquisition − freeway speed.

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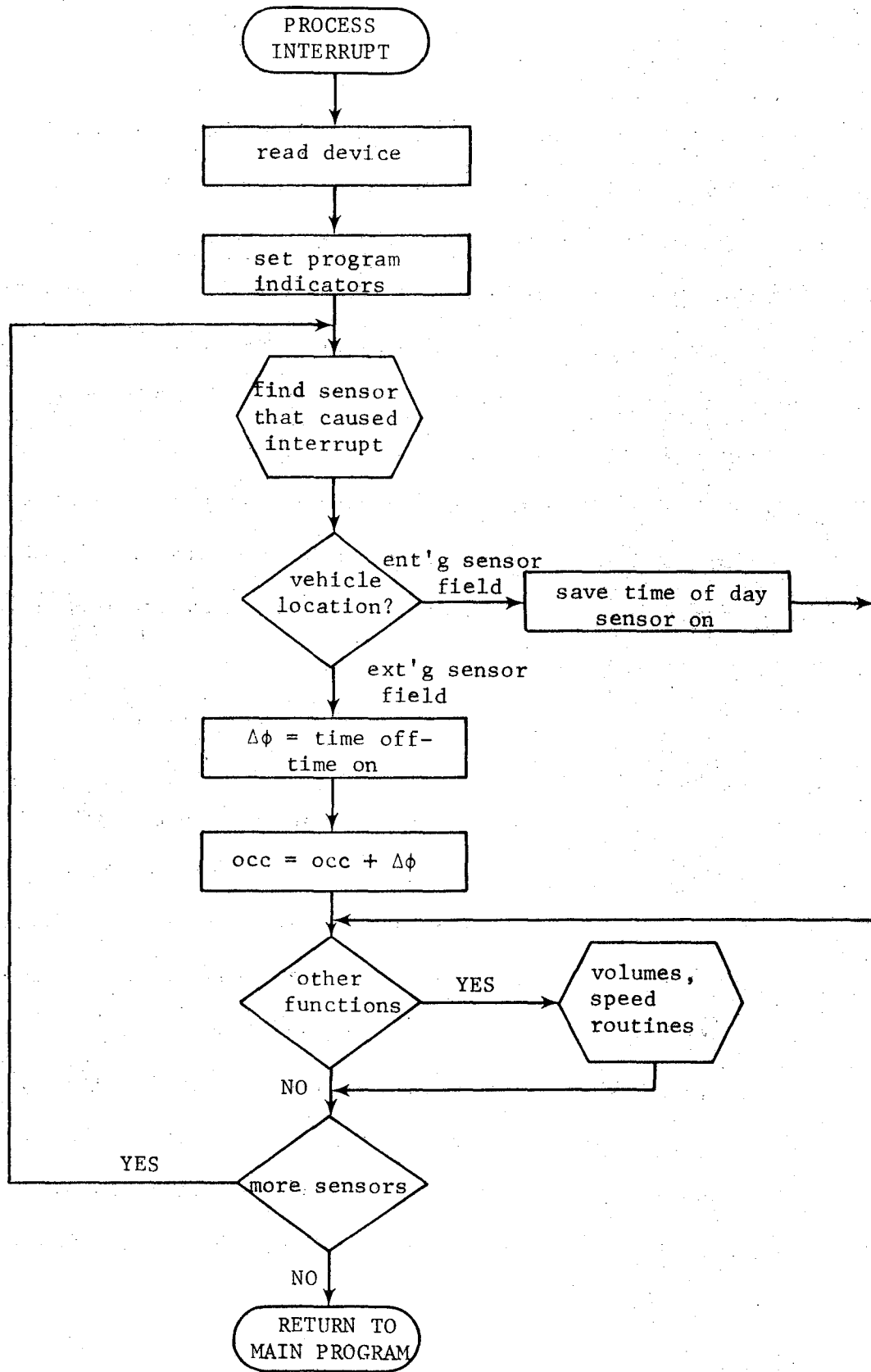
Figure 6. Data acquisition - freeway occupancy.

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The logic of the data acquisition subroutines that provides the sensor indications for the ramp control program is similar to those shown in Figures 4 through 6. However, the information retained from a ramp sensor actuation is different from the information needed on the freeway. Since the ramp control program must necessarily make control decisions based on real-time sensor actuations, the servicing subroutines provide indications of time when the sensor 'came on' or 'went off.'

The orderly recognition and servicing of the sensor actuations provided by the data acquisition subroutines enables accurate, real-time, and properly arranged data to be available for usage by the ramp and system supervisor control programs.

Ramp Control Program

The process control computer used for freeway ramp control provides the ability to initiate program execution on a regular time basis. This programming function enables the metering operation at each entrance ramp to be evaluated every one-tenth of a second. The evaluation, performed by the ramp control program, CNTRL, as shown in Figure 7, achieves the following: 1) measures, projects, and selects acceptable freeway gaps, 2) determines status of metering operation, and 3) issues control commands to the ramp signal controllers. Discussions of the general metering philosophy employed and the ramp control program logic are included in the following subsections.

Control Philosophy - Freeway ramp control does not increase the capacity of the freeway; it regulates the entrance ramp traffic so that the traffic flow on the freeway will be at or near capacity for longer periods

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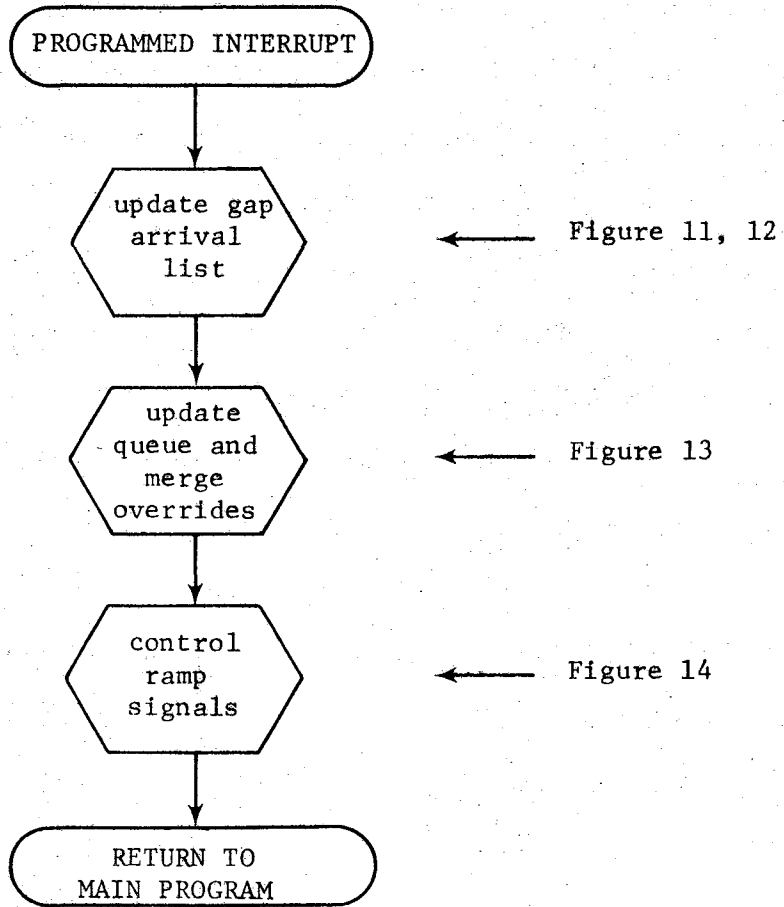
Figure 7. Ramp control execution sequence.

of time (1). To achieve this control, capacity-demand relationships establish the maximum number of ramp vehicles that may enter the freeway during each minute of control. The release time of each vehicle is evenly distributed throughout the minute to provide green signals at fixed intervals. The integration of gap acceptance into the fixed rate metering mode utilizes a portion of the red phase in the signal cycle for the gap release operation. Regardless of which mode of vehicle release is chosen by the ramp control program, two conditions must be sensed:

1) a vehicle is waiting at the signal (DI sensor is on) and

2) no vehicle is occupying the merge area (DM sensor is not on).
These are but two of several control overrides that change the normal sequence of events in the metering process.

In the fixed rate metering mode there are time intervals which must be considered as dead time; these are the green, amber, and minimum red phases. These time sequences (dead time) must be present in each cycle and are considered unusable for gap selection. The dead time components remain fixed regardless of the cycle length. An example of the fixed rate components that are utilized by the ramp control program in one-tenth second intervals is shown in Figure 8.

At the beginning of each green signal, the cycle ending time is computed from the cycle length and the present time of day. The time interval between the end of the minimum red and the cycle ending times is usable in the sense that the signal may be changed to green at any time in this interval. It is during this time interval, or window time, that vehicles may be released under gap acceptance conditions. Large fixed

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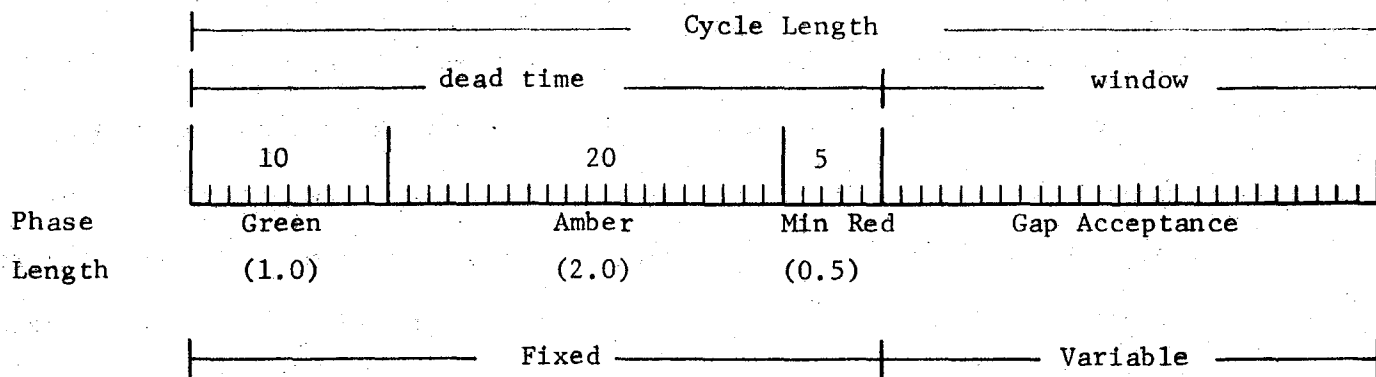
Figure 8. Fixed rate components.

metering rates, 10-12 vehicles per minute (VPM), result in minimal window times while small rates, 2-4 VPM, yield large window times. Table 2 indicates different window values for several metering rates using a fixed or dead time of 3.5 seconds.

If limiting the number of ramp vehicles entering the freeway during peak periods is indicated by the control objectives (2), then unrestrained use of gap acceptance is unacceptable. Even when both modes of control are in effect, a fixed rate that yields large window times (4.0 seconds or greater) could result in higher metering rates if vehicles are released for gaps immediately after the minimum red phase has ended. To restrain the use of the gap acceptance mode of control, only selected portions of the available window time may be used. Figure 9 indicates four examples of window time percentages. By choosing the correct percentage of the available window time for the gap acceptance operation, the number of vehicles released will not exceed the established fixed rate.

The mode of metering ramp vehicles should operate adequately under all conditions. However, there are three operational conditions that may affect the metering operation:

1) a ramp vehicle stopping in the merge area,

2) ramp queues affecting traffic operation on streets adjacent to the freeways

3) excessively long red phases due to sensor failures or unusual events.

TABLE 2

METERING RATE COMPONENT VALUES

Rates	12	10	8	6	4	2	veh/min
Cycle Time	5.0	6.0	7.5	10.0	15.0	30.0	Time/veh (sec)
Fixed time	3.5	3.5	3.5	3.5	3.5	3.5	(sec)
Window time	1.5	2.5	4.0	6.5	11.5	26.5	(sec)
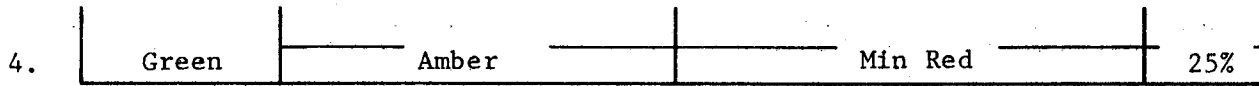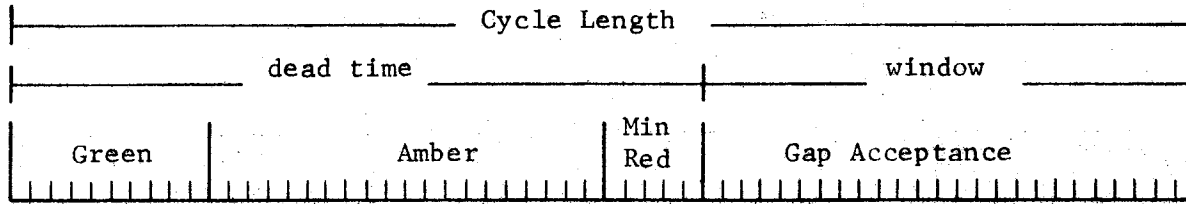
Figure 9. Four examples of window percentages.

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The first condition will inhibit the green signal for all circumstances except for condition three. By keeping the merge area clear of ramp vehicles, a degree of merging safety and efficiency is afforded the motorist. When the ramp control program senses the merge area is clear (by means of the DM sensor), signal operation resumes normal sequencing.

Excessively long ramp queues are sensed through the DQ ramp sensor (see Figure 1). Adjustments to the metering rates in the CNTRL program are made by the system supervisor program. The adjustments result in an increase in traffic flow through the ramp to reduce the queue and clear the ramp traffic from other traffic systems.

