

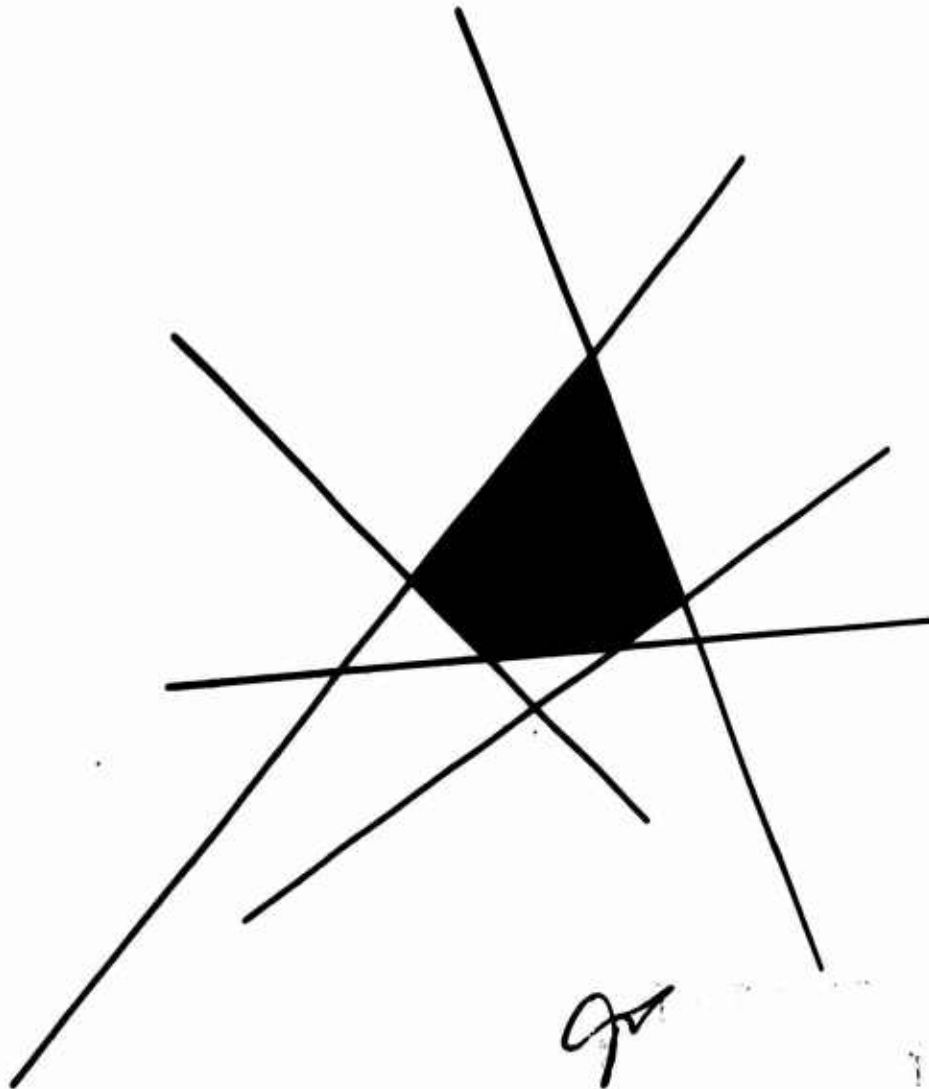
ORC 69-20  
AUGUST 1969

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# AN ANALYSIS OF FREEWAY EMERGENCY SERVICE SYSTEMS

by  
HARTMUT KELLER

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**Hartmut Keller  
Operations Research Center  
University of California, Berkeley**

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This research has been supported by the National Science Foundation under Grant GK-1684 with the University of California. Reproduction in whole or in part is permitted for any purpose of the United States Government.

#### ACKNOWLEDGEMENTS

The committee in charge of this dissertation were Professors Adolf D. May (Chairman), C. Roger Glassey, and Michael B. Teitz. The author wants to express his appreciation to Professors Adolf D. May and C. Roger Glassey for their helpful suggestions, constructive criticism and continuing support. He is also very grateful to Professor Michael B. Teitz for his encouragements and his review of the manuscript.

Most data used in the empirical study were obtained from the California Division of Bay Toll Crossings, thanks are due particularly to Mr. Ray Murphy of the San Francisco-Oakland Bay Bridge.

The cooperation of Mr. Walter L. Byers, M.D., of the Alameda Surgeon Institutions, Highland General Hospital, Oakland is gratefully acknowledged.

Most valuable was the support provided by the Institute of Transportation and Traffic Engineering and the Operations Research Center of the University of California, Berkeley.

The research has been supported in part by the National Science Foundation under Grant GK-1684.

## ABSTRACT

The provision of emergency services to the stranded motorist on freeways requires a coordinated effort of all related agencies. A schematic model for a systems analysis structure has been designed for responding to freeway incidents.

The operation of an emergency service system has been represented in an activity model. It describes the chronological sequence of events and activities performed by the major components: police, mechanical, fire, and medical service of the detection and service subsystems. The performance of alternative emergency service systems was analyzed on the basis of cost and effectiveness.

The activity model has been applied to analyze selected detection and service systems on a linear urban freeway with high average daily traffic flows. Stationary and patrolling units for the police and mechanical service components were subjected to a detailed analysis. Deterministic and stochastic models were developed for the major activities: detection, travel to the scene of incident, on-site service, and return travel to normal position. The activity model then was used as a basis for a next event simulation process.

A cost and effectiveness study was employed to test the operation of the selected emergency service systems on a set

of historical incident data. The detection time and the time of arrival of first service was used as the measure of effectiveness for the individual stranded motorist. The number of vehicles delayed and the total delay due to capacity reducing incidents was used as the measure of effectiveness for passing motorists.

The general approach and the analytical procedures developed in this study permit an analysis of the effects of changes in various parameters relevant in emergency service systems. The model has the potential to be applied to different locations, or with some adaptations, to different detection and service subsystems.

## NOTATION

The basic structure of this study and designations of its sections are apparent from the Table of Contents. Figures are numbered consecutively throughout, while equations are numbered in each subsection separately, beginning with (1).

References are given together in alphabetical order at the end of the study. In the text, references are designated by square parentheses, [ ], while the equations are in common parentheses, ( ).

Referring to any specific equation within the same subsection is given by its number. If the reference subject is in another subsection, both the subsection number and subject number are given. For example, reference to Equation 3 in Subsection 5.1.5 is marked as (5.1.5 - 3).

A list of symbols is given at the end of the study. It contains all symbols used in the study except for those which are used only locally and defined immediately in the text.

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## CHAPTER 1

### INTRODUCTION

#### 1.1 THE PROBLEM

Freeways in urban areas carry large amounts of traffic during certain periods of the day, so that an interruption of the traffic flow through capacity reducing incidents and accidents cause traffic congestion and delays to the passing motorist affected by the roadway blockage. On rural freeways where the traffic demand is low in comparison to the urban freeways, the stoppage of individual vehicles may not affect the traffic flow, but the waiting for necessary service can possibly be vital to the survival of the stranded motorist. Both consequences are not exclusive for either location, but describe the typical effects on nonrecurrent incidents. The two examples indicate the area of research on which this study will concentrate, that is the analysis of a response system to assist the stranded motorist and the study of the effects of this system on the negative consequences of traffic incidents on access controlled highways.

The analysis of the emergency service system should put some light on possible ways of improving existing or designing new detection and service systems. An efficient response system then should be helpfull in the reduction of the mortatality rate of accident victims and in the attempt to increase the safety on the freeways.

A traffic incident may be visualized as progressing through a series of phases. Each phase is a process of interaction among many factors associated with the driver, the vehicle and the environment. These natural phases can be combined to three stages; the pre-incident stage, the intra-incident stage and the post-incident stage [50]. The pre-incident stage involves the period that transforms travel into a stoppage. It is the period where incidents or accidents start and become inevitable. The intra-incident

stage starts when the incident or collision physically begins until the instant that it is over. The post-incident stage starts when a possible immediate damage has just been done and involves the process until that damage is transformed into the ultimate damage, such as death, disability, property damage, delays, secondary accidents, or financial and social loss. It is the chronological sequence of events during this last stage with which this study is concerned. While the importance of the first two stages is recognized, because they are the input to the third stage, they will not be analyzed and therefore will be considered as given for this study.

## 1.2 PREVIOUS RESEARCH AND PRESENT PROCEDURES

The theoretical treatment of freeway emergency service systems has been given little attention to date. In this section a review of the historical development of emergency services on highways and access controlled roadways will be given. The relevant literature on existing detection and service systems will be presented in a reference matrix, which at the same time displays the types of detection methods used and the main components of the service subsystem. Reference to mathematical models and theoretical approaches, which are concerned with subsystems of the problem is given in Chapters 2 and 5, where those subsystems are discussed. Present procedures applied in designing and operating emergency service systems are discussed at the end of this section.

### 1.2.1 Historical Development

The need of service for a traveler exists since man started to leave his residence. All Roman roads had halting stations for travelers to rest and to change their horses [55]. The first organized way stations seem to have been built by the Assyrians as early as 680 B.C. On the Royal Road in Persia between Sardis and Susa, a distance of 1600 miles, there were

official post stations every 15 miles [43]. Only the establishment of these way stations allowed messengers at that time to travel long distances safely in relatively short intervals of time, because they could rely on the services and protection provided by these stations.

A system as well organized as that by the Persians, adjusted to the service needs of traffic incidents on modern highways, would already be one step toward the solution of the problem.

With the motorization of the 20th Century and the construction of access controlled highways [82], the need for service to the motorist became even more apparent. Starting with the construction of the Automobil Verkehrs- und Uebungs-Strasse (AVUS) in Berlin 1913 (completed after World War I, 1923) [27], high speed freeways were developed which led; e.g., to the German Autobahn network as well as the Interstate Highway System in the United States. As long as the traffic flow on the freeways was low as compared to their capacity, the major concern after an incident was for the individual stranded motorist, who needed assistance and not the blockage of the roadway. But the public concern was still small, considering the problem with which the stranded motorist was confronted. The establishment of emergency telephones spaced at about one mile along the German Autobahn, which were connected with maintenance stations was one of the first attempts to provide assistance (1939) [106].

Only the high traffic demand, which exists on some urban highways, has alarmed the public which is now influenced by the effects of congestion due to capacity reducing incidents [51, 77, 78, 86, 138, 141]. Today there are still very few links on the urban freeway networks which have detection or service systems to respond to traffic incidents. A number of examples in the United States are toll facilities operated by agencies who benefit from maintaining an adequate level of service, as it is desired by the

motorists. Examples are the Lincoln and Holland Tunnels in New York and the toll bridges in the San Francisco Bay Area [123].

The concern for the individual motorist led organizations like the AAA (American Automobile Association) to establish locally stationed tow vehicles along highways [12], or the ADAC (Allgemeiner Deutscher Automobil Club) to operate service patrols on the German Autobahn [2, 145]. These services are mostly only available to members of these private associations.

A new era for the detection and servicing of stranded freeway motorists started with the creation of Traffic Surveillance and Control Projects in various United States cities; e.g., Chicago [83, 84], Detroit [22] and Houston [134] in the early sixties. Established to study and control the traffic flow at most critical links of the urban freeway systems, the projects were able to study the causes and consequences of vehicle stoppages [35, 36, 37]. But the emphasis was more on the detection of the stoppages than on the summoning of appropriate service to the stranded motorist.

Another move toward the solution of this problem came from the necessity to care for the injured in automobile accidents. Some efficient medical emergency care systems were developed through local efforts, e.g., in the City and County of San Francisco [71] and in New York City [114]. Since the creation of the Highway Safety Act in 1966 and the subsequent establishment of the Department of Transportation, research was sponsored in this field, in particular by the National Highway Safety Bureau (NHSB). The efforts of NHSB are expressed through numerous research contracts and demonstration projects in the field of Emergency Medical Systems [127] and Traffic Safety Systems in general [50].

### 1.2.2 Description of Detection and Service Systems in Operation

Numerous detection and service systems are presently in operation or in the development stage [4, 92, 122, 133]. To provide a basis for a systematic

analysis of emergency service systems, in the following subsections a structure of emergency services will be given and relevant systems are described.

#### 1.2.2.1 Detection Methods and Service Components

Stoppages on freeways are detected in various ways and different methods are employed to render necessary service to the stranded motorist. In this study the term detection will be used to describe the first phase after the occurrence of an incident<sup>†</sup> until the operating agency knows about this occurrence and initializes the next phase of the response system, which is the dispatching of necessary service.

The presently used detection methods can be divided into three groups. The first group encompasses aerial and ground patrols along the highway which watch for the occurrence of incidents. These patrol vehicles may be used for detection only or may also serve as a service vehicle.

The second group contains those detection systems which allow the individual motorist to signal a call for service from his car with a build-in transmitter and/or receiver. This includes systems like Citizens Band Radio, or the use of an adjusted car radio.

The last group consists of all discrete detection units which are located along the roadway. For example, observers positioned along the highway, TV cameras, emergency telephones, call boxes, presence, flow and optical detectors.

The service subsystem is dependent on the type of services required by the incidents. A typical distribution of stop types is given in Figure 1 which is adapted from [102]. Basically four separate components may respond to the requests for assistance from these stoppages.

---

<sup>†</sup> An incident as described in this context and study is defined as any stoppage of a vehicle on the roadway or shoulder, whether it influences the traffic flow or not.

| Type of Stop    | Probability of Occurrence<br>(1) | Probability that Aid is Required<br>(2) | Urgency Relative Need of Aid Weighting Factor<br>(3) | Service Requirement Product<br>(4) = (1)(2)(3) | Per Cent of Total Service<br>(5) = (4)100/.201 |
|-----------------|----------------------------------|-----------------------------------------|------------------------------------------------------|------------------------------------------------|------------------------------------------------|
| Rest            | .12 <input type="checkbox"/>     | .0 <input type="checkbox"/>             | .0 <input type="checkbox"/>                          | .0 <input type="checkbox"/>                    | .0 <input type="checkbox"/>                    |
| Nonemergency    | .30 <input type="checkbox"/>     | .10 <input type="checkbox"/>            | .10 <input type="checkbox"/>                         | .003 <input type="checkbox"/>                  | 1.5 <input type="checkbox"/>                   |
| Tire            | .15 <input type="checkbox"/>     | .40 <input type="checkbox"/>            | .40 <input type="checkbox"/>                         | .024 <input type="checkbox"/>                  | 11.9 <input type="checkbox"/>                  |
| Information     | .16 <input type="checkbox"/>     | .50 <input type="checkbox"/>            | .50 <input type="checkbox"/>                         | .040 <input type="checkbox"/>                  | 19.9 <input type="checkbox"/>                  |
| Medical Help    | .01 <input type="checkbox"/>     | .70 <input type="checkbox"/>            | 1.00 <input type="checkbox"/>                        | .007 <input type="checkbox"/>                  | 3.5 <input type="checkbox"/>                   |
| Fire            | .01 <input type="checkbox"/>     | .90 <input type="checkbox"/>            | 1.00 <input type="checkbox"/>                        | .009 <input type="checkbox"/>                  | 4.5 <input type="checkbox"/>                   |
| Mechanical      | .15 <input type="checkbox"/>     | .90 <input type="checkbox"/>            | .50 <input type="checkbox"/>                         | .068 <input type="checkbox"/>                  | 33.8 <input type="checkbox"/>                  |
| Gas, Oil, Water | .10 <input type="checkbox"/>     | 1.00 <input type="checkbox"/>           | .50 <input type="checkbox"/>                         | .050 <input type="checkbox"/>                  | 24.9 <input type="checkbox"/>                  |
| 1.00            | TOTAL SERVICE LEVEL REQUIRED     |                                         |                                                      | .201                                           |                                                |

FIGURE 1: STOP-TYPE DISTRIBUTION

(Adapted from Airborne Instruments  
Lab. Report [102])

Police units respond as soon as an accident of certain characteristics is reported for the purpose of accident investigation and law enforcement [26, 112]. At the same time they provide for the protection at the scene of the incident and control the traffic flow.

Service vehicles, tow vehicles and wreckers provide the service necessary for the disabled vehicle and for the removal of roadway obstructing debris.

Fire trucks and fire rescue squads are called to extinguish fires and at the same time can be of assistance in the extrication of trapped accident victims from their cars and in the removal of vehicles and debris.

Ambulances are used basically for the transportation of the injured, but their staff also provides first aid service and in some cases on-site medical treatment or treatment during transportation [88, 107].

At the same time all components can provide the following services to a certain extent: information, first aid, protection at the site, control of traffic and extrication of trapped victims.

In some cases it might be necessary to activate other service units, e.g., highway maintenance crews and vehicles, and the coroners department for the transportation of fatal accident victims.

#### 1.2.2.2 Detection-Service System Matrix

The interrelation between the described detection methods and service components is used in the reference matrix, Figure 2. The intersection between a row and a column in the matrix represents a unique combination of a detection and service subsystem, implied herein is the communication between the two. Reference to particular emergency systems is only given if direct communication is established between the detection subsystem and the service component. Figure 2 indicates how important and useful a role the passing motorist can play. Direct communication means that he informs the required service components himself.



The numbers in each cell refer to the entries in the reference list. Only references which describe systems in operation or methods proposed to certain locations are included. A bibliography on motorist-aid systems exists in [59, 129] and in detailed annotated bibliography on emergency service systems and related fields was prepared by [104]. The relative few entries of references show two characteristics. First, few systems have been explored or proved successful enough to report about them and second, few agencies operating these schemes considered it worth to write about the experiences and installations.

#### 1.2.2.3 Review of Some Established Detection and Service Systems

Some of the highlights of the review of the literature and the observation of detection and service systems presently in operation [68] are presented in this section. A brief description will be given of three service components as to point out some of their operational characteristics to which will be referred in the later analysis.

Except for a few highways where roadside communication exists such as call boxes or emergency telephones the stranded motorist has to rely on the passing motorist or on the service of the police. In urban areas the police frequently patrols the freeways in linear beats, i.e., a police unit is assigned to a stretch of freeway which it has to patrol. In rural areas the beats are often area beats, i.e., the police officer has to patrol several freeway or highway sections and therefore he responds only after the request for his service. The beats are mostly limited by on and off ramps, but sometimes historically by city or county limits. In urban areas the linear beats have a length from one to three or five miles. An officer in an area beat might have to patrol in excess of 25 miles of roadway. The beat-length is designed so that one police unit can patrol the beat reasonably. The

deployment of police personnel to the beats is accomplished on the basis of accident frequencies and the number of personnel available.

In California police patrols are presently the primary means of detecting a stranded motorist on freeways [52, 73]. Equipped with an excellent two-way communication system a police unit at the scene of an incident is able to request further service for the motorist immediately. The police officer in the field can rely on the police communication center which can relay any request to the appropriate service unit. Since the police is the primary element of detection for vehicle stoppages and because the basic communication equipment is already available, the communication centers have partly developed into dispatch centers for any emergency service. Excellent examples are those of the City of Chicago [14] and Detroit [26] and the California Highway Patrol in Oakland [68]. It is questionable, if the police want to take the major responsibility for service to the motorist, but at present police are taking this responsibility. A point in favor of the police patrol is the high correlation observed between accident occurrence and the patrol frequency.

The Oakland and San Leandro dispatch center of the California Highway Patrol are responsible for the freeways in Alameda County and a portion of Contra Costa County, as well as for highways outside of incorporated cities. Figure 3 shows the beat structure for the County of Alameda. The county was subdivided into tow and ambulance zones in accordance with the cities concerned and the location of tow vehicles and ambulance owners. If the stranded motorist requests a particular service, but does not specify an organization, the central dispatch requests tow and ambulance units on a rotating basis. The Oakland central dispatch, for example, has up to four officers on duty to dispatch and direct appropriate services to the scene of an incident for approximately 60 miles of roadway.

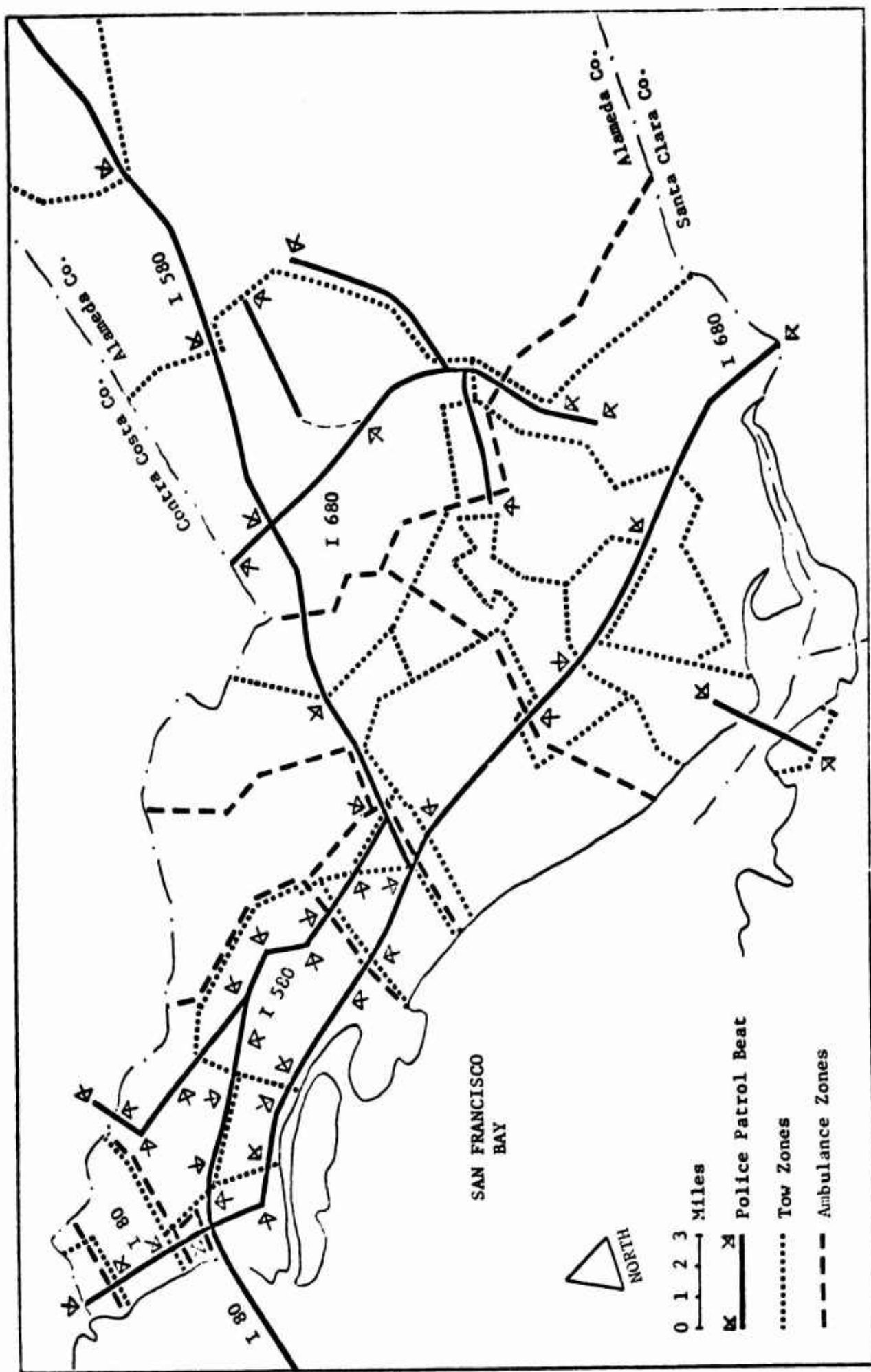


FIGURE 3: PATROL BEATS OF THE CALIFORNIA HIGHWAY PATROL, TOW AND AMBULANCE ZONES IN ALAMEDA COUNTY

This type of operation is not typical, for example across the bay in San Francisco, the dispatch center of the California Highway Patrol relays requests of their patrolling officers to the city police and central ambulance dispatch center. The city police then requests tow and wrecker services from individual tow companies located closest to the incident. The ambulance center dispatches the closest ambulance to the scene of injury. The different types of operation are largely due to the different size and degree of urbanization of the City.

Except for some toll facilities and some critical links of the highway network little coordinate effort is made to provide service and tow vehicles which patrol the freeways or are on stand by at critical locations.

One exception is in the City of Chicago, where along the Metropolitan Expressway System "Emergency Patrol Vehicles" are assigned to certain stretches of the network [87]. The length of these sections, 3 to 12 miles, is dependent on operational factors as well as on the accident frequency along these expressway sections. The service vehicles used can cope with nearly any situation except with very heavy vehicles, very large fires or the transportation of the injured. If one recalls Figure 1, this means more than 90% of all services requested can be handled by these vehicles. The operation of this system is very successful and in addition to the incident detection and servicing, provides freeway maintenance. As an average seventeen vehicles are in operation per eight hour day shift. Figure 4 shows an example of a typical deployment of the vehicles for a day shift on a weekday, while Figure 5 gives the distribution of accidents along the expressway system [13].

A unique patrol system is operated by the New York Port Authority in the Lincoln Tunnel. The tunnel is a toll facility under the Hudson River connecting New York City with New Jersey. During the night shift (only two

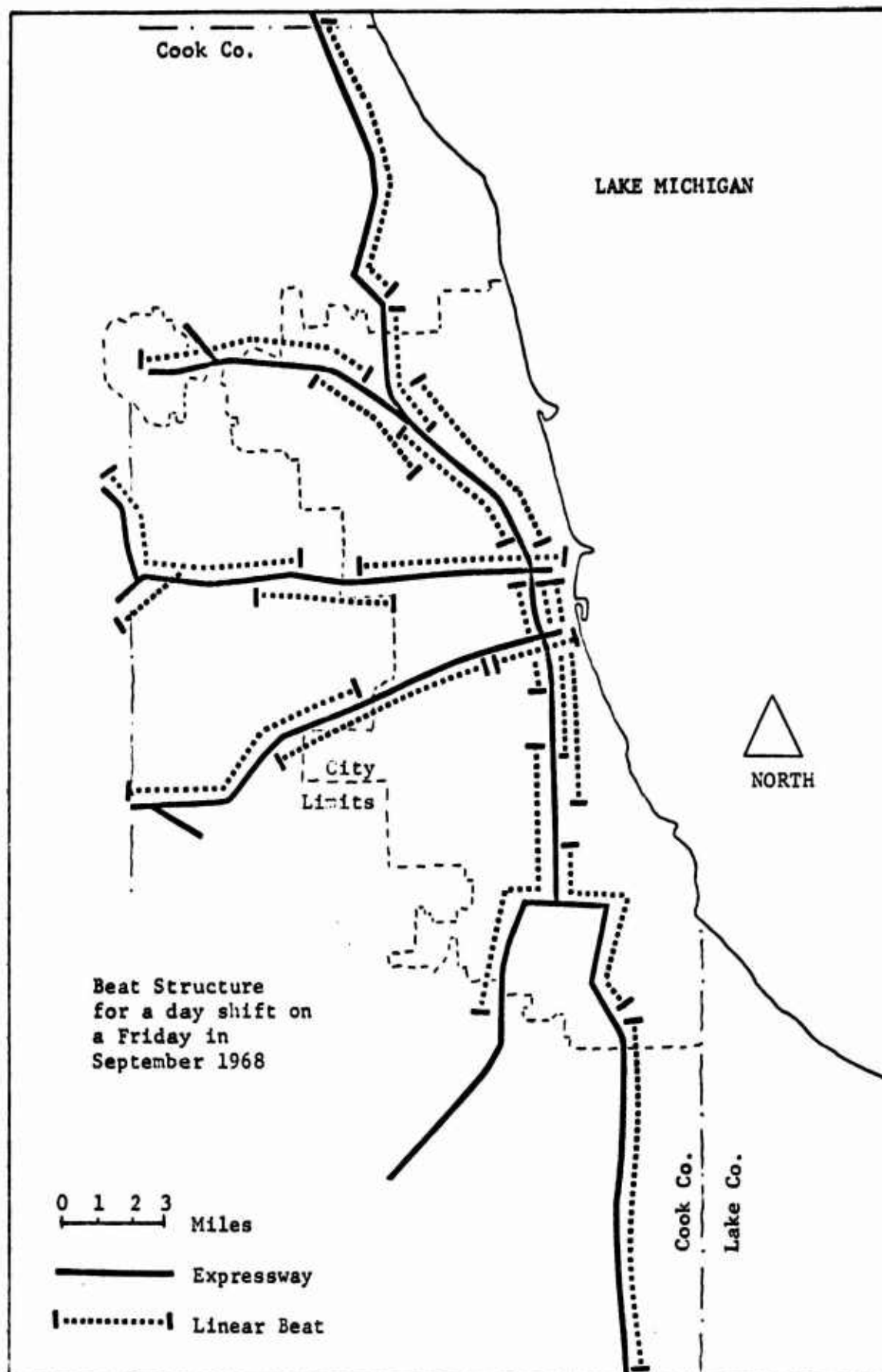


FIGURE 4: LINEAR BEAT STRUCTURE FOR EMERGENCY PATROL VEHICLES ON THE CHICAGO METROPOLITAN EXPRESSWAY SYSTEM

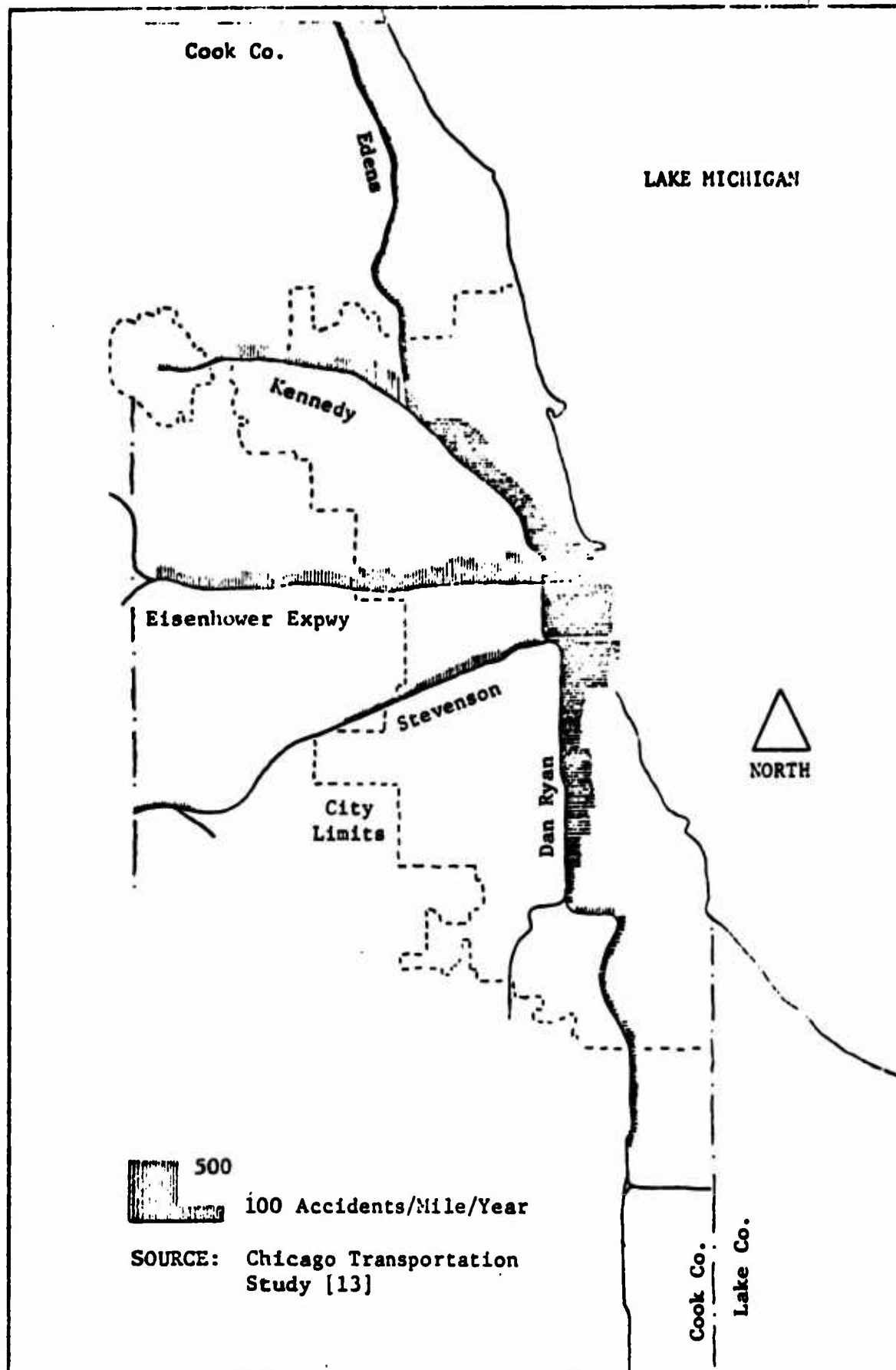


FIGURE 5: DISTRIBUTION OF ACCIDENTS ON THE CHICAGO METROPOLITAN EXPRESSWAY SYSTEM FOR THE YEAR 1967

tubes are in operation, one per direction) three cars are assigned to patrol the two tunnel tubes with a strictly observed two minute headway. To each car two men are assigned. At three control points police officers are stationed who serve as a replacement, if the rider of a police car has to be dropped at the scene of an incident. This operation with standby crews at the control points allows a very efficient surveillance, control and emergency service in the tunnel [68]. It is also interesting to observe that the personnel of the New York Port Authority concerned with the emergency service for the tunnel are police officers [42].

The transportation of the injured in traffic accidents was, until recently, not seen as a specific task, but was handled in the framework of normal medical emergencies. The ambulances are operated by a variety of agencies such as funeral homes, volunteer groups, hospitals and fire departments [17, 101, 115]. An efficient service is given by the city of San Francisco. The city is divided into five hospital zones, each of which contains an emergency hospital. Assigned to each hospital is at least one ambulance, staffed with a driver and medical steward. All ambulances have two-way communication systems and are dispatched centrally on the city police frequency. The service is maintained 24 hours a day, all year long and is free of charge. All points of the city can be reached in less than 20 minutes. The location of the hospitals and the ambulances in relation to the freeway system is shown in Figure 6. The San Francisco Emergency Medical System is successful, because of the joint operation of ambulance and emergency hospitals. One of the large deficiencies in this field, in urban areas as well as in rural environments is that only few hospitals are equipped with emergency wards and have on-duty physicians able to cope with the injuries resulting from traffic accidents [1, 49, 54, 132].

The use of helicopters for the transportation of the injured proves to be successful and fast [16]. An efficient example is given by a private

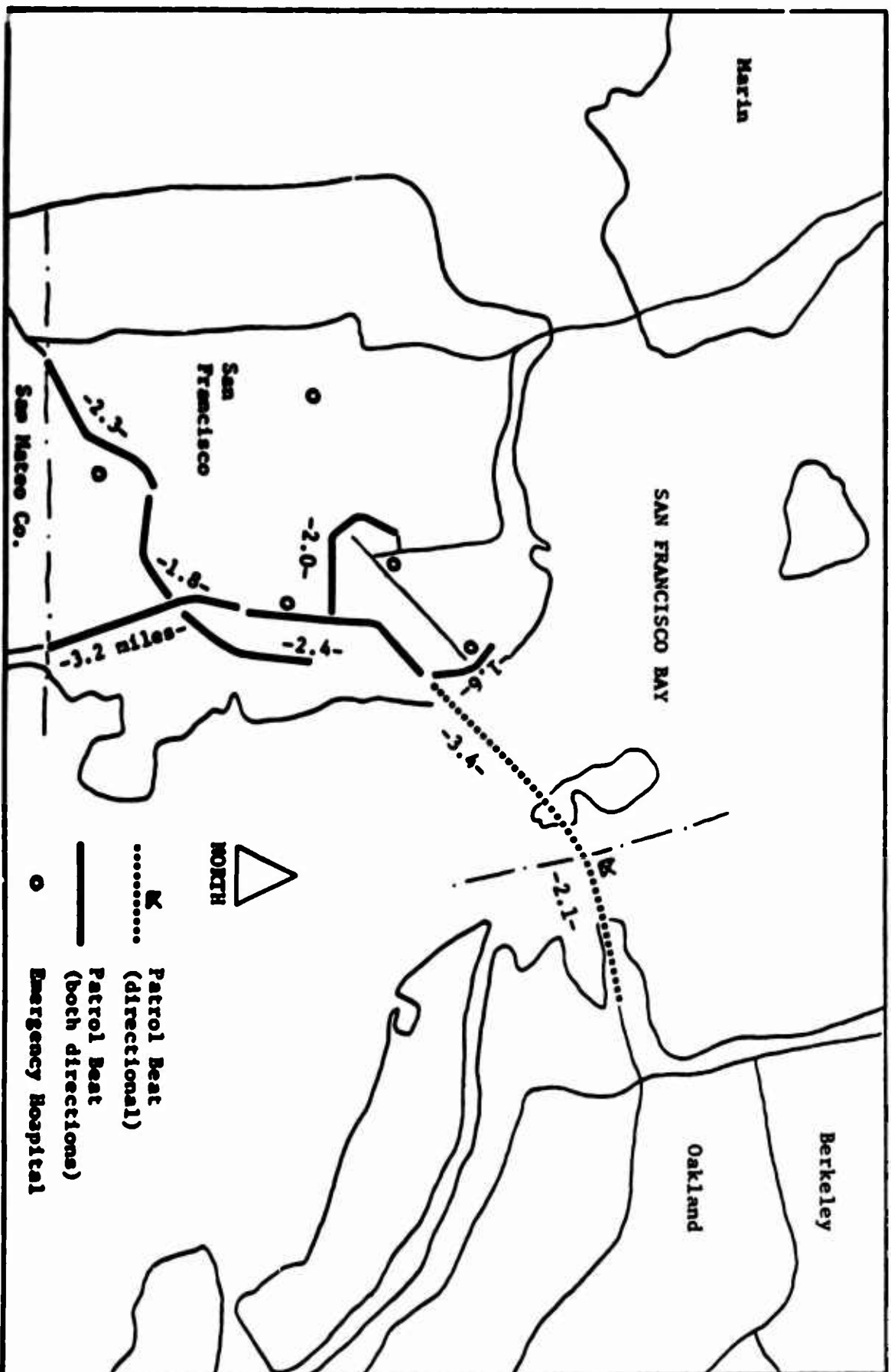


FIGURE 6: LOCATION OF EMERGENCY HOSPITALS AND STRUCTURE OF LINEAR BEATS OF THE CALIFORNIA HIGHWAY PATROL ON FREEWAYS IN SAN FRANCISCO

physician who flies a helicopter over congested areas of the German Autobahn network, waiting for the request of his services [38]. He can give first aid and actual medical treatment and provides fast transportation of the injured to the emergency hospitals. Experimental studies using the combat experience of helicopter evacuation are underway [16, 45, 61, 110].

The described methods of operation of some service components on freeways and in some communities are unique and outstanding when compared with the standard for the majority of the highway network. Even in the given examples one realizes that these systems developed historically and that only in few cases a systems analysis was undertaken for detecting and servicing stoppages and accidents on highways. Yet the complexity of the problem requires a joint effort of all interest groups, which are concerned with achieving an efficient system for responding to freeway incidents. This effort has to be based on a systematic analysis of all factors and elements influencing the system, so that alternative solutions to the problem can be evaluated with respect to their cost and benefit.

## CHAPTER 2

### SYSTEMS APPROACH

The review of the literature indicates that little research has been done considering the detection and service system for freeway incidents as a whole. Research sponsored by the Department of Transportation led recently to comprehensive studies of the traffic safety system [50, 143, 144], and in particular to the study of the emergency medical systems for traffic accidents [17, 30, 45, 90, 115, 116].

This study is concerned with response systems to traffic incidents and in particular with the post incident stage; i.e., the chronological sequence of events and activities after the occurrence of an incident. A systematic analytic method is developed based on the study of existing emergency service systems. The response system is described in relation to its objectives and the costs and benefits implied by alternative solutions. After the formulation of this approach different detection and servicing subsystems will be analyzed and evaluated.

#### 2.1 SCHEMATIC MODEL OF THE FREEWAY EMERGENCY SERVICE SYSTEM

A schematic model of a systems analysis structure for responding to freeway incidents is presented. A description of the model is given in Figure 7, which gives an impression of the overall structure of the problem [119]. The model considers four parts:

The input of the system corresponds to the situation immediately after the intra-incident stage and is a description of the incident; i.e., the time and location of the incident, type of incident, i.e., stoppage, accident, injury, property damage, traffic flow conditions and environment.

The activity model consists of the main phases (1) detection, (2) evaluation, (3) on-site actions, and (4) evacuation of victims and debris from the

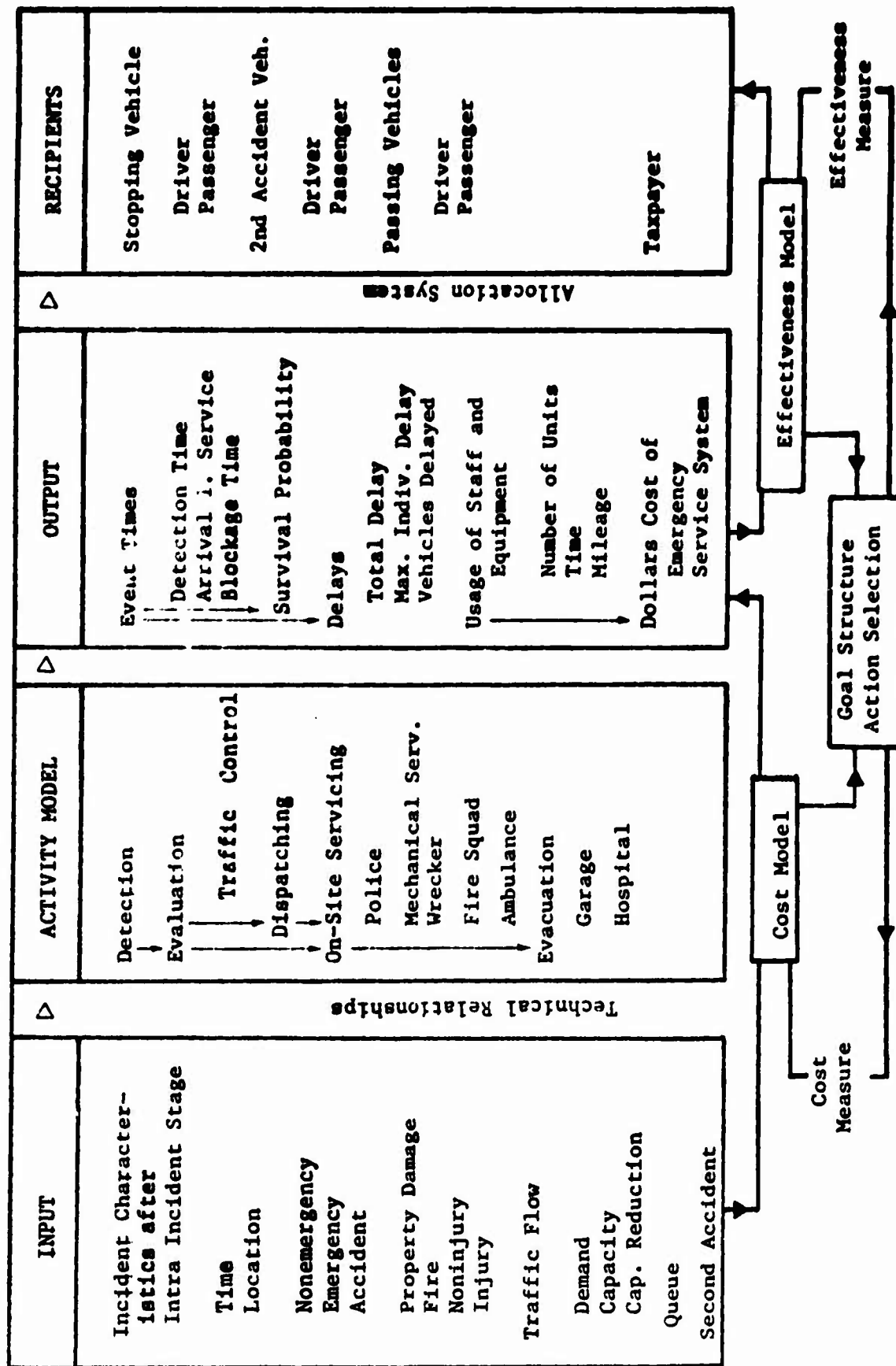


FIGURE 7: SCHEMATIC MODEL OF A SYSTEMS ANALYSIS STRUCTURE FOR FREEWAY EMERGENCY SERVICE SYSTEMS

roadway. A detailed description of these activities will be given in Section 2.4. The model considers all activities to be performed by alternate detection and service systems.

The output of the activity model reflects the performance of the system with respect to the evaluation criteria selected.

The fourth part called recipients, contains those persons who benefit or suffer from the output.

These four parts of the model are connected to each other through technical relationships and an allocation system.

The lower part of the diagram, Figure 7, describes the means to evaluate different detection and service methods, with respect to cost and effectiveness on the basis of selected objectives. Several measures can be anticipated, which describe the performance and cost of the system. Here only two measures of the output from the activity model are listed. One is the completion time of certain activities which is a measure of effectiveness. The other measure is the number and usage of detection and service units, needed to perform the activities which reflect the cost.

After the definition of cost and effectiveness models, the total system can be analyzed for a given set of goals and selected actions.

## 2.2 OBJECTIVES

The evaluation of alternate detection and service methods is based on the achievement of certain objectives. These objectives have to be specified operationally as to be able to relate the output of alternate systems to the achievement of objectives. The specification of objectives is rather difficult and in general it is not easy to obtain satisfactory definitions [119].

The range of objectives in a traffic safety system is wide. Considering the system for responding to traffic incidents, in particular the post-incident

stage, the objectives of the systems analysis are limited to the reduction of the incident severity; i.e., the seriousness of the ultimate consequence of an incident or accident [50].

A hierarchy of three principal objectives was established in [102]:

1. Maintain capacity
2. Increase safety to the
  - (a) vehicle stopped in the lane
  - (b) remainder of vehicles on the facility
  - (c) vehicle off the traveled lanes

Increase the probability of survival in an accident

3. Provide motorist service.

In this study the systems objectives are limited to the following:

1. Reduce the mortality rate of the victims of accidents
2. Reduce the delay experienced by vehicles passing the incident
3. Reduce the number of secondary accidents caused by an incident.

### 2.3 COST AND EFFECTIVENESS

In the schematic model, presented in Figure 7, the cost and effectiveness approach is suggested for the evaluation of alternate detection and service systems [56, 109, 135]. This technique has the relative advantage that a monetary formulation of benefits is replaced by a measure of effectiveness. A disadvantage of this method is that only one measure of effectiveness can be considered at a time.

The compilation of costs can be carried out under a single system of measurements, namely Dollars. The estimation of costs is a difficult problem, even if many of the indirect costs are ignored. The availability of data is

complicated through the fact that they are seldom stratified to the desired detail of the activities and output considered.

The effectiveness establishes the link between the output characteristics of the activity system and the selected objectives. The measure of effectiveness should reflect the achievement of the objectives. Basically two groups of effectivenesses are significant in achieving selected goals for the detection and service system.

The first group, here called *individual* effectiveness, encompasses those effects which are allocated to the individual stranded motorist.

They are:

- (a) Probability of detection
- (b) Detection time
- (c) Time, when victim knows it is detected
- (d) Arrival time of first service
- (e) On-site service time
- (f) Stop duration
- (g) Appropriate medical treatment of the injured: first aid;  
treatment on-site, during transportation and at hospital;  
probability of survival
- (h) Appropriate service for the disabled vehicle: on-site, tow,  
in garage.

The second group, here called *collective* effectiveness, contains outputs which are allocated to the passing motorist or those who are affected through the incident.

- (a) Increased travel time, due to roadway blockage, expressed as
  - 1. total delay in vehicle hours
  - 2. maximum individual delay

3. percent or number of people delayed for longer than  $x$  min.

(b) Hazard of second accident, reflected through the number of vehicles affected through the blockage [24] and the upstream shockwave velocity.

After comparing the list of objectives and the actual outputs of the activity model, the consideration has been limited to the following measures of effectiveness:

|                      |                                             |
|----------------------|---------------------------------------------|
| individual measures: | detection time                              |
|                      | arrival time of first service               |
|                      | probability of survival                     |
| collective measures: | blockage time                               |
|                      | total delay                                 |
|                      | number of vehicles affected (2nd accident). |

#### 2.4 THE ACTIVITY MODEL

The schematic model described in Section 2.1 gives the framework for the analysis of detection and service systems. It consists of the four parts; input, output, activity model and recipients. In this section the third part, the activity model, is described in greater detail.

The emergency service system for freeway incidents consists of proper men and equipment assigned to this task. The mission of this system is to detect incidents and to dispatch appropriate service units to the scene of the incident, which can treat and evacuate possible victims and remove disabled vehicles from the site. In performing this task, the objective is to reduce the time required for the mission to be accomplished.

To study the functioning of the response system under different incident situations a model must be designed, which represents a realistic interpretation of the real world. This model then can be used to design a

simulation routine, which allows the study of the performance of the system under varied input parameters. A similar approach was used for a simulation study of medical evacuation of war casualties [34].

The purpose of the study is to determine to what extent the response systems objectives are attainable and mutually compatible and at the same time to discover possible changes that might be made in the system to improve its functioning.

#### 2.4.1 Chronological Sequence of Events and Activities

The following phases of the system are considered in this model. Their description will indicate what information is necessary in order to evaluate the detection and service system.

##### Detection

This phase starts after the intra-incident stage and encompasses all activities, which lead to the detection of the incident and the request for service. Means for detection of vehicle stoppages presently in operation are given in the reference matrix, Figure 2 and some are described in Section 1.2.2.1. The communication center of the detection subsystem obtains information of an incident either from the motorist via a in-vehicle communication device, from a fixed communication terminal along the roadway, or from people observing the roadway.

##### Evaluation and Dispatch

The type of necessary service is determined during the evaluation phase. The dispatching of service units to the scene of the incident follows the evaluation. The evaluation of the situation of an incident relies largely on the detection system. Either the information received through the detection subsystem is sufficient, or additional information is obtained through the dispatching of men to the scene. A dispatch center gets its

requests either through the detection subsystem directly or from the communication center which maintains the detection subsystem.

#### On-Site Action

The on-site action includes all activities which have to be performed on the traffic lanes and on the shoulder of the highway. The on-site action depends on the type of incident and its environment. The men and equipment which are dispatched to the scene are limited to four components; (1) accident investigation and law enforcement (police), (2) mechanical aid and clearing wreckage from the roadway (service vehicle, wrecker), (3) extrication of victim and first aid medical treatment (ambulance), and (4) fire extinguishing (fire rescue squad).

#### Evacuation

This phase includes the evacuation of the victims and the removal of disabled vehicles from the site. Equipment for these activities is needed which is suitable, (1) for the transportation of the injured, and (2) for the removal of the disabled vehicles and debris.

#### Reavailability

The last phase considers the reavailability of the men and equipment after the fulfilling of an assigned task. This includes:

- (1) availability of an ambulance after unloading of the injured at an emergency hospital,
- (2) the availability of service vehicles, wreckers and fire extinguisher equipment after the completion of the work and unloading of possible wrecks at a garage or service station,
- (3) availability of police personnel after the investigation of the incident which might include a trip to the hospital or accompanying

of the victims to collect further information.

The model might be simplified by requiring that a service vehicle is only reavailable if it has returned to its normal position.

A summary of the chronological sequence of the events after the occurrence of an incident is shown schematically in Figure 8. The horizontal scale is an indicator of the time passed after the occurrence of an incident. In the vertical direction the different components of necessary services are represented, each as a coordinate system, where the abscissa is the time after the occurrence of an incident and the ordinate the distance away from the scene of the incident. Each square dot represents an event and the links connecting the events are the activities which the events engender. The upper portion of the diagram shows for a given demand and capacity configuration qualitatively the possible delays to the motorists, due to blockage of the roadway after an incident. There is no scale to the coordinate system, but the events are so arranged that the relation between the events and their effects on the queueing characteristics become visible. For example, the event "end of roadway blockage" which corresponds to the end of the activity "second service," is assumed to occur at the same time for all service components; i.e., they are all on the vertical line which indicates the capacity increase to its original level.

#### 2.4.2 Main Features of the Activity Model

The previous subsection provided a description of the events and activities which make up the activity model for detecting and servicing of incidents. The purpose of the study establishes the degree of detail required and the specific components of the real system which must be considered. The real world is, therefore, abstracted to a series of events and activities which represent the real system sufficiently. This simplifies

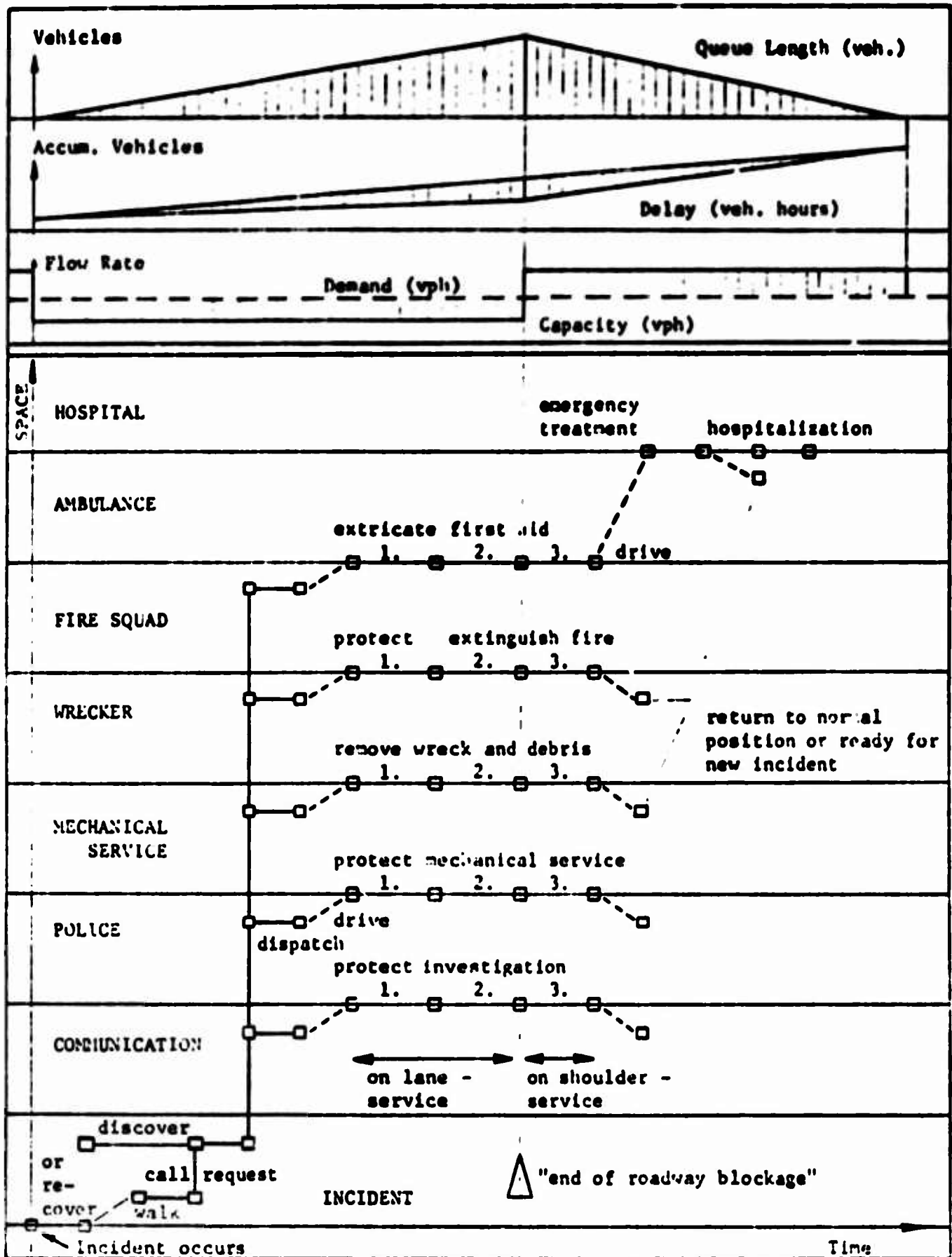


FIGURE 8: CHRONOLOGICAL SEQUENCE OF EVENTS OF INCIDENT RESPONSE SYSTEM

the model and is permissible as long as it is compatible with the purpose of the study.

The following components are represented in the activity model:

- I , incident vehicle
- P , police units
- S , mechanical service vehicles
- W , wreckers
- A , ambulances
- F , fire rescue squad
- C , communication center
- H , emergency hospital .

For each service component it is assumed that it is sufficiently staffed and equipped to fulfill its assigned task.

After having limited the representation of the model to the above components, one has to consider only those operating rules and those activities which concern these eight components. The activities and operating rules are defined in terms of 65 allowable events for all components. The occurrence of an event may change the state of any component of the model. A simulation routine can be designed to represent and process the events at any stage of the model. The events that define the activities of the components (e.g., police units, ambulance) are presented in the event matrix of Figure 9.

The events occur at three geographic locations for each component:

- C , Communication or dispatch center of each entity
- M , Position between incident and center
- L , Scene of the incident.

| Event<br>Com-<br>ponent    | OCCUR-<br>ENCE | RE/DIS<br>COVERY | RE-<br>PORT | RE-<br>QUEST | DIS-<br>PATCH | AR-<br>RIVE | END OF<br>1.<br>TREAT-<br>MENT | END OF<br>2.<br>TREAT-<br>MENT | END OF<br>3.<br>TREAT-<br>MENT | DIS-<br>CHARGE |
|----------------------------|----------------|------------------|-------------|--------------|---------------|-------------|--------------------------------|--------------------------------|--------------------------------|----------------|
| HOSPITAL                   |                |                  |             | REQHC        | DISHC         | ARRHC       | FIRHC                          | FINHC                          | ENDHC                          | RELHC          |
| AM-<br>BULANCE             |                |                  |             | REQAC        | DISAC         | ARRAC       |                                |                                |                                |                |
|                            |                |                  |             |              | DISAM         | ARRAM       |                                |                                |                                | RELAM          |
|                            |                |                  |             |              |               | ARRAL       | FIRAL                          | FINAL                          | ENDAL                          |                |
| FIRE<br>SQUAD              |                |                  |             | REQFC        | DISFC         | ARRFC       |                                |                                |                                | RELFC          |
|                            |                |                  |             |              |               | ARRFL       | FIRFL                          | FINFL                          | ENDFL                          |                |
| WRECKER                    |                |                  |             | REQWC        | DISWC         | ARRWC       |                                |                                |                                | RELWC          |
|                            |                |                  |             |              |               | ARRWL       | FIRWL                          | FINWL                          | ENDWL                          |                |
| SERVICE/<br>TOW<br>VEHICLE |                |                  |             | REQSC        | DISSC         | ARRSC       |                                |                                |                                | RELSC          |
|                            |                |                  |             |              | DISSM         | ARRSM       |                                |                                |                                | RELSCM         |
|                            |                | RECCL            |             |              |               | ARRSL       | FIRSL                          | FINSL                          | ENDSL                          |                |
| POLICE                     |                |                  |             | REQPC        | DISPC         | ARRPC       |                                |                                |                                |                |
|                            |                |                  |             | REQPM        | DISPM         | ARRPM       |                                |                                |                                | RELPM          |
|                            |                | RECPL            |             |              |               | ARRPL       | FIRPL                          | FINPL                          | ENDPL                          |                |
| COMMUNI-<br>CATION         |                |                  |             | REQCC        |               |             |                                |                                |                                |                |
|                            |                |                  | REPCM       |              |               |             |                                |                                |                                |                |
|                            |                | RECCL            |             |              |               |             |                                |                                |                                |                |
| INCIDENT                   | OCCIL          | RECIL            |             |              |               |             | FIRIL                          | FINIL                          | ENDIL                          |                |

FIGURE 9: MATRIX OF EVENTS OF THE ACTIVITY MODEL

Ten categories of events are considered:

- OCC , Occurance of the incident
- REC , Recovery of the stranded motorist or discovery of the incident  
by a patrol or motorist
- REP , Report of incident at a communication terminal
- REQ , Request for assistance
- DIS , Dispatching of service
- ARR , Arrival at a location
- FIR , End of first service or treatment
- FIN , End of second service or treatment
- END , End of third service or treatment
- REL , Discharge patient or vehicle.

Some of these events explicitly involve only the stranded motorist, some explicitly involve the vehicle and some involve the components and others involve all or a mix of the three. Additional events could possibly occur, but including more detail adds complexity to the model without adding significant reality.

The events are represented by five digit symbols, where the first three digits indicate the type of the event, the fourth digit indicates the component, while the fifth digit gives the location of the event. For example, ARRAL stands for the event arrival (ARR) of an ambulance (A) at the incident location (L). The symbols describe therefore quite sufficiently the type, the component and the location of the event considered.

In Figure 10 the event matrix of Figure 9 is transformed into a network where the nodes represent the events and the links the activities. The links also indicate the decisions to be made after the occurrence of each event. The decision procedure which determines the consequences of a

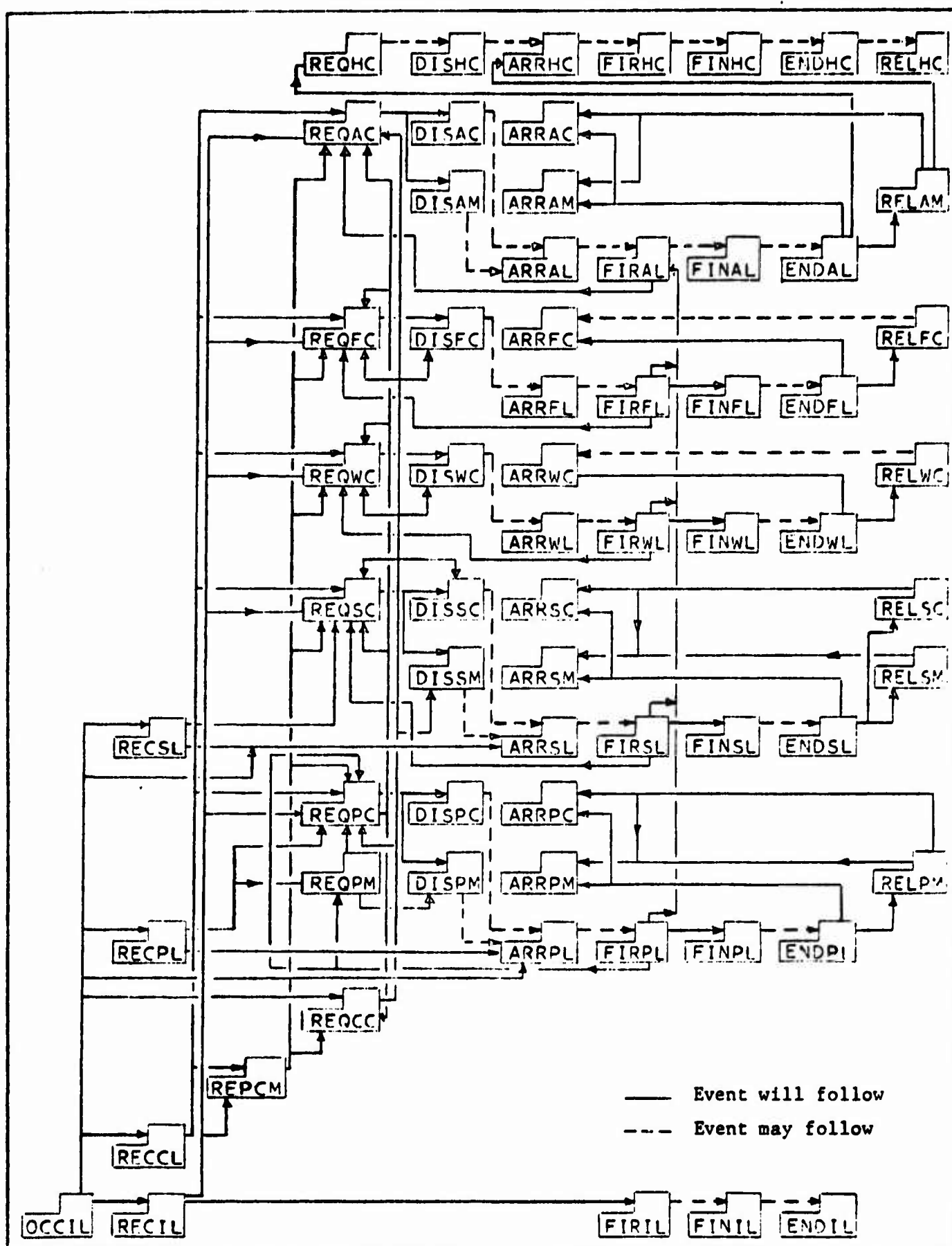


Figure 10 NETWORK OF EVENTS AND ACTIVITIES FOR ACTIVITY MODEL

decision event would be stated in a subroutine of a simulation program. It is important that these procedures can be varied during a simulation study to be able to test the sensitivity of the response system to changes in the operating rules. In Figure 10 it is also differentiated between decision and nondecision events. These events separate the links into activities which may follow and which will follow an event.

There are also some events which are conditioned by the availability of the appropriate service. This is represented by two types of queues. One type is the service-available queue for each component. If, for example, one wrecker is waiting to be dispatched, then there is an entry of one in the wrecker-available queue, if two are available, the entry is two. The other type of queue would, e.g., be the request-for-wrecker queue. As soon as a request for a wrecker is reported, it is entered in this queue and if in the wrecker-available queue is an entry, this wrecker would be dispatched. As soon as the wrecker arrives again at the dispatch center, back from duty, it would reenter the wrecker-available queue.

The Figure 9 gives a simple representation of the multiple events possible after the occurrence of an incident. The chronological sequence of these events is indicated in Figure 10 by the links connecting the events. The table of events shown in Figure 9 is in this way changed into a network of activities and events. There are 65 events and 121 activities presented in the model. These relative large numbers can be subdivided into the different groups of components to simplify the interpretation. The 121 activities can also be differentiated into the activities which are only communications (33%), those which are dependent on location or involve walking or driving (50%) and those which involve actual treatment (17%), Figure 11. 80% of the activities are the consequence of decision events.

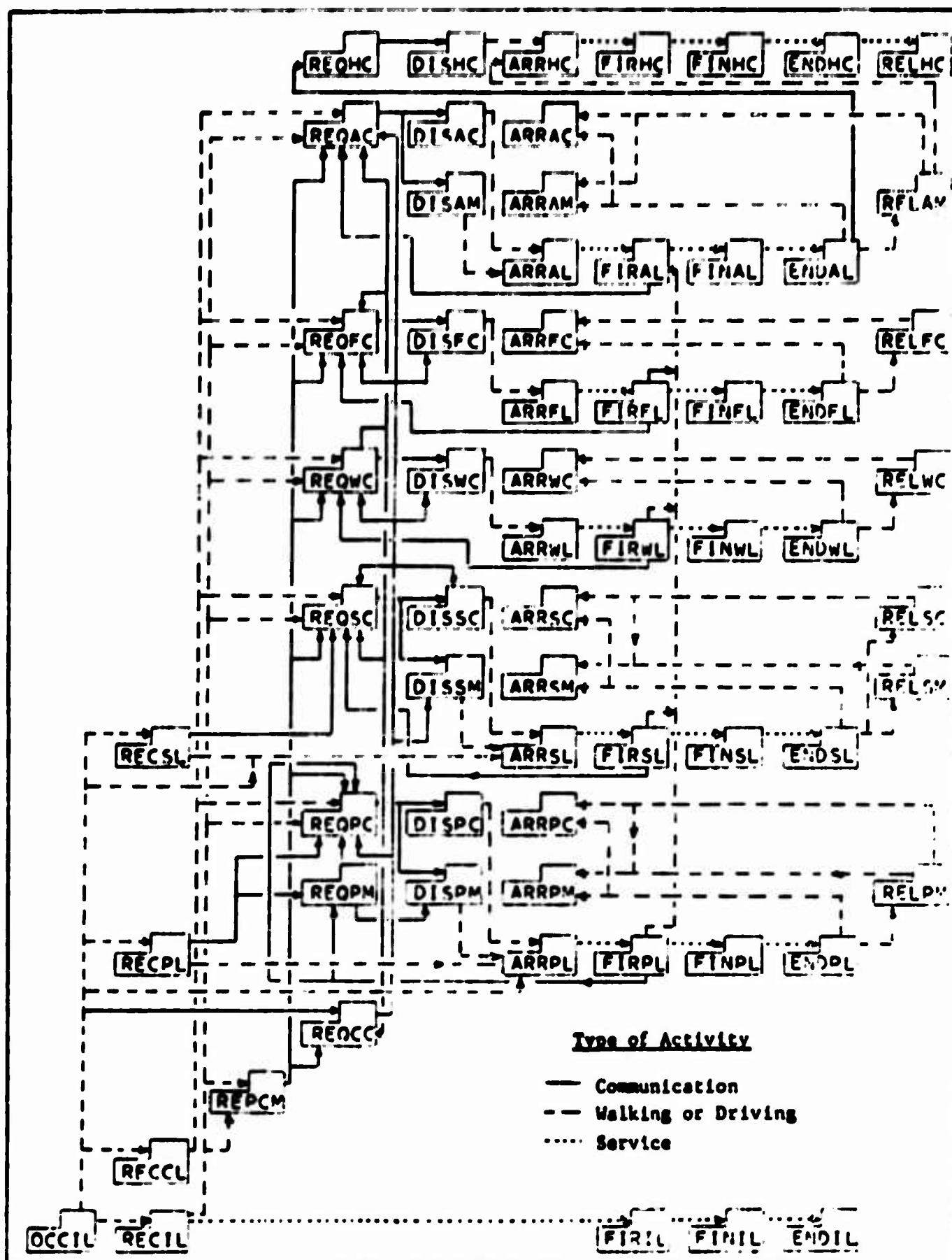


Figure 11 ACTIVITY MODEL - TYPE OF ACTIVITIES

### 2.4.3 Application of the Activity Model

An example will now be given as to how the model functions. Assume an incident has occurred which results in an injured driver and a disabled vehicle which blocks the roadway. The following events would describe the response of the emergency service system in the activity model:

The accident occurs (OCCIL) and after period of time a passing motorist detects the incident (RECCL). The passing motorist drives to the next roadside communication terminal to report the accident (REPCM). There he requests appropriate service for the incident (REQCC). Then the communication center requests an ambulance (REQAC), a service vehicle (REQSC) and a police unit (REQPC).

The centers of the three components involved [ambulance (A), service vehicle (S) and police vehicle (P)] dispatch units to the scene of the accident [(DISAM), (DISM), (DISPM)]. The dispatched vehicles travel from their current location and arrive at the scene of the accident [(ARRAL), (ARRSL), (ARRPL)].

At the scene of the accident each component performs its assigned activity. In case of the police this might be first the protection of the scene (FIRPL), then the investigation of the accident on the blocked lanes (FIMPL) and then further investigation while the vehicle is on the shoulder of the freeway (ENDPL). In case of the ambulance the sequence of events might be, extricate the injured person from the vehicle (FIRAL), first aid treatment on the traffic lane (FINAL), continued medical treatment on the shoulder and loading of the ambulance (ENDAL). The first activity of the service vehicle might be also to protect the scene (FIRSL), then handling the vehicle in the lane and the removal of the wreck from the lane to the shoulder (FINS'). After the service on the shoulder the vehicle might be hitched by the tow vehicle (ENDSL).

The service vehicle will then tow the car to a garage and unload it there (RELSC) and then arrive again at its patrol beat (ARRSM). The police unit might return direct to its patrol beat and arrive there (ARRPM). The ambulance might drive to a hospital and unload the injured there (RELAM) and then return to its original location (ARRAM).

After the arrival of the injured at the hospital (ARRHC) the patient would be released (RELHC) after a series of medical treatments (FIRHC), (FINHC), (ENDHC).