The failure of a DI or DM sensor (shown in Figure 1) during a control period can cause the ramp signal to experience long red phases even though a vehicle is waiting to enter the ramp or the merging area is clear. Therefore, a maximum time limit for a red phase is maintained in CNTRL; normally sixty seconds. When the maximum time limit is exceeded, the signal is changed to green regardless of any other control overrides.

Program Logic

Ramp control is said to be a merge control system if freeway gap acceptance characteristics are employed in the control decision (2). Methods of detecting, measuring, and projecting freeway gaps are accomplished by the combination of the DA data acquisition subroutine and CNTRL so that vehicles, which are stopped at a signal on the ramp, can merge into a properly selected freeway gap. An illustration of the gap acceptance

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mode is shown in Figure 10.*

Detection - Whenever a vehicle in the outside freeway lane passes over the leading edge of the ramp's upstream approach sensor (DA in Figure 10), the event is recorded in two time measurements by a data acquisition routine. One time, to the nearest millisecond, is used in calculating speed while the other time, accurate to the nearest one-tenth second, is saved and used for the gap measurement portion of CNTRL. When the freeway vehicle leaves the sensor, the event is again recorded. The difference between the leading and lagging time is a travel time. If the effective distance of the sensor's detection field is known, then speed across the sensor can be calculated. The speed of the freeway vehicle and the distance from the DA sensor to the ramp merging area is used to calculate a travel time. This travel or projection time is used by the CNTRL program to project gap arrivals. Every vehicle that passes over the DA sensor, regardless of the trailing gap size, is used to update the speed indicator and projection time.

Measurement - The gap measuring indicators are reinitiated each time the DA sensor is actuated. The measurement of the gap size is accomplished every one-tenth second in the ramp control program. When an acceptable gap is measured, the arrival time of the freeway vehicle is placed into an arrival list. In addition, any excess gap that may occur behind the meas-

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*NOTE: The detection subsystem enables time headways to be measured and projected. However, in the merging control discussions, the term 'gap' refers to time headways, not vehicular gaps as depicted in Figure 10.

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ACCEPTABLE GAP

DA SENSOR

RAMP SIGNAL

DETECTION OF ACCEPTABLE GAP

ACCEPTABLE GAP

RAMP SIGNAL

PROJECTION OF ACCEPTABLE GAP

RAMP SIGNAL

VEHICLE MERGE
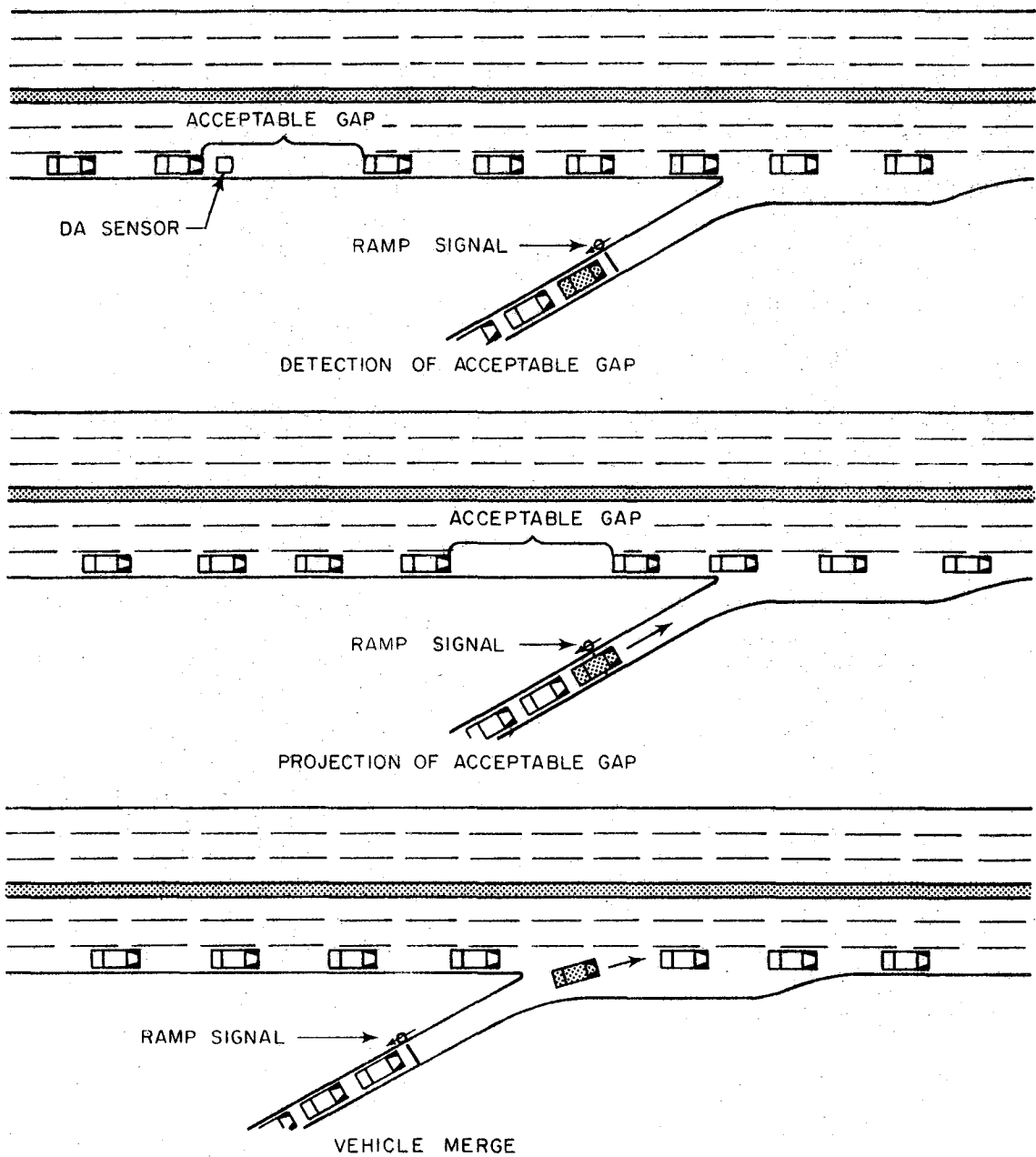
Figure 10. Illustration of Gap Acceptance Mode of Ramp Control.

ured gap is recorded. This enables the gap selection routine of CNTRL to utilize as much of any acceptable gap as possible (Figure 11). This measurement method enables ramp vehicles to be metered only into acceptable freeway gaps by the gap acceptance mode of CNTRL.

Projection - The projection technique places only those freeway vehicles with trailing acceptable gaps into the arrival list. As the acceptable gap is measured, the vehicle's arrival time at the merge area (DA on-time plus the projected travel time from DA to merge area) is placed into an arrival list that may contain up to twenty arrivals. Projected vehicles that have additional gap time (for example 0.3 second) are placed into the gap arrival list by adding the excess gap time to the previous arrival time (See Figure 11). This technique enables the ramp control program to make optimum use of any projected gap.

Selection - The selection routine performs a search of the arrival list to determine the availability of an acceptable gap for utilization by a ramp vehicle. If the chosen gap arrival time is past the point in time where it could have been used by a ramp vehicle, the selection routine chooses the next arrival time. This search and compare is continued until:

1) the gap can be utilized, or

2) the arrival list has been exhausted as indicated in Figure 12. Once an arriving gap is usable, it remains for the ramp control program to determine if the ramp vehicle will be released.

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                    ┌─────────────┐
                    │  Figure 7   │
                    └──────┬──────┘
                           │
                           ▼
                 ┌────────────────────┐
                 │ set ramp indicators│
                 └─────────┬──────────┘
                           │
                           ▼
                        ╱       ╲
                      ╱    gap    ╲
                    ╱    behind    ╲
                  ╱   last vehicle   ╲        NO
                 ⟨        ≥           ⟩ ─────────────────────────┐
                  ╲  acceptable gap  ╱                           │
                    ╲              ╱                             │
                      ╲          ╱                               │
                        ╲  YES ╱                                 │
                           │                                     │
                           ▼                                     │
                        ╱      ╲                                 │
                      ╱   just   ╲       YES                     │
                    ⟨  measured   ⟩ ──────────────┐             │
                      ╲          ╱                 │             │
                        ╲  NO  ╱                   │             │
                           │                       │             │
                           ▼                       ▼             │
                        ╱      ╲        ┌────────────────────┐   │
                      ╱   any    ╲ YES  │ place (travel time +│   │
                    ⟨   excess    ⟩────▶│      time of day)   │   │
                      ╲   gap    ╱      │  into arrival list. │   │
                        ╲      ╱        └──────────┬──────────┘   │
                         ╲   ╱                     │              │
                          NO│                      │              │
                            ▼◀─────────────────────┴──────────────┘
        ┌──────────────┐ ╱      ╲
        │ increment ramp│╱  last   ╲
        │  indicators   ◀  ramp     ⟩
        └───────┬───────┘╲ serviced ╱
                │    NO    ╲      ╱
                │           ╲   ╱
                │             │YES
                │             ▼
                │      ┌─────────────┐
                │      │  Figure 12  │
                │      └─────────────┘
                │
                └──────────(loop back to gap decision)
```
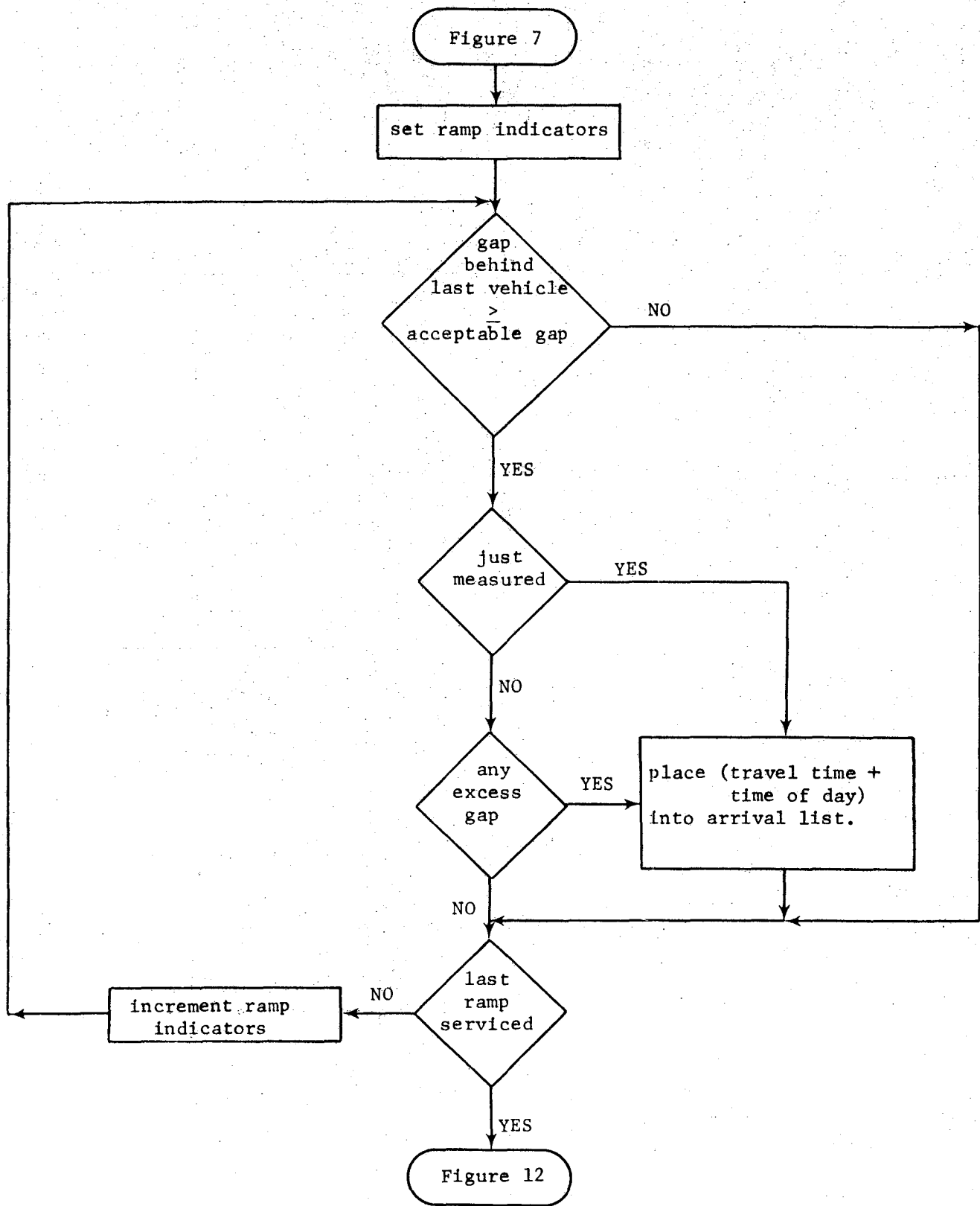
Figure 11.   Gap arrival list generation.

```
        ┌──────────────┐
        │  Figure 11   │
        └──────────────┘
               │
               ▼
        ┌──────────────┐
        │  set ramp    │                    ╭───╮
        │  indicators  │                    │ 1 │
        └──────────────┘                    ╰───╯
               │                              │
               ▼                              │
          ╱──────────╲                        │
         ╱ find next  ╲                       │
        ⟨ gap arrival  ⟩◄──────────────────────────────────────┐
         ╲   time     ╱                                         │
          ╲──────────╱                                          │
               │                                          NO    │
               ▼                                                │
          ╱─────────╲         ┌──────────────┐          ╱───────────╲
         ╱  passed   ╲  YES   │ update list  │         ╱    list      ╲
        ⟨  decision   ⟩──────►│   pointer    │────────►⟨  exhausted    ⟩
         ╲   point   ╱        └──────────────┘          ╲───────────╱
          ╲─────────╱                                         │
               │ NO                                           │ YES
               ▼                                              │
          ╱─────────╲                                         │
         ╱   at      ╲        NO                               │
        ⟨  decision   ⟩──────────────────────┐                │
         ╲ point now ╱                        │                ▼
          ╲─────────╱                         │         ┌──────────────┐
               │                              │         │  set gap     │
               │ YES                          └────────►│  arrival off │
               ▼                                        └──────────────┘
        ┌──────────────┐                                       │
        │  set gap     │                                       │
        │  arrival on  │                                       │
        └──────────────┘                                       │
               │                                               │
               ▼                                               │
          ╱─────────╲         ┌──────────────┐          ╭───╮
         ╱   all     ╲  NO    │ update ramp  │          │ 1 │
        ⟨   ramps     ⟩──────►│    index     │─────────►╰───╯
         ╲ serviced  ╱        └──────────────┘
          ╲─────────╱
               │ YES
               ▼
        ┌──────────────┐
        │  Figure 13   │
        └──────────────┘
```
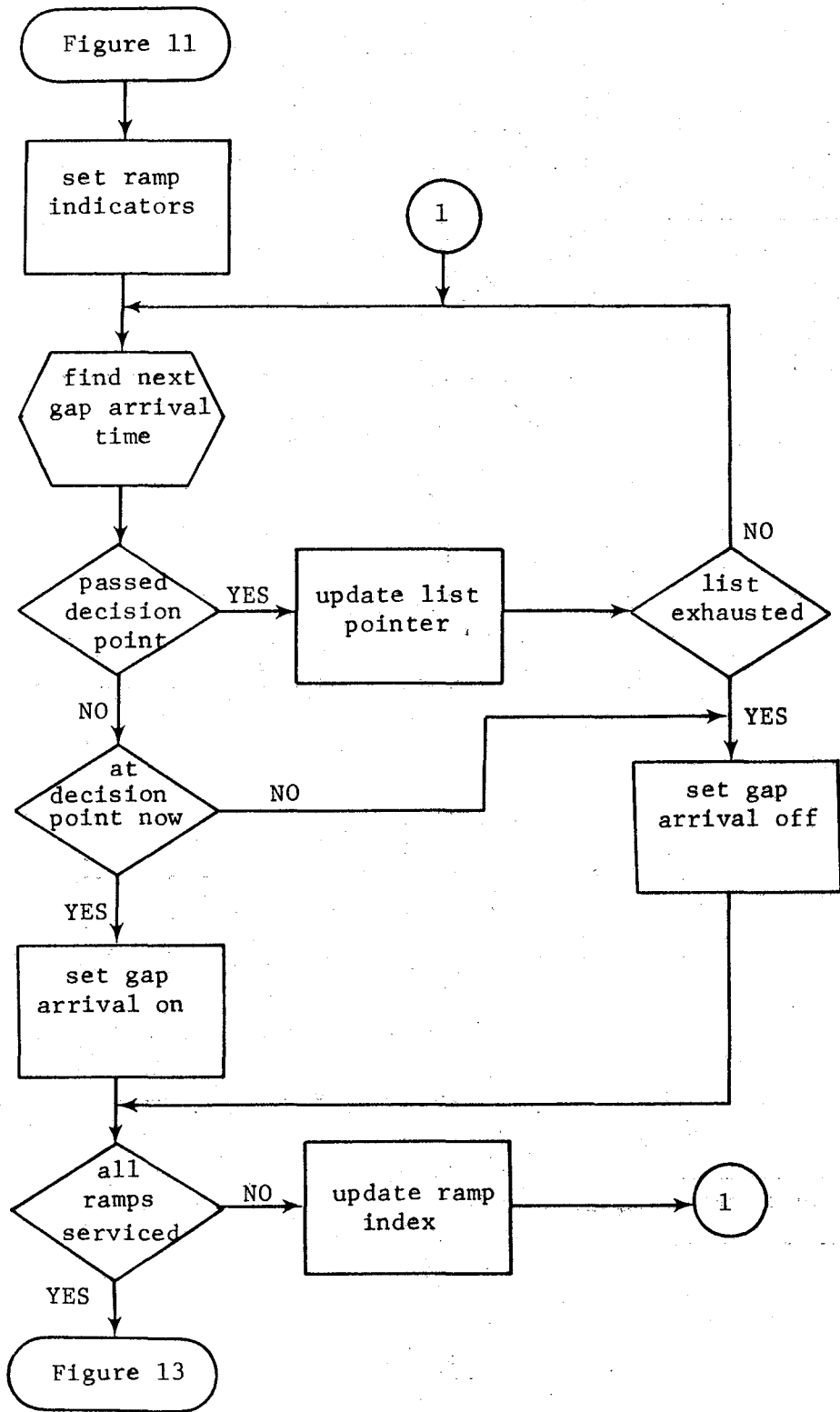
Figure 12.   Gap arrival list update.

30

Overrides - Figure 13 shows the logic for determining queue and merge overrides. The queue and merge sensor actuations, recorded by a data acquisition subroutine, are used to establish occupancy and lag intervals which activate the override indicators. The queue override enables the metering operation to be increased so that interference with other traffic systems by the ramp vehicles may be decreased. The merge override provides a means of temporarily halting the metering operations.

Signal Control - The first two functions completed by the ramp control program, CNTRL (Figure 7), are executed regardless of the control status. This is to insure the proper functioning of gap acceptance and the overrides, once control is instigated. The control status can be in one of four modes as indicated in Figure 14. If the control status is in any mode other than 'on,' the function completed by CNTRL is straight forward as indicated by Figure 14.

Two important data items that direct the program execution are the signal phase and signal phase ending time. When a signal changes indications or phases, the time when the new phase is to end is recorded. No further action is then taken for that ramp until the phase ending time has elapsed, at which time the signal again changes, and a new ending time is found, except during the gap acceptance operation. Once the minimum red phase time has elapsed, the signal may be changed to green by the gap acceptance operation if:

1) a gap is available (established by the gap selection routine),

2) a vehicle is waiting at the signal (DI on), and

3) the merge override is clear (DM off).

31
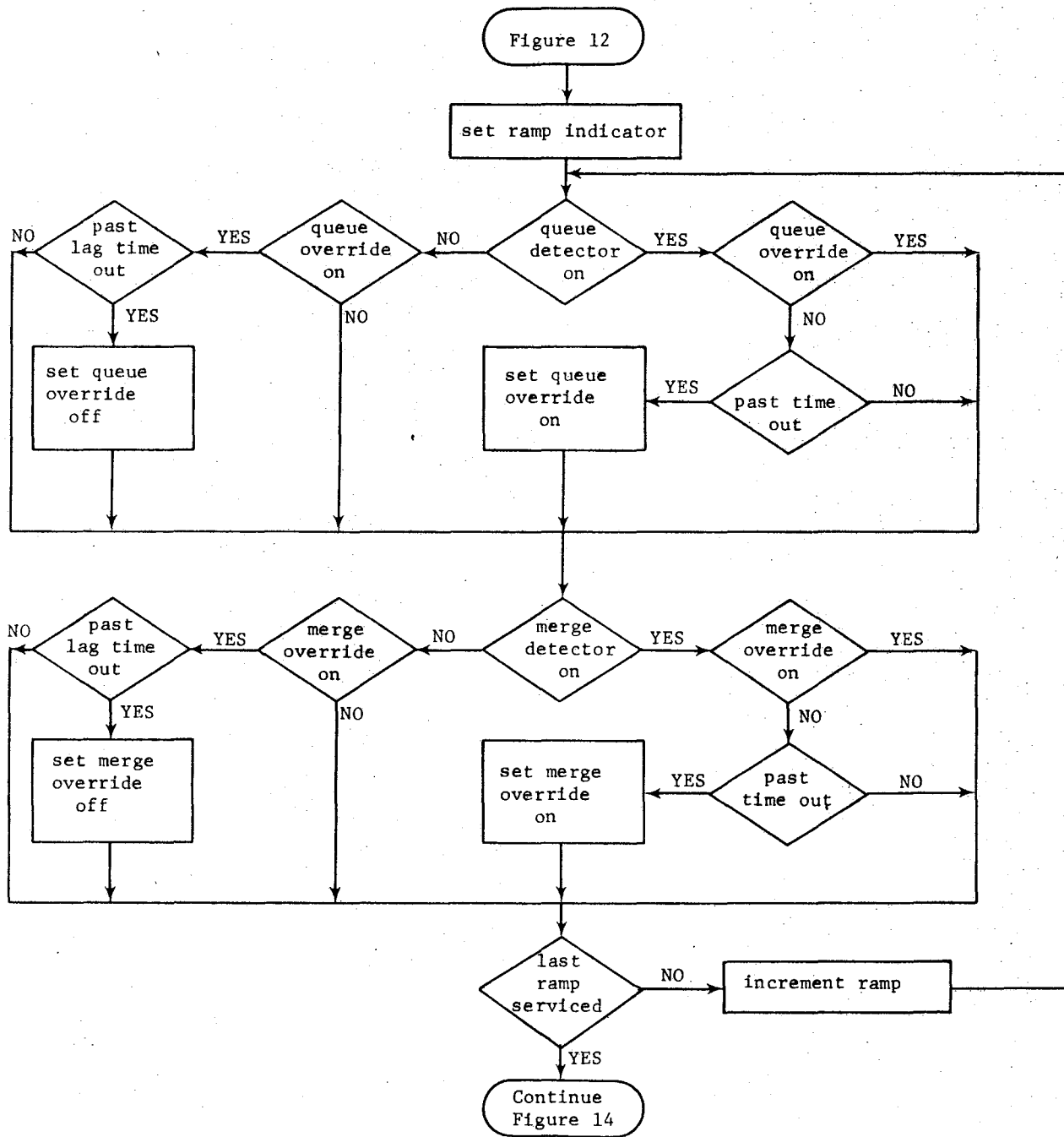
Figure 13. Queue and merge overrides
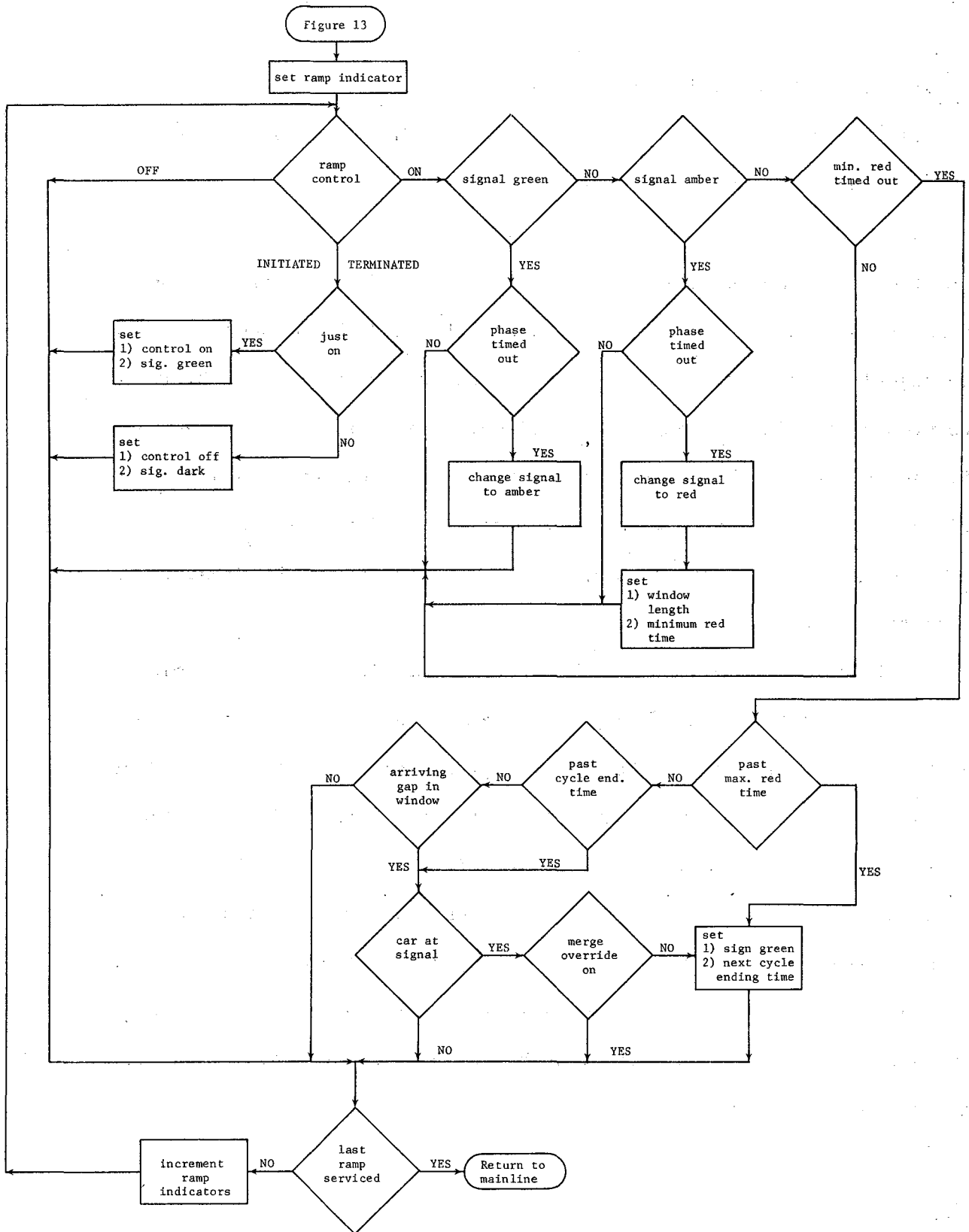
Figure 14. Signal control logic.

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The preceding three conditions are checked until:

1) all are satisfied, and the signal is changed to green under
   gap acceptance, or

2) the cycle ending time elapses.

Once the cycle ending time elapses, only the DI-DM indicators are used
to meter ramp vehicles. If the DI is occupied and the DM unoccupied,
the signal is changed to green in the fixed rate mode. If the DI is un-
occupied or the DM is occupied, the signal is held in the red state un-
til the correct DI-DM relationship is found. If for any reason the sig-
nal remains in the red state until the maximum red time elapses, the
background cycle is used to change the signal to green regardless of any
other conditions.

As indicated in Figure 14, the primary data items that determine
the direction taken during the program execution are the signal phase
and the signal phase ending time. This programming structure is indici-
tive of an application of sequential events or, as applied to the free-
way ramp control process; fixed rate metering. The utilization of ac-
ceptable freeway gaps for merging control only occurs during a preselec-
ted portion of the red signal phase. The determination of the rate set-
ting and, in turn, event times is reserved for a higher level program;
a program that can provide decisions based on an evaluation of the real-
time freeway operations.

System Supervisor Program

The system supervisor program, SUPER, is executed at the end of each
minute of the day. The primary functions of SUPER, as indicated in Figure

15, are:

1) to collect and store the last minute of freeway and ramp operation data on the mass storage disks,

2) evaluate freeway and ramp operations and provide, if necessary, any metering parameter changes, and

3) to provide control decisions for initiating and terminating ramp control.

The programming logic is separated into subroutines to facilitate in functional descriptions.

INPUT - The first subroutine, shown in Figure 16, collects the volumes, speeds, and occupancies associated with freeway operations. These data arrays are rearranged into subsystem values for use by the MCSAL and OUTPT subroutines. The data are ordered and stored on the remote mass storage disks, indexed by the time of day collected.

MONST - The subroutine MONST (Figure 17) collects those data items pertinent to the metering operation at each entrance ramp. The one minute data include: 1) ramp volume, 2) outside freeway lane volume, 3) meter rate, 4) acceptable gap sought, etc. as established under the next section in this report.

MCSAL - The freeway system is divided into five subsystems for the real-time evaluation of control operations as shown in Figure 18. Each subsystem has a set of limit values which are compared against the data items collected by subroutine INPUT. The subsystem data used to establish the metering rate, acceptable gap, and window percentage of each ramp are:

1) occupancy,

2) moderate and critical speed,

35

Subroutine name:

PROGRAMMED
INTERRUPT

Refer to:

INPUT

data
collection,
storage, and
formatting

Figure 16

MONST

special
ramp data
collection
and storage

Figure 17

MCSAL

freeway
subsystem
analysis and
parameter
control

Figure 18

OUTPT

total
system
output
information

Figure 19

TONOF

subsystem
initiation
and
termination

Figure 20

RETURN TO
SYSTEM
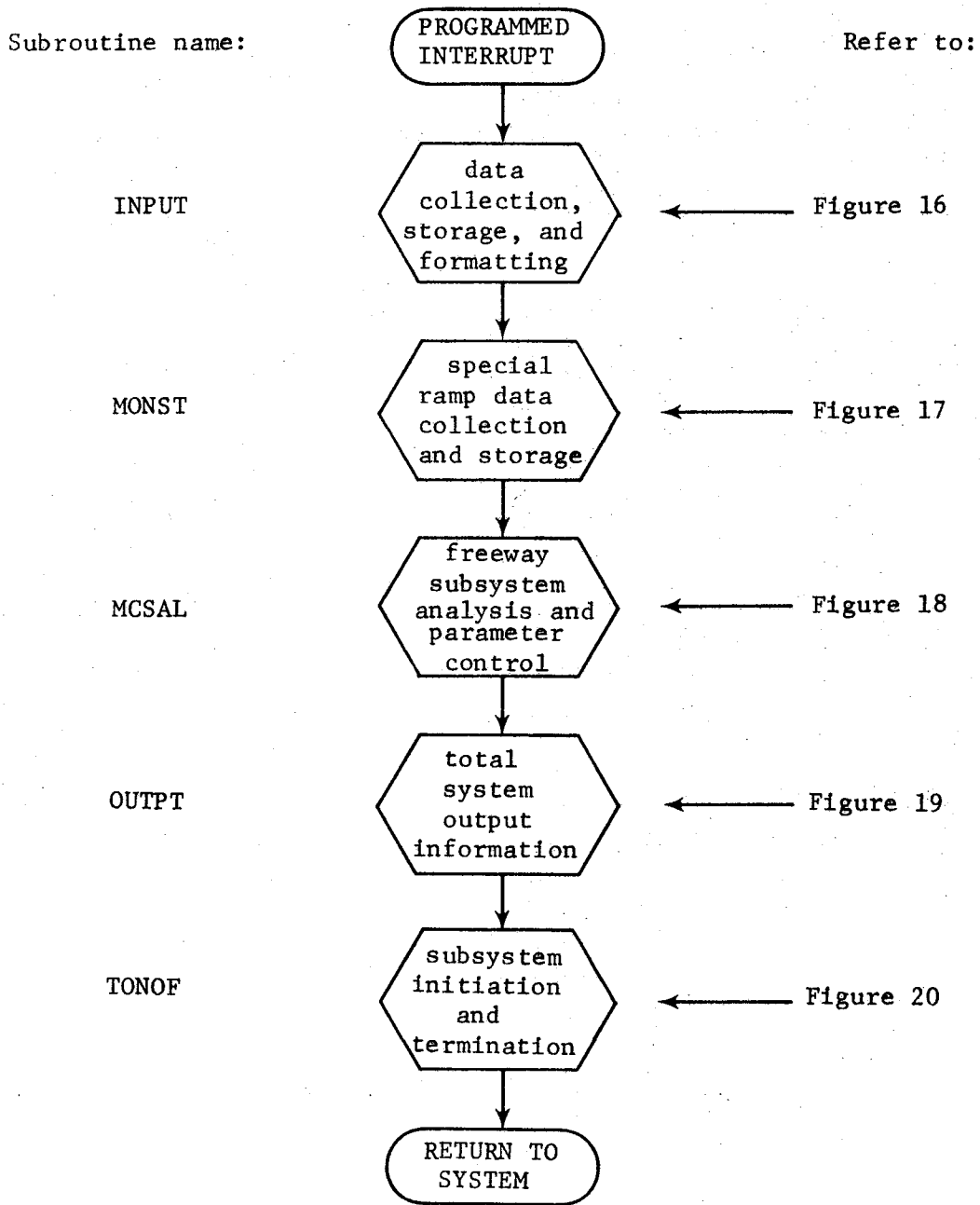
Figure 15.   Freeway system supervisory program logic.

Subroutine-INPUT