## 2.5 NETWORK ANALYSIS USING CPM AND PERT

The suggested model is designed for the analysis of alternate solutions to the problem of detecting and servicing of traffic incidents. An optimal solution of the problem could be achieved through the analysis of the measures of cost and effectiveness for a selected set of objectives. It would be desirable to achieve the highest effectiveness at the lowest cost, but the set of given objectives makes it questionable, if this goal can be achieved at the same time. This might be explained by the conflicting interest of the different service components. The blockage of the roadway through an injured accident victim conflicts with the joint consideration of the two objectives (1) increase the survival probability of the victim and (2) reduce the delays to the passing motorist. While a lengthy first aid treatment on the traffic lane can be vital for the survival of the traffic accident victim, any additional blockage time means further delays for the passing motorist. At the present time it appears not to be feasible to devise an analytical optimization procedure for the whole detection and service system. It will be necessary to subdivide the system either by reducing the number of components or their degree of representation. To arrive at an optimal solution for the detection and service system, it also would have to be applied at least to a specific highway network and traffic

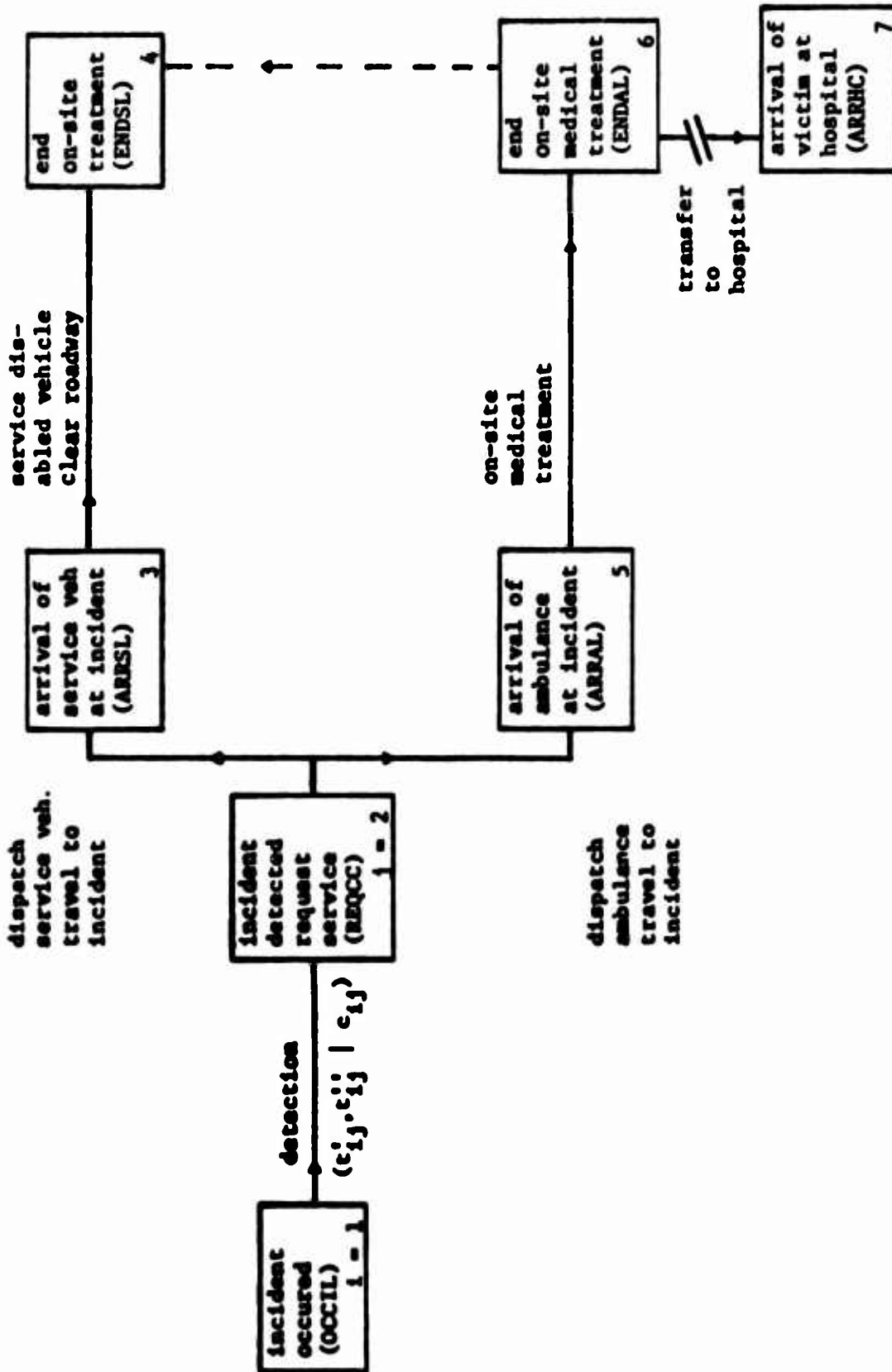
demand configuration, in order to be able to formulate the problem completely.

One available technique of optimization is the Critical Path Method (CPM) [21, 33, 76]. If one wants to apply this approach to the detection and servicing of traffic incidents, the activity model has to be transformed into CPM network and the detail of representation of the real world has to be reduced. The number of events and activities is of little influence to CPM, but the stochastic properties of the incidents and activities cannot be handled by CPM. CPM should therefore only be considered for a preliminary analysis, because the stochastic property is one of the main features of the occurrence and servicing of traffic incidents. The distribution of incidents over time and space would have to be approximated by representative incidents types, using a mean value for the time and location of the incidents on a studied facility. Similarly, the activities would have to be represented by the mean of their completion time distributions and by corresponding costs.

A reduction of the activity model to a CPM network is presented in Figure 12. Each link between the events represents an activity and it is characterized by the average completion time,  $t'_{ij}$ , the crash time,  $t''_{ij}$ , and the cost of shortening the activity duration from  $t'_{ij}$  to  $t''_{ij}$ ,  $c_{ij}$ . Using the time dependent approximate cost functions for each activity, the CPM can be the tool to evaluate different detection and service systems with respect to their total cost and the minimum overall response time,  $T$ . Only major phases of the system are represented, however a more detailed network can be anticipated, if sufficient data are available.

A qualitative time dependent cost function for the activity "detection" is shown in Figure 13. The crash time in this case would correspond to the shortest reasonable patrol headway or emergency telephone spacing. The CPM formulation in Figure 12 considers two goals, which one wants to achieve. Because the CPM allows only one final completion time, the analysis of goal

T<sub>1</sub> - Goal I



T<sub>2</sub> - Goal II

FIGURE 12: CPM FORMULATION OF SYSTEMS FOR RESPONDING TO TRAFFIC INCIDENTS

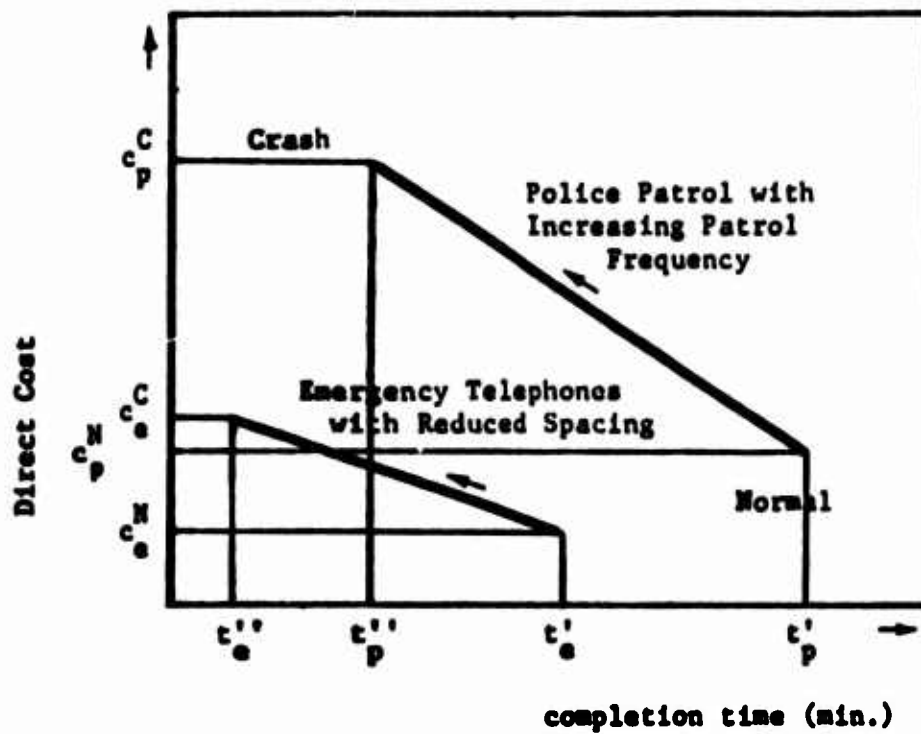


FIGURE 13: LINEAR APPROXIMATION OF THE TIME DEPENDENT COST FUNCTION FOR THE ACTIVITY DETECTION

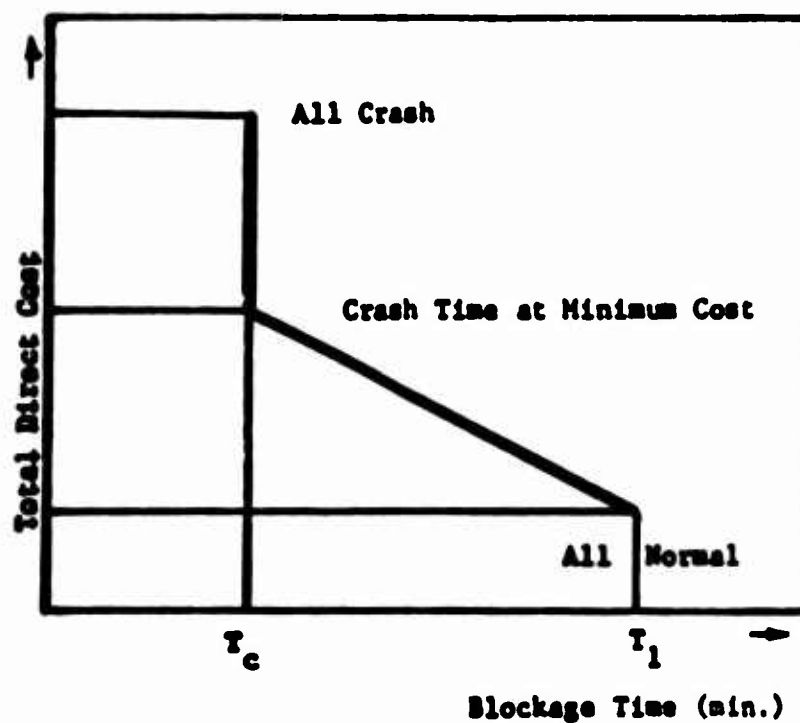


FIGURE 14: TOTAL DIRECT COST PLOTTED AGAINST TOTAL COMPLETION TIME

one, (delay, minimum blockage time,  $T_1$ ) would have to be analyzed separately from goal two (probability of survival, minimum arrival time at the hospital,  $T_2$ ) .

In Figure 14, the total completion time  $T_1$  is plotted against the total cost, required to complete all activities. The curve shows, that for a certain completion time,  $T_c$  , the cost can no more be reduced for a given detection and service system. In this presentation only the direct costs are mentioned, but the indirect and utility costs can also be incorporated into the CPM approach.

The CPM might be useful for a preliminary analysis of this system. For this study the approach is dismissed, because the stochastic properties of the activities would have to be neglected.

Consideration was given to the Project Evaluation and Review Technique (PERT) which is specifically designed to cope with the stochastic properties of the activities to be analyzed [32, 75]. A similar formulation as the one given for CPM would be possible, but in the framework of a cost effectiveness analysis PERT has the disadvantage that no costs are included in the technique.

### CHAPTER 3

#### REDUCTION OF THE ANALYSIS

The example given in Subsection 2.4.3 shows that the activity model is very flexible to various types of consequences of an anticipated incident. It is, therefore, possible to simulate numerous situations as long as sufficient details are specified. One therefore has to decide, what aspects of the emergency service system can be analyzed with the amount of information and data available.

Several measurements can be assigned to the links connecting the events. Since the objectives are related to the reduction of the completion time of the activities, the measurement assigned to the links was also time. Other measurements which could be assigned to the arcs would be costs in Dollars and possibly a weighing factor which would stress the importance of certain more critical services, like the medical treatment over less critical ones, like mechanical services.

The completion time for most activities is a random variable whose distribution has to be known before it can be incorporated into the model. The cost estimates for the activities should then be related to the expectation and variance of these distributions. This means for each of the 121 links, a model would have to be designed which would reasonably represent the real world as measured in cost and completion time. Because this is beyond the scope of this study, the activity model will be reduced to a modified model with less detail of representation. In this chapter some explanation will be given as to how the initial, more comprehensive model was modified.

#### 3.1 INCIDENTS

In the course of the further analysis only incidents will be investigated, which occur on a specific location during a limited period of time, and which

require service and are capacity reducing in their effects. A justification for this simplification will be given in the following subsections.

### 3.1.1 Type of Incident

The initial model can cope with all types of incidents occurring along the highway. However it is questionable, if one wants to analyze or serve all possible incidents. Figure 1 indicates that 40 to 60% of the stoppages of vehicles on the roadway may not require any service. As long as these stoppages occur on the shoulder, not seriously affecting the traffic flow, the incidents are less critical. But it is desirable to detect all stops, because any one could need service. However, to respond to all stops without evaluating the service need would reduce the effectiveness of the service system. The policy to service incidents, maintained by the Emergency Patrol Vehicles on the Chicago Metropolitan Expressway network, reflects this problem. The patrol vehicles pass by a car which has stopped on the shoulder, and only if the motorist asks for help or if the car is still there when they pass for the second time, the vehicles stop to offer service [100].

The stop-duration is an indicator for the need of service and it is suggested to neglect all stops shorter than a certain critical time,  $t_c$  and those incidents where the motorists help themselves. The evaluation of service systems should therefore be limited to the incidents, (1) which have a stop-duration greater than the critical duration,  $t_c$  and (2) those which obstruct the traffic flow, reducing the level of service of the facility.

One type of stop, classified as "need for information," requires special attention. The evaluation of emergency telephone calls show that there is a definite demand for information by the motorist. As a pilot study of a motorist aid phone in Chicago showed up to 62% of the calls were connected with information [40]. For this study, however, the provision of information will have to be considered as additional.

### 3.1.2 Incidents in Time and Space

The evaluation of detection and service systems is highly dependent on the time and location of the occurrence of an incident [24]. The probability of an incident,  $I$ , occurring in the space  $(x,y)$  at time  $(t)$  could be represented through the joint distribution function:

$$(1) \quad F_I(x,y,t) = \int_{-\infty}^x dx' \int_{-\infty}^y dy' \int_{-\infty}^t dt' f_I(x',y',t') .$$

Dependent on this distribution of three random variables, a response system has to be designed and thereafter evaluated. But the function  $F(x,y,t)$  is largely unknown and different for certain demographical and geographical areas and corresponding highway network configurations. To be able to evaluate the different service components, this distribution function has still to be stratified into the different incident types. Even with the knowledge of this function an analysis of the response system is highly affected through the design of the highway in the  $(x,y)$  space and the distribution of the traffic demand over the time of the day  $(t)$ . To provide a general solution to the problem is beyond the scope of this study and it will be necessary to limit the space  $(x,t)$  to a unique area, possibly to a linear space  $(x)$ ; i.e., a stretch of freeway and to consider only a limited period of time, like a day or a week.

### 3.2 REDUCTION OF THE SYSTEM

The matrix of events of the activity model gives an amount of detail, which appears to be desirable, but which is at the present time not feasible because data on cost and duration of the activities are not readily available in this detail. The model is, therefore, modified (1) by reducing its size and (2) by eliminating certain activities due to unavailable data. This

will be achieved by reducing the number of components represented in the model and by combining some sequences of events to fewer events.

The components "ambulance" and "hospital" represent distinct subsystems of the model, because they are only activated if a medical emergency arises. In a similar way, the components "wrecker" and "fire" are unique in their services, because they are only requested respectively for removing very heavy loads and to extinguish fires.

The following sections will give reasons why these four important components were separated from the evaluation process and subsequently will not be considered further.

### 3.2.1 Emergency Medical System

The emergency medical system is represented in the activity model through the entities "ambulance" and "hospital." It was proposed to evaluate the performance of this system on the basis of the survival probability of the injured.

• But until now no appropriate survival probability model has been developed [25, 53, 102]. A qualitative form of a survival probability model is given in [102]. It shows the probability of survival as a function of the delay time before medical treatment. This time includes the detection time and the transit time required to get aid to the injured persons. The model is graphically shown in Figure 15. Recent attempts to build a survival probability model for traffic accidents failed because of insufficient data [25]. In an attempt to extend this work, data from the emergency records of the Highland General Hospital in Oakland [58] were examined and the following conclusions were derived from this analysis.

In constructing such a model one has to realize that for only a portion of the injuries the survival of the victim depends on the time. Also the same type of injury can still have different effects, depending on the

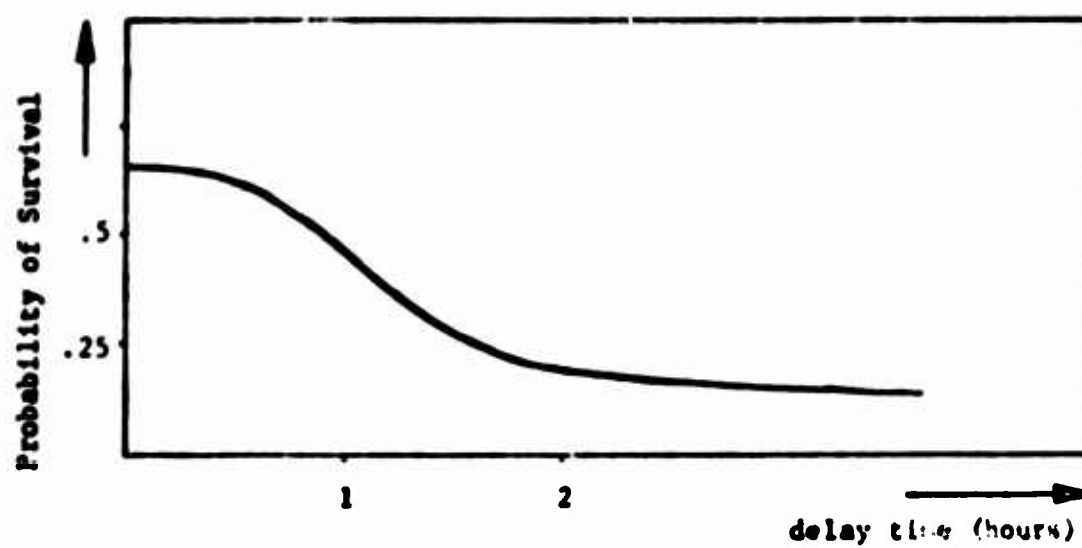


FIGURE 15: SURVIVAL PROBABILITY MODEL (from [102])

victim and his past health record. Another significant factor is the type of treatment which the victim receives. This might be either first aid at the scene of the accident or medical treatment in the emergency department of a hospital [188, 189, 194, 195]. The fact that the more severe the injury is, the faster the service usually arrives also complicates the analysis.

One has to be aware of the above variables, if one studies data of emergency medical systems. It appears therefore to be necessary to trace individual cases from the scene of the accident to the final medical treatment, keeping track of these variables if one wants to draw realistic conclusions from the data.

The first objective of this analysis was to select those cases where the time elapsing between the occurrence of the accident and the arrival of the injured victims at the hospital was of any influence on the recovery of the victims.

238 patients were hospitalized during the year of 1966 under the International Classification of Disease Code E 825 (Road Vehicle Accident) [125]. From the records, which give detailed information on type and time of medical treatment of the patients, the seriously injured nonfatal cases and the noninstantaneous fatal cases were selected. These were presented to a qualified physician, who is in charge of the emergency department, for his final personal appraisal [11]. Hereby the cases were further subdivided by the following characteristics:

For nonfatal victims:

- (1) time was of no influence (within 2 hours),
- (2) the victim would have died, if it was brought to the hospital thirty minutes later.

For fatal victims:

- (1) time was of no influence,
- (2) the life of the victim could have been saved, if he would have been brought to the emergency department thirty minutes earlier.

A breakdown of the results is given in Figure 16.

The table shows, that in about 2% of all hospitalized victims, time was of critical influence to the injured. About 1.5% of the hospitalized nonfatal cases might have been fatal, if they might have arrived up to 30 minutes later. While about 10% of the fatalities could have been saved, if they would have arrived up to 30 minutes earlier than they did. While the sample size is too small to draw any definite conclusions, the results show at least that a very large sample of emergency records has to be analyzed to create a data base for the development of a survival probability model. It has to be considered that the outcome of this kind of analysis is also dependent on the individual judgement of the physician who reviews the emergency records. Another important factor that influences the survival of the victim is the on-site treatment or the treatment during the transportation to the hospital and, unfortunately, the data was not available.

It, therefore, must be concluded that the development of a survival probability model will require more data and analysis than is available in this study. But the results from several current demonstration projects and research contracts sponsored presently by the Department of Transportation, may put some light on these problems [115, 116, 127].

The fact that no relation between the combined detection and service time and the probability of survival has been established, excludes the possibility to evaluate the emergency medical system with the goal of maximizing the probability of survival. While other measures of effectiveness

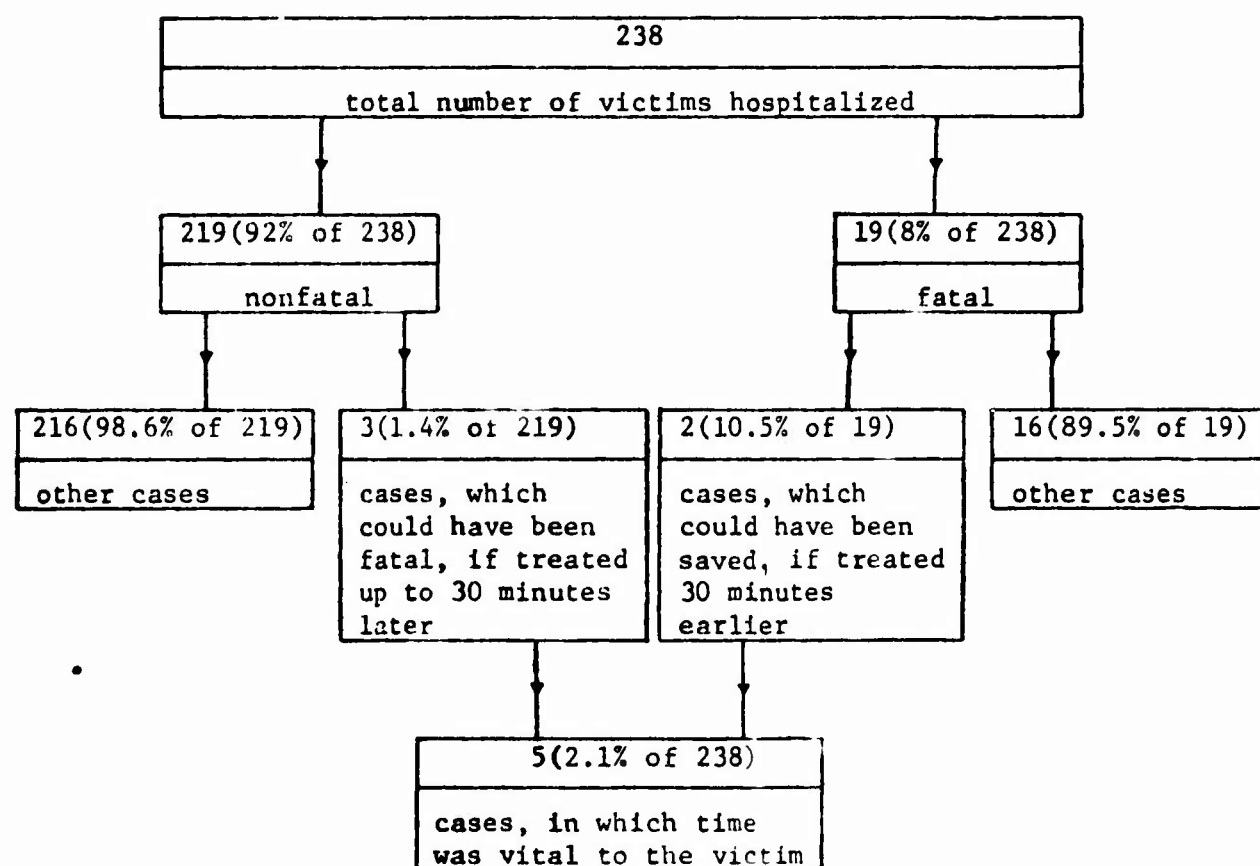


FIGURE 16: INFLUENCE OF TIME ON THE SURVIVAL OF ACCIDENT VICTIMS

could be used, the analysis of the Emergency Medical System, still is too complex to be included in this study. Too little is known about the completion times and corresponding costs of most medical activities.

### 3.2.2 Wrecker and Fire Rescue Squad System

Fire is the cause of about one percent or less of all stoppages on highways as Figure 1 shows. Most service vehicles are equipped with water or fire extinguishing chemicals so that small fires can be fought [87, 96]. The fire rescue squad, therefore, has to be called for large fires only for which the probability is even smaller.

A similar situation arises for the service of the wrecker. In the case that very heavy vehicles or debris are blocking the roadway, only a wrecker can clear the road. But the probability of these types of blockages is relatively small, too. The wrecker service is a very critical component of the system, because only a few wreckers are stationed in most regions. The wrecker arrives, therefore, in most cases very late at the scene of the incident, which is critical to the blockage time and the resulting delays to the motorists.

Both components, "fire" and "wrecker" have the same characteristics, namely, that their service is needed only for very few stoppages; but the relative need for these services is very high, if not equal to one, because once they are needed, stoppages cannot be resolved without their service.

Because of the small number of requests for the components "fire" and "wrecker" their influence on the overall evaluation of the detection and service system would generally be small. This fact and the complexity of the data collection and the subsequent model development are the reasons why both components will not be pursued any further.

By neglecting these two components in the model, only two types of services remain: the service of the police, for law enforcement and

accident investigation, and the assistance of the service and tow vehicles to the stranded motorist.

### 3.2.3 Reduction of Activities and Events

In the framework of this study it is necessary not only to reduce the number of components analyzed, but also the number of activities and events considered. This will reduce the complexity of the analysis and make the analysis possible, because data on the cost and completion times are available in this detail.

The following cycle of activities and events will be considered for each service component responding to an incident:

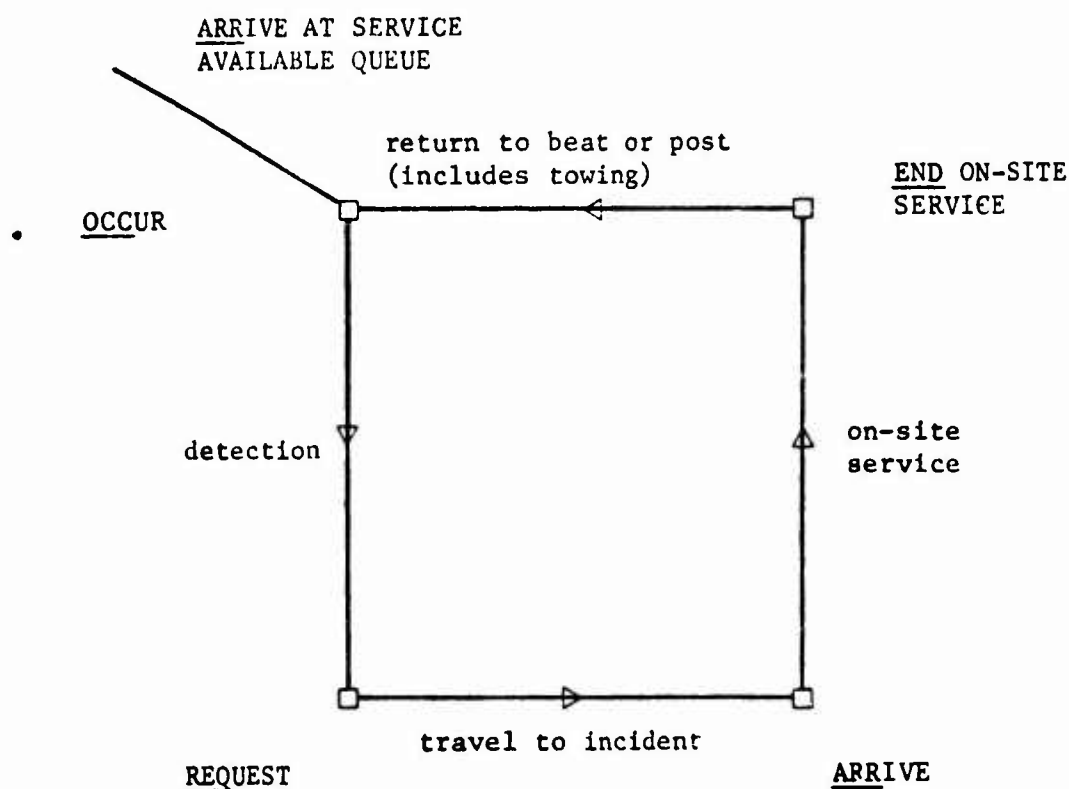


FIGURE 17: CYCLE OF DETECTION AND SERVICE ACTIVITIES

This cycle of events can be short cut, if a detection/service unit passes the incident, so that it arrives at the scene of the incident at the same time it detects the incident. In this case a request for other service might come from the scene of the incident. Similarly, if the service unit arrives at the scene and no service is necessary, the unit returns directly to its post again.

The cycle consists of four activities and five events. One might consider the time interval between the events "re-available" and "occur" as an additional activity as, for example, waiting for assignment. But in this analysis one is only interested in the fact that the unit has returned and is available for reassignment. If it is not available, the waiting for a service unit results in a queueing process, which will be described in detail later in Subsection 5.1.3.2. Other events or activities will not be considered in this analysis.

### 3.3 ACTIVITY SYSTEM FOR DETAILED ANALYSIS

• Having reduced the number of service components as well as the events and activities as described in the previous subsection, the *modified* activity model, given in Figure 18, remains from the original activity model shown in Figure 9 and 10. There are two components, the police and the mechanical service. Their tasks are represented by 17 activities and 12 events.

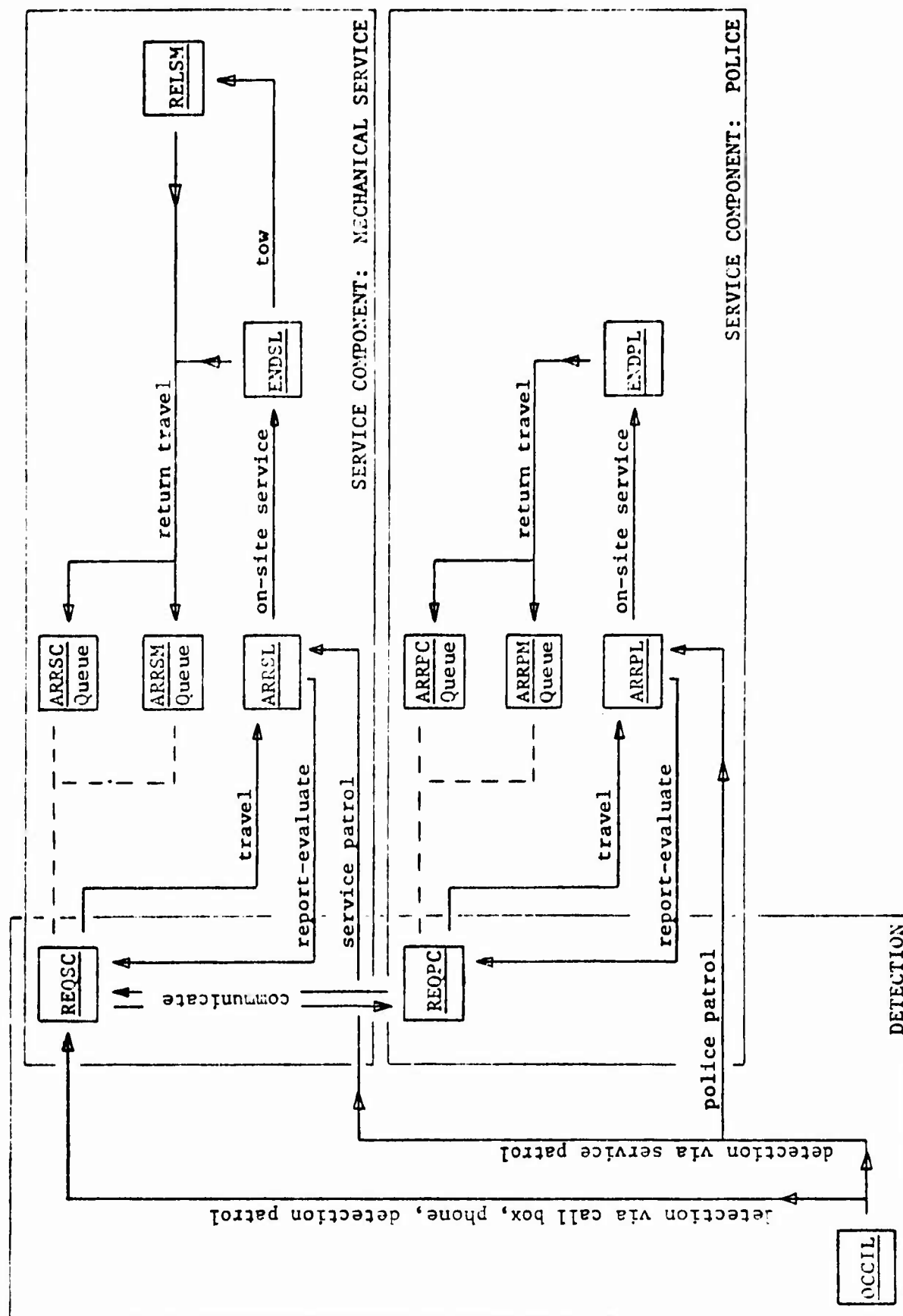


FIGURE 18: EVENTS AND ACTIVITIES OF THE MODIFIED ACTIVITY MODEL FOR DETECTING AND SERVICING FREEWAY INCIDENTS

## CHAPTER 4

### MODEL ADJUSTMENT DUE TO APPLICATION

The model for analyzing alternative emergency service systems can be applied to various types of highway facilities and various traffic flow patterns on it. But to limit the analysis, the model will be applied to a linear freeway with basically uniform flow along its length. As a basis of data collection and for a later application of the model, the San Francisco-Oakland Bay Bridge (SFOBB) was selected. A description of the operation of the emergency service system along that bridge is given in the following section.

The second and third section of the chapter are devoted to the location and the emergency service systems, which were selected for the detailed analysis.

#### 4.1 EMERGENCY SERVICE SYSTEM ON THE SAN FRANCISCO-OAKLAND BAY BRIDGE

##### 4.1.1 The San Francisco-Oakland Bay Bridge

The SFOBB connects the San Francisco Peninsula with the East Bay area via the Yerba Buena Island (see Figure 19). The bridge is a toll facility and is owned by San Francisco Bay Toll Division. The toll is collected at the East end of the bridge at the Toll Plaza, where the 10 lanes of the bridge expand to 34 toll gates. It is a double deck structure with 5 lanes per deck in each direction. The Bridge and its approaches are about 8.5 miles long, while the actual bridge (from now on just called the Bridge) with 5 lanes per direction extends about 5 miles. There are basically no shoulders on the Bridge, except for some stretches on curves and at the ramps on the Yerba Buena Island [123]



The Bridge carries a heavy traffic load, including a large number of commuters to and from San Francisco. A distribution to the traffic over time of day is given in Figure 20 for Tuesday, October 8, 1968 [63]. On that day, 158,000 vehicles crossed the Bridge.

#### 4.1.2 Description of Emergency Services on the SFOBB

Several detection and service systems are used on the Bridge by the California Bay Toll Division. This subsection describes the basic system.

##### 4.1.2.1 Detection

Incidents on the Bridge are detected in several ways. The basic detection subsystem is a series of call boxes spaced at about 600 feet, with two push buttons, one for "service" and one for "fire." The call box signals are monitored at the dispatchers office of the tow and service vehicles. In addition, service vehicles of the SFOBB patrol the Bridge during peak hours in a pattern as shown in Figure 21. The California Highway Patrol has divided the Bridge into four linear beats, which are shown in Figures 6 and 21.