```
          ┌─────────────┐
          │    Main     │
          │   program   │
          └──────┬──────┘
                 │
                 ▼
          ┌─────────────┐
          │   gather    │
          │volume, speed,│
          │ occupancy & │
          │  rearrange  │
          └──────┬──────┘
                 │
                 ▼
          ┌─────────────┐
          │   log to    │
          │  disk-file  │
          │   "SYSTM"   │
          └──────┬──────┘
                 │
                 ▼
          ┌─────────────┐
          │  calculate  │
          │   volume    │
          │ substitutes │
          │  in case of │
          │sensor failure│
          └──────┬──────┘
                 │
                 ▼
          ┌─────────────┐
          │  Figure 7   │
          └─────────────┘
```
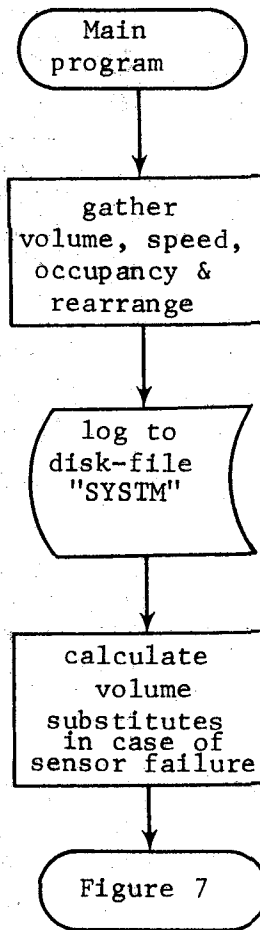
Figure 16.   Data collection and storage.

Subroutine-MONST

```
                    ╭──────────────╮
                    │  Figure 16   │
                    ╰──────┬───────╯
                           │
                           ▼
                  ┌──────────────────┐
                  │ gather DO and    │
                  │ DN volumes for   │
                  │ last minute      │
                  └────────┬─────────┘
                           │
                           ▼
                  ┌──────────────────┐
                  │ gather meter     │
                  │ rate, gap set,   │
                  │ and freeway      │
                  │ condition        │
                  └────────┬─────────┘
                           │
                           ▼
                  ┌──────────────────┐
                  │ gather No. of    │
                  │ gaps > gap       │
                  │ setting          │
                  └────────┬─────────┘
                           │
                           ▼
                  ┌──────────────────┐
                  │ gather No. of    │
                  │ greens given     │
                  │ for gaps, rate   │
                  │ and total        │
                  └────────┬─────────┘
                           │
                           ▼
                  ┌──────────────────┐
                  │ gather DM        │
                  │ override time    │
                  │                  │
                  └────────┬─────────┘
                           │
                           ▼
                      ╱────────╲                    ┌──────────────────┐
                     ╱   is     ╲      YES           │ store            │
                    ╱  control   ╲──────────────────▶│ data onto        │
                     ╲    on     ╱                    │ disk file        │
                      ╲────────╱                      │ "RDATA"          │
                           │                          └────────┬─────────┘
                          NO                                   │
                           ▼                                   │
                    ╭──────────────╮                           │
                    │  Figure 18   │◀──────────────────────────┘
                    ╰──────────────╯
```
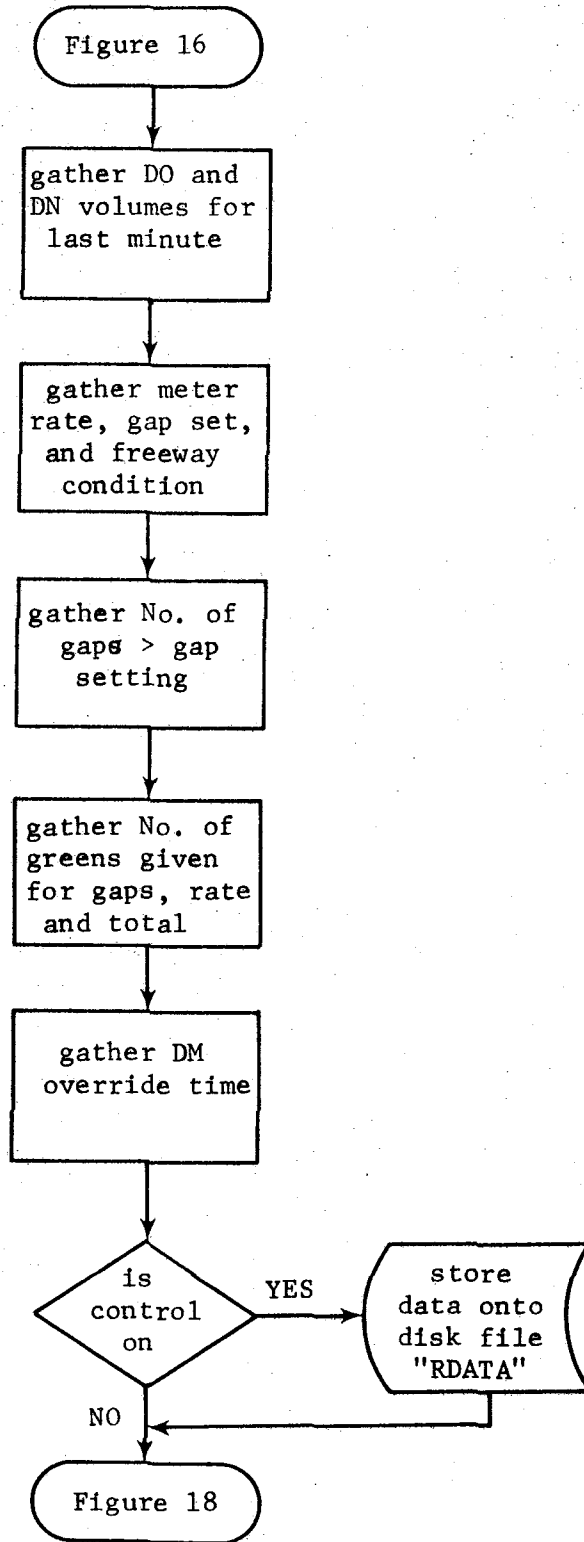
Figure 17. Special ramp data collection and storage.

38
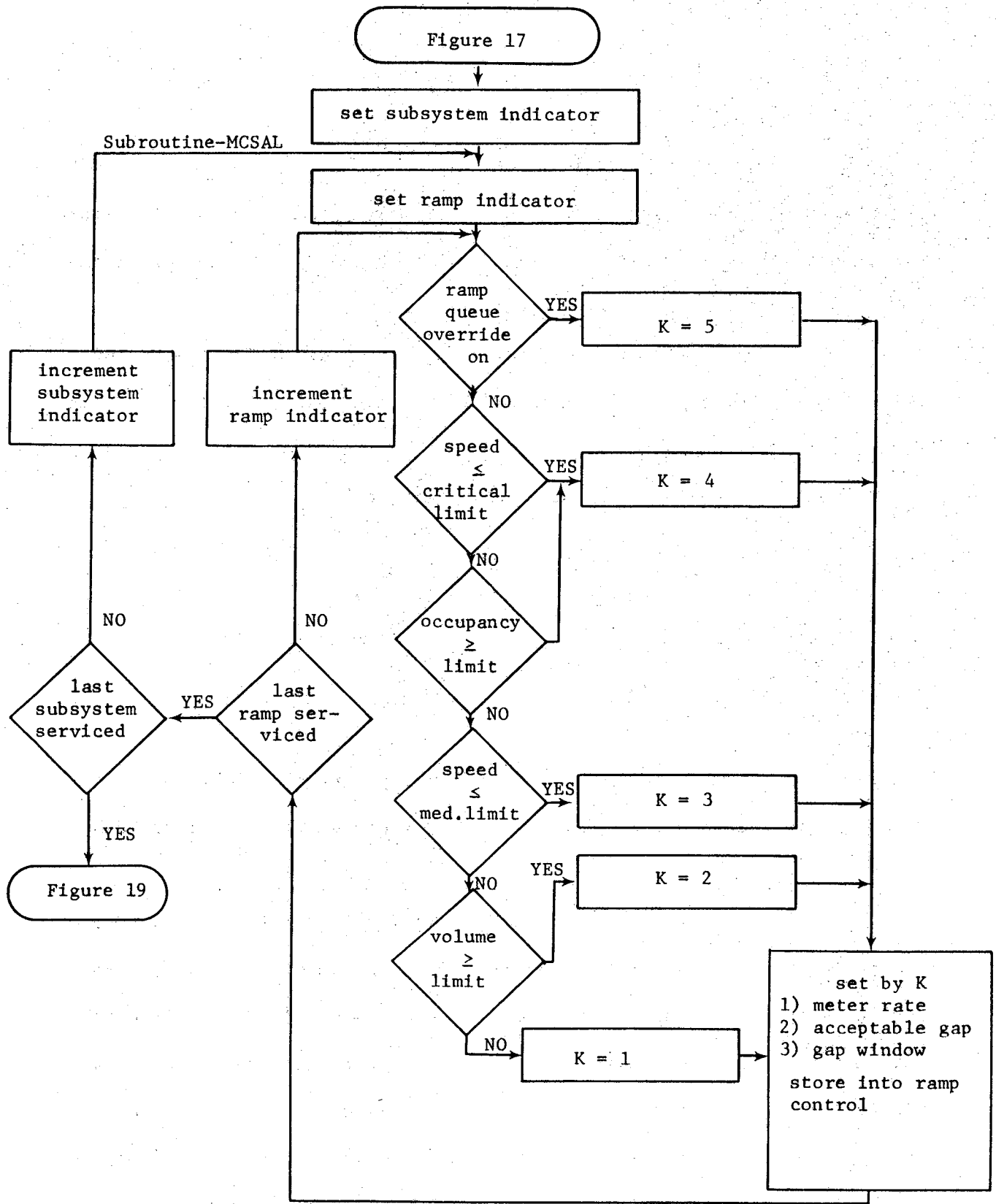
Figure 18. Freeway subsystem analysis and control.

3) heavy volume, and

4) ramp queue override.

A limit comparison that indicates the subsystem is in free flow or light flow condition will normally establish high metering rates, small acceptable gaps and large window percentages.

OUTPT - During the control period the subroutine OUTPT will print, upon request, the real-time performance of the freeway operations. This documentation includes:

1) freeway entrance and exit ramp flowrates,

2) speeds,

3) occupancies,

4) meter rates,

5) acceptable gaps,

6) window percentages, and

7) subsystem freeway conditions as determined by MCSAL.

Figure 19 indicates a general description of the functions performed by OUTPT.

TONOF - The subroutine TONOF (Figure 20) utilizes information from the performance of each freeway subsystem to initiate or terminate ramp control within that subsystem. Each subsystem has time limits in which ramp control will operate regardless of freeway conditions. The average middle lane speed and occupancy, and the subsystem's three lane freeway output flow rate over the last five minutes is used by TONOF. If any one of the three data items lies outside the limit range for two consecutive minutes, ramp control will be initiated at each ramp within the subsystem.

40
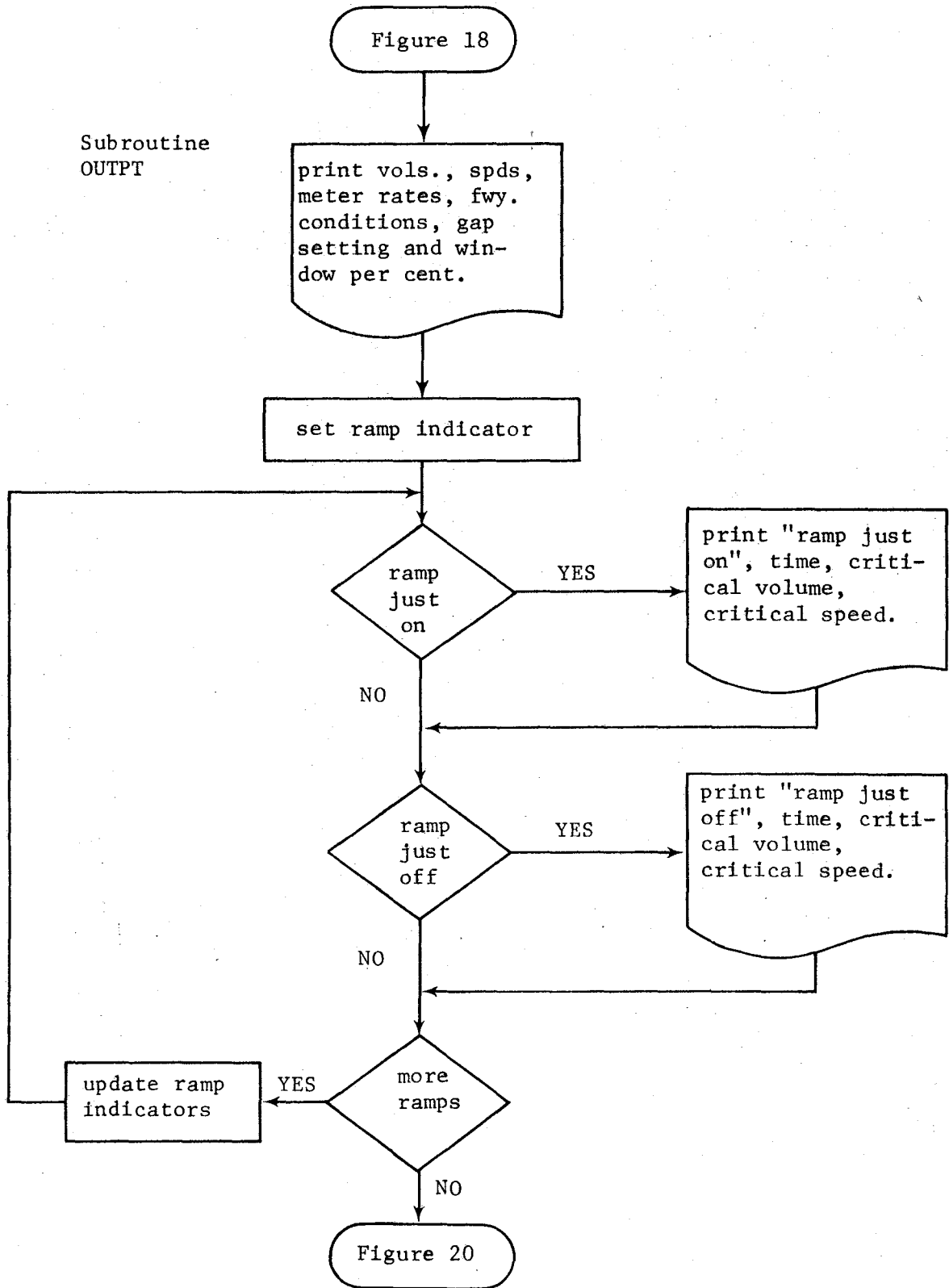
Figure 19.   Total system output information.
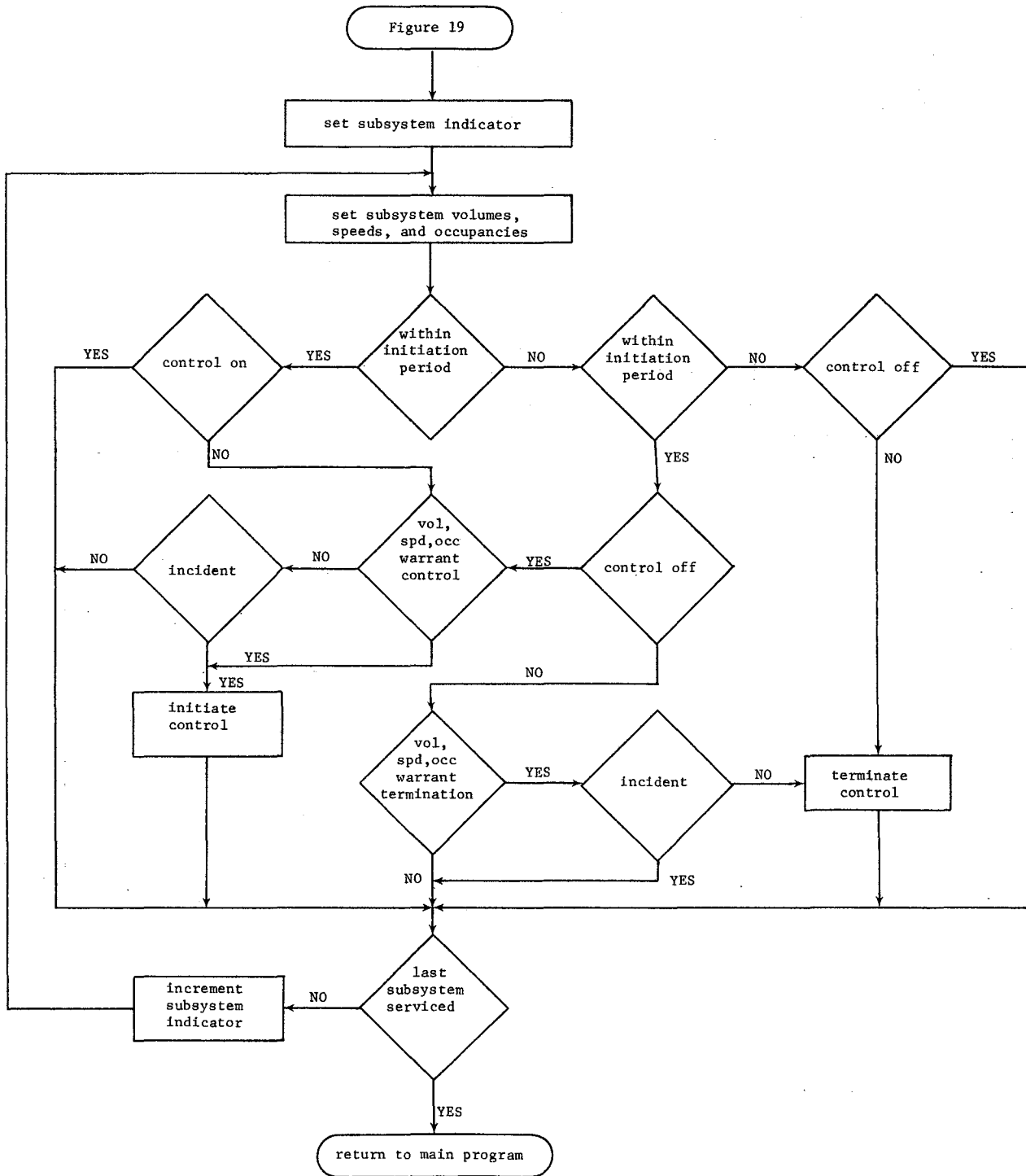
Figure 20. Subsystem initiation and termination.

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Two of the three data items must lie within limits for two consecutive minutes before termination of ramp control. In addition, the control of a ramp can be re-initiated if the subsystem or time limit warrants.

The role assigned to the system supervisor program, SUPER, is more significant than just fulfilling the previously described functions. SUPER, in a broader sense, serves as a communication link between the real-time control of each entrance ramp (CNTRL) and the immediate and past history of the total freeway operations. The immediate history of the freeway operations is used by MCSAL (Figure 18) to establish the ramp metering variables, and by TONOF (Figure 20) to initiate or terminate the ramp metering control. The comparison limits used by these subroutines are established after examination of the past histories of the freeway operation as presented by the ramp and system analysis programs.

Summary – The programs developed to monitor and control the freeway and ramp traffic operations execute within the priority assigned interrupt structure of the digital computer. The data acquisition programs provide real-time sensor information for interrogation by the ramp and system supervisor programs. The metering of vehicles by the ramp control program operates basically in a fixed rate mode. Gap acceptance characteristics are utilized whenever possible with the monitored ramp operation providing overrides to the metering process. Freeway and ramp traffic operations are examined and evaluated each minute by the system supervisor program and, if necessary, adjustments to the ramp metering proeess are made. The interaction of data acquisition, ramp, and system supervisor programs constitutes the real-time freeway ramp control programming system.

EVALUATIONAL PROGRAMS

The evaluation and analysis programs used to measure the daily free-
way control operations are executed at the end of each control period
(See Figure 2) and are arranged into three distinctive groups. The first
set of programs evaluates the performance of the total freeway by examin-
ing in detailed analysis the five subsystems shown in Figure 21. A sec-
ond set of programs examines the metering and merging operations of each
controlled entrance ramp. Finally, the freeway conditions and parameters
used to initiate and terminate ramp control are analyzed by the third
group of analysis programs. Each set of analysis subprograms will be
described in greater detail in the following subsections.

Operations Analysis by Freeway Subsystem

The first phase in the evaluation of the overall freeway control op-
eration is a set of programs that analyzes the data stored on the remote
mass storage disks during the real-time control period. The printed out-
put of this program set is arranged by freeway subsystem and consists of
the following data quantities:

1) One minute totals over a predetermined time period for:

    a) flowrate by sensor location

    b) average speeds

    c) number of vehicles within freeway subsystem

2) Summarization of flowrates by sensor location over:

    a) two and one-half hours (6:30 to 9:00 a.m. & 3:30 to 6:00 p.m.)

    b) peak control hour (7:00 to 8:00 a.m. & 4:00 to 5:00 p.m.)
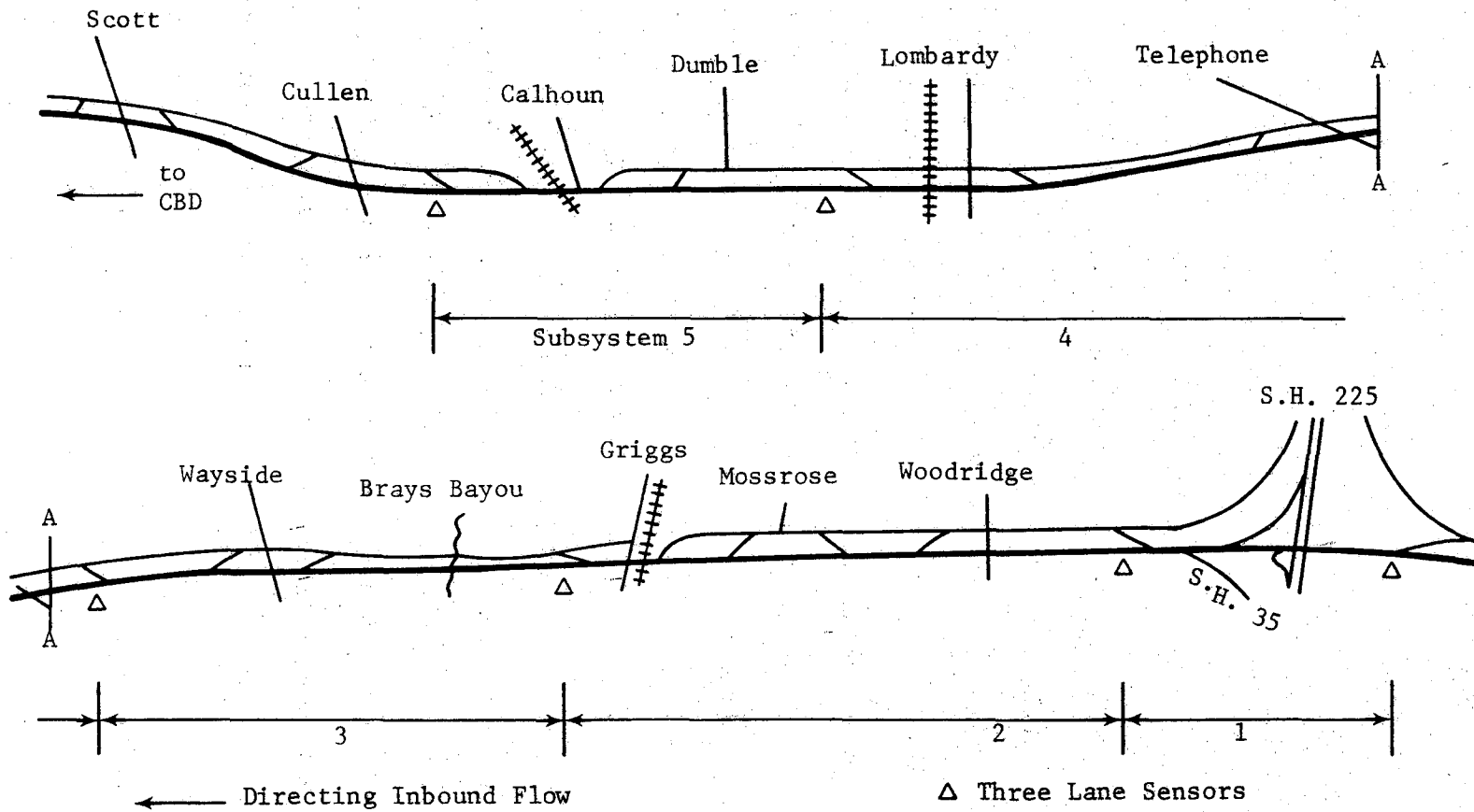
Figure 21. Diagram of the inbound Gulf Freeway.

c) peak hour

d) peak half-hour

3) Subsystem performance factors of:

a) total travel,

b) total travel time,

c) kinetic energy, and

d) average subsystem speed.

A discussion of the methods and programs that are used to calculate the various quantities is included in the following subsections.

Number in Subsystem - The program TESTI (Figure 22) first calculates the initial and final number of vehicles in each subsystem. The number of vehicles in a subsystem is calculated by using measured speed, flow-rate, and length of the subsystem. Two assumptions are made: (1) that flowrates are uniform with respect to time; and (2) the freeway operation is in a free flow condition. To insure that these assumptions are honored, the analysis period can be extended beyond the time limits of the control period. Normally, the initial and final number of vehicles in a subsystem is calculated immediately before and after the control period. This method yields an average number over a five minute period to accommodate individual subsystem characteristics. These characteristics include the number of entrance and exit ramps and length of the subsystem or extraneous conditions, such as freeway incidents, sensor failures, or computer malfunctions.

In the program TESTI, the initial and final number of vehicles in each subsystem is calculated in the following manner:
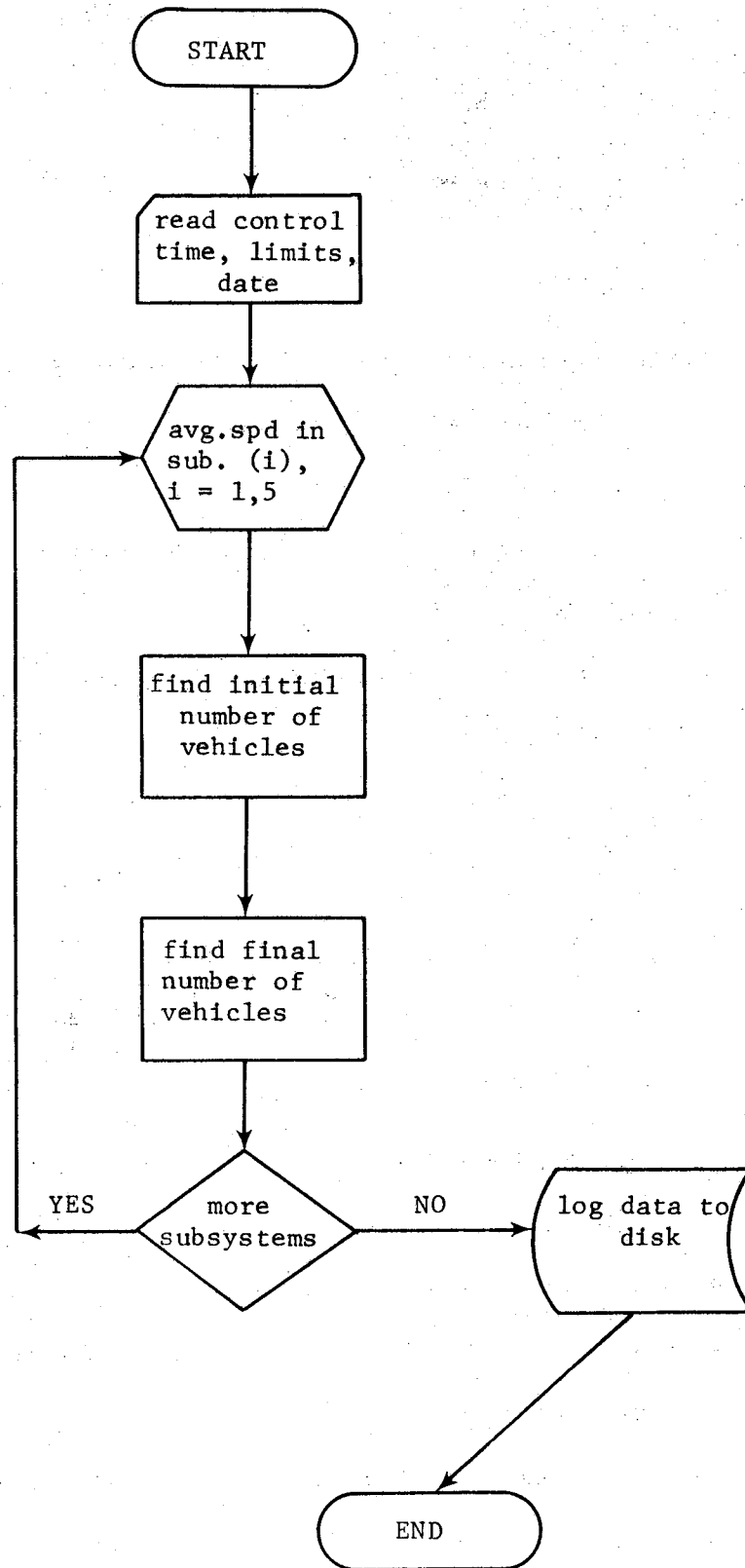
Figure 22. Program TESTI logic.

$$NYSAV = \frac{\sum_{k=KK}^{KK+4} NSY_k}{5} \qquad (1)$$

where

NYSAV = the average number in the subsystem for the preceding five-
minute period which is saved in file NUMSM for later use by
the TIGER program

KK = the minute of day past midnight that the analysis period is
to begin or end

NSY_k = the number of vehicles in a subsystem calculated on one min-
ute data.

The equation used to calculate the number in each subsystem for each min-
ute k is:

$$NSY_k = FO_k * \frac{D_1}{\mu} + \sum_{i=1}^{N} RX_i * \frac{D_{2i}}{\mu} - \sum_{j=1}^{M} RE_j * \frac{D_{3i}}{\mu} \qquad (2)$$

where

FO = the freeway flowrate of the output of the subsystem for the k^{th}
minute

RX = the flowrate of the i^{th} exit ramp for the k^{th} minute

RE = the flowrate of the j^{th} entrance ramp for the k^{th} minute

D_1 = length of subsystem

D_2 = distance from start of subsystem to the i^{th} exit ramp

D_3 = distance from the j^{th} entrance ramp to freeway output point

μ = average speed during the minute in the subsystem

N = number of exit ramps in the subsystem

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M = number of entrance ramps in the subsystem.

The first phase of program TIGER (Figure 23) utilizes the initial number in each subsystem as calculated by TESTI, and does an input/output summarization throughout the analysis period as follows:

$$NSYS_K = NSYS_{K-1} + \sum_{i=1}^{N} SI_k - \sum_{j=1}^{M} SO_k \qquad (3)$$

where

$NSYS_K$ = number of vehicles in subsystem for K^{th} minute of control period.*

$NSYS_{K-1}$ = number of vehicles in subsystem derived from last minute of control period. When K = 1, $NSYS_{K-1}$ is equal to NYSAV; the initial number is calculated by TESTI

SI_k = subsystem input volumes for k^{th} minute of day

SO_k = subsystem output volumes for k^{th} minute of day

k = present minute of day past midnight

K = present minute of control period

N = number of subsystem sensor input points

M = number of subsystem sensor output points

The final number in each subsystem, $NSYS_K$, at the end of the analysis period as calculated above, is compared against the final value, NYSAV, found by TESTI. The difference between these values represents an error

---

*NOTE: The number of vehicles in a subsystem of the k^{th} minute of day is placed into an array, NSYS, at the K^{th} minute of the control period for ease in description and computation.
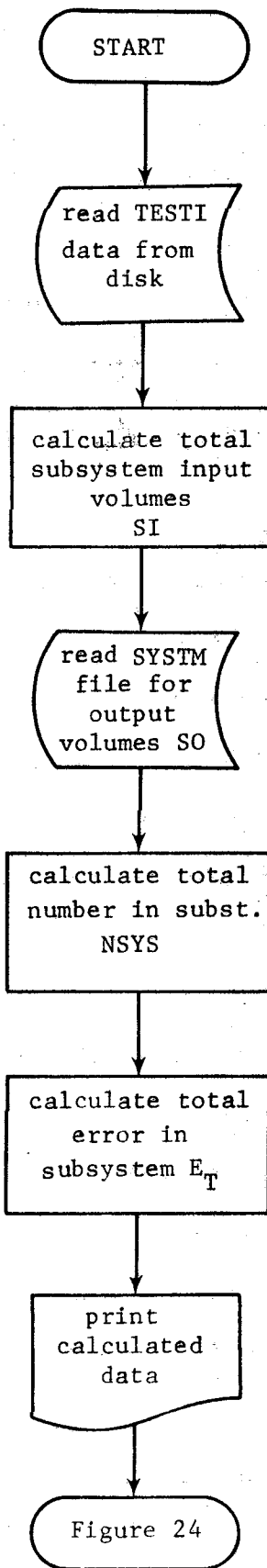
Figure 23. Program TIGER logic.

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of closure. The closure error is distributed by subroutine SUBSY, Figure 24, based on the total subsystem input volumes over the entire analysis period and the subsystem input volume for the last minute of the day in the following manner:

$$NSYSC_K = NSYS_K + E_K$$

where $\quad E_K = E_{K-1} - ((E_T * V_{I_k})/V_T)$

and

$NSYSC_K$ = the corrected number in subsystem for minute K of the control period

$NSYS_K$ = the uncorrected number in subsystem for minute K of the control period as previously calculated by TIGER based on the input/output summarization

E_K = the cumulative error distributed to NSYS for the K^{th} minute of the control period

E_{K-1} = the cumulative error from the previous minute of the control period

E_T = the total error of closure

V_{I_k} = the input volume to the subsystem during the k^{th} minute of the day

V_T = the total input volume to the subsystem during the control period.

Subroutine SUBSY, in addition to distributing the closure error to the number of vehicles in each subsystem, logs onto the printer the one minute data outlined in a previous section. The remaining subroutines of pro-