A distribution of the origins of service requests is given in Figure 22. It can be seen that a large percentage of requests originates from the toll collectors and the toll sargent. These requests result either from cooperative motorists, who report incidents which they passed, or from observers of an incident at the Toll Plaza. For the 5 lane section of the Bridge it can be seen that about 50% of the requests come from the call boxes, while the rest are reported from the passing police and from SFOBB owned vehicles. There is little difference in the figures, if one differentiates between the peak and off peak hours, except that the

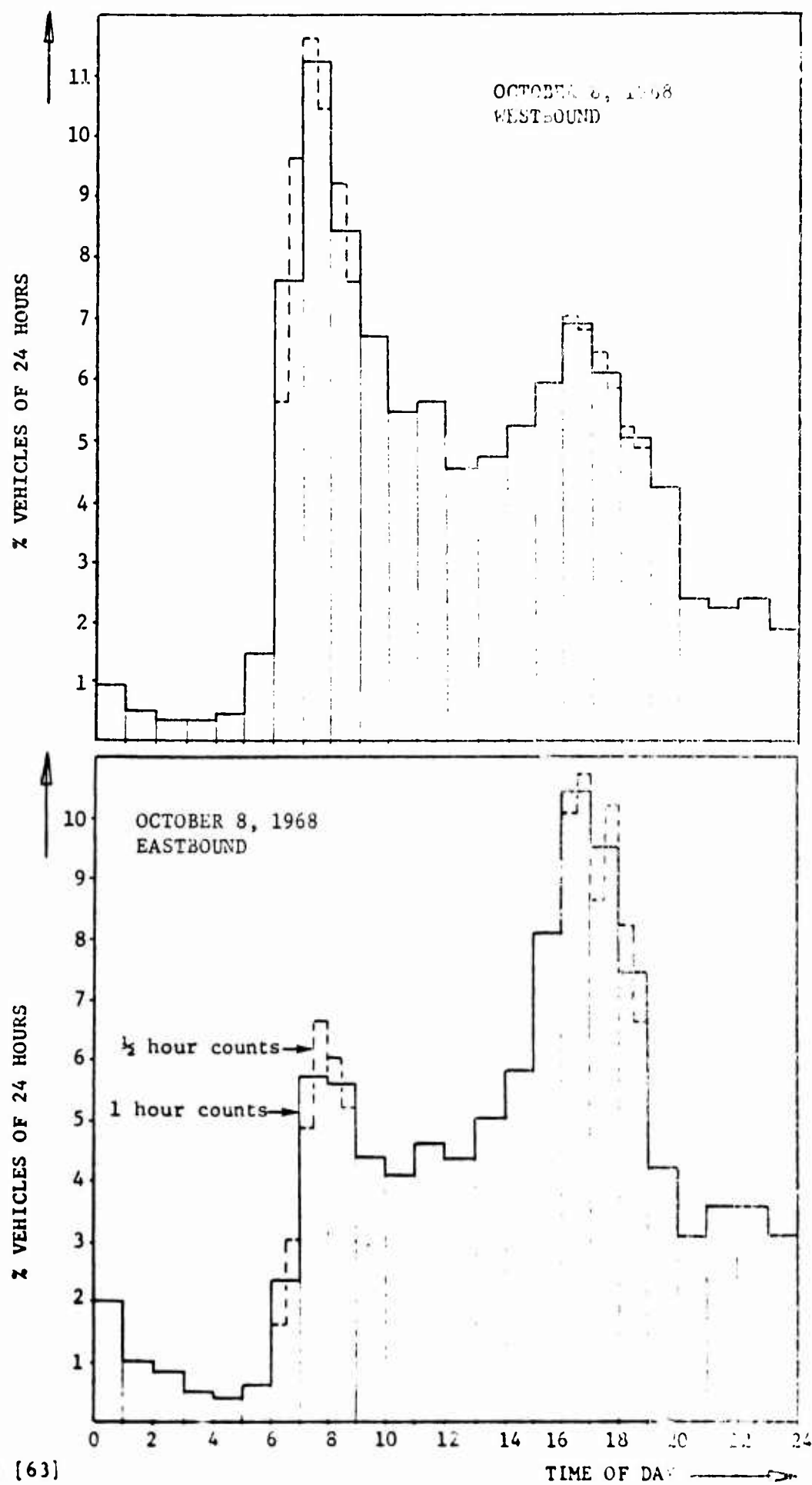


FIGURE 20: TRAFFIC DISTRIBUTION AT SFOEB TOLL PLAZA

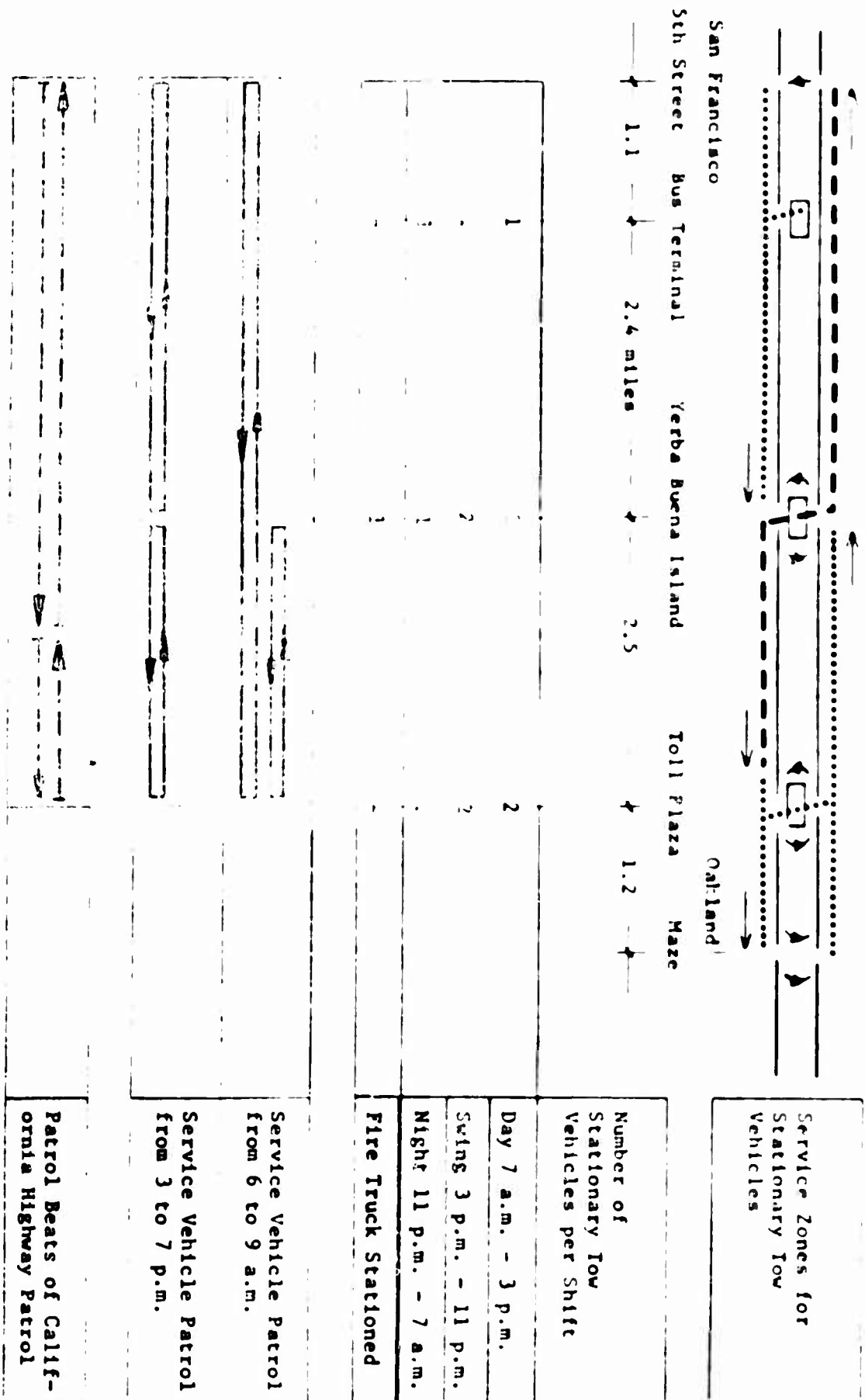


FIGURE 21: OPERATION OF TOW SERVICE ON THE SAN FRANCISCO OAKLAND BAY BRIDGE (1968)

detection via SFOBB vehicles increases during the peak hours due to the service vehicle patrols.

#### 4.1.2.2 Service

Services to the motorist are rendered by the Bay Toll Division's service and tow vehicles, the wreckers and the fire truck. These vehicles are dispatched by a dispatcher located at the Toll Plaza. Two-way radio communication between the dispatcher and all SFOBB vehicles guarantees fast and clear communication between the personnel. In addition to the already mentioned patrolling service vehicles, tow trucks are stationed at 3 posts along the bridge and a fire truck is positioned at the Yerba Buena Island. Figure 21 gives the details about their number and location during the different work shifts. The dispatcher tries to have at least one vehicle stationed at each post so that if, for example, the two trucks on the Yerba Buena Island are dispatched, he orders one of the two vehicles stationed at the Toll Plaza to the Island. While the service vehicles provide basically minor services (gasoline, water, tire change, etc.) the tow trucks provide major mechanical services and tow disabled vehicles out of the SFOBB area. Figure 23 gives a tabulation of the different types of services rendered by the SFOBB vehicles [93].

If the services of the police are necessary, the dispatcher has a direct line to the police communication center from where the police unit, assigned to the beat in which the incident occurred, is dispatched. A police officer was present in about 12% of the incidents. This figure does not really reflect the service need for police, since it also includes incidents which were detected by the police patrol.

| Origin of Request     | Bay Bridge and Approaches |       |     |           | Section of Bay Bridge,<br>where Call Boxes are<br>spaced ~ 600 ft. |       |     |           |
|-----------------------|---------------------------|-------|-----|-----------|--------------------------------------------------------------------|-------|-----|-----------|
|                       | A                         |       |     |           | B                                                                  |       |     |           |
|                       | Incidents                 |       |     | Accidents | Incidents                                                          |       |     | Accidents |
|                       | Off                       | Peak  |     |           | Off                                                                | Peak  |     |           |
|                       | Peak                      | Hours | All |           | Peak                                                               | Hours | All |           |
| Call Box              | 23                        | 23    | 23  | 38        | 49                                                                 | 52    | 51  | 50        |
| SFOBB Vehicle ( + )   | 17                        | 25    | 21  | 25        | 25                                                                 | 31    | 28  | 27        |
| Police Patrol (++)    | 19                        | 19    | 19  | 25        | 22                                                                 | 13    | 17  | 19        |
| Toll Sargent          | 32                        | 26    | 29  | 8         | -                                                                  | -     | -   | -         |
| Other (+++)           | 9                         | 6     | 8   | 4         | 4                                                                  | 4     | 4   | 4         |
| Total Number (Sample) | 156                       | 132   | 288 | 218       | 68                                                                 | 64    | 132 | 161       |

(+ service vehicles, service patrols, other SFOBB vehicles with two way communication)

(++ California Highway Patrol)

(+++ Patron, dispatcher, phone calls; for B also toll sargent (passing motorist))

(Incidents during weekdays, Oct. 7-11, 1968; Accidents during Sept., Oct., Nov., 1968).

(Data courtesy of SFOBB, California Bay Toll Crossings, [93])

**FIGURE 22: ORIGIN OF REQUEST FOR SERVICE SAN FRANCISCO - OAKLAND BAY BRIDGE**

(Per Cent of Total Number of Requests per Column)

| Type of Service<br>or Incident                                    | Number of<br>Dispatches<br>in the<br>Year 1967 | Per Cent<br>of Total<br>Services | Per Cent<br>of Total | Average<br>Service<br>Time<br>(min.) | Range<br>(min.) |
|-------------------------------------------------------------------|------------------------------------------------|----------------------------------|----------------------|--------------------------------------|-----------------|
| Vehicles Towed (+)                                                | 7,339                                          | 38.0                             | 34.8                 | 9                                    | 3 - 17          |
| Miscellaneous Services                                            | 6,493                                          | 33.6                             | 30.9                 | -                                    | - - -           |
| Gasoline, Diesel Fuel<br>Supplied                                 | 3,093                                          | 16.0                             | 14.6                 | 10                                   | 6 - 20          |
| Tire Changes                                                      | 2,337                                          | 12.1                             | 11.1                 | 10                                   | 6 - 14          |
| Fire                                                              | 53                                             | .3                               | .3                   | -                                    | - - -           |
| Total Vehicles Serviced                                           | 19,315                                         | 100.0                            |                      |                                      |                 |
| False Alarms                                                      | 1,109                                          |                                  | 5.3                  |                                      |                 |
| No Services Requested                                             | 667                                            |                                  | 3.2                  |                                      |                 |
| Total                                                             | 21,091                                         |                                  | 100.0                |                                      |                 |
| Maintenance Services                                              | 678                                            |                                  |                      |                                      |                 |
| Total Dispatches                                                  | 21,769                                         |                                  |                      |                                      |                 |
| Average Number of<br>Vehicles Serviced<br>per Day                 |                                                |                                  |                      |                                      |                 |
| 53                                                                |                                                |                                  |                      |                                      |                 |
| Number of Vehicles<br>Crossing the Bridge<br>per Vehicle Serviced |                                                |                                  |                      |                                      |                 |
| 2,854                                                             |                                                |                                  |                      |                                      |                 |

(+ mechanical trouble, no spare tire, accidents, etc.)

FIGURE 23: ROAD SIDE SERVICES AND ON-SITE SERVICE DURATIONS  
SAN FRANCISCO - OAKLAND BAY BRIDGE AND APPROACHES  
FOR THE YEAR 1967 (Source-[93])

In case of injuries or the need of an ambulance, the police communication center is contacted and an ambulance is ordered from either the city of San Francisco or Oakland.

#### 4.1.3 Data Base for Incidents and Emergency Service Operation on the SFOBB

The Bay Toll Division keeps an excellent record of all incidents and the services rendered to the motorists and their disabled vehicles. This information is collected by the dispatcher.

For every incident an entry is made in the "dispatcher's log," giving the location and time of the incident, the source of request, the type of service rendered; and the completion times for the activities "dispatch," "travel to scene," "on-site service," "towing," and "return time" of a service unit to its original post. Data on incidents were analyzed for 5 weekdays (October 7-11, 1968), while accident data were analyzed for a 3 month period (September, October and November, 1968). [93]. A summary of the analysis of the data is given in the following sections.

##### 4.1.3.1 Distribution of Incidents Over Time and Space

The location of incidents is identified by the number of the call box which is closest to the incident. Figure 24 gives the distribution of incidents and accidents over the Bridge and its approaches by direction. Although the sample size is limited (290 incidents and 218 accidents), except for the high frequency of incidents at the Toll Plaza, no location appears unique. There are some accumulations of incidents and accidents at the ramps to and from the Bridge, but these are also the locations where shoulders exist. For the other sections of the bridge it appears that there is a uniform distribution of incidents and accidents.

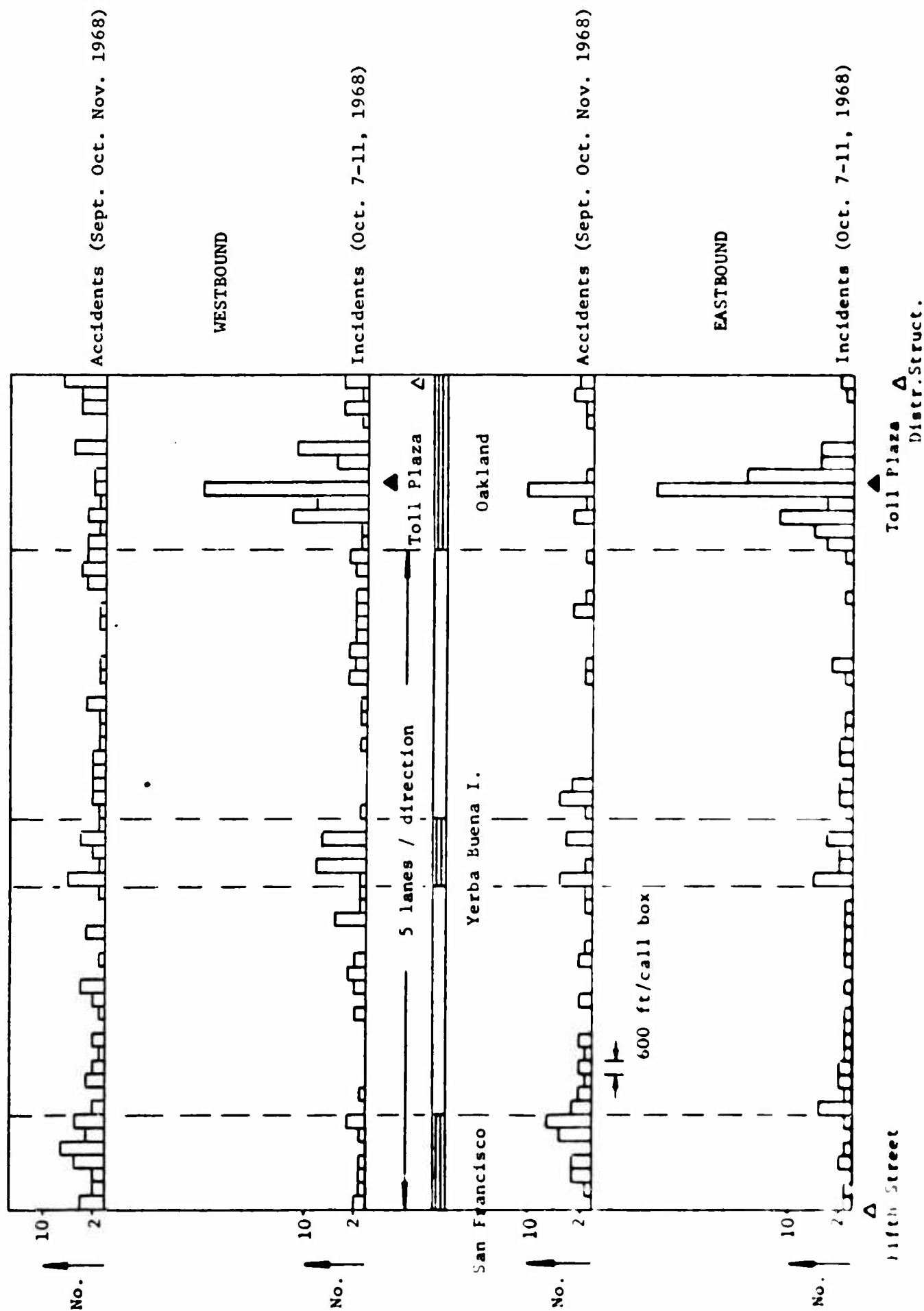


FIGURE 24: SPATIAL DISTRIBUTION OF INCIDENTS AND ACCIDENTS ON THE SAN FRANCISCO - OAKLAND BAY BRIDGE

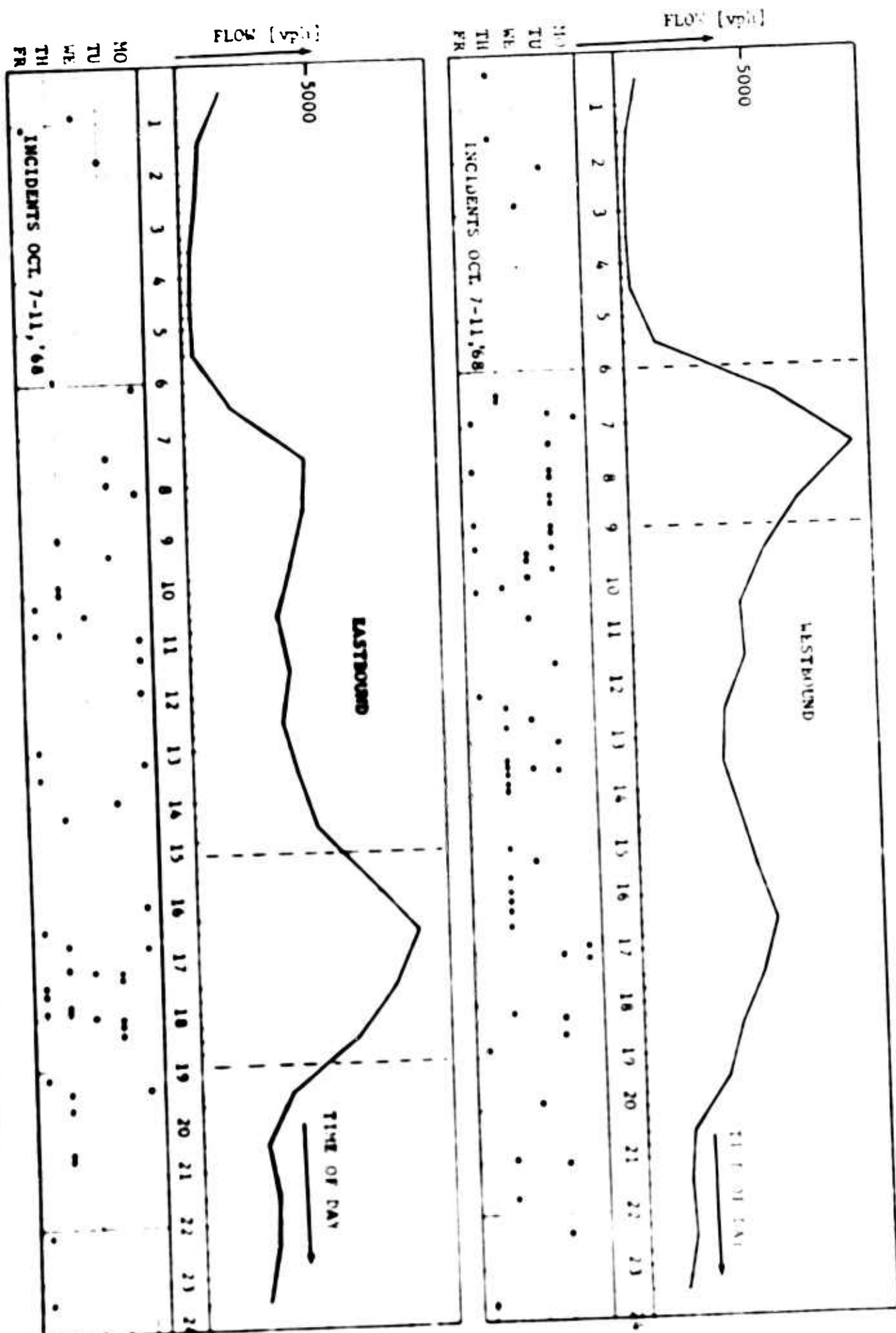


FIGURE 25: DISTRIBUTION OF TRAFFIC AND INCIDENTS OVER TIME OF DAY - S.F.O. BAY BRIDGE

|                             | Bay Bridge and<br>Approaches<br>- 8.00 miles - | Section of Bay Bridge<br>with 5 lanes, no shoulders<br>- 5.25 miles - |       |       |
|-----------------------------|------------------------------------------------|-----------------------------------------------------------------------|-------|-------|
| Direction                   | both                                           | both                                                                  | West  | East  |
| Sample size N               | 290                                            | 134                                                                   | 71    | 63    |
| veh.serviced/day            | 58                                             | 26.8                                                                  | 14.2  | 12.6  |
| inc./day/mile               | 7.2                                            | 5.1                                                                   | 2.7   | 2.4   |
| inc./hour/mile              | .30                                            | .21                                                                   | .11   | .10   |
| hour/inc./mile              | 3.3                                            | 4.77                                                                  | 9.10  | 10.0  |
| inc./hour/section           | 2.42                                           | 1.11                                                                  | .59   | .52   |
| min./inc./section           | 25.                                            | 54.                                                                   | 102.  | 116.  |
| veh.crossing<br>bridge/inc. | 2730                                           | 5900                                                                  | 5570  | 6280  |
| veh.miles/inc.              | 21820                                          | 31000                                                                 | 29200 | 32900 |

**FIGURE 26: FREQUENCY OF INCIDENTS PER TIME AND PER DISTANCE  
ON THE SAN FRANCISCO - OAKLAND BAY BRIDGE  
(Oct. 7-11, 1968)**

The distribution of the incidents over time of day is given in Figure 25. They are shown for the 5 lane section for the five weekdays in relation to the actual traffic flow on Tuesday, October 8, 1968. Most incidents occur during the time of high traffic flow rates. The frequency of incidents per time and distance is presented in Figure 26. There is a significant difference for these frequencies on the Bay Bridge and Approaches, and for those on the Bridge only. The difference results from the fact that there are no shoulders on the bridge, so that one can assume that the incidents on the Bridge are only emergency stops.

#### 4.1.3.2 Operation and Characteristics of Emergency Services on the SFOBB

The operation of the emergency services on the SFOBB is reflected in the completion times for the major activities reported in the dispatcher's log. An analysis of the activity completion times is presented in Figures 27 through 32 for incidents and accidents.

The frequency diagrams for 1 min. time intervals show basically similar distributions for the same activities for incidents and accidents, except that the means and variances are larger for accidents.

The arrival time at the scene of an incident has a mean of 3.7 min. and a standard deviation of 3.2 min. In Figure 29 the arrival times are stratified by the type of dispatch. The figure shows that the high frequency of arrival times in the class 0 to .5 min. results from the dispatch of patrolling vehicles, or from the dispatch of service vehicles directly from one incident to another. The arrival times for vehicles dispatched from posts are longer. The return time of the service vehicles from an incident to the original post is generally longer than the arrival time. This results from the "directional strategy" of dispatch

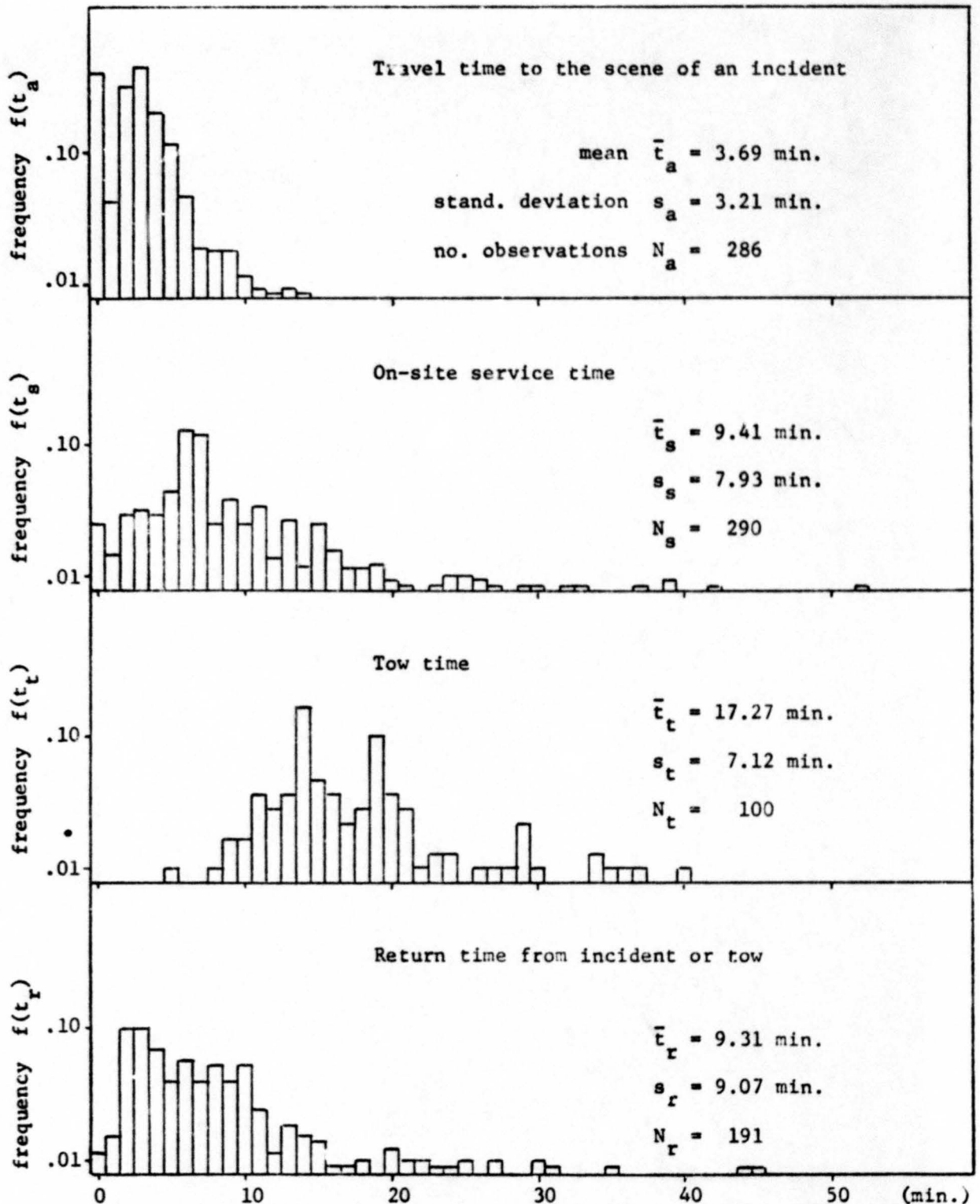


FIGURE 27: DISTRIBUTION OF VARIOUS COMPLETION TIMES FOR SERVICE ACTIVITIES ON THE SAN FRANCISCO - OAKLAND BAY BRIDGE

Incidents reported during the five weekdays October 7-11, 1968

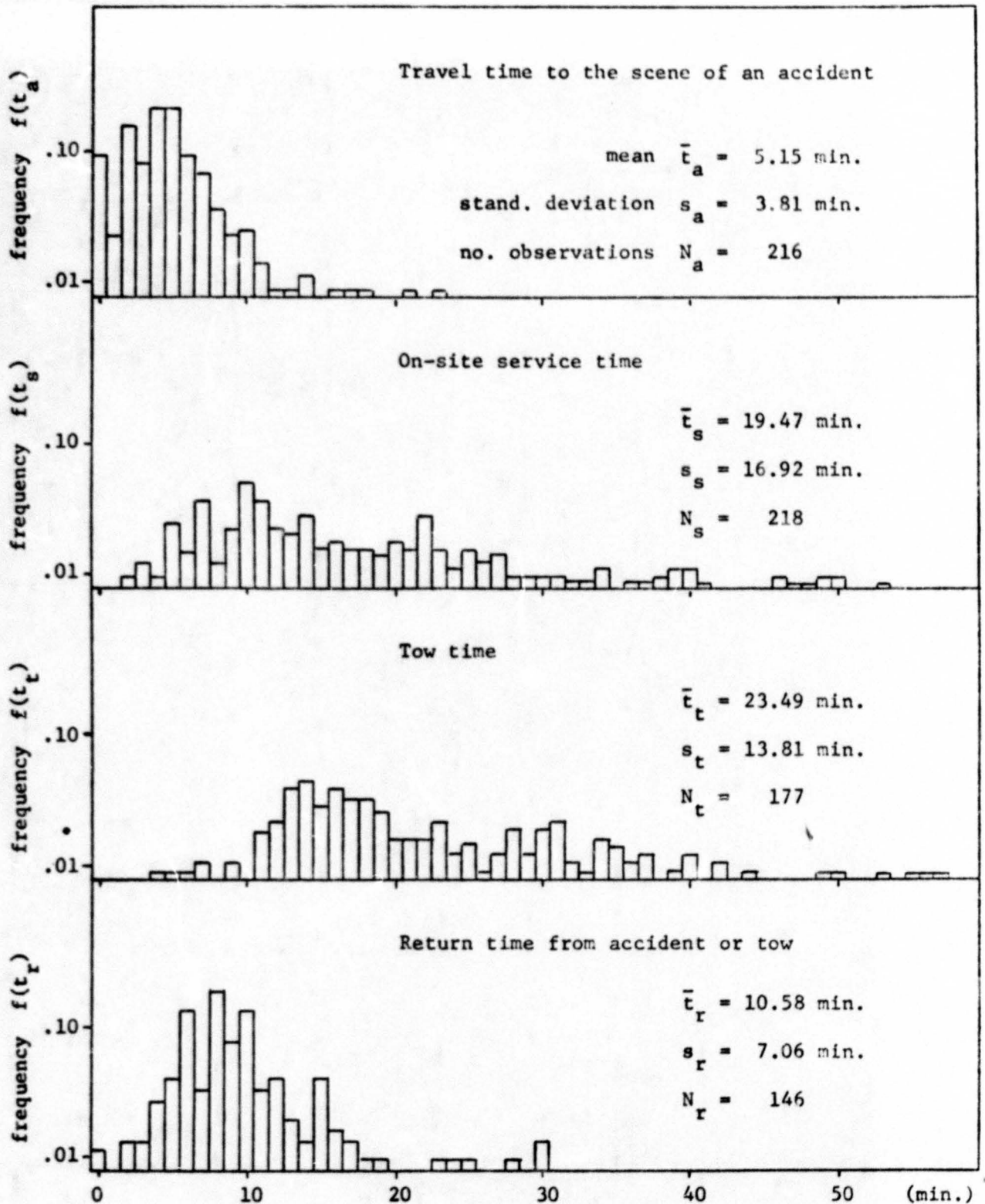


FIGURE 28: DISTRIBUTION OF COMPLETION TIMES FOR VARIOUS SERVICE ACTIVITIES ON THE SAN FRANCISCO - OAKLAND BAY BRIDGE

Accidents reported during the three months Sept.Oct.Nov. 1968

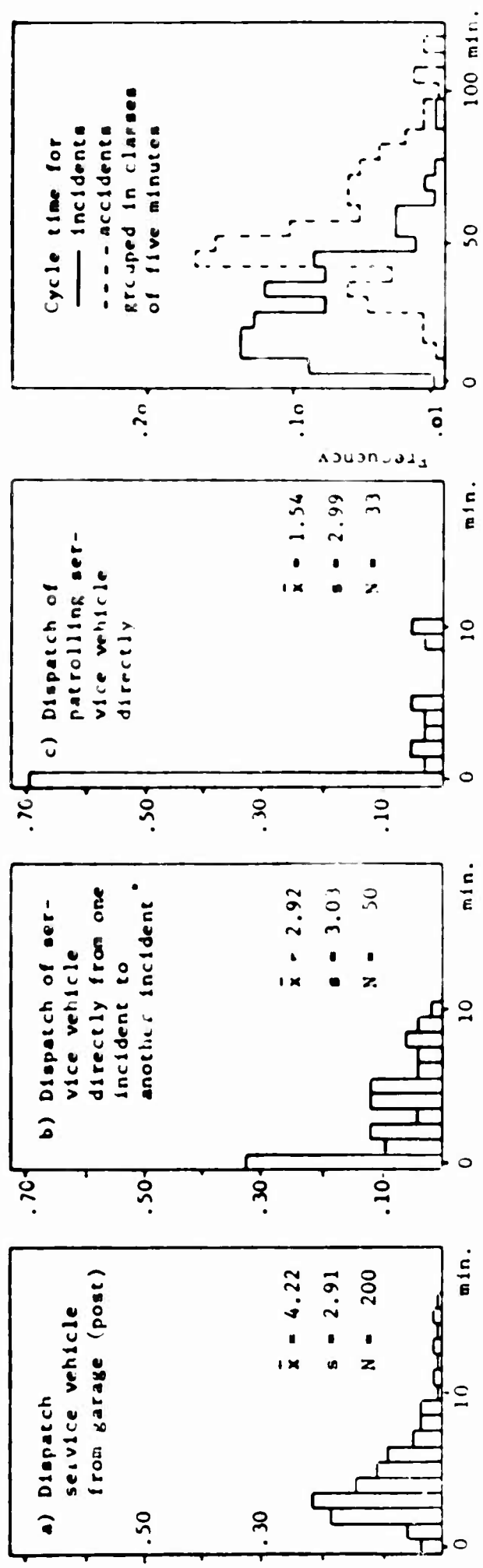


FIGURE 29: DISTRIBUTION OF TRAVEL TIME FROM DISPATCH TO ARRIVAL AT THE SCENE OF AN INCIDENT ON THE SAN FRANCISCO - OAKLAND BAY BRIDGE