```
        ╭─────────────╮
        │  Figure 23  │
        ╰──────┬──────╯
               │
               ▼
        ┌─────────────┐
        │ calculate total │
        │ input volume by │
        │     minute      │
        └──────┬──────┘
               │
               ▼
        ┌─────────────┐
        │ calculate cumult. │
        │ error distributed │
        │  by minute E_k    │
        └──────┬──────┘
               │
               ▼
        ┌─────────────┐
        │ calculate number │
        │ in subsystem NSY │
        │    by minute     │
        └──────┬──────┘
               │
               ▼
        ┌─────────────┐
        │    calculate     │
        │    corrected     │
        │ number in system │
        │      NSYSC       │
        └──────┬──────┘
               │
               ▼
        ┌─────────────┐
        │ calculate cumult. │
        │   number in      │
        │  system MSYS     │
        └──────┬──────┘
               │
               ▼
        ┌─────────────┐
        │ calculate volumes │
        │  and peaks by    │
        │     minute       │
        └──────┬──────┘
               │
               ▼
        ┌─────────────┐
        │ print volumes    │
        │ pk. error, &     │
        │ num in syst.     │
        └──────┬──────┘
               │
               ▼
        ╭─────────────╮
        │  Figure 25  │
        ╰─────────────╯
```
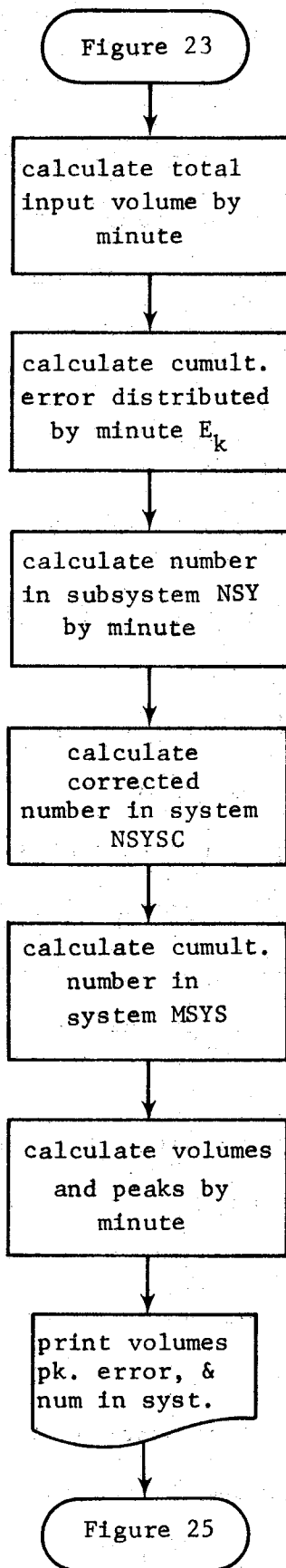
Figure 24. Subroutine SUBSY logic.

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gram TIGER are used to summarize subsystem flowrates and derive the performance factors. The first set of programs evaluates the performance of the total freeway by examining in detailed analysis the five subsystems shown in Figure 21. A second set of programs examines the metering and merging operations of each controlled entrance ramp.

Performance Factors - At the conclusion of the one minute subsystem data printouts, subroutines STOTL and STUFF are executed (Figure 25). These subroutines summarize and arrange the flowrate data into pre-established time periods as follows:

$$VC_{p,i} = \sum_{K=KK}^{LK} VT_{K,i} \qquad (i = 1,2,\ldots,N) \qquad (6)$$

where

$VC_{p,i}$ = cumulative flowrate for the i^{th} input or output location in the subsystem for time period p.

$VT_{K,i}$ = flowrate for the i^{th} input or output location in the subsystem for the K^{th} minute of the control period

K = minute of control period

KK = the minute of the control period where summarization is to start; KK = 1 for the 2.5 and 2.0 hour periods and KK = 30 for the one hour periods

LK = the minute of the control period where summarization is to stop; LK = 150 for 2.5 hour period, LK = 120 for 2.0 hour period and LK = 90 for 1 hour period

p = time periods of summarization: p = 1 for 2.5 hour period, p = 2 for 2.0 hour period, and p = 3 for 1 hour period

N = the number of input and output locations in the subsystem.

53