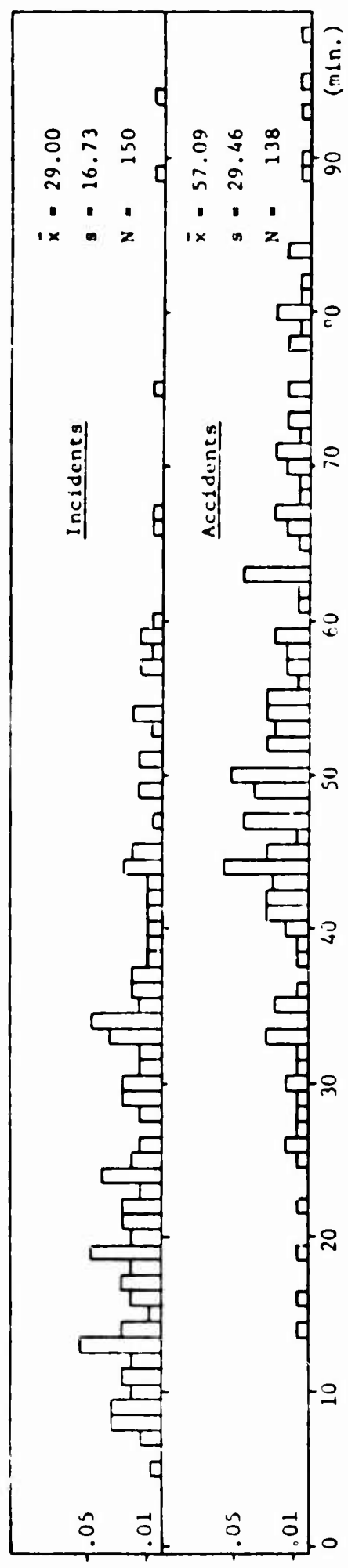


FIGURE 31: DISTRIBUTION OF CYCLE TIME OF SERVICE VEHICLES TO SINGLE INCIDENTS ON THE SAN FRANCISCO - OAKLAND BAY BRIDGE

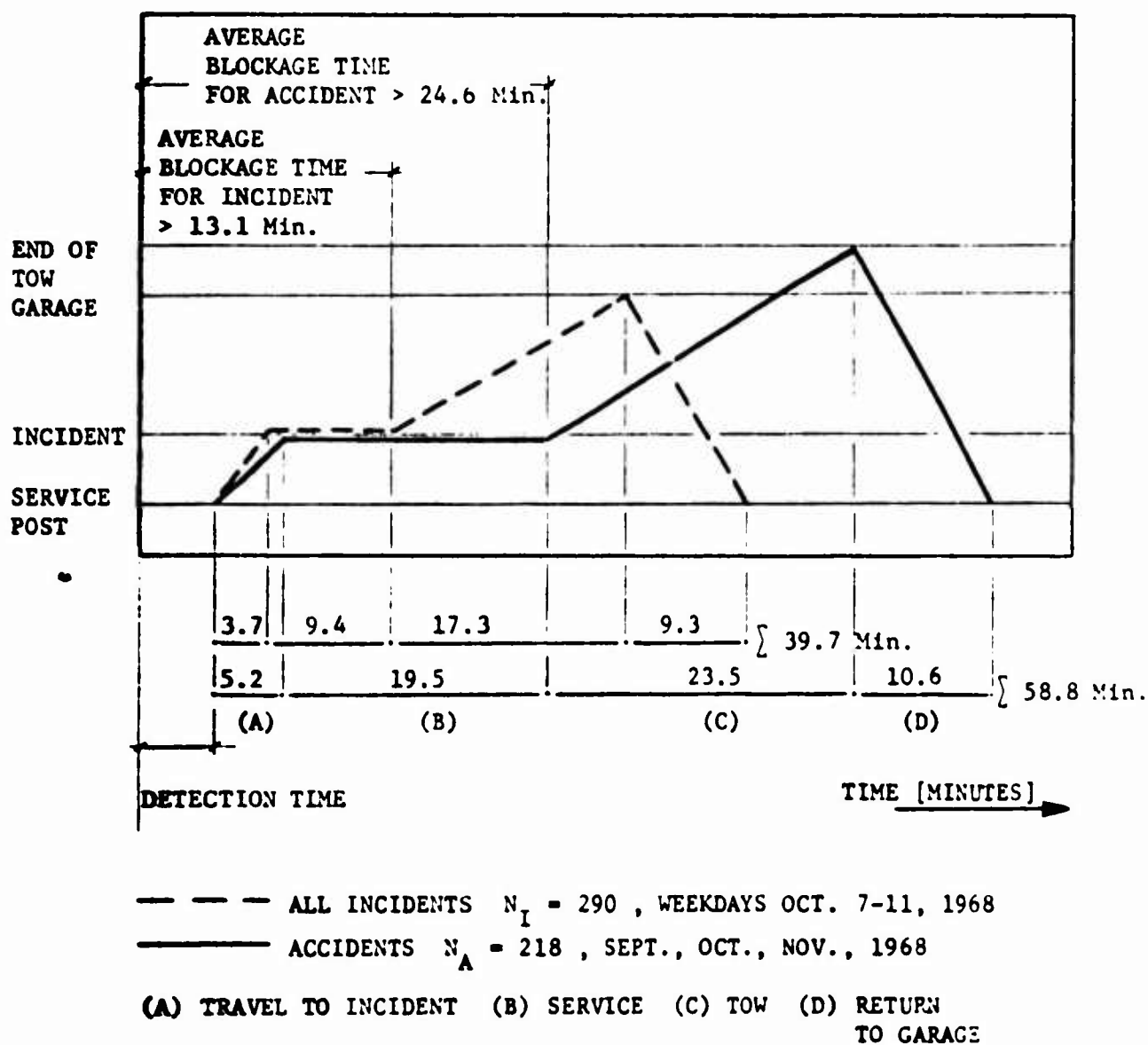


FIGURE 32: RESPONSE TIMES TO INCIDENTS AND ACCIDENTS  
SAN FRANCISCO - OAKLAND BAY BRIDGE SEPT., OCT., NOV., 1968

which is used, i.e., the service unit stationed closest to the incident is dispatched. After the on-site service, the vehicle has to travel to the next turn around point to return to its original post which results in the longer trip back. Figure 31 shows the distribution of the time a service vehicle needs to complete one cycle in serving single incidents on the Bay Bridge and its Approaches for 1 min. intervals. The grouping of the cycle time data into 5 min. classes given the distribution shown in Figure 30. If one includes the cycle times for multiple services, the variance increases even more while the mean is hardly changed.

A summary of the activity completion times is given in Figure 32. It can be seen that the average blockage time of the road-way is  $\geq 13.1$  min. for incidents and  $\geq 24.6$  min. for accidents. The figures 13.1 and 24.6 min. exclude the detection time which is unknown for all the analyzed incidents. The average on site service time is 9.4 min. for incidents and 19.5 min. for accidents. The average cycle time for the service units is about 40 min. for incidents and 1 hour for accidents.

#### 4.2 LINEAR FREEWAY

The activity model proposed in Chapter 2 and 3 will be applied to a linear freeway. The SFOBB with its geometrical layout, traffic flow pattern and emergency service system is considered to be representative for this linear freeway model. However, only that section of the bay crossing which has 5 lanes per direction will be considered. This will omit the bias in the occurrence of incidents which is introduced by the high frequency of incidents at the Toll Plaza and limits the analysis to the emergency stops on the Bridge.

It is therefore assumed that one considers a linear access controlled freeway of length,  $L$ , where incidents occur at location  $\pm x$  and at time  $t$ , see Figure 33.

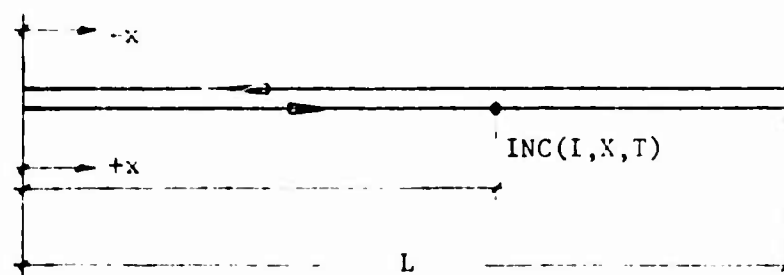


FIGURE 33: LINEAR FREEWAY

Turn around points exist at both ends of the Freeway (which correspond to the Toll Plaza and the 5th Street ramps in San Francisco). For the further analysis it is assumed that other turn around points can be introduced at other locations. (A turn around point in the half way length would correspond to the ramps at the Yerba Buena Island.)

#### 4.3 DETECTION AND SERVICE SYSTEMS ANALYZED

The analysis of alternate detection and service systems with respect to their cost and effectiveness is limited to a group of systems which are commonly accepted and used. By formulating the emergency systems in general terms, the results of the analysis then can be used and interpreted for methods which are similar to the systems investigated. In this section a short description of these emergency service systems is given.

##### 4.3.1 Detection Subsystems

Five types of detection systems are considered:

##### “(a) Discrete Communication Terminals

- (aa) Unidirectional, single signal terminals spaced at a distance,  $l_c$ , (miles) and connected to a dispatch center which can send men and equipment to the scene of call to evaluate the type of incident, (subsystem C). (E. g., call boxes. Some call boxes have a multiple choice of signals, like request of service vehicles, tow, ambulance, fire, etc. These types of call boxes could possibly be analyzed as part of the following detection type, ab system, because the service need is sufficiently defined.)
- (ab) Bidirectional, voice communication terminals spaced at a distance,  $l_e$ , (miles) and connected to a dispatch center of appropriate service vehicles, (subsystem E). (E.g.

emergency telephones. In this case it is assumed that the evaluation of the incident can be done via communication with the person calling.) Requests from the call boxes and emergency telephones are assumed to be monitored by the dispatcher of mechanical service vehicles (see 4.3.2).

(b) Patrols

This group encompasses all patrolling units which patrol the freeway with the intention to detect incidents. It is assumed that all patrol units have two-way communication with their dispatch and communication center.

(ba) Detection Patrols are motorcycles patrolling the freeway continuously on beats of length  $\ell_f$  (miles) (subsystem F). It is assumed that these patrols only detect incidents on that side of the freeway on which they travel and that they do not provide any services. The travel time of the motorcycle patrol is not dependent on the prevailing traffic flow on the freeway.

(bb) Service Patrols are patrol vehicles which patrol designated linear beats along the freeway to detect and service incidents. The patrol might be able to detect incidents on both sides of the freeway, but it seldom can evaluate the service need. It is therefore assumed, that patrols detect incidents only on that side of the freeway on which they travel. In this study two types of service patrols will be considered. Patrol A, police patrol with beat length  $\ell_a$ , which provides the services of a police unit, (subsystem A);

(bc) and patrol B, mechanical patrol with beat length  $\ell_b$  which provides the services of a tow and mechanical service vehicle, (subsystem B).

#### 4.3.2 Service Subsystems

As stated in Chapter 3, the service subsystem has been reduced to two service components, the police and the mechanical service. Two types of operation of these service systems are studied:

- (a) **Service Patrols.** Service patrols are vehicles which detect and service incidents as described in 4.3.1. The operation of the police patrol (A), and the mechanical patrol (B) are assumed to be similar.
- (b) **Stationary Service Units.** These are vehicles stationed at designated posts. The police vehicles (subsystem G) are spaced at a distance  $l_g$  and the mechanical service vehicles (subsystem H) are spaced at  $l_h$ . The vehicles are dispatched to incidents by their communication center and they return after assignment to their original location. Several assignment or dispatch patterns are possible in the operation [68], but for this study only the directional dispatch strategy is analyzed, see Figure 33.

#### 4.3.3 Communication

It is assumed that two-way communication is established with all patrol and service vehicles from their dispatch center, and that the two communication and dispatch centers have a direct telephone line.

#### 4.3.4 Candidate Systems

Figure 34 summarizes the basic design of individual detection and service subsystems. Several combinations of these individual subsystems are possible and reasonable. For this study 15 candidate systems were designed where different detection subsystems were mixed with either service patrols or stationary service units. Figure 35 depicts a matrix

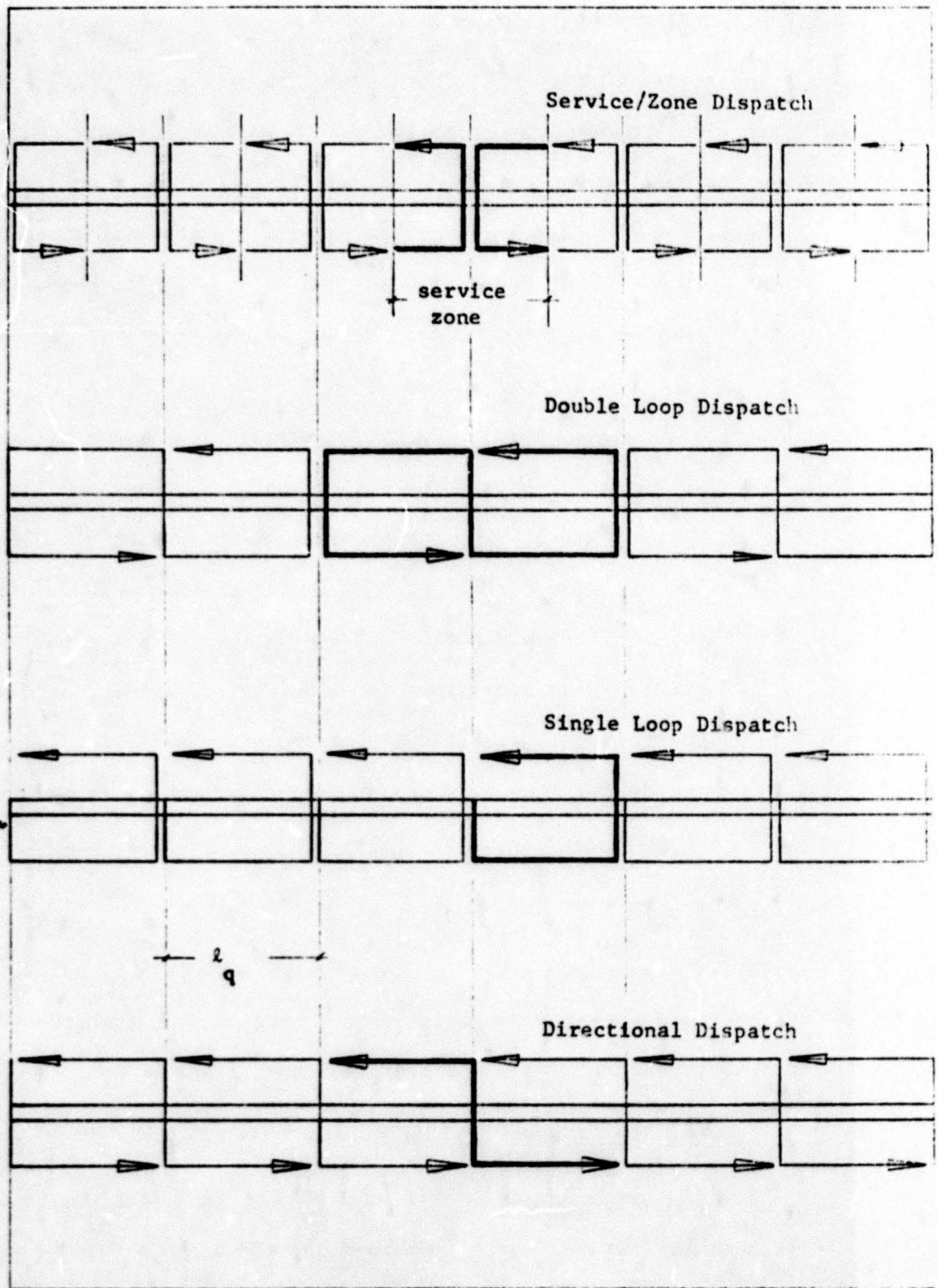


FIGURE 34: ALTERNATIVE SCHEMES FOR DISPATCHING OF STATIONARY SERVICE VEHICLES TO TRAFFIC INCIDENTS ON A LINEAR FREEWAY

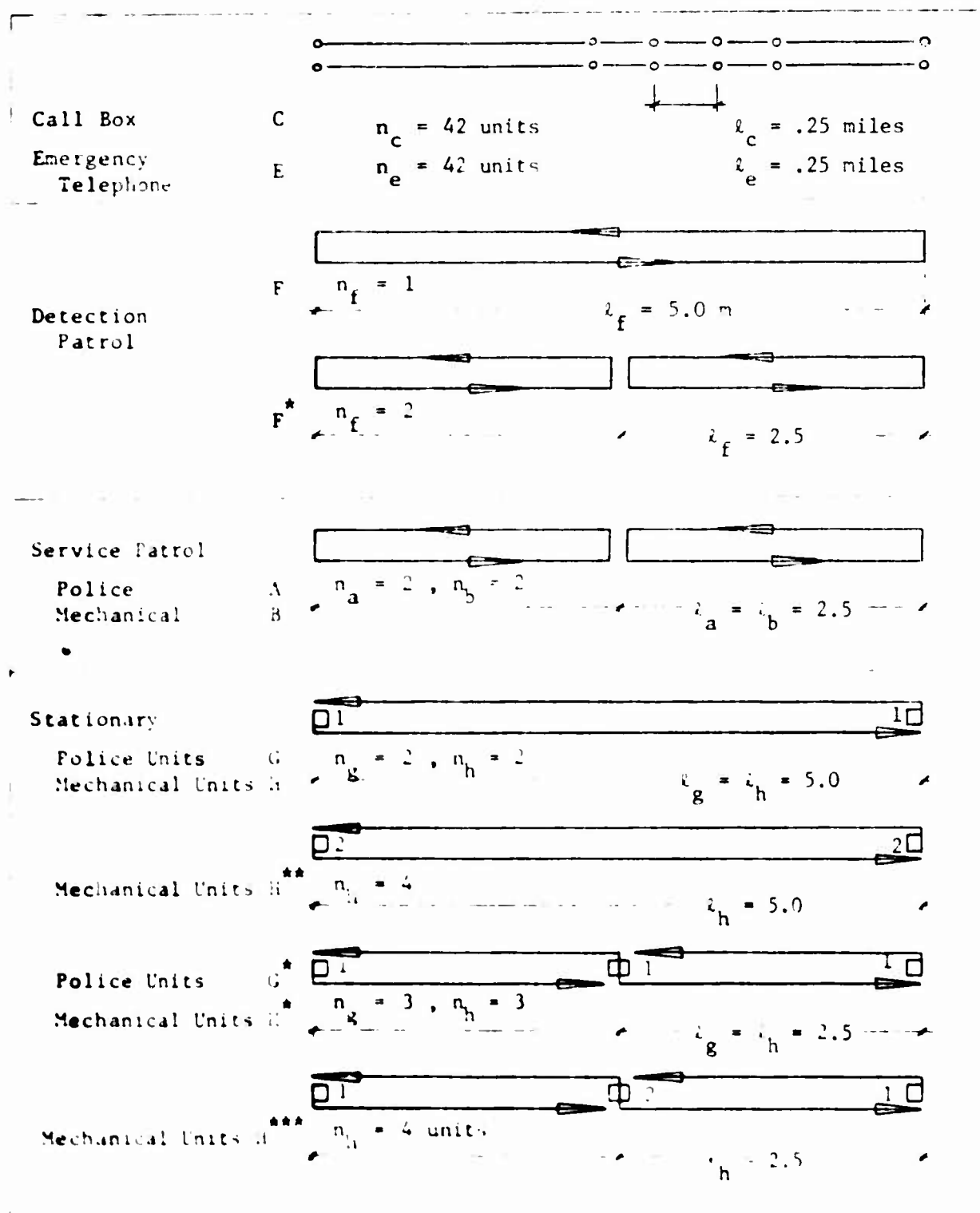


FIGURE 35. DETECTION AND SERVICE SUBSYSTEMS

**FIGURE 36: CANDIDATE SYSTEMS FOR RESPONDING TO FREEWAY INCIDENTS**

**FIGURE 36: CANDIDATE SYSTEMS FOR RESPONDING TO FREEWAY INCIDENTS**

of the 15 candidate systems which will be subjected to a cost and effectiveness analysis in the further study.

## CHAPTER 5

### APPLICATION OF THE MODEL

The approach outlined in the schematic model for a systems analysis structure of the emergency service system and the modified activity model, presented in Chapters 2 and 3, will be applied to the 15 candidate systems selected in Chapter 4. A detailed description of the submodels developed for this analysis and the framework for these models are given in this chapter.

The first section is devoted to the description of the modified activity model which consists of the four categories of activities: (1) detection, (2) travel to the scene of incident, (3) on-site service, and (4) return travel to normal position. Mathematical models designed for the occurrence of events and the four categories of activities are described and discussed.

Cost and effectiveness measures and models are summarized for the detailed analysis in the second section.

In the last section the simulation routine is presented which combines the submodels of the activity and cost and effectiveness models to the evaluation process.

#### 5.1 DESCRIPTION OF THE SUBMODELS OF THE MODIFIED ACTIVITY MODEL

In this section a discussion and description is given of the mathematical models which are used to simulate the occurrence of events and activities in the simulation routine. The models are specific to the 15 candidate systems and to their location, the linear freeway, but they have the potential to be applied to different locations and emergency service systems after some adaptations.

##### 5.1.1 Incident Occurrence

Traffic incidents and their characteristics are an input to the activity model. There are two approaches to obtain this information: (1) historical

data from a representative location could be collected, or (2) the incidents could be generated by the use of mathematical models.

Several authors have developed models to estimate the occurrence of incidents and, particularly, accidents on highways [31, 102, 121]. These models relate the incident frequency to the driver, the vehicle and the environment. Yet no satisfying relation has been established, which would predict incidents in space and time and which would justify a general use.

In the following paragraphs a mathematical model for the prediction of incidents over time and space will be discussed; and reasons will be given why the analysis of the 15 candidate systems was based on a set of historical data from the San Francisco-Oakland Bay Bridge for a period of five days.

#### 5.1.1.1 Occurrence of Incidents as a Poisson Process

A simple model for the occurrence of incidents in time and space can be built on the following assumptions:

The occurrence of incidents at a given point on a freeway is a Poisson Process. The probability of a single incident occurring on the location interval  $(x, x + dx)$  during the time interval  $(t, t + dt)$  is  $\lambda(x, t) dx dt$ .  $\lambda(x, t)$  is the mean rate of incidents at point  $x$  at time  $t$ . It is further assumed that the occurrence of an incident, INC at time  $t$  is independent of its location  $x$ , so that

$$(1) \quad P_{INC}(x, t) = \lambda(x) \lambda(t) dx dt$$

(by neglecting higher order terms).

Assuming an equal distribution of the incidents over the freeway length  $L$ , the probability of the occurrence of an incident is equal to  $P(INC) = \lambda(t) dx dt / L$ .

For  $\lambda(t) = \lambda$  the time interval between two successive incidents of the

Poisson process can be described through the negative exponential distribution

$$(2) \quad P(H \leq (t_2 - t_1)) = 1 - e^{-\lambda(t_2 - t_1)} \quad H \geq 0$$

where  $H$  is the time which passes until the occurrence of the next incident after time  $t_1$ . The expectation of the random variable,  $H$  is  $E(H) = 1/\lambda$  and its variance  $\text{Var}(H) = 1/\lambda^2$ .

An estimation of a time dependent parameter  $\lambda = \lambda(\Delta t_1)$  could be based on a functional relationship with the prevailing rate of traffic flow  $q(\Delta t_1)$ , during certain time periods  $\Delta t_1$ , so that  $\lambda = \lambda(\Delta t_1) = f(q(\Delta t_1))$ . However, to preserve the negative exponential distribution process of the time headways, only incidents with  $\lambda(\Delta t_1)$  and occurring during  $\Delta t_1$ , can be considered. If an incident generated with  $\lambda(\Delta t_1)$  occurs in a following time interval  $\Delta t_j$ , it will have to be discarded. The next incident would then have to be generated in the time interval  $\Delta t_j$  with  $\lambda(\Delta t_j)$  starting the process again at the beginning of that time interval.

• The occurrence of incidents,  $I$  over time  $(t)$  and space  $(x)$  would then be simulated using pseudo uniform  $(0,1)$  random numbers,  $R_{1,2}$  by generating the time interval between incidents,  $h_I$  from

$$(3) \quad h_I = -\frac{1}{\lambda} \ln(1 - R_1),$$

so that the times of occurrences are  $t_I = t_{I-1} + h_I$ . Correspondingly, the location of incidents would be determined from

$$(4) \quad x_I = R_2 \cdot L,$$

where  $L$  is the length of the study section.

The model has the disadvantage that it is rather crude and that it does not generate incidents by the type of necessary service. For the

purpose of this study it was therefore decided to use historical data of incident occurrences for a particular time period on the San Francisco-Oakland Bay Bridge.

#### 5.1.1.2 Historical Data on Incident Occurrences

Historical data of incident occurrences are available from the dispatcher's log of the SFOBB. As study period, the week from October 7-11, 1968 was selected, because for October 8, 1968 detailed data on the traffic flow distribution over the time of day existed from an earlier study on this facility [63].

The incidents are characterized by the following parameters:

$$INC(I, X, T, K, CR)$$

$I$  = number of incidents  $I = 1, \dots, N_0$

$X$  = location on the freeway  $|X| \leq L$

$X \geq 0$  Westbound,  $X < 0$  Eastbound

$T$  = time of occurrence in minutes of time of day  $0 \leq T \leq 1440$  min.

$K$  = type of necessary service

$K = P = 1$  police service is necessary,  $P = 0$  not necessary

$K = S = 1$  mechanical service is necessary,  $S = 0$  not necessary

$K = V = 1$  disabled vehicle has to be towed,  $V = 0$  no tow necessary

$CR$  = percent reduction of freeway capacity due to roadway blockage  
derived from the number of lanes blocked.

Figure 37 gives a plot of the incidents over times of day and the length of the Bay Bridge for October 7-11, 1968.

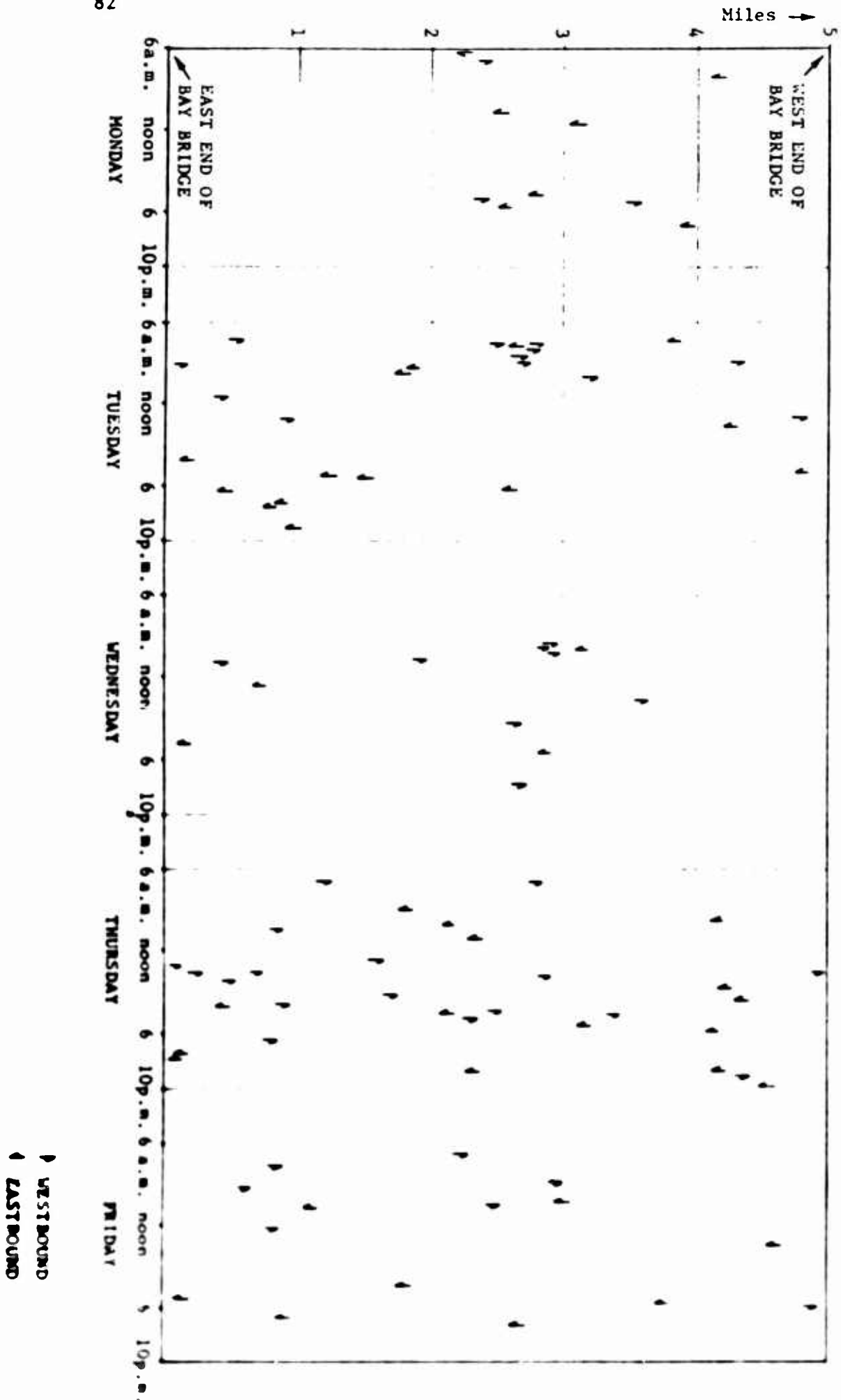


FIGURE 37: DISTRIBUTION OF INCIDENTS ON SPOBs FOR THE WEEK OCTOBER 7-11, 1968

### 5.1.2 Detection Models

The detection phase of the post-incident stage has been analyzed in several studies of the emergency service system. This is reflected (1) in the fact that models were developed to predict the detection time of incidents for certain patrol methods [24, 44, 102]; and (2) in the design of optimal strategies to patrol access controlled highways [89, 108].

The operational characteristics of some of the detection systems studied are similar, so that the same model with different parameters can be applied to describe their operation. In this section the developed detection models are therefore presented by groups of similar systems: bi-directional and unidirectional communication terminals, detection and service patrols.

#### 5.1.2.1 Bidirectional Communication Terminals (Emergency Telephone)

Emergency telephones are spaced at  $\frac{1}{4}$  to  $\frac{1}{2}$  mile along urban freeways, and 1 to 2 miles along rural freeways [79]. Their reported usage is relatively low, because of their large spacing and of the reluctance of the motorist to pay for possible expenses resulting from using the phone system. In this analysis where the emergency services are rendered to stranded motorists whose stops are capacity reducing in their effect it is assumed that all motorists are captive to use the phones. In some cases, e.g., when the motorist is injured and is not able to walk to the nearest emergency phone, it is assumed that he can rely on the passing motorists using the emergency phone.

The detection time for the "captive" motorist is then simply a function of the distance he is away from the closest emergency telephone. If one considers also the time until the motorist recovers from the incident and evaluates his service needs,  $t_{re}$  and the time to request the service  $t_c$ , the detection time for an emergency telephone system is the sum of these

and the walking time to the telephone,  $w_e$  :

$$(1) \quad t_d^e = t_{re} + w_e + t_c .$$

For the emergency stops on the Bay Bridge the estimate used for  $t_{re}$  and  $t_c$  was respectively 1.5 and one minute. It is assumed that the terminals are spaced at equal distance  $l_e$  one on each side of the freeway. The terminals are numbered consecutively,  $e_1 = 1, e_2 = 2, \dots, n+1$  with  $e_1 = 1$  at  $x = 0$  and  $e_{n+1}$  at  $x = L$ , see Figure 38. The terminal  $e_0$ , which will be used by the motorist, is the closest one to the incident:

$$(2) \quad e_0 = \begin{cases} \left\lfloor \frac{|X|}{l_e} \right\rfloor^+ & \text{if } (X/l_e - .5) \leq 0 & x' = X - e_0 \cdot l_e \\ \left\lfloor \frac{|X|}{l_e} \right\rfloor + 1 & \text{if } (X/l_e - .5) > 0 & x'' = e_0 \cdot l_e - |X| \end{cases}$$

$x'$  or  $x''$  are the walking distance to the telephone. The walking time  $w_e$  can then be computed from Figure 39,

$$(3) \quad w_e = \begin{cases} x'/v_w & \text{if } (x' - l_e/2) > 0 & e_1 = e_0 \\ (l_e - x')/v_w & \text{if } (x' - l_e/2) \leq 0 & e_{1+1} = e_0 \end{cases}$$

where  $v_w$  is the walking speed here assumed to be 3 m.p.h.

The expectation of  $w_e$  is for uniformly distributed incidents over the length  $l_e$

$$(4) \quad E(w_e) = \int_0^{l_e/2} \frac{2}{l_e \cdot v_w} x' dx' = \frac{1}{4v_w} l_e .$$

\*  $\lfloor \cdot \rfloor$  stands for truncation, i.e.,  $\lfloor 82.3 \rfloor = 82$ .

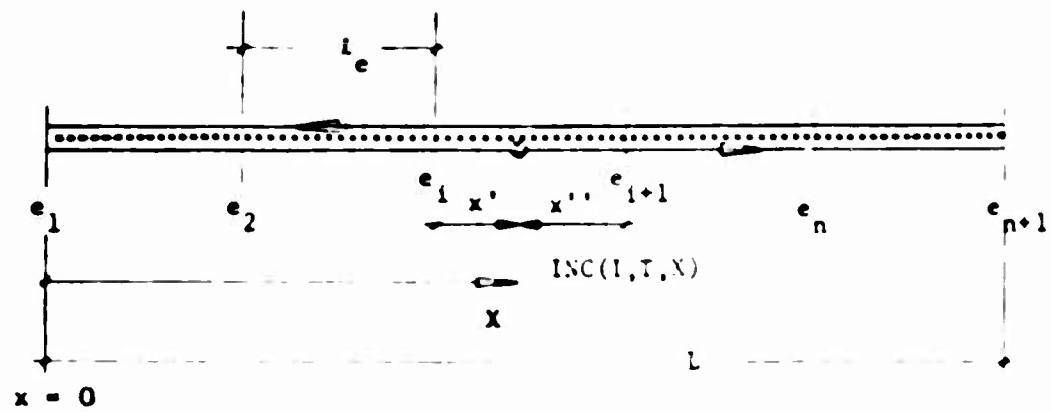


FIGURE 38: LINEAR FREEWAY WITH COMMUNICATION TERMINALS  $e_i$  SPACED AT  $l_e$  MILES

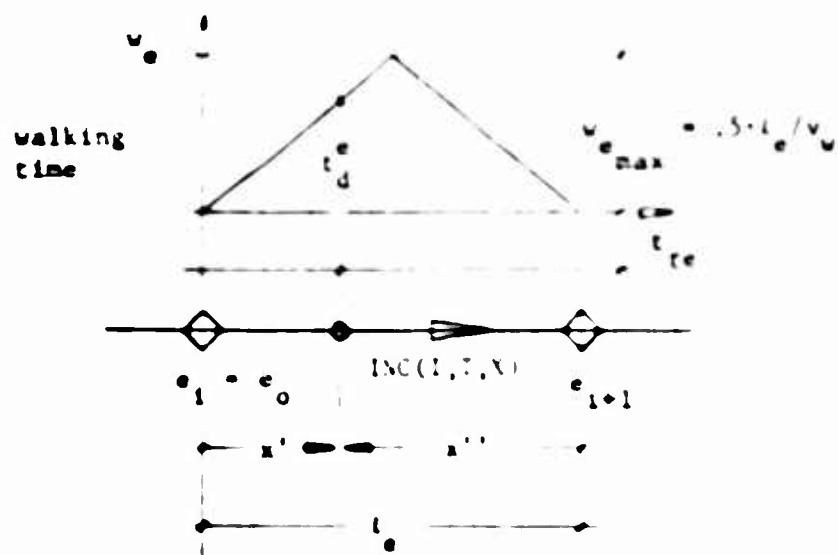


FIGURE 39: DETECTION TIME FOR EMERGENCY TELEPHONES

### 5.1.2.2 Unidirectional Communication Terminals (Call Boxes)

The analysis of the detection time via call boxes is very similar to the one of the emergency telephones, and the same formulas can be applied by replacing the index  $e$  by  $c$ . It is also assumed that the motorists are captive to use the call boxes. But because only a single signal can be transmitted to the communication center, an observer has to be dispatched to the scene to evaluate the service need. This additional time,  $t_e$ , is equal to the travel of a service vehicle to the scene and will be analyzed in Section 5.1.2 and 5.1.6. (It is assumed that the communication terminals are monitored at the dispatch center of mechanical service vehicles.) The detection time for all call boxes is, therefore,

$$(1) \quad t_d^c = t_{re} + w_c + t_e.$$

### 5.1.2.3 Detection Patrol

A detection patrol may consist of a motorcyclist, who patrols a designated patrol beat of length  $l_f$  in a closed looping fashion with speed  $u_f$ . It is assumed that the patrol cruises at constant speed and is not affected by the prevailing traffic flow. It patrols only with the intention to detect incidents, and not to provide any service. A detection patrol could also be represented as an aerial patrol, e.g., a helicopter. The two systems would then basically differ only in the cruising speed. A model for the probability of detecting stopped vehicles on the patrol beat can be based on the fact that the motorcycle continuously patrols the beat and is, therefore, a certain time interval away from the incident at the time it occurs.

The section of freeway is divided into an integer number of patrol beats,  $n_f$ , where  $n_f = L/l_f$ . The time to complete one patrol loop is then equal to the headway between consecutive patrols,  $h_f$ , or the passing of the same vehicle at the same point of the freeway is

$$(1) \quad h_f = 2 \cdot l_f / v_f .$$

The patrol frequency (number of patrols arriving at the same location per time) is then

$$(2) \quad p_f = 1/h_f$$

or

$$(2') \quad p_f = v_f / 2 \cdot l_f .$$

The probability that a stop will be detected by time  $\tau = t_d$  is then

$$(3) \quad P_d(t \leq \tau) = \begin{cases} 0 & \tau < 0 \\ \frac{v_f}{2 \cdot l_f} \tau d\tau & 0 \leq \tau \leq h_f \\ 1 & \tau > h_f . \end{cases}$$

A graphical representation of this model is given in Figure 40. The detection time is then simulated in a computer, by using a random number generator, which generates pseudo uniform (0,1) random numbers,  $R$ . The random numbers are converted to the appropriate random deviates by equating  $R = P_d(t \leq t_d)$ , so that the detection time is

$$(4) \quad t_d = R \frac{2 \cdot l_f}{v_f} .$$

The expectation of the detection time is then

$$(5) \quad E(t_d) = \int_0^{2 \cdot l_f / v_f} \frac{v_f}{2 \cdot l_f} \tau d\tau = l_f / v_f$$

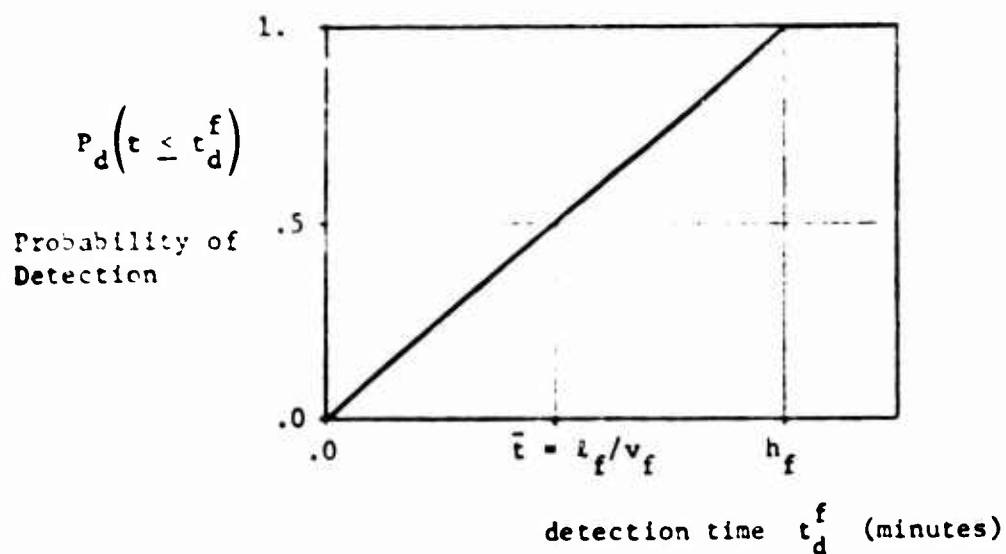
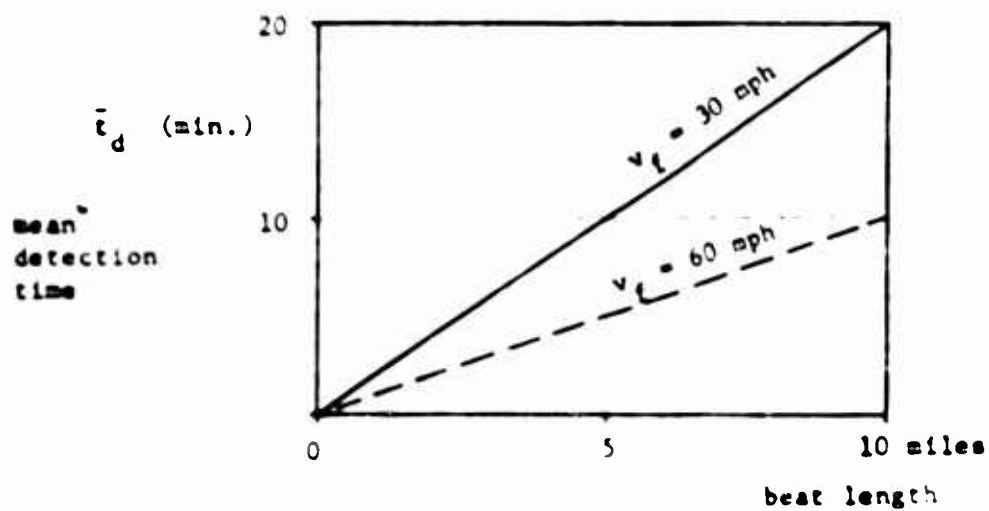


FIGURE 40: PROBABILITY OF DETECTION FOR DETECTION PATROL

FIGURE 41: MEAN DETECTION TIME FOR DETECTION PATROL  
VERSUS BEAT LENGTH

and its variance

$$(6) \quad \text{Var}(t_d) = E[t_d^2] - E^2[t_d] = \lambda_f^2 / 3 \cdot v_f^2.$$

The detection patrol does not detect short time stops which are shorter than the detection time,  $t_d$ . Assuming a patrol speed of 60 to 30 m.p.h. and various patrol beat length, the mean detection time from this model is plotted in Figure 41.

#### 5.1.2.4 Service Patrols

It is assumed that certain sections of the freeway are assigned to patrolling vehicles which are then responsible for the detection and servicing of stoppages along these beats. The model assumed for the detection patrol would, therefore, not be applicable because the patrol frequency is a function of the service times and other influencing variables such as the prevailing traffic flow conditions on the roadway. Some police departments [68] allow the officer to leave his assigned beat and patrol adjacent beats, while he alone has the responsibility for his own beat. An example for such a beat structure is shown in Figure 42. These overlapping patrol beats reduce the detection time, but also introduce a stochastic element into the detection time analysis because the patrols do not follow strict schedules.

Observations of time headways between successive service patrols on freeways, analyzed by [108], show that a negative exponential distribution fits the data well. This model will be used in this analysis to predict the detection of incidents. The detection time is then a function of the headways between police patrol,  $h_a$  and mechanical patrols,  $h_b$ . The density function for the negative exponential probability law is

$$(7) \quad f(t) = \lambda e^{-\lambda t}$$

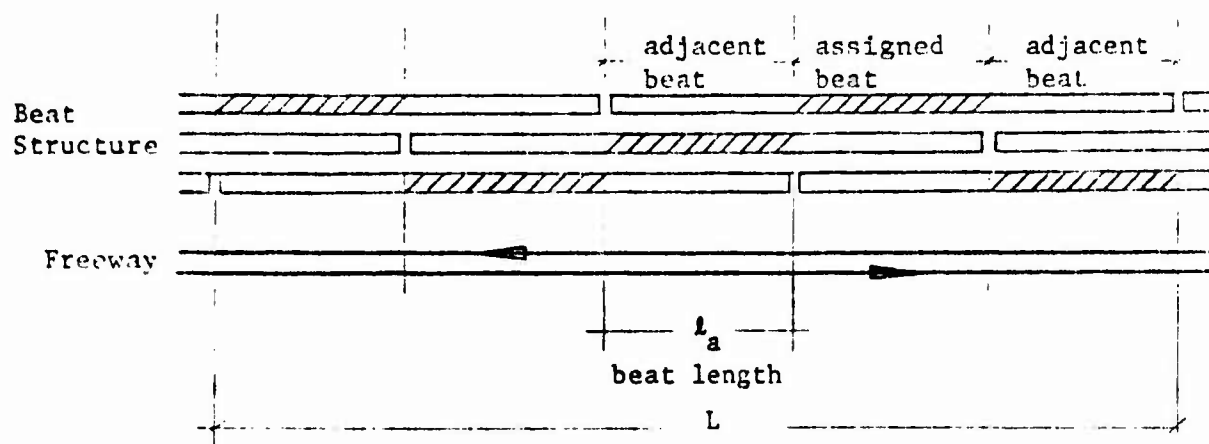


FIGURE 42: BEAT STRUCTURE WITH OVERLAPPING PATROL BEATS

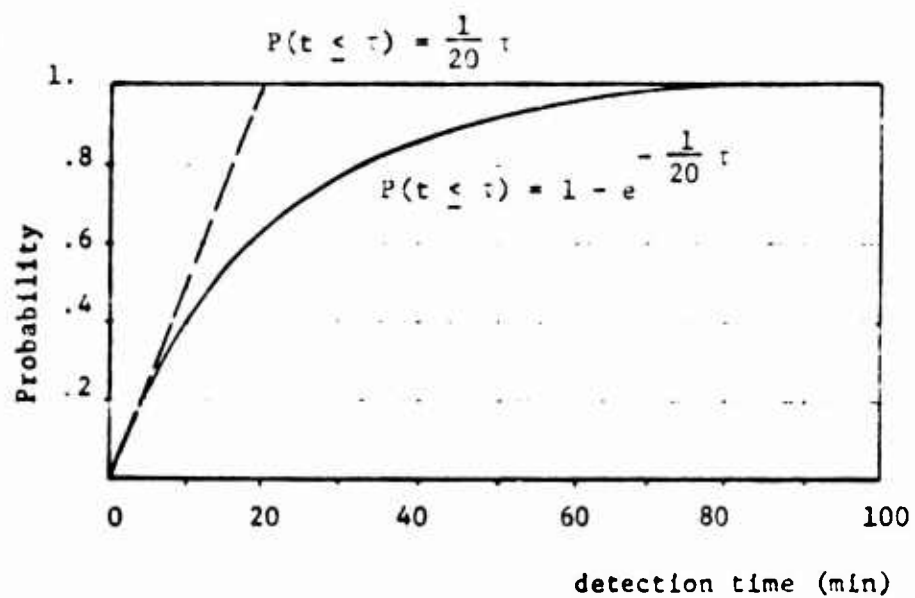


FIGURE 43: COMPARISON OF UNIFORM AND NEGATIVE EXPONENTIAL LAW AS DETECTION TIME MODEL

where  $\tau = t_d$ , the detection time and  $\lambda$  patrol frequency (patrols/time interval).

The probability that a stop is detected by time  $t_d = \tau$  is then

$$(2) \quad P_d(t \leq \tau) = \int_0^{\tau} \lambda e^{-\lambda \tau} d\tau = 1 - e^{-\lambda \tau}.$$

The parameter  $\lambda$  can be estimated from the expectation of the observed headways

$$(3) \quad E(t) = 1/\lambda$$

or

$$(4) \quad \lambda = 1/E(t).$$

Because of the lack of observations for individual beats, the patrol frequency used for the uniform probability law  $p_a = v_a/2 \cdot l_a$  (patrols/time) (see 5.1.2.3) will be used to estimate  $\lambda$ ,

$$(4') \quad \lambda = v_a/2 \cdot l_a.$$

The probability of a stop to be detected by time  $t_d = \tau$  is then

$$(5) \quad P_d(t \leq \tau) = 1 - e^{-[v_a/2 \cdot l_a] \cdot \tau}.$$

By generating random numbers,  $R$  and equating  $R = P_d(t \leq \tau)$ , the detection time for a police patrol  $t_d^a = \tau$  can be simulated from

$$(6) \quad t_d^a = -\frac{2 \cdot l_a}{v_a} \ln(1 - R).$$

The effect of using the patrol frequency from the uniform probability law as an estimate for the negative exponential probability law is shown in Figure 43. The negative exponential distribution is plotted for  $\lambda = 1/20$ , which corresponds to the headway of consecutive patrols of the uniform distribution for a beat of 20 miles length and 60 m.p.h. cruising speed. The variance for the exponential law is  $\text{Var}(t) = 1/\lambda^2 = 400$ , while for the uniform law it is 133. The increased spread of possible detection times becomes obvious from Figure 43.

The presented detection model will be used for the police patrol and the mechanical patrol. The models are identified by using the subscript, a for police and, b for mechanical patrols.  $t_d^a$  is the detection time for a police patrol, while  $t_d^b$  is the detection time for a mechanical patrol.

### 5.1.3 Dispatch of Service Vehicles and Travel to Scene of Incident

Service units are dispatched to the scene of an incident after request from the communication center of the component. A dispatch is not necessary if the appropriate service patrol unit already arrived at the scene. In all other cases vehicles are dispatched. The dispatch initializes the second phase of the emergency service system, the service phase.

Patrols are not dispatched, but they arrive at the scene according to the patrolling strategy on their beat. Service vehicles stationed at posts are dispatched so that the vehicle closest to the incident travels to the scene ("directional strategy").

#### 5.1.3.1 Dispatch and Travel Time to Incident

The travel time to the scene for patrolling units is set equal to the detection time  $t_d^a$  or  $t_d^b$  for the particular patrol. In case of stationary service units, the travel time is derived from the geometrics of the freeway, as well as from the incident and service post location.

The layout shown in Figure 44 is assumed for the service posts of the police ( $g_1$ ) and service ( $h_1$ ) vehicles. The freeway is subdivided into  $n_g$  subsections and the area of service responsibility is shown in Figure 44 through arrows. It is assumed that the service units are located at the freeway. This pattern corresponds to the operation of such facilities as the San Francisco - Oakland Bay Bridge and Hudson Tunnel in New York. It could also be assumed that the vehicles are actually located at a distance away from the freeway, and that they would just enter the freeway at the designated posts. The travel time to the freeway would then require an additional analysis.

The travel time from dispatch to arrival at the scene of an incident is then determined from the geometrics given in Figure 45. The service unit to be dispatched is the closest one to the scene of the incident. Its location  $g_1$  is determined by the location of the incident  $X$ ,

$$(1) \quad g_1 = \begin{cases} \left\lfloor \frac{|X|}{l_g} \right\rfloor & X \geq 0 \\ \left\lfloor \frac{|X|}{l_g} \right\rfloor + 1 & X < 0 \end{cases} \quad \begin{aligned} x' &= X - g_1 \cdot l_g \\ x'' &= g_1 \cdot l_g - |X| \end{aligned}$$

where  $x'$  and  $x''$  are the distance from the service post to the incident. The travel time to the scene becomes then

$$(2) \quad t_a = t_p + \frac{1}{v_a} x' \quad x' = \begin{cases} x' & \text{for } X \geq 0 \\ x'' & \text{for } X < 0 \end{cases}$$

where  $t_p$  includes the time to dispatch the vehicle and the time until the vehicle actually starts to travel.

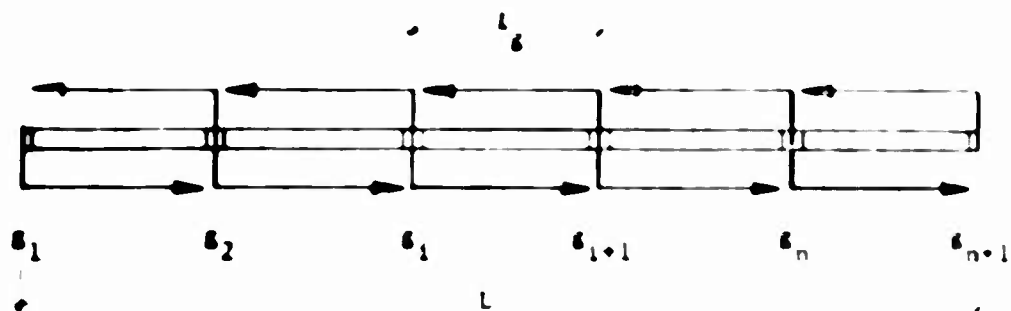


FIGURE 44: DIRECTIONAL DISPATCH OF SERIES UNITS FROM  $s_1$

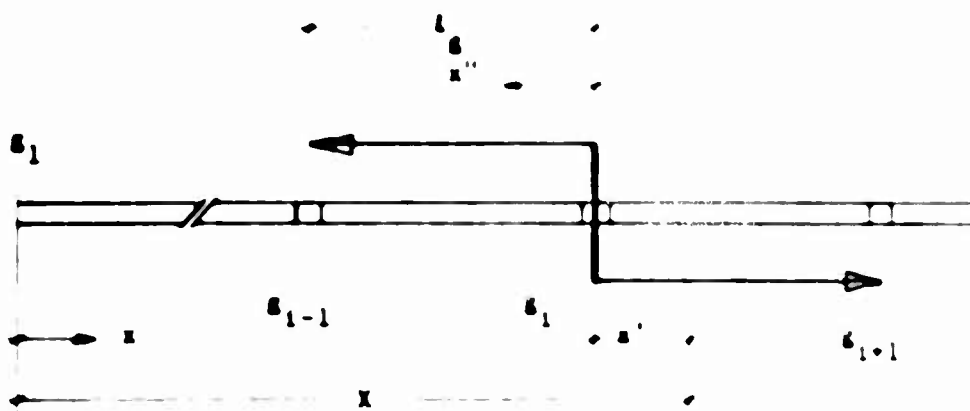


FIGURE 45: NOTATION FOR DIRECTIONAL DISPATCH FROM  $s_1$

A flow dependent travel time function of the form  $v_g = v_g(t) = f(q(t))$  is used to consider the different traffic flow rates over the time of day. The curve for an average highway speed of 60 m.p.h. with a speed limit at 50 m.p.h. (Figure 3.41 and 9.1 in [60]) adjusted to the Bridge capacity is assumed to be a representative flow/speed relationship for the Bay Bridge. The distribution of the traffic flow,  $q(t)$  over the time of day is given in Figure 25.

### 3.1.3.2 Service Available - Service Request Queues

As indicated in Chapter 2, one has to consider if a service unit is actually available or not at the time of its request for service. A counting system is, therefore, established, which keeps record on the requests and dispatches of vehicles in the form of service available and request queues. A vehicle can only be dispatched if there is an entry in the service available queue. If there is no entry in the queue, the next closest available service unit will be dispatched.

The travel time is, therefore, for the geometric layout of the linear freeway, actually

$$(1) \quad t_A = t_p + \frac{1}{v_g} (x' + s \cdot l_g) + t_{ay} \quad x' = \begin{cases} x' & \text{for } x \geq 0 \\ x'' & \text{for } x < 0 \end{cases}$$

$s = 0$ , if there is an entry in the queue at  $g_1$ ,  $s = 1$ , if the next closest service vehicle is dispatched, and  $s = 2$ , if the second closest unit has to be dispatched.

If neither of these service vehicles are available, or if all vehicles are busy at the time of request of service, a delay time,  $t_{ay}$ , has to be considered. This time is equal to the difference between the detection time  $st_d^I$  for incident  $I$  and the return time for the next available service vehicle  $IL$ ,  $st_r^{IL}$ :

$$(2) \quad t_{ay} = (T_{IL} + st_r^{IL}) - (T_I + st_d^I).$$

The service available queue and service request queues are represented as a matrix  $M$ , where the coefficients  $m_{ij}$  are equal to the number of service units available at each post. The rows correspond to the type of service. Row 1 represents the police units  $m_{1j} = g_{1j}$  and row 2 represents the mechanical service units  $m_{2j} = h_{2j}$ .

$$(3) \quad M_1 = \begin{bmatrix} g_{11} & g_{12} & \dots & g_{1n_g+1} \\ h_{21} & h_{22} & \dots & h_{2n_h+1} \end{bmatrix} = \begin{bmatrix} 1 \times (n_g+1) \\ g_1 \\ 1 \times (n_h+1) \\ h_1 \end{bmatrix}.$$

As soon as a vehicle is dispatched, the corresponding entry  $m_{ij}$  is reduced by 1 and an entry of 1 is made at  $r_{ij,1}$  in a "dispatch" vector,  $r_{1,1}$ , if the dispatched service unit is a police vehicle, or in vector  $r_{2,1}$ , if a mechanical service vehicle is dispatched.

For the police service available + request queue the dispatch vector  $r_{1,1}$  gets then an entry of 1 at  $r_{1j,1}$  while all other entries of the vector are zero, e.g.,

$$(4) \quad r_{1,1} = [0 \ 0 \ 0 \ 0 \ 1 \ 0 \ 0] = [r_{1j,1}] \quad r_{1j,1} = \begin{cases} 0 & \text{not busy} \\ 1 & \text{busy} \end{cases}$$

Before the dispatch of every unit, a check is made whether the service units have returned from incidents  $(1-1)$ ,  $(1-2)$ ,  $(1-3)$ , ..., to their original post and the vectors  $g$  and  $h$  are updated in the form

$$(5) \quad \begin{aligned} g_1 &= g_{1-1} + r_{1,1-1} & I &= 2 \\ g_1 &= g_{1-1} + r_{1,1-1} + r_{1,1-2} & I &= 3 \\ &\vdots & & \\ &\vdots & & \\ &\vdots & & \\ g_1 &= g_{1-1} + \sum_{L=1}^{I-1} r_{1,1-L} & I &\geq 2 \text{ and } L \geq 1 \end{aligned}$$

and in the vectors  $r_{1,1-L}$  the entries  $r_{1j}$  are set again equal to zero.

Matrix  $M_1$  with the vectors  $g_1$  and  $h_1$  gives, therefore, always the actual number of service units available at the time of a request of service for incident 1.

#### 3.1.4 On-Site Service

The activity "on-site service" encompasses all services provided at the location of the incident; such as protection of the scene, removal of blockages from the traffic lanes, service on the shoulders, law enforcement and accident investigation, hitching of vehicles to be towed away, etc. That means all services necessary, so that the status quo ante is achieved.

Little is known about the duration of stops. For the operation of a service system only the actual on-site time of a service vehicle is of interest. But if one looks at the total detection and service system, it would be desirable to know about the complete stop duration distribution, as to be able to decide which emergency service system fits best the given service need.

In the following section the stop-duration and later the on-site service time will be analyzed.

#### 5.1.4.1 Stop-Duration

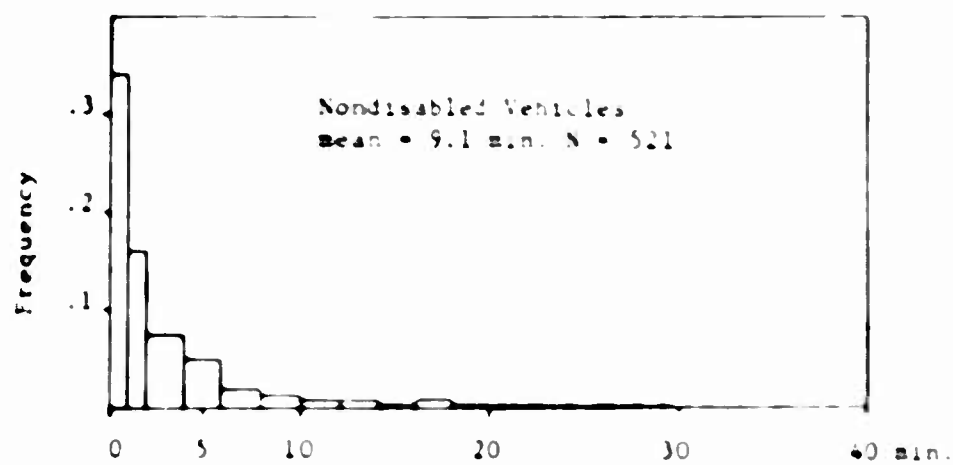
Very few studies report on the duration of incidents on freeways. The difficulty is to estimate the stoppage time before the detection of the incidents. This time is reduced in case of visual observation and the monitoring of TV surveillance systems. The data collected for study of stoppages on the John Lodge Freeway TV Surveillance Project in Detroit suggests a negative exponential distribution for the stop duration [23].

A similar study was conducted at the Eisenhower Expressway Surveillance Project in Chicago [37], where the stop duration was determined by observers positioned along the freeway. The data were presented by two stop types (1) disabled vehicles, and (2) nondisabled vehicles, see Figure 46. While for the nondisabled vehicle stoppages a negative exponential distribution appears to fit the data, the distribution of the disabled vehicle stoppage seems to be bi-modal. This might indicate that the duration of stoppages of vehicles follows a probability law which is a superposition of several distributions for the different types of stoppages.

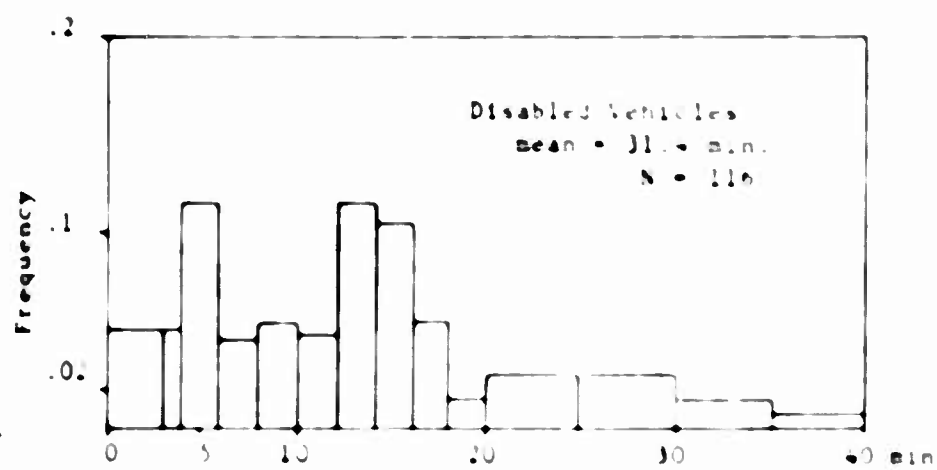
A superposition of an exponential probability law representing the nondisabled vehicle stops, and a normal probability law representing the disabled vehicle stops might fit the observation already quite well.

If  $p$  is the proportion of stops of nondisabled vehicles, and  $1 - p$  the proportion of disabled vehicles, then the mixed density function for a negative exponential and normal law would be

$$(1) \quad f(x) = p[e^{-\lambda x}] + (1 - p) \left[ \frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{1}{2} \left( \frac{x - \mu}{\sigma} \right)^2} \right].$$



Stoplevelth Frequencies for Nondisabled Vehicles



Stoplevelth Frequencies for Disabled Vehicles

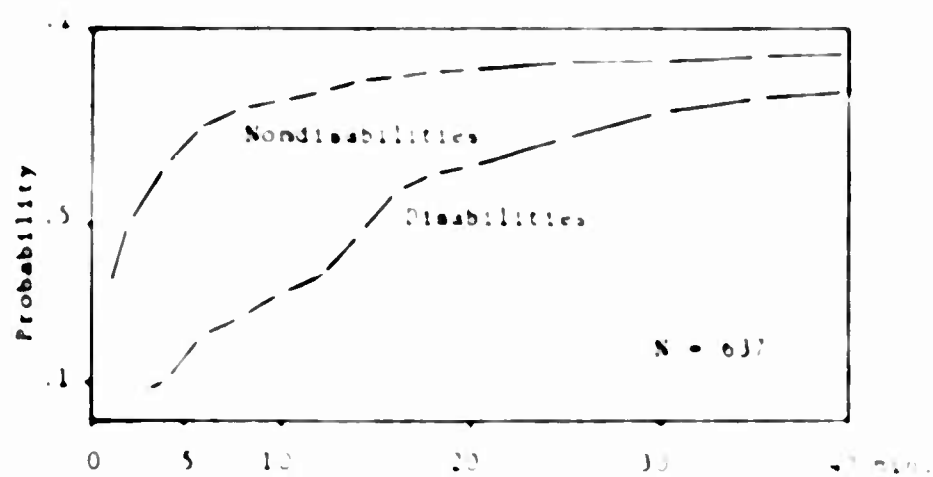
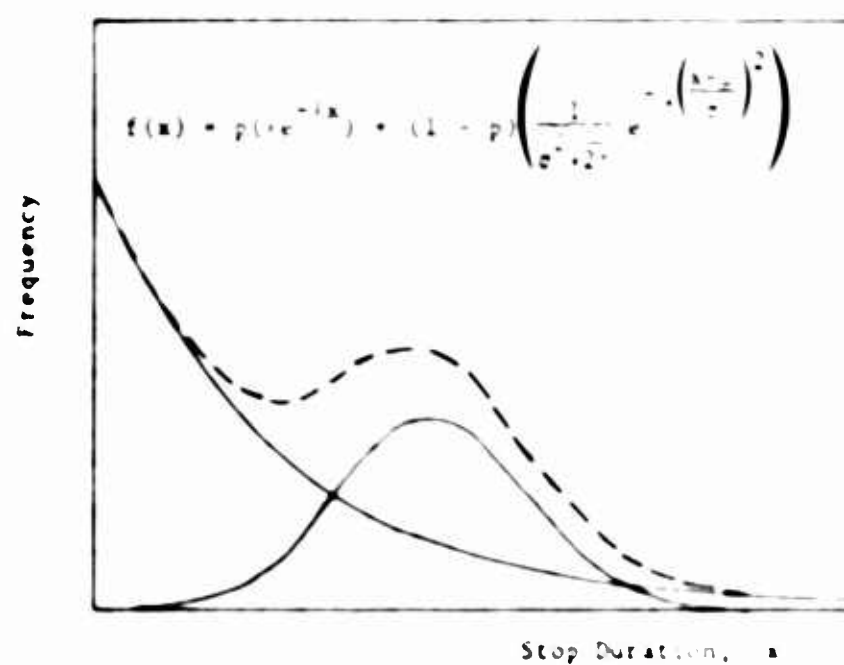
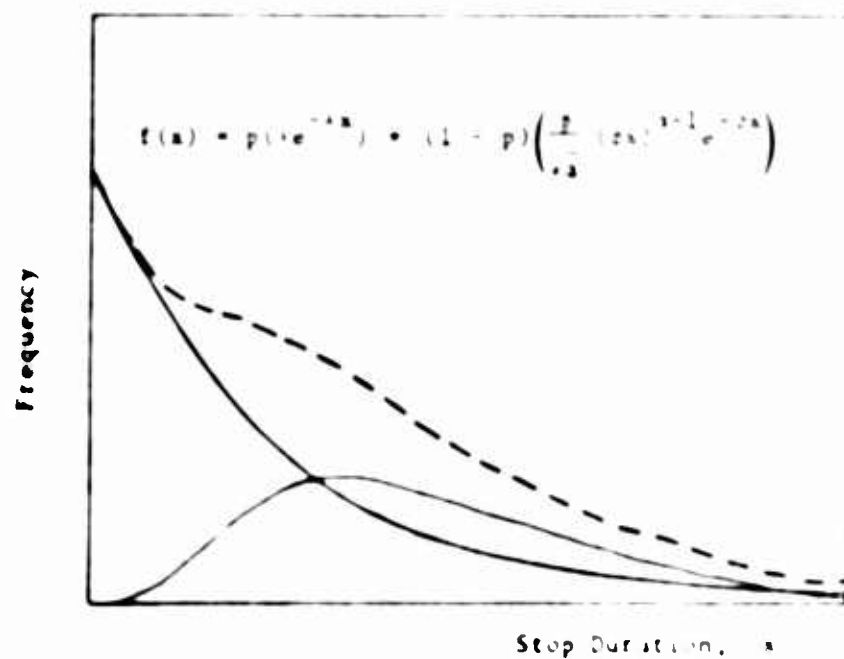


FIGURE 46 STOPLENGTH DISTRIBUTIONS FOR DISABLED AND NONDISABLED VEHICLES

EISENHOWER EXPRESSWAY, CHICAGO, 1962 (Adapted from [37])



Mixed Exponential - Normal Distribution



Mixed Exponential - Gamma Distribution

FIGURE 4. MIXED DISTRIBUTION FUNCTIONS FOR STOP DURATIONS

with expectation and variance

$$(2) \quad E(x) = p\lambda^{-1} + (1-p)\mu$$

$$(3) \quad \text{Var}(x) = -(\lambda^{-1} - \mu)^2 \cdot p^2 + (\lambda^{-1})^2 + (\lambda^{-1} - \mu)^2 \cdot p + \sigma^2.$$

The method for the estimation of these parameters is given in [130].

A similar density function for a mixed exponential and a gamma probability law can be anticipated of the form

$$(4) \quad f(x) = p[1e^{-\lambda x}] + (1-p) \frac{a}{\sqrt{a}} (ax)^{a-1} e^{-ax}.$$

Because of the lack of appropriate data, the models of mixed distribution could not be analyzed. A qualitative plot of these mixed distributions is shown in Figure 47.

#### 5.1.4.2 On-Site Service Time

For this study it is justified to look just at the actual observed on-site service times on the San Francisco - Oakland Bay Bridge and to neglect the nondisabled vehicles, because the analysis of emergency service systems is based on historical data of actual emergency services provided. The data on the on-site service time shown in Figure 27 proved not to be sufficient to derive a satisfying model from it. The observations were, therefore, extended to 12 weekdays (October 1-5, 2-11, 14-15, 1968) so that the sample size increased from 290 to 716 incidents. The observations are shown in Figure 48, stratified for different locations of the service rendered.

For all locations a goodness of fit test for a gamma distribution was made.

The Gamma density function has the form

$$(1) \quad f(x) = \begin{cases} \frac{\beta}{\sqrt{\alpha}} (\beta x)^{\alpha-1} e^{-\beta x} & x > 0 \\ 0 & \text{otherwise} \end{cases}$$

where  $x$  is the variate,  $\alpha$  the shape parameter and  $\beta$  the scale parameter. The parameters can be estimated via the maximum likelihood estimators as follows:

$$(2) \quad \hat{\alpha} = \frac{E^2(x)}{\text{Var}(x)} \quad \text{and} \quad \hat{\beta} = \frac{E(x)}{\text{Var}(x)}.$$

$\hat{\alpha}$  and  $\hat{\beta}$  were used as preliminary estimate in performing a  $\chi^2$  goodness of fit test. The estimates were then adjusted to  $\hat{\hat{\alpha}}$  and  $\hat{\hat{\beta}}$ , which provided in a smaller  $\chi^2$  value. For the  $\chi^2$  test the computational simpler form

$$(3) \quad \chi^2 = \frac{\sum_{i=1}^k (o_i - e_i)^2}{e_i} = \sum_{i=1}^k \frac{o_i^2}{e_i} - n$$

was used, where  $o_i$  is the observed frequency,  $e_i$  the theoretical frequency,  $n$  is the sample size and  $k$  the number of classes. The results of this analysis are presented in Figure 49, where also the level of significance is given against which the distributions are tested.

The analysis showed that one can assume that the gamma (Erlang) probability law can be used to represent the distribution of on-site times.

A better understanding of the distribution function for on-site service could be reached by stratifying the service times by type of services rendered, see Figure 23. One might presume then, that the former distribution is an enveloping distribution of a sum of distributions where possibly each is a normal law for each particular type of service. For this study the density function with  $\alpha = 3.0$  and  $\beta = .30$  (Figure 48c) is assumed to be representative for the service times on the Bay Bridge.