```
                              ╭──────────────╮
                              │  Figure 24   │
                              ╰──────┬───────╯
                                     │
                                     ▼
                              ┌──────────────┐
                              │ cal. vol. over│
Subroutine STOTL              │ 2.5 hours, 2.0│
                              │ hours and 1.0 hr.│
                              │ control period │
                              └──────┬───────┘
                                     │
                                     ▼
                              ┌──────────────┐
                              │ calculate peak│
Subroutine STUFF              │ hour/hlf. hr. &│
                              │ volumes for all│
                              │   locations   │
                              └──────┬───────┘
                                     │
                                     ▼
                              ┌──────────────┐
                              │ calculate total│
Subroutine SSPEL              │ travel $TT_p$ │
                              └──────┬───────┘
                                     │
                                     ▼
                              ┌──────────────┐
                              │ calculate total│
                              │ travel time   │
                              │   $TTT_p$     │
                              └──────┬───────┘
                                     │
                                     ▼
                              ┌──────────────┐
                              │ calculate total│
                              │   energy      │
                              │   $KE_p$      │
                              └──────┬───────┘
                                     │
                                     ▼
                              ┌──────────────┐
                              │ calculate avg.│
                              │   speed $u_p$ │
                              └──────┬───────┘
                                     │
                                     ▼
                              ╭──────────────╮
                              │  Figure 26   │
                              ╰──────────────╯
```
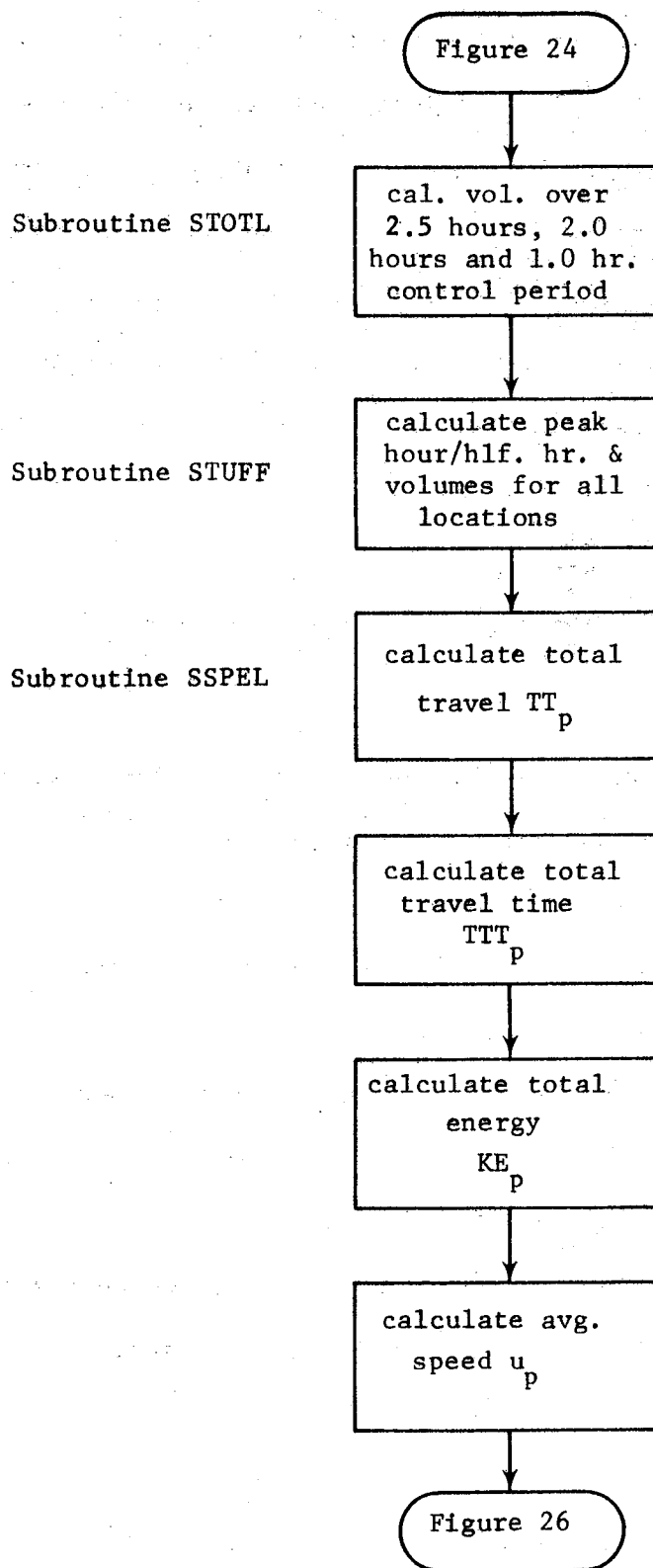
Figure 25. Performance factors calculations.

The corrected number of vehicles in the subsystem for each time period is summed in the following manner:

$$MSYS_p = \sum_{n = KK}^{LK} NSYSC_n \qquad (7)$$

where

$MSYS_p$ = sum of the total travel time in vehicle-minutes for the number of vehicles that were observed occupying a subsystem for a specific time period p.

$NSYSC_n$ = the corrected number of vehicles in a subsystem at the n^{th} minute of the control period

KK = starting minute of the control period;

KK = 1 for p = 1 and 2

KK = 31 for p = 3

LK = ending minute of the control period;

LK = 150 for p = 1

LK = 120 for p = 2

LK = 90 for p = 3

p = selected time periods;

p = 1 for 2.5 hours

p = 2 for 2.0 hours

p = 3 for 1.0 hours

To calculate the total travel (TT in vehicle-miles), Figure 25, for each time period, the summed flowrates within each subsystem for the time period, p, are multiplied by the distances traveled, D, in the following manner:

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$$TT_p = \sum_{j=1}^{N} \left[S_j * VC_{p,j} \sum_{i=j}^{N} D_i \right] \quad \text{(VEH-MI)} \quad (8)$$

where

TT_p = total travel in vehicle-miles in a subsystem for time period p

N = total number of input and output locations in a subsystem, excluding the freeway output location of the subsystem

S_j = sign notation for the j^{th} location:

S = +1 if input location

S = -1 if output location

$VC_{p,j}$ = flowrate at location j in the subsystem for time period p

D_i = distance in miles between the i^{th} location and the i^{th} +1 location in the subsystem

p = time periods:

p = 1 for 2.5 hours

p = 2 for 2.0 hours

p = 3 for 1.0 hours

Total travel time, TTT, is found by:

$$TTT_p = \frac{MSYS_p}{60} \quad \text{(VEH-HR)} \quad (9)$$

where

TTT_p = is the total travel time of the subsystem for time period p in vehicle hours

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$MSYS_p$ = sum of the corrected number of vehicles in the subsystem for

time period p as calculated in equation 7.

From the total travel, TT, and the total travel time, TTT, another

traffic measure, kinetic energy or KE, can be found for time periods p for

each subsystem by:

$$KE_p = \frac{TT_p^2}{TTT_p} \qquad \frac{VEH-MI^2}{HR} \qquad (10)$$

The final calculated performance factor is average speed, μ, for the

subsystem within each time period p. The equation is in the form:

$$\mu_p = \frac{TT_p}{TTT_p} \qquad \frac{MI}{HR} \qquad (11)$$

Subroutine IPRIN (Figure 26) is used to print;

1) summarized peak flowrates at each location within each subsystem, and

2) performance factor for each period of each subsystem.

The subroutine FINAL (Figure 26) combines the subsystem performance

factors into an entire controlled system factors in the following manner:

$$TTS_p = \sum_{i=1}^{N} TT_{p,i} \qquad (VEH-MI) \qquad (12)$$

and

$$TTTS_p = \sum_{i=1}^{N} TTT_{p,i} \qquad (VEH-HR) \qquad (13)$$

where

TTS_p = total travel of entire controlled system for time period p

$TT_{p,i}$ = total travel for the i^{th} subsystem for time period p

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                          ┌──────────────┐
                          │  Figure 25   │
                          └──────┬───────┘
                                 │
                                 ▼
                          ┌──────────────┐
                          │ print by     │
                          │ subsystem    │
                          │1) peak period│
                          │   volumes    │
Subroutine                │2) perform-   │
IPRIN                     │   ance by    │
                          │   time       │
                          │   periods.   │
                          └──────┬───────┘
                                 │
                                 ▼
                    combine subsystem performance
Subroutine           factors into a total system
FINAL                       by time periods.
                                 │
                                 ▼
                          ┌──────────────┐
                          │print system  │
                          │performance   │
                          │factors by    │
                          │time periods. │
                          └──────┬───────┘
                                 │
                                 ▼
                          ╭──────────────╮
                          │ RETURN TO    │
                          │ MAINLINE     │
                          ╰──────────────╯
```
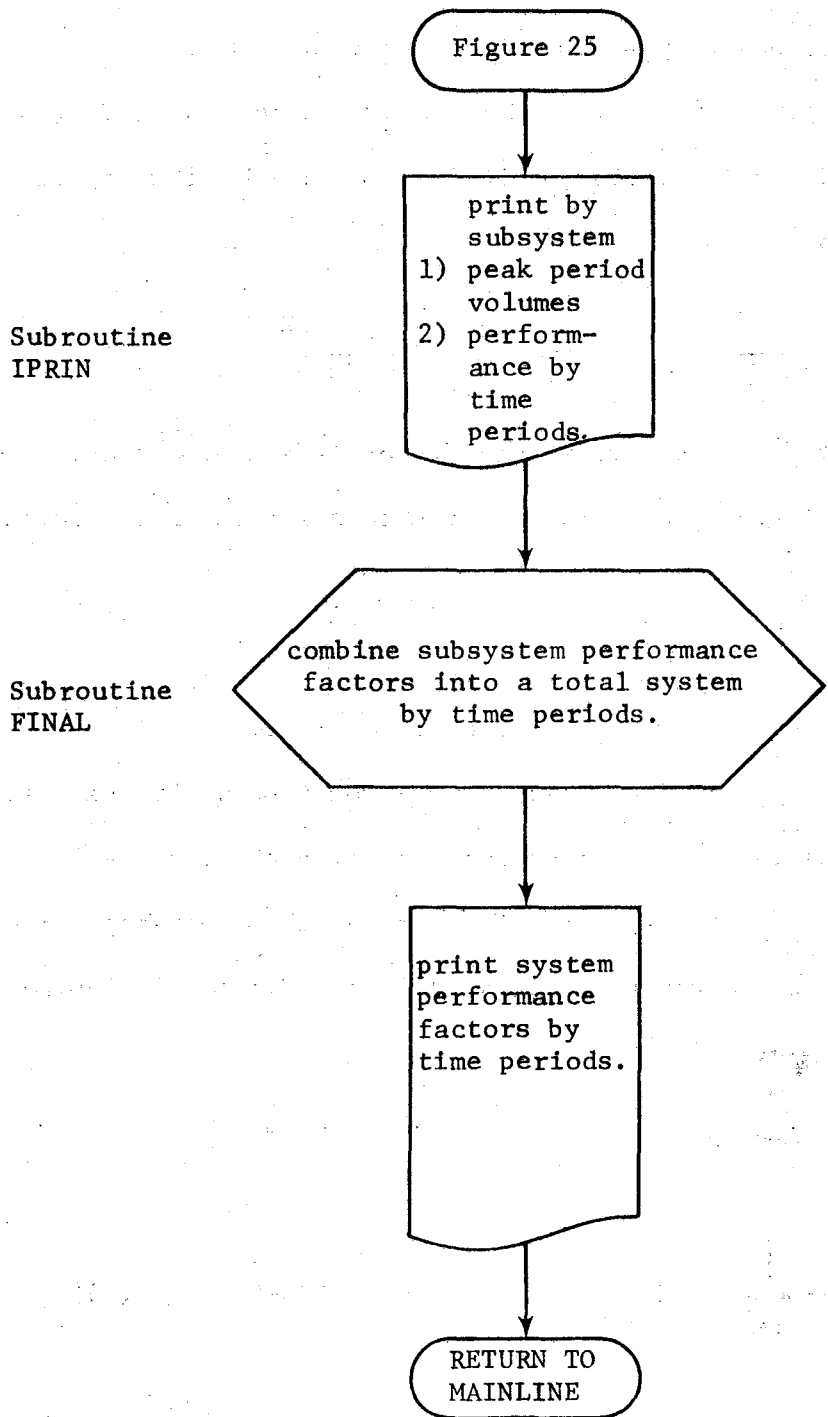
Figure 26.   Subroutine IPRIN and FINAL.