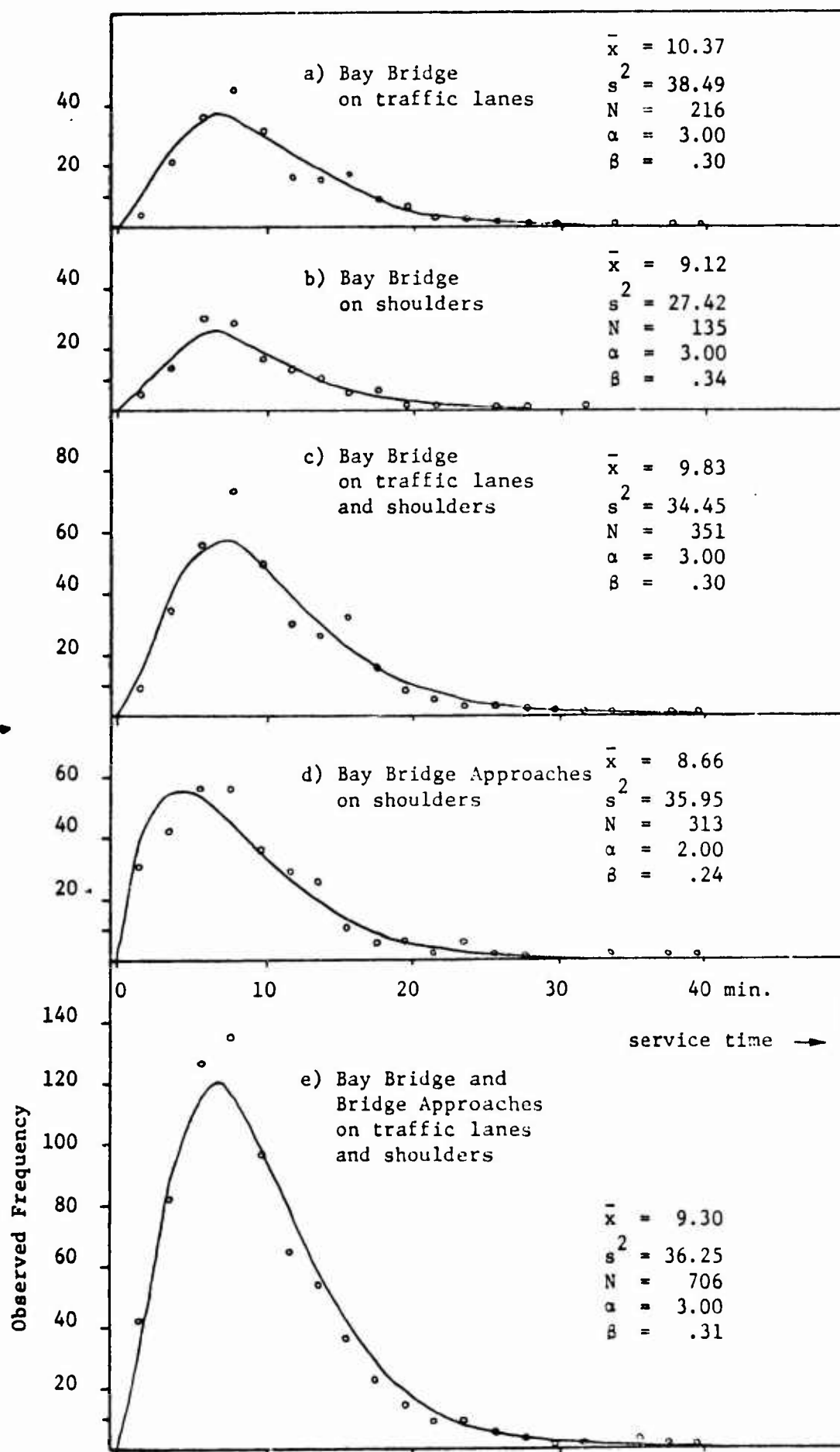


FIGURE 48: GAMMA (ERLANG) DISTRIBUTION FITTED TO SERVICE TIME DATA OF THE SAN FRANCISCO - OAKLAND BAY BRIDGE

| Location                                          | Number<br>Observations | mean<br>$\bar{x}$ | variance<br>$s^2$ | preliminary<br>estimate |     | adjusted<br>estimate |     | $\chi^2_c$ | d.o.f. | level of<br>significance<br>$\alpha$ |
|---------------------------------------------------|------------------------|-------------------|-------------------|-------------------------|-----|----------------------|-----|------------|--------|--------------------------------------|
| Bay Bridge<br>on traffic lanes                    | 216                    | 10.37             | 38.49             | 2.8                     | .27 | 3.                   | .30 | 13.94      | 7      | .05                                  |
| Bay Bridge<br>on shoulders                        | 135                    | 9.12              | 27.42             | 3.0                     | .33 | 3.                   | .34 | 5.95       | 6      | .05                                  |
| Bay Bridge Approaches<br>on shoulders             | 313                    | 8.66              | 35.95             | 2.1                     | .24 | 2.                   | .24 | 14.70      | 9      | .05                                  |
| Bay Bridge<br>on lanes & shoulders                | 351                    | 9.83              | 34.45             | 2.8                     | .29 | 3.                   | .30 | 19.62      | 10     | .02                                  |
| Bay Bridge & Approaches<br>on lanes and shoulders | 706                    | 9.30              | 36.25             | 2.4                     | .26 | 3.                   | .31 | 22.22      | 11     | .02                                  |

FIGURE 49: RESULTS OF  $\chi^2$  TESTS FOR ERLANG DISTRIBUTION FITTED TO  
ON-SITE SERVICE TIME DISTRIBUTIONS ON SF-O BAY BRIDGE

(Data for 12 weekdays, Oct. 1-5, 7-11, 14-15, 1968)

In the simulation routine variates from the gamma distribution cannot be directly generated from the cumulative distribution, because it is not defined explicitly [95]. Erlang variates can be generated by reproducing the random process on which the Erlang distribution is based.

This can be achieved by taking the sum of  $m$  exponential variates  $x_1, x_2, \dots, x_m$  with identical expectation  $1/\beta$ . Therefore, the Erlang variate  $x$  can be expressed as

$$(4) \quad x = \sum_{i=1}^m x_i = -\frac{1}{\beta} \sum_{i=1}^m \log R_i = -\frac{1}{\beta} \left( \log \prod_{i=1}^m R_i \right).$$

This form is then used in the simulation routine to generate Erlang variates where  $R_i$  are generated pseudo uniform  $(0,1)$  random numbers.

#### 5.1.5 Return Travel - Reavailability

The travel time of detection and service units from the scene of the incident back to the posts where they are stationed is called return travel time.

In case of patrols, the return travel time is assumed to be zero, because the vehicle just continues its patrol after it was interrupted by the on-site service activity.

The return travel time for service units at posts is computed from the distance which the service unit is away from its terminal or post. This distance is a function of the geometric layout of the freeway, the location of the incident and the terminal of the service unit as shown in Figure 50.

The return time for a police vehicle,  $t_r^g$  is then

$$(1) \quad t_r^g = (2 l_g - x')/v_g + s \cdot l_g / v_g \quad x' = \begin{cases} x' & X > g_1 l_g \\ x'' & X \leq g_1 l_g \end{cases}$$



where  $s = 0, 1, 2, 3$  dependent on the location where the service unit originated.  $g_1$  is the closest post to this incident, if no vehicle is available for service there, the next closest available post is  $g_0 = g_1 \pm s$  according to 5.1.3.2.

It is assumed that the speed of travel is flow and time dependent  $v_g = v_g(t, q(t))$ . The flow dependent travel time is then

$$(2) \quad t_r^g = \begin{cases} (l_g - x')/v_{gW} + l_g(1+s)/v_{gE} & X > g_1 l_g \\ (l_g - x'')/v_{gE} + l_g(1+s)/v_{gW} & X \leq g_1 l_g \end{cases}$$

because the service unit has to use the East and Westbound direction of the freeway.  $v_{gW}$  is the speed Westbound and  $v_{gE}$  the speed Eastbound.

The return travel time for mechanical service vehicles,  $t_r^h$  is determined in the same way as for the police vehicles, so that in the previous equations the index  $g$  is replaced by  $h$ .

If the mechanical service vehicle has to tow a disabled vehicle to a garage the return time  $t_r^h$  is increased by  $t_t$ , the towing time.

$$(3) \quad t_r^h = \begin{cases} t_t + (l_h - x')/v_{hW} + l_h(1+s)/v_{hE} & X > h_1 l_h \\ t_t + (l_h - x'')/v_{hE} + l_h(1+s)/v_{hW} & X \leq h_1 l_h \end{cases}$$

If a disabled vehicle has to be towed, it is assumed that the tow truck leaves the freeway at the closest exit and releases the vehicle at a garage in the adjacent tow zone. A tow zone is an area of size  $l_h \cdot 2 \cdot l_h'$ , with its center being an exit of the freeway, see Figure 51. For an urban environment  $l_h'$  is assumed to be two miles [68]. If one assumes that the garages are uniformly distributed over the area and that the street network is rectangular, the average distance from an exit to any garage is

$$(4) \quad \bar{d} = \int_0^{.5 \cdot l_h} \int_0^{l'_h} (x + y) f(x, y) dx dy$$

$$(4') \quad \bar{d} = \int_0^{.5 \cdot l_h} \int_0^{l'_h} \frac{1}{.5 \cdot l_h \cdot l'_h} (x + y) dx dy = 1 + \frac{1}{2} l'_h .$$

The travel time for a tow truck to and from the garage is then

$$(5) \quad t_t = (.5 \cdot l_h + 2) / v_h .$$

The reavailability of service units was already discussed in Section 5.1.3.2.

#### 5.1.6 Evaluation of Service Need

For the analyzed detection methods it is assumed, that through two-way communication the service need at the scene of the incident can be transmitted to the dispatcher of service vehicles. Only in case of single signal call boxes where no two-way communication exists, some time delay will be caused until the service need is determined.

Call boxes are assumed to be connected with the dispatcher of mechanical service. The evaluation time for call boxes is then equal to the time which passes from receiving of a call until the service unit arrives at the scene,  $t_e = t_a^h$ . If several detection and service systems interact on the freeway, the evaluation time,  $t_e$  is assumed to be the minimum of all arrival times of those systems which are in operation:

$$(1) \quad t_e = \min(t_a^a, t_a^b, t_a^f, t_a^h) \quad t_a^q > 0, q = a, b, f, h .$$

Any detection or service unit which arrives at the scene can identify the need for police and mechanical service.

### 5.1.7 Interacting Detection Systems

The detection models presented in Section 5.1.2 apply for individual detection subsystems. If several subsystems interact on one facility, a decision routine must be designed which decides, via which method the incident will be actually detected. It would be logical to take that method which gives the shortest detection time for a given incident. But if discrete communication terminals and patrolling vehicles for detection of incidents are operated at the same time, one has to consider the different characteristics of the methods. A patrolling unit will always detect an incident when it passes it, but a stranded motorist might not always use the communication terminal because he might think he can help himself.

The average walking time to a call box, spaced at 600 feet (e.g., SFOBB), is about half a minute, for a spacing of  $\frac{1}{2}$  mile this walking time is 2.5 minutes. On urban freeways the spacing is kept less than half a mile, and therefore, 2.5 minutes would be the longest average walking time. No other considered detection subsystem can achieve this average time economically. The data of the SFOBB show that about 50% of the incidents are reported from call boxes, Figure 22. This percentage could be used to decide which detection system was used or not.

For this study it was assumed that the stranded motorist is captive to use the communication terminals, so that he will use the emergency phone or box, if he arrives there before the incident is detected via a patrol.

If a call box is used, the routine described in the previous Subsection 5.1.6 applies. In case that a patrol detects the incident, the detection time is determined from the minimum arrival time of all detection systems,  $q$  in operations,

$$(1) \quad t_d = \min(t_a^a, t_a^b, t_a^f) \quad t_a^q > 0, q = a, b, f.$$

## 5.2 COST AND EFFECTIVENESS MEASURES AND MODELS

A general discussion of cost and effectiveness approach was given in Chapter 2.3. It was decided to take Dollars as the cost measurement. As measure of effectiveness three individual measures and three collective measurements were selected. In this section the costs of various emergency service systems are summarized, and models for the estimation of the effectiveness measures are discussed.

### 5.2.1 Cost Measure and Data for Emergency Service Systems

Section 4.3 describes the emergency service systems which are analyzed in this study. The estimation of costs is difficult, first because of the nonavailability of detailed data and second, because the costs change for different locations. To have a consistent basis, the costs compiled and determined by [102] were used for this analysis with adjustments where necessary.

Figure 42 summarizes these costs for the individual detection and service systems. In Appendix A, the basic assumptions behind the cost figures are listed. The costs are determined for Dollars/mile/year. Because in this study the operation of emergency service systems is evaluated on a daily basis, it is assumed that the yearly figure can be divided by 365 and then be applied for one day of operation. If one considers alternate candidate systems, it has to be recognized, that some costs can be reduced through the combination of several systems; e.g., the auxiliary equipment and manpower costs for a communication center of an emergency telephone system, if it is connected to a dispatch center of a mechanical service system.

If a call box or emergency telephone or detection patrol system is analyzed, its communication center is assumed to be also the dispatch center of the mechanical service.

|                        | Total<br>Cost<br>(\$/m/y) | Equipment<br>Cost<br>$c_{eq}$ (\$/u/y)      | Installation<br>Cost<br>$c_{in}$ (\$/u/y) | Operating<br>Maintenance<br>Cost<br>$c_{op}$ (\$/u/y)<br>$c_{op}'$ (\$/u/m) | Manpower<br>Cost<br>$c_{ma}$ (\$/u/y) | Auxiliary<br>Equipment<br>Cost<br>$c_{ac}$ (\$/y)<br>$c_{ac}'$ (\$/u/y) | Auxiliary<br>Manpower<br>Cost<br>$c_{am}$ (\$/y) |
|------------------------|---------------------------|---------------------------------------------|-------------------------------------------|-----------------------------------------------------------------------------|---------------------------------------|-------------------------------------------------------------------------|--------------------------------------------------|
|                        | 1                         | 2                                           | 3                                         | 4                                                                           | 5                                     | 6                                                                       | 7                                                |
| Call Box               | (1)                       | $c_c = 30 \cdot n_c / L + 60 \cdot n_c / L$ | $60 \cdot n_c / L$                        | $20 \cdot n_c / L$                                                          | ---                                   | $3000 / L$                                                              | $60000 / L$                                      |
| Emerg. Phone           | (2)                       | $c_e = 40 \cdot n_e / L + 80 \cdot n_e / L$ | $80 \cdot n_e / L$                        | $40 \cdot n_e / L$                                                          | ---                                   | $3000 / L$                                                              | $60000 / L$                                      |
| Detect. Patrol         | (3)                       | $c_f = 3000 \cdot n_f / L + \dots$          | ---                                       | $.08 \cdot n_f \cdot d_f / L$                                               | $30000 \cdot n_f / L$                 | $3000 / L + 300 \cdot n_f / L$                                          | $60000 / L$                                      |
| Police Patrol<br>Post  | (4)                       | $c_a = 4000 \cdot n_a / L + \dots$          | ---                                       | $.06 \cdot n_a \cdot d_a / L$                                               | $30000 \cdot n_a / L$                 | $3000 / L + 400 \cdot n_a / L$                                          | $60000 / L$                                      |
| Service Patrol<br>Post | (5)                       | $c_b = 8000 \cdot n_b / L + \dots$          | ---                                       | $.12 \cdot n_b \cdot d_b / L$                                               | $30000 \cdot n_b / L$                 | $3000 / L + 800 \cdot n_b / L$                                          | $60000 / L$                                      |

u = unit, e.g. communication terminal, patrol or service vehicle

$n_q$  = number of units of type q = a,b,c,e,f,g,h per study section of length, L (miles)

$d_q$  = (miles/unit/year) distance travelled per unit per year.  $c_g = c_a$  for  $g = a$

in (4)  $c_n = c_b$  for  $h = b$ . in (5)

FIGURE 52: COSTS FOR INDIVIDUAL DETECTION AND SERVICE SYSTEMS ([68] and adapted from [102])

### 5.2.2 Effectiveness Measures

The measures of effectiveness which will be used in this study are defined in Section 2.3, where it was differentiated between individual and collective measures. The individual effectiveness measures which apply to the stranded motorist, the detection time and the arrival of first service at the scene, can be derived directly from the models presented in 5.1. However, the collective measures, total delay and hazard of secondary accident (number of vehicles affected through the roadway blockage) have to be estimated via queueing models. The computation and estimation of these measures is discussed in the following paragraphs.

#### 5.2.2.1 Individual Effectiveness Measures

The primary interest of a stranded motorist, who needs help, is that he is detected quickly and that he can be sure that a service agency knows about his incident. A call box does not assure him that his request for service was received by the service agency. In this regard an emergency telephone has a definite advantage. The detection time and the arrival of first service are, therefore, used as the individual effectiveness measures.

The detection time for alternate emergency service systems can be derived from the models presented in 5.1.2. It is the minimum detection time which can be achieved through the different types of emergency service systems,  $q$

$$(1) \quad t_d = \min(t_d^a, t_d^b, t_d^c, t_d^e, t_d^f) \quad \text{for } t_d^q > 0$$

for  $q = a, b, c, e, f$ .

The arrival time of first service at the scene of either police or mechanical service is of great psychological importance for the stranded motorist and a fast arrival of service is necessary for his safety.

The arrival time of first service is determined from the minimum of all arrival times of the emergency service systems,  $q$  in operation

$$(2) \quad t_a = \min(st_a^a, st_a^g, st_a^b, st_a^h) \quad st_a^q > 0, q = a, g, b, h,$$

where  $st_a^q$  is the arrival time of a patrol or service unit of type  $q = a, b, g, h$ , at the scene of the incident after the occurrence of the incident.

#### 5.2.2.2 Collective Effectiveness Measures

The collective measures of effectiveness describe the effectiveness of the emergency service system to the passing motorists who are affected by the roadway blockage due to an incident. These are the blockage time, the total delay and the number of vehicles delayed.

The blockage of the roadway or a capacity reduction of the freeway is a hazard to the passing motorist. The shorter the blockage time is, due to an incident, the less danger exists for secondary accidents and the smaller are the delays imposed on the motorists.

The blockage time is the time period which passes from the occurrence of an incident until the event "end of on-site service." This time,  $t_b$ , is determined from the maximum blockage time of the roadway which is computed for the different service needs

$$(1) \quad t_b = \max(st_s^a, st_s^g, st_s^b, st_s^h) \quad st_s^q > 0, q = a, b, g, h$$

where  $q$  indicates the emergency service system studied and where  $st_s^q$  is the time of the end of on-site service. The blockage time is used as input to the queueing models as the time of reduced capacity,  $CR(I)$  due to incident  $I$ . The capacity reduction is assumed to be constant during the blockage time and proportional to the traffic lanes blocked as reported

in the San Francisco - Oakland Bay Bridge dispatcher's log. Only the capacity reduction caused in the intra-incident stage is considered.

### 5.2.3 Time Dependent Queueing Models

The delays caused through capacity reductions of a roadway can be estimated from models of queueing theory, in which from the input and output rate of a queueing system, predictions can be made on the number of delayed vehicles and the total queueing time. Two approaches are used to interpret the traffic flow in a queueing system. Either the input-output rate is treated as a stochastic process, or one disregards the discrete nature of vehicles and treats them as a continuous fluid.

For simple demand and capacity patterns mathematical formulations and solutions to deterministic and stochastic models exist [20, 98]. The analysis of time dependent arrival and departures rates complicates the mathematics of the queueing theory, in particular, the stochastic analysis [46, 85, 99]. The fluid approximation in which the cumulative arrival of vehicles  $A(t)$  is replaced by  $E[A(t)]$  always underestimates the queue length [98]. The analysis of sudden capacity reductions during rush hours with high traffic demand rates shows that the simpler deterministic model provides results for the means of queue length, delay and queueing time which are very close to those obtained by stochastic simulation [94]. For this study the deterministic approach is therefore used.

#### 5.2.3.1 Notation and Derivation of Queueing Characteristics for a Deterministic Queueing Model

$\lambda(t)$  denotes the arrival rate of vehicles which corresponds to the traffic demand rate at time of day,  $t$ . In Figure 25 the demand rate for the SFOBB is approximated by a piece-wise linear function for a typical weekday. The symbol  $\mu(t)$  represents the departure rate of the vehicles

from the queueing system which is assumed to be equal to the capacity of the roadway.  $\mu(t)$  is assumed to be constant over the length of the freeway. A recent engineering study determined that the capacity of the Bay Bridge is  $\mu_W = 8600$  vph (1720 vph per lane) Westbound, and  $\mu_E = 9000$  vph (1800 vph per lane) Eastbound, [113]. Higher flows are actually measured, but only for 15 minute periods [62]. It is assumed that the capacity is constant over time of day except during the blockage time during a traffic incident, when it is reduced to  $\mu(t) = \mu_{CR}(t)$  from time  $t = T$  to  $t = T + t_b$ .

$A(t)$  represents the cumulative arrivals of vehicles to time  $t$ ,  $A(t) = \int_0^t \lambda(t)dt$ , with a stepwise integration of the piece-wise linear demand rate  $\lambda(t)$ .  $D(t)$  is the cumulative number of departures from the system,  $D(t) = \int_0^t \mu(t)dt$ , and  $D^*(t)$  denotes the cumulative departures from the queue. The difference between  $D(t)$  and  $D^*(t)$  can be neglected for the fluid approximation, because there are at most a few vehicles in service.

According to the deterministic queueing approach, no delay is encountered until the demand rate  $\lambda(t)$  exceeds the capacity  $\mu(t)$ . As soon as  $\lambda(t) > \mu(t)$ , a queue starts to grow with time until  $\lambda(t) < \mu(t)$ , where the queue starts decreasing and then eventually vanishes.

If the queueing discipline in which the vehicles are served is in the order of their arrival (first in first out, FIFO) and as long as the starting time  $t$  is equal to zero, when the system is idle, the number of vehicles in the system at time  $t$  is the queue length,  $Q(t)$

$$(1) \quad Q(t) = A(t) - D(t) = \int_0^t (\lambda(t) - \mu(t))dt.$$

The queueing time lasts as long as there are vehicles in the system, one can

use, therefore, this expression to determine the queueing time,  $TQ$ .

In the computer program the integration is substituted by summations per time interval  $\Delta t$ . The analysis is done on a discrete time basis, the time interval  $\Delta t$  used being in the order of one minute. For each time interval  $i$  the number of arrivals  $\lambda(t_i)$  and departures  $\mu(t_i)$  are obtained. The process is started at  $\lambda(t_1) \geq \mu(t_1)$ , which is at time  $T$ , the occurrence of the capacity reduction where  $t_1 = 0$ ,  $i = 1$ , and  $Q(0) = 0$ . The number in the system at time  $t_j$  is updated in the form

$$(2) \quad Q(t_j) = \Delta t \sum_{i=1}^{j-1} (\lambda(t_i) - \mu(t_i)),$$

and a check is made whether the queue has dissipated or not. If it has not, the process is repeated with the appropriate value  $\lambda(t_i)$ ,  $\mu(t_i)$  for the next time interval. When the queue is dissipated, the queueing time can be obtained from

$$(3) \quad TQ = \Delta t \cdot nm \text{ where } nm = i \text{ at } Q(TQ) = 0.$$

The total queueing time,  $W$ , during the time interval  $TQ$ , is

$$(4) \quad W = \int_0^{TQ} Q(t) dt = \int_0^{TQ} (A(t) - D(t)) dt$$

or

$$(5) \quad W = \Delta t \cdot \sum_{i=1}^{nm} Q(t_i),$$

which is also geometrically interpreted as the area bounded by  $A(t)$  and  $D(t)$ . The total number of vehicles affected through the blockage,  $N$  which is used as an indicator for secondary accidents or incidents is

$$(6) \quad N = \mu(t) \cdot TQ = \sum_{i=1}^{i=nm} \lambda(t_i) .$$

In addition to the above measurements of effectiveness,  $N$  and  $W$ , two other characteristics are meaningful and can easily be derived from the already known equations.

The maximum queue length,  $Q_{\max}$  can be computed from the individual queue length at time  $t_i$  by

$$(7) \quad Q_{\max} = \max(Q(t_i)) \quad 1 \leq i \leq nm$$

it occurs at time  $t_{i=\max}$  where  $Q(t_i) = Q(t_{i=\max})$ . The average individual delay to the motorist in the queue,  $\bar{w}$  is

$$(8) \quad \bar{w} = W/N .$$

The use of the measure total delay,  $W$  has the disadvantage that it does not reflect the microscopic situation of the queueing system. It would be desirable to have an indication how long the individual vehicle was delayed, because it is quite a difference if 1000 vehicles are delayed for half an hour or 10,000 vehicles are delayed for 3 minutes even though both result in 500 vehicle hours total delay. The number of vehicles affected,  $N$  can be used to compute an average delay,  $\bar{w} = W/N$ , but this still does not say anything about the distribution of the individual delays. It would be more meaningful to determine the percentage or probability of  $y$  vehicles being delayed for  $x$  or less minutes.

#### 5.2.3.2 Multiple Incidents

With the formulas derived in the previous paragraph the collective measures of effectiveness, the total delay,  $W$  and the total number of

vehicles affected,  $N$  can be computed for each incident and also for a time period like a day for a specified number of simulation runs.

A complexity arises when several incidents occur at about the same time and the same location. In this case the arrival and departure rates of one incident influence those of the other incidents. A separate analysis of these incidents, not taking into account the changes in the input and output rates, would not give representative results. Incidents which block the roadway at about the same location (i.e., one call box spacing, ~600 feet on the SFOBB) are treated, therefore, as one incident; if the roadway is still blocked from incident 1 when incident 2 occurs. The total blockage time for two incidents occurring at time  $T_1$  and  $T_2$  is then assumed to be

$$(1) \quad t_b = \max(T_1 + t_{b,1}, T_2 + t_{b,2}) - T_1 \quad \text{if } T_1 + t_{b,1} \geq T_2.$$

If several incidents occur not at the same location, but about at the same time, so that the output rate of one incident affects the input rate at a downstream incident or the shock wave traveling back from one incident affects the output rate of an upstream incident location, the analysis becomes quite complicated. The queueing model can easily cope with the problem, but the formulation of the transient demand and service functions over time and space is beyond the scope of this study.

### 5.3 SIMULATION PROCESS

The analysis of alternative emergency service systems is performed with a computer program which combines the proposed models for the various activities to a next event simulation routine. Cost and effectiveness are computed using the output of the activity model and the models developed in Section 5.2.

Simulation in this context has dual interpretation. First, the program is used to simulate the operation of alternate detection and service systems

as a stochastic process where probabilistic models are used. Second, in the case that deterministic models are used, the routine just serves as a convenient means to perform elementary computations in a short time and as a housekeeping system to keep track of all events, activities, parameters and statistics analyzed in the evaluation of emergency service systems.

Most details of the routine concerning individual events and activities are already described in Section 5.1, so that in this section the overall concept of the program and simulation routine are discussed.

#### 5.3.1 Overall Structure of the Program DESERV

The computer program, "DESERV" is organized as a next event simulation routine where each major activity is represented as one or more subroutines. Consideration is given to each individual incident,  $I$ , and the sequence of events after the incident occurrence is simulated until all service requirements are fulfilled and the detection and service units are in a stage of reavailability for the next incident,  $I + 1$ . After each incident the summations for the statistics, mean and variance of the output values are updated. The same procedure is followed for the incidents  $I + 1, I + 2, \dots$ , until  $I = NO$ , the total number of incidents (e.g., per day) analyzed. If all  $NO$  incidents are analyzed once, one iteration,  $J$  of the simulation is completed. At the end of each iteration, the mean and variance are computed for the  $NO$  incidents. The entire process is repeated then for as many iterations,  $JJ$  as needed. Finally, the mean and variance are computed for the output values after  $JJ$  iterations. If more than one day is studied, the daily statistics are stored and the program is restarted by reading the input characteristics for the next day to be analyzed. After all days are analyzed the statistics mean, variance and standard deviation are computed from the stored daily data (see Appendix B.). A flow chart of this program is presented in Figure 53.

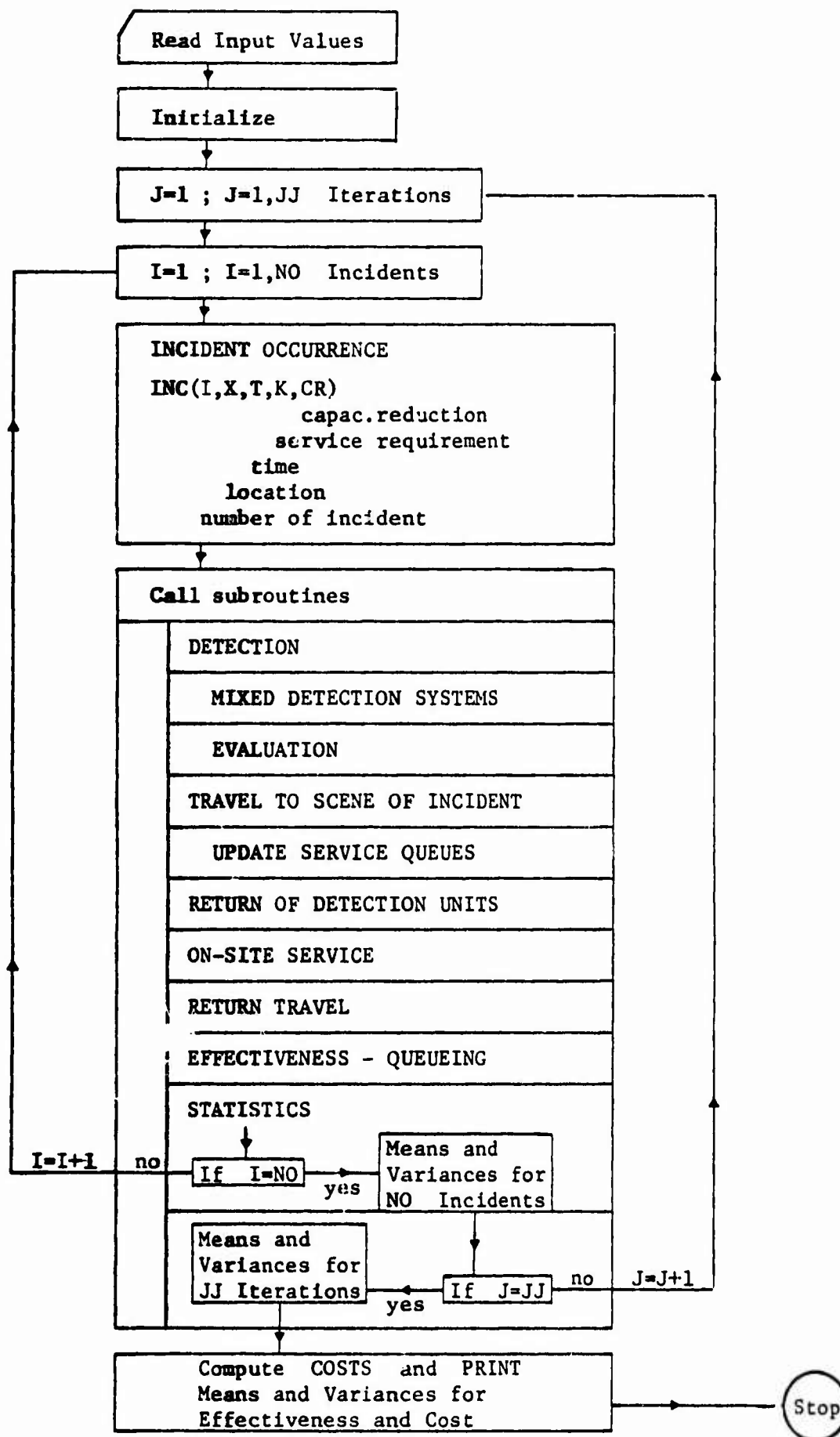


FIGURE 53: FLOW CHART FOR SIMULATION PROGRAM "DESERV"

The program is written in FORTRAN IV language for a CDC 6400 computer. The program has about 5,000 statements and it takes 60 seconds to compile from the source deck and 5 seconds to start from a binary deck. To run 100 iterations for one incident takes about 3-4 seconds, depending on the type of incident and emergency service system studied.

### 5.3.2 Details of the Simulation Program

An incident is identified in the simulation routine by its number,  $I$  the time of occurrence,  $T_I$  and location of  $X_I$  and its service requirement  $K_I$ .  $T$  is the time of day in minutes. Any activity time generated for incident  $I$  is added to the clock time  $T$ , so that at any time of the simulation the state of service of an incident can be derived from the clock time. This becomes important when several incidents have to be served simultaneously, and the queueing process for service vehicles occurs.

The computation of the queueing characteristics through numerical integration, see Section 5.2.3.1, is very time consuming. For each incident a check is therefore made, if during the time of blockage  $t_b$ , the capacity rate  $\mu$ , is smaller than the demand rate  $\lambda$ , and only if  $\lambda > \mu$  during  $t_b$ , the queueing model has to be used. This fact reduces the average computation time from about .1 seconds to .015 seconds per incident and iteration.

The analysis of alternate emergency service systems has to be based on equal assumptions, so that the results later can be compared. This becomes important in the simulation of stochastic processes, where the random variates are determined from pseudo uniform random numbers. For this study a distinct set of random numbers is therefore generated for each probability model in the program, so that, for example, for each combination of detection and service systems the same series of on-site service time variates is generated. Or, of the police patrol model (A) is matched with 2, 3 or 4

stationary mechanical service posts  $(H, H^*, H^{**})$ , the same series of random variates is used for the police arrival times for the different mechanical service patterns.

In case that interacting detection subsystems are studied, each detection subsystem is identified by a binary number, that is a number of power  $e$  of base 2. For example, the police patrol is assigned the number 8, which is equal to  $2^3$  for  $e = 3$ . The emergency telephone system has code  $2 = 2^1$ ,  $e = 1$ . An interacting detection system is then uniquely characterized by the sum of the corresponding binary numbers, e.g.,  $2 + 8 = 10$  for police patrol and emergency telephones.

### 5.3.3 Determination of Statistics and the Number of Realizations

In the simulation routine the effectiveness data (e.g. detection time, total delay),  $x_{ijk}$  are computed for each incident  $i$  on day  $k$  for iteration  $j$  as indicated in Subsection 5.3.1. The mean and pooled variance for the five days are computed from  $x_{ijk}$  according to the Equation (B-5, B-6 and B-11, B-12) in Appendix B to obtain the individual and collective measures of effectiveness representative for the total study period. In the case where the dimension of the effectiveness measure was time (detection time, arrival time of service, and blockage time) these computations were based on the means,  $x_{.jk}$ , which are the average times per day  $k$  and iteration  $j$  (see Equation (B-1)). For the other two measures, total delay and number of delayed vehicles, the basis for the computations was the sum of, for example, the total delays for one day (16 hour period),  $x_{\Sigma,jk}$  (see Equation (B-8)).

A preliminary analysis was made to determine the number of iterations to be used in the computation of the effectiveness measures. For the candidate system 13, (Police and Mechanical Service Patrol), with highly stochastic model representations, the mean and pooled variances for the total

number of vehicles affected through a blockage, were plotted in Figure 54. The results indicate that the mean of  $N$ , the number of delayed vehicles for Tuesday and Thursday reaches a level which is hardly changed after 100 realizations. A similar analysis is shown for the system 3, (Emergency Telephone, Stationary Police and Mechanical Service Units), see Figure 55. While  $N$  is highly dependent on the number of iterations  $n_j$ , the influence of  $n_j$  on the blockage time is minimal after 50 iterations. The reason that  $N$  is more dependent on  $n_j$  lies in the fact, that only about 20% of the incidents generate delays, so that actually at 100 iterations only about 20  $N$ 's are simulated. For this study each candidate system is, therefore, analyzed with 100 realizations of each day.