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$TTTS_p$ = total travel time for the entire controlled system for time period p

$TTT_{p,i}$ = total travel time for the ith subsystem for time period p.

From equations 12 and 13, the kinetic energy and average speed for the entire controlled system for each time period, p, are calculated by:

$$KES_p = \frac{TTS_p^2}{TTTS_p} \qquad \frac{VEH-MI^2}{HR} \qquad (14)$$

and

$$\mu S_p = \frac{TTS_p}{TTTS_p} \qquad \frac{MI}{HR} \qquad (15)$$

where

KES_p = the kinetic energy for total system for time period p

TTS_p = total travel of the system for time period, p, from Eq. 12

$TTTS_p$ = total travel time of the system for time period p from Eq. 13

μS_p = average speed in the system for time period p.

The operations analysis performed by the preceding programs provides basic information that is used to evaluate the effectiveness of freeway ramp control. In addition, the subsystemimal analysis printouts enable historical data files of daily ramp control performances to be built.

Ramp Metering Analysis

During each minute of the control period, pertinent data from the metering and merging operation at each entrance ramp are collected and filed on the storage disks by the system supervisory program, SUPER. The analysis of the operation of each ramp provides daily operational patterns and assists in determining if any changes are required in the control variables. Ana-

lyzed data are presented in two forms. The first data set indicates metering performance for different freeway conditions. For each minute of operation, the second set of data shows the time during which the merge override function was activated and the speed of the merging freeway lane. Detailed descriptions of the data sets are included in the following discussions.

Performance by Condition - Ramp data, stored on disks during real time, are not ordered by freeway condition. Therefore, ramp analysis program, ANAYS (Figure 27), summarizes the collected data according to freeway conditions.

Condition	Description
0	light flow
1	moderate flow
2	heavy flow
3	forced flow and
4	queue override

The first four conditions decrease metering rates as freeway operations become heavier, and the queue override, which indicates a blockage of non-freeway traffic lanes, increases the metering rates. The analysis for each of the five conditions includes the following items:

1) upstream freeway volume in merging lane,

2) number of acceptable gaps into which a ramp vehicle could merge,

3) number of green signals given for arriving gaps,

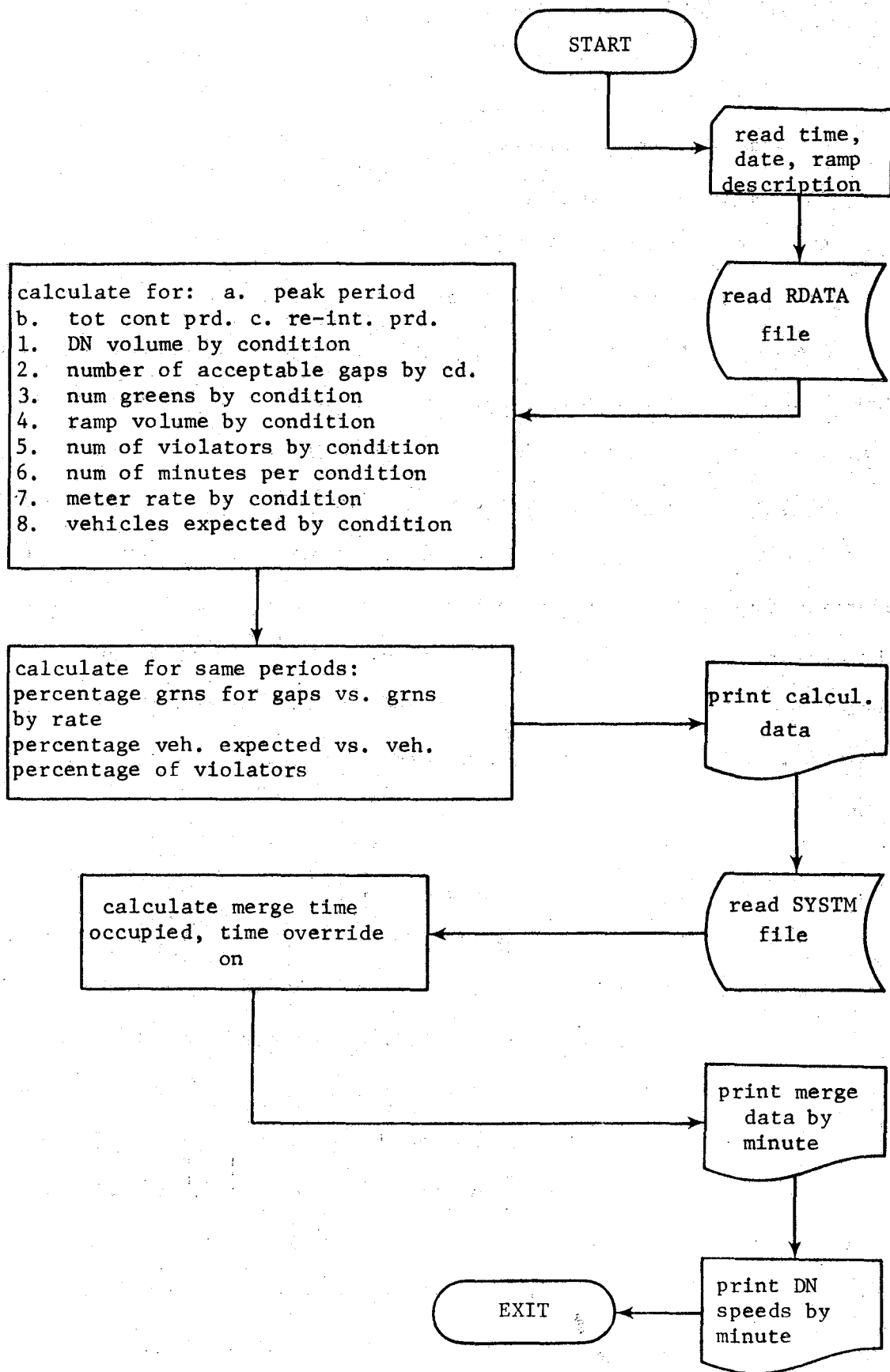4) number of green signals given at fixed rate,

5) total number of green signals,

```
                                    ╭────────────╮
                                    │   START    │
                                    ╰─────┬──────╯
                                          │
                            ┌─────────────────────┐
                            │    read time,       │
                            │    date, ramp       │
                            │    description      │
                            └──────────┬──────────┘
                                       │
                            ╭──────────────────────╮
                            │    read RDATA        │
                            │       file           │
                            ╰──────────┬───────────╯
┌────────────────────────────────┐    │
│ calculate for:  a.  peak period│◄───┘
│ b.  tot cont prd. c. re-int. prd.│
│ 1.  DN volume by condition     │
│ 2.  number of acceptable gaps by cd.│
│ 3.  num greens by condition    │
│ 4.  ramp volume by condition   │
│ 5.  num of violators by condition│
│ 6.  num of minutes per condition│
│ 7.  meter rate by condition    │
│ 8.  vehicles expected by condition│
└───────────────┬────────────────┘
                │
┌────────────────────────────────┐          ╭──────────────────╮
│ calculate for same periods:    │          │  print calcul.   │
│ percentage grns for gaps vs. grns│────────►│     data         │
│ by rate                        │          ╰────────┬─────────╯
│ percentage veh. expected vs. veh.│                 │
│ percentage of violators        │                   │
└────────────────────────────────┘                   │
                                          ╭───────────────────────╮
┌──────────────────────┐                  │    read SYSTM         │
│ calculate merge time │◄─────────────────│       file            │
│ occupied, time override│                ╰───────────────────────╯
│        on            │
└──────────┬───────────┘
           │                              ┌──────────────────────┐
           │                              │   print merge        │
           └─────────────────────────────►│   data by            │
                                          │   minute             │
                                          └──────────┬───────────┘
                                                     │
                              ╭────────╮   ┌──────────────────────┐
                              │  EXIT  │◄──│   print DN           │
                              ╰────────╯   │   speeds by          │
                                          │   minute             │
                                          └──────────────────────┘
```

Figure 27.   Ramp data analysis logic.

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6) expected and actual ramp volume,

7) number of violators,

8) number of minutes condition is in effect, and

9) metering rate set for condition

The data set is summarized for three time periods; the total time ramp control is in effect, the peak control hour, and the re-initialization periods. A sample printout is included in the appendix.

Merging Operations - The second data set presented by program ANAYS is a minute printout of the operation of the merge occupancy and the merge override function for each ramp during the control period, and speeds over the sensor, upstream in the merging lane. These data items used in conjunction with the real-time data, presented by SUPER and the above metering analysis, enable more comprehensive evaluation of the total control operation.

Initiation and Termination Analysis

The third phase in the overall analysis of the control system is a summarization of the freeway conditions that existed during the control period. The traffic data retained on the remote storage disks by SUPER during the control period is used. Traffic information, in the form of flowrates, speeds, and occupancies, is determined and printed for each minute of the control period for those locations that are used for initiation and termination of ramp control (See Figure 28). This data set, along with the operations analysis by subsystem and the daily television surveillance information, enables adjustments to be made to the parameters governing the initiation, termination, and re-initiation of the ramp signal controls.
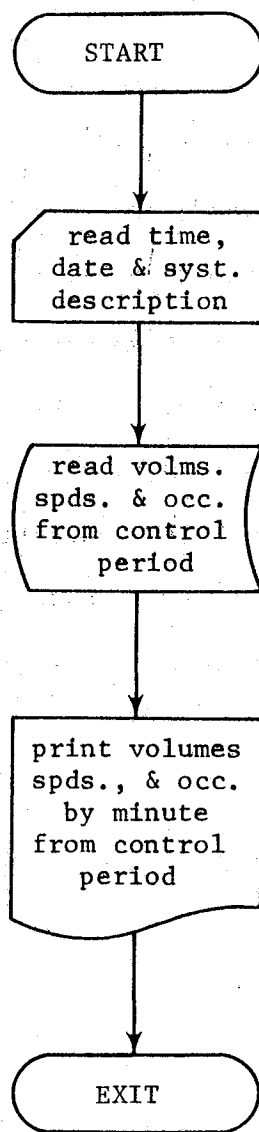
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Figure 28. Initiation-termination parameter dump.

Summary

The analysis programs provide a daily evaluation of the performance on the control system. Optimal control operation occurs when certain criteria are maximized and others are minimized. Four types of functional adjustments can be made in order to approach the desired goals:

1) metering variables, such as metering rates, acceptable gap sizes, and percentages of cycle time during which gap searches are accommodated (window size),

2) parameters which determine freeway conditions,

3) override criteria, and

4) initiation and termination parameters.

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1. McCasland, W.R., Freeway Ramp Control System. Texas Transportation Institute, Research Report 24-26F, August, 1969.

2. Gap Acceptance and Traffic Interaction in the Freeway Merging Process, Division of Designing Engineers. Texas Transportation Institute, Research Report 504F.