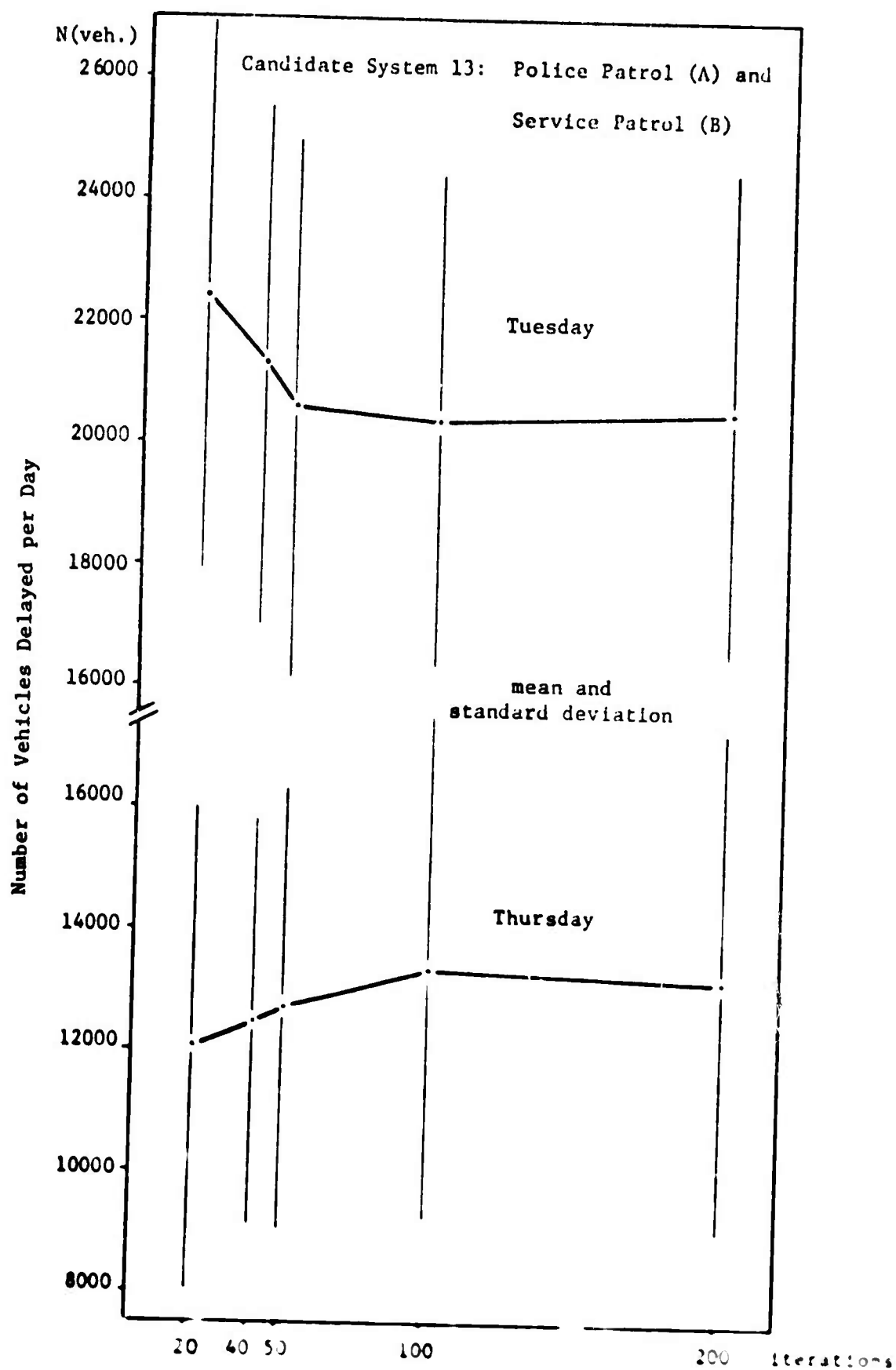


FIGURE 54. EFFECT OF NUMBER OF ITERATIONS ON QUEUING CHARACTERISTICS

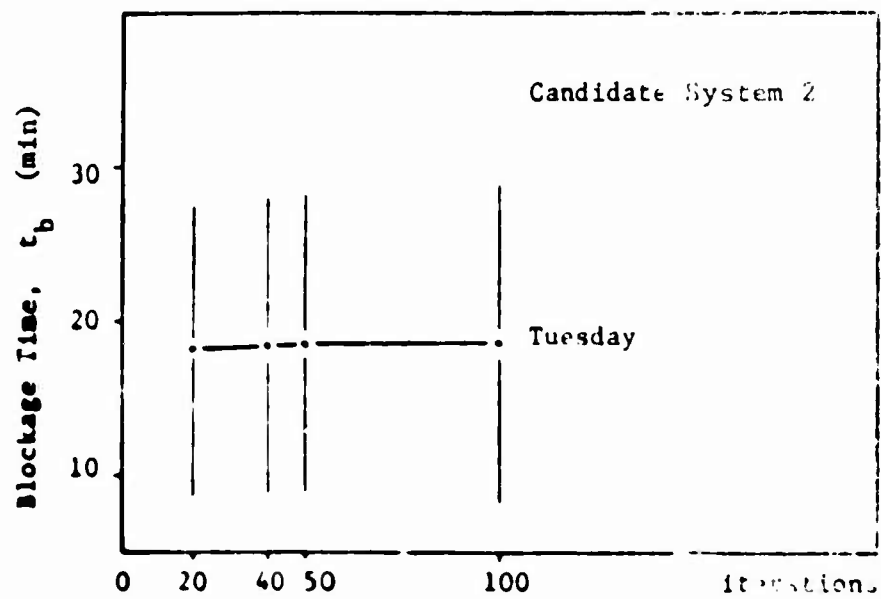
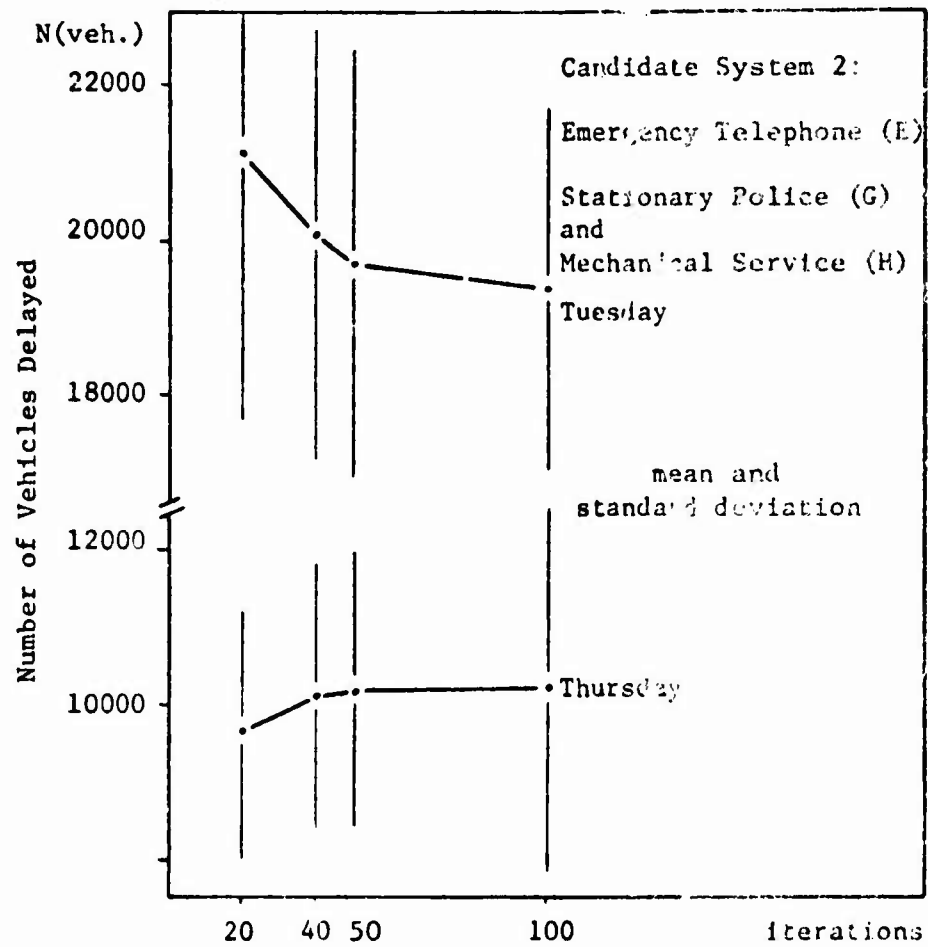


FIGURE 55 EFFECT OF NUMBER OF ITERATIONS ON QUEUEING CHARACTERISTICS

## CHAPTER 6

### ANALYSIS AND RESULTS

The fifteen candidate systems which will be analyzed in this study are presented as a blend of detection and service subsystems in Section 4.3. A difficulty in analyzing the emergency service systems lies in the fact that a large number of parameters influence the systems. It is, therefore, necessary to look at very basic designs so as to be able to compare the results of the study. In Figure 56 these candidate systems are again summarized and codes are attached to them with which they will be identified in the further text.

The variation of the operations of various subsystems over the day is excluded by investigating only incidents occurring during the day and swing shift, i.e., during 16 hours from 6 a.m. to 10 p.m. During one shift the assignment of personnel changes little and the swing and day shift have about the same manning. The cost figures derived in Subsection 5.2.1 are, therefore, scaled down linearly from Dollars/Mile/Day to Dollars/Mile/16 Hours.

The analysis of alternate emergency service systems is based on a sample of incidents occurring from Monday through Friday of one week on the San Francisco-Oakland Bay Bridge. (See Subsections 4.1.3.1, 5.1.1.2 and Appendix E.) For all five days it is assumed that the traffic demand rate, measured for the Tuesday can be taken as representative for all five days. This will introduce some errors in the computation of delays, particularly for Monday and Friday when the demand rate differs from that of midweek.

In the first section of this chapter the multiplicity of effectiveness measures analyzed is reviewed and a justification is given for why the total delay was chosen as the representative measure of effectiveness for the cost/effectiveness analysis.

| Candidate System                                 | Detection and Service Subsystems                                                       |
|--------------------------------------------------|----------------------------------------------------------------------------------------|
| 1. [box; stat. pol. + mech. (1-1)]               | Call Box<br>Stationary Police (1-1) and Mechanical (1-1) Service Units                 |
| 2. [box; stat. pol. + mech. (1-1-1)]             | Call Box<br>Stationary Police (1-1) and Mechanical (1-1-1) Service Units               |
| 3. [phone; stat. pol. + mech. (1-1)]             | Emergency Telephone<br>Stationary Police (1-1) and Mechanical (1-1) Service Units      |
| 4. [phone; stat. pol. + mech. (1-1-1)]           | Emergency Telephone<br>Stationary Police (1-1) and Mechanical (1-1-1) Service Units    |
| 5. [phone; stat. pol. + mech. (1-2-1)]           | Emergency Telephone<br>Stationary Police (1-1) and Mechanical (1-2-1) Service Units    |
| 6. [phone; stat. pol. + mech. (2-2)]             | Emergency Telephone<br>Stationary Police (1-1) and Mechanical (2-2) Service Units      |
| 7. [pat. det. (1); stat. pol. + mech. (1-1-1)]   | Detection Patrol (1)<br>Stationary Police (1-1) and Mechanical (1-1-1) Service Units   |
| 8. [pat. det. (1,1); stat. pol. + mech. (1-1-1)] | Detection Patrol (1,1)<br>Stationary Police (1-1) and Mechanical (1-1-1) Service Units |
| 9. [pat. pol.; stat. mech. (1-1)]                | Police Patrol (1,1)<br>Stationary Mechanical (1-1) Service Units                       |
| 10. [pat. pol.; stat. mech (1-1-1)]              | Police Patrol (1,1)<br>Stationary Mechanical (1-1-1) Service Units                     |
| 11. [pat. mech.; stat. pol.]                     | Mechanical Service Patrol (1,1)<br>Stationary Police (1-1) Units                       |
| 12. [pat. mech.; stat. pol. (1-1-1)]             | Mechanical Service Patrol (1,1)<br>Stationary Police (1-1-1) Units                     |

FIGURE 56: DETECTION AND SERVICE SUBSYSTEMS OF THE 15 CANDIDATE SYSTEMS

| Candidate System                             | Detection and Service Subsystems                                                           |
|----------------------------------------------|--------------------------------------------------------------------------------------------|
| 13. [pat. pol. + pat. mech.]                 | Police (1,1) and Mechanical (1,1) Service Patrol                                           |
| 14. [phone + pat. pol.; stat. mech. (1-1-1)] | Emergency Telephone and Police Patrol (1,1)<br>Stationary Mechanical (1-1-1) Service Units |
| 15. [pat. det. + pat. mech.; stat. pol.]     | Detection (1) and Mechanical (1,1) Service Patrol<br>Stationary Police (1-1) Units         |

FIGURE 56 (CONTINUED): DETECTION AND SERVICE SUBSYSTEMS OF THE 15 CANDIDATE SYSTEMS

In the second section an overall discussion is presented of the results of the cost/effectiveness analysis of emergency service systems and the dominating candidate systems are identified.

The variation of the effectiveness measures for the different days of the week is studied in section three, where also an analysis of variance is performed for the variation of the total delay for the fifteen candidate systems.

Qualitative and quantitative differences of the candidate systems are discussed in the Section 6.4. The optimum number and location is determined for mechanical service units assigned to posts along the freeway in this section, too.

In the last section the individual effectiveness measures detection time and arrival time of service are analyzed which give an insight why certain candidate systems dominated others in the cost/effectiveness analysis.

#### 6.1 CORRELATION BETWEEN EFFECTIVENESS MEASURES

The fifteen emergency service systems were analyzed with the next-event simulation routine. The results of this study are summarized in Figure 57, where the 15 candidates systems are arranged in ranking order for the cost and effectiveness measures considered. The data refer to average values per day<sup>†</sup> (16 hours) computed for the total study period of the day and swing shifts (16 hours) of the five days from a Monday to a Friday (see Appendix B).

From the ranking of the candidate systems of Figure 57 it becomes apparent that for all systems studied the effectiveness measures follow the same trend per system if compared with the other systems. Further analysis of the results indicate that there exists a high correlation between the

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<sup>†</sup>The term day is used in the further text synonymous to the 16 hour period from 6 a.m. to 10 p.m. per 24 hour day.

FIGURE 57: RANKING OF RESULTS OF COST AND EFFECTIVENESS MEASURES FOR THE 15 CANDIDATE SYSTEMS

arrival time of mechanical service and the collective measures of effectiveness, particularly with the blockage time. This is due to the fact that the on-site service time assumed in this analysis is independent of the service subsystem and equal for all candidate systems (see Subsection 5.3.2). The blockage time itself is, therefore, of little further information, but its effect on the total delay and the number of delayed vehicles is very critical.

The blockage time is computed as an average for all 95 incidents. The total delay and the number of vehicles delayed, however, are estimated from the blockage time of the 15 to 16 incidents, which cause delays during the study period. Nevertheless, the results of the study indicate a strong correlation between the mean daily blockage time,  $t_b$ , and  $N$  the mean sum of vehicles delayed per day, see Figure 58a. It is less significant for  $t_b$  and  $W$  the mean sum of delays per day; see Figure 58b. The variations are explainable, because  $N$  and  $W$  are sums of all delays occurring at different times over the day and, therefore, at different traffic demands.

The total delay and the number of delayed vehicles are highly correlated for the given data range as Figure 59 shows. For both measures of effectiveness a decrease in their value indicates an improvement; however, as the regression line indicates, there are still some variations in the data.

For the interpretation of the results of the analysis of the fifteen candidate systems, the total delay,  $W$ , is assumed to be the representative measure of effectiveness. This measure has the advantage that implied in it is a measure of time. If one wants then to assign a cost measure to time in this case, dollars per vehicle hour, the total delay plotted in a cost/effectiveness diagram becomes very informative.

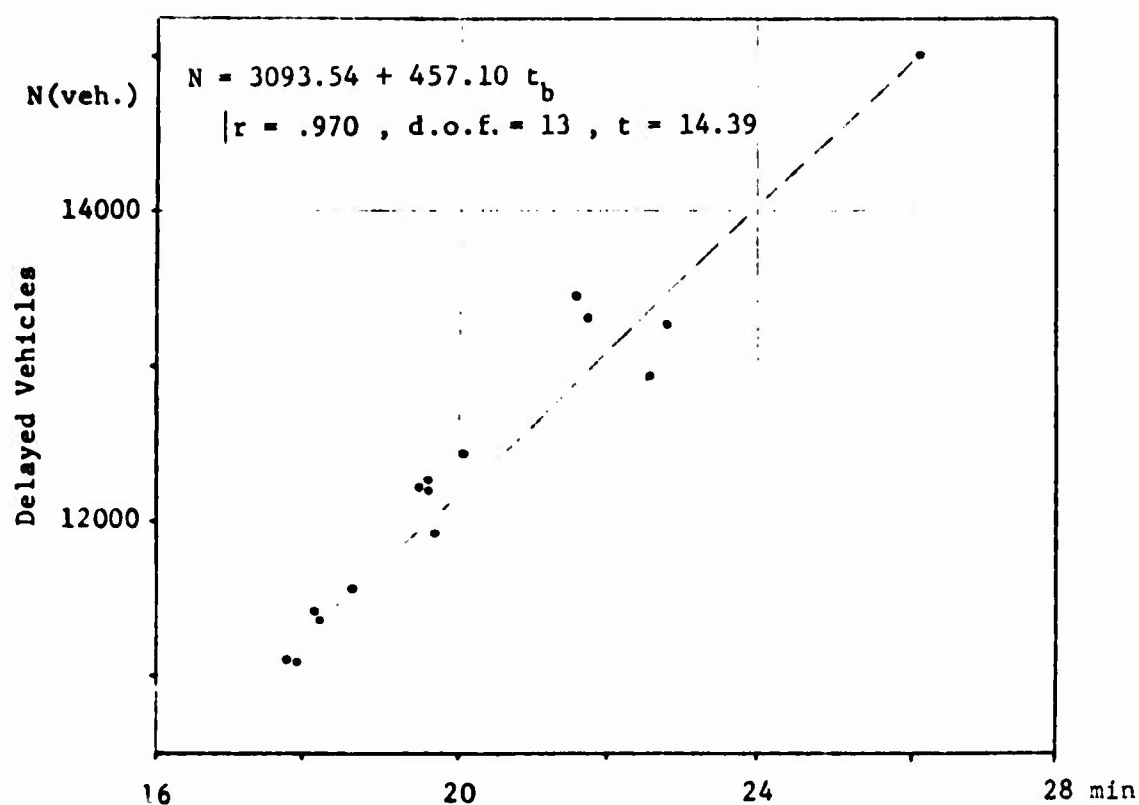


FIGURE 58a: TOTAL NUMBER OF VEHICLES DELAYED AS A FUNCTION OF THE BLOCKAGE TIME

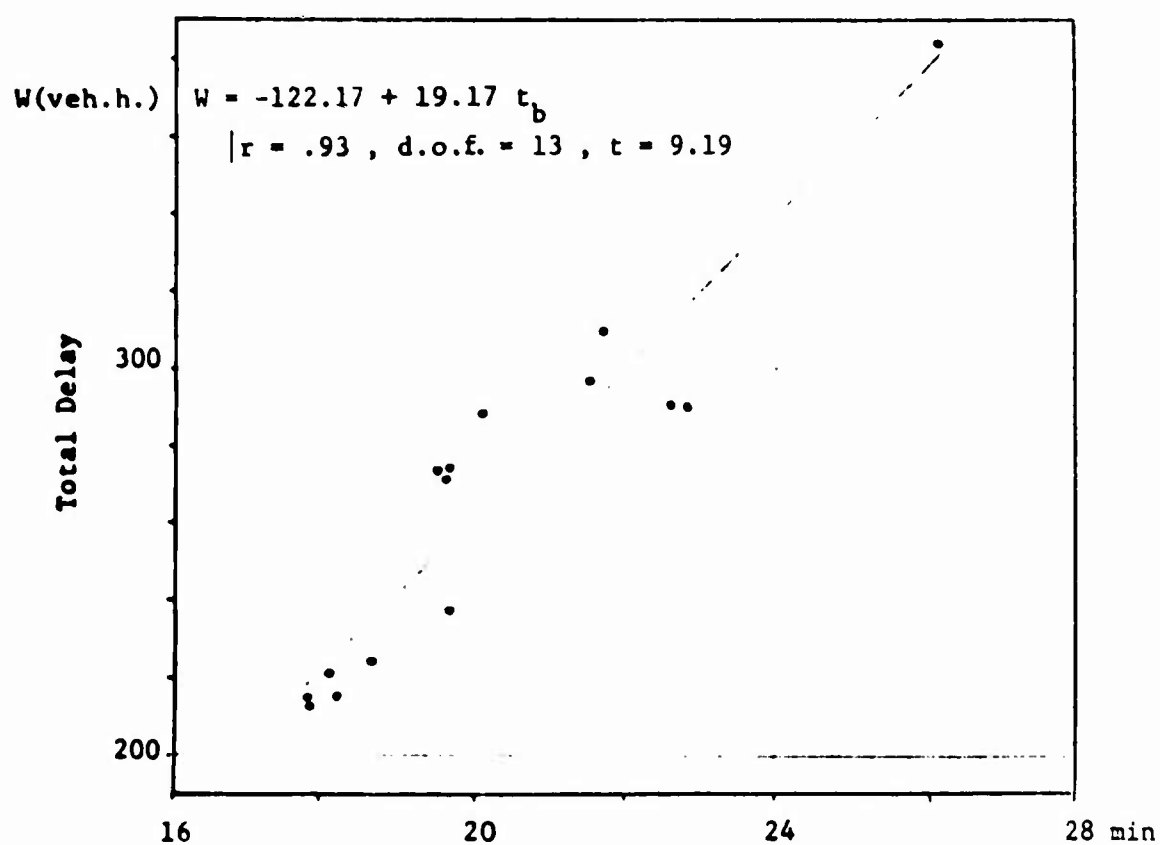


FIGURE 58b: TOTAL DELAY AS A FUNCTION OF BLOCKAGE TIME FOR THE 15 CANDIDATE SYSTEMS

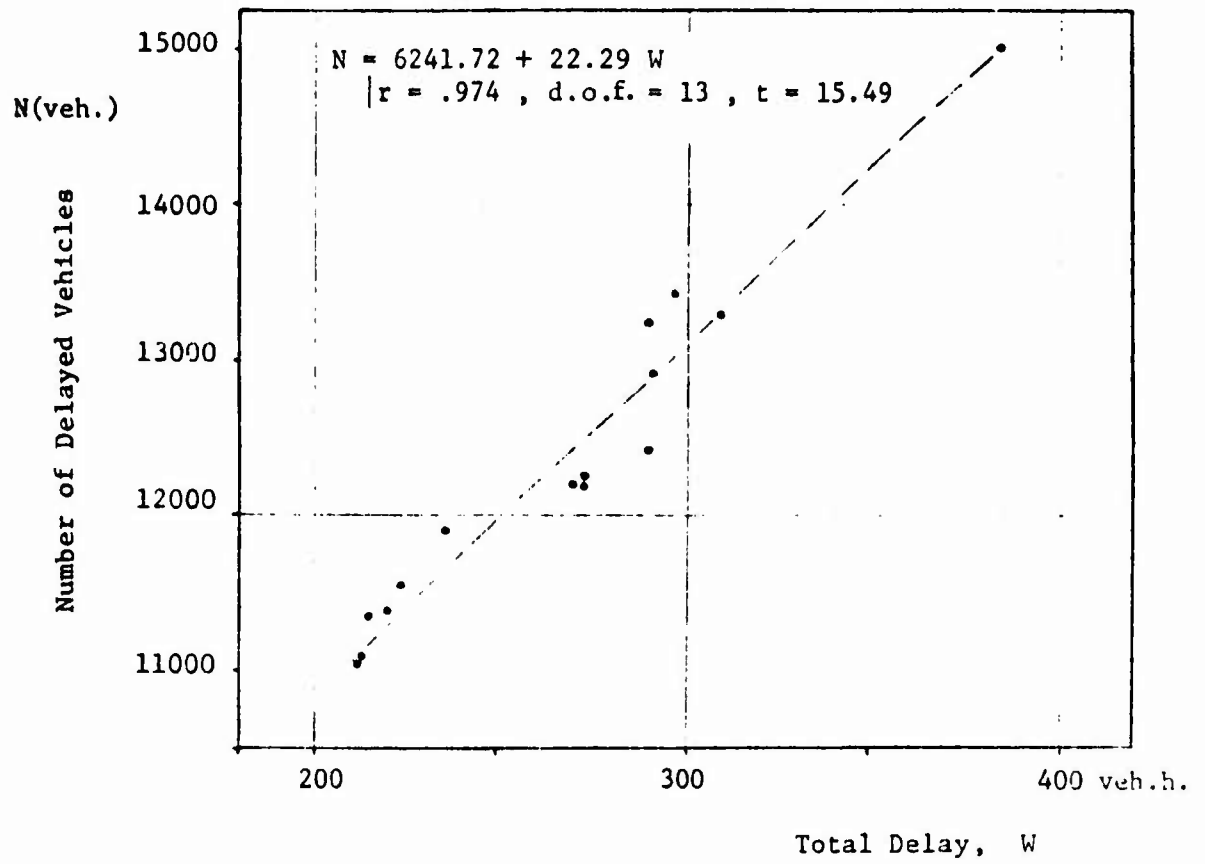


FIGURE 59: RELATION BETWEEN TOTAL DELAY AND NO VEHICLES DELAYED FOR THE 11 CANDIDATE SYSTEMS

## 6.2 COST AND EFFECTIVENESS ANALYSIS

In the preceding section it was shown that the total delay can be considered as a representative measure of effectiveness for the evaluation of alternate emergency service systems. Figure 55 indicates that candidate system 1 [box; stat. pol. + mech. (1 - 1)] is the least expensive system to install. Relative to this system the other 14 candidate systems are plotted in the cost/effectiveness diagram of Figure 60. In this diagram the abscissa gives the additional expenditures necessary to install any of the 14 other candidate systems and the ordinate gives the reduction of total delay which can be achieved. The numbers assigned to the data points refer to the candidate systems and if data points are connected with a line, it means that the systems are directly comparable, i.e., in system 7 and 8 the service subsystem [stat. pol. + mech. (1 - 1 - 1)] is kept the same, while the detection subsystem varies from one detection patrol (system 7) to two patrols (system 8) per study section.

The cost/effectiveness diagram indicates clearly that systems 1 [box; stat. pol. + mech. (1 - 1)] and system 3 [phone; stat. pol. + mech. (1 - 1)] are the most economical candidate systems. System 2 [box; stat. pol. + mech. (1 - 1 - 1)] and system 4 [phone, stat. pol. + mech. (1 - 1 - 1)] achieve the lowest cost/effectiveness and prove, therefore, to be the best systems analyzed in this study. All four systems rely on the discrete communication terminals as the detection subsystem and on stationary service vehicles spaced at 5, or 2.5 miles intervals. The gain achieved by improving the basic emergency service system (system 1) to system 2 is unmatched by any of the other candidate systems. The reduction in total delay in this case is achieved by stationing one more mechanical service unit in the middle of the study section. This improvement is also reflected in the reduction of delays by changing system 3 [phone; stat. pol. + mech. (1 - 1)]

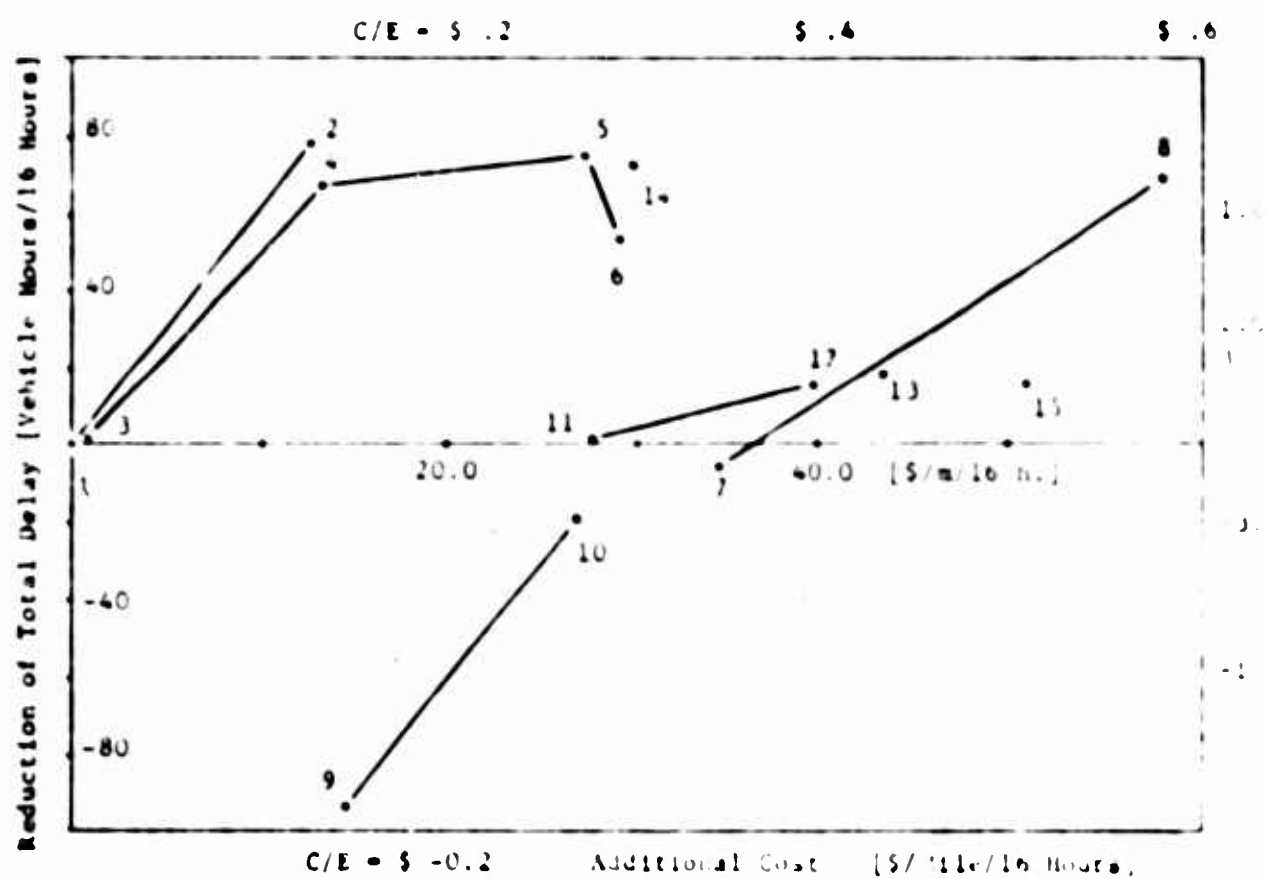


FIGURE 60: COST/EFFECTIVENESS DIAGRAM FOR 15 CANDIDATE SYSTEMS  
(Reduction of Total Delay and Increase of Cost for  
14 Candidate Systems Relative to Candidate System 1)

to system 4 [phone, stat. pol. + mech. (1 - 1 - 1)], and system 9 [pat. pol.; stat. mech. (1 - 1)] to system 10 [pat. pol.; stat. mech. (1 - 1 - 1)]

All candidate systems which rely on either detection or service patrols (systems 7, 8, 9, 10, 11, 12, 13 and 14) are less cost/effective than the ones which rely on discrete communication terminals. This becomes obvious if one looks at the relative position of these systems to the basic system 1:

The worst results are achieved with systems 9 and 10. The blend of police patrols with two (system 9) or three (system 10) stationary mechanical service units, results in a negative cost/effectiveness ratio relative to system 1.

If the detection occurs through mechanical service patrols (systems 11 and 12) some delay reduction can be achieved, but the increased cost make these systems still not preferable to system 1.

The use of detection patrols, i.e., motorcycles patrolling the freeway only for the purpose of incident detection, are also not competitive (systems 7 and 8).

Of the candidate systems with mixed detection systems only system 14 [phone + pat. pol.; stat. mech. (1 - 1 - 1)] achieves a cost/effectiveness ratio relative to system 1 which makes it compatible.

### 6.3 VARIATION OF COST AND EFFECTIVENESS MEASURES

The cost figures used in this analysis are rather crude and are subject to change over time so that better estimates might be available, which would change the relative position of some candidate systems in the cost and effectiveness diagrams. To allow a later refinement of these results the intermediate output of the simulation routine relevant to the cost models of Subsection 5.2.1 are presented in Appendix E.

The emphasis in the interpretation of the results has been on the mean values computed for the measures of effectiveness per study period.

However, if one looks at the variation of these means which are computed from pooled variances per study period (see Equations (B-6) and (B-12)) one realizes that almost every mean for a candidate system lies in the range of the standard deviation of the other candidate systems, see Figure 61.

The large variations can be explained if one looks at the analysis of individual days where the total delay differs drastically, depending on the number and the occurrence of the incidents over the time of day. Figure 62 shows the total delay for the individual five days of the week (Equations (B-9) and (B-10)) as well as the mean for the five days and their pooled standard deviation (Equations (B-11) and (B-12)). These statistics are plotted for candidate systems 2 and 9, two systems which give extreme results in Figure 57. In Figure 63 the mean and standard deviation of the blockage time (Equations (B-5) and (B-6)) are displayed for the same systems and days.

The pooled variances take into account the variations in the delays due to the day by day fluctuations of the incident occurrences over time and space. The result, however, can be improved by taking advantage of a feature of the simulation routine, which is that all candidate systems were analyzed with the same array of random numbers to generate the completion times for the relevant activities for each system (see Subsection 5.3.2).

Taking into account this property of the simulation process and considering the relation between the performance of the candidate systems,  $t_i$ , on the different days an analysis of variance model for a two-way layout was designed. For this model the usual made assumption of equal variances,  $\sigma^2$ , [11] does not hold true so that the individual variances for each candidate system had to be determined from a set of 15 simultaneous equations. (See Appendix D for the analysis of variance model and the derivation of the  $\sigma_i^2$ .)

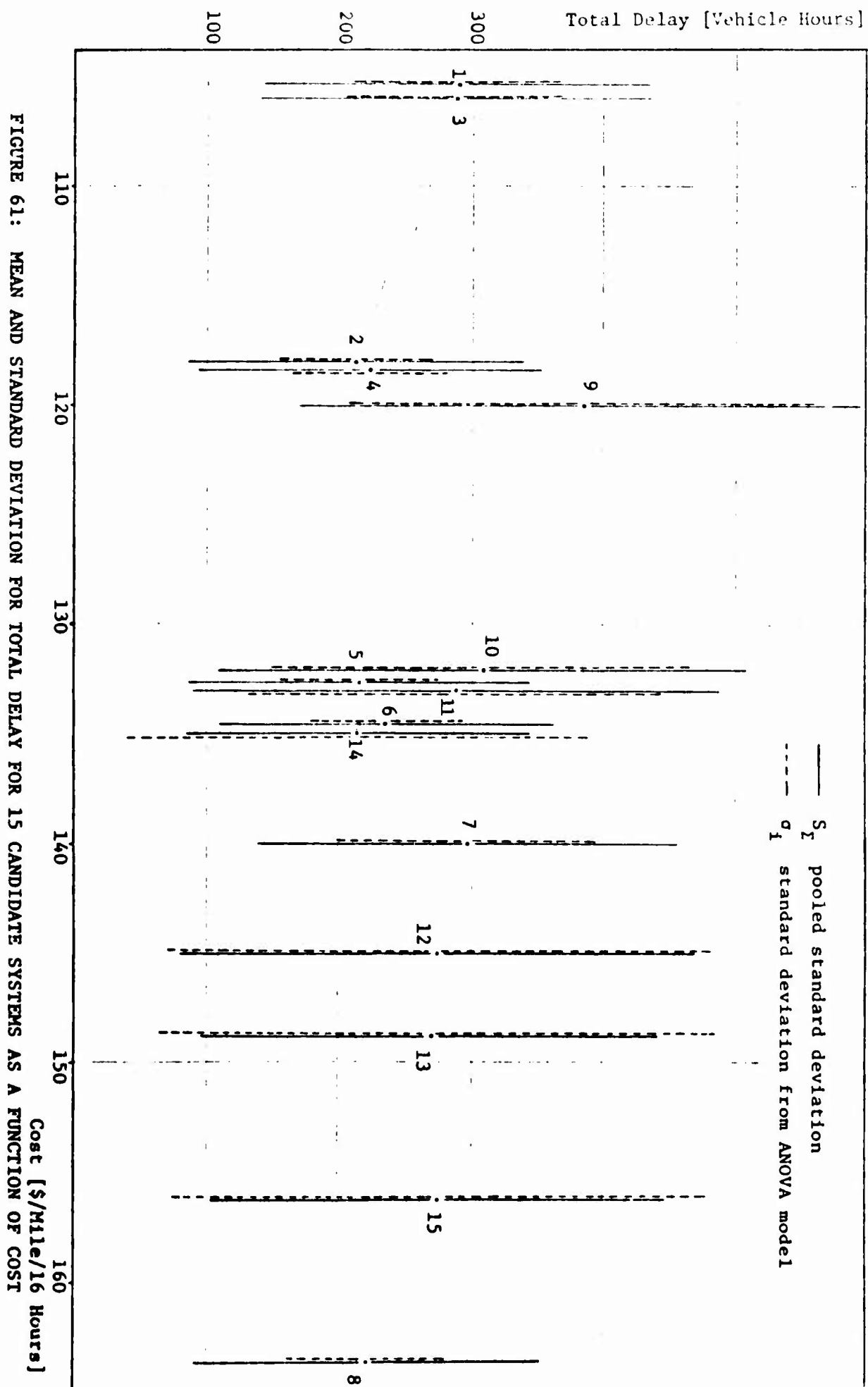


FIGURE 61: MEAN AND STANDARD DEVIATION FOR TOTAL DELAY FOR 15 CANDIDATE SYSTEMS AS A FUNCTION OF COST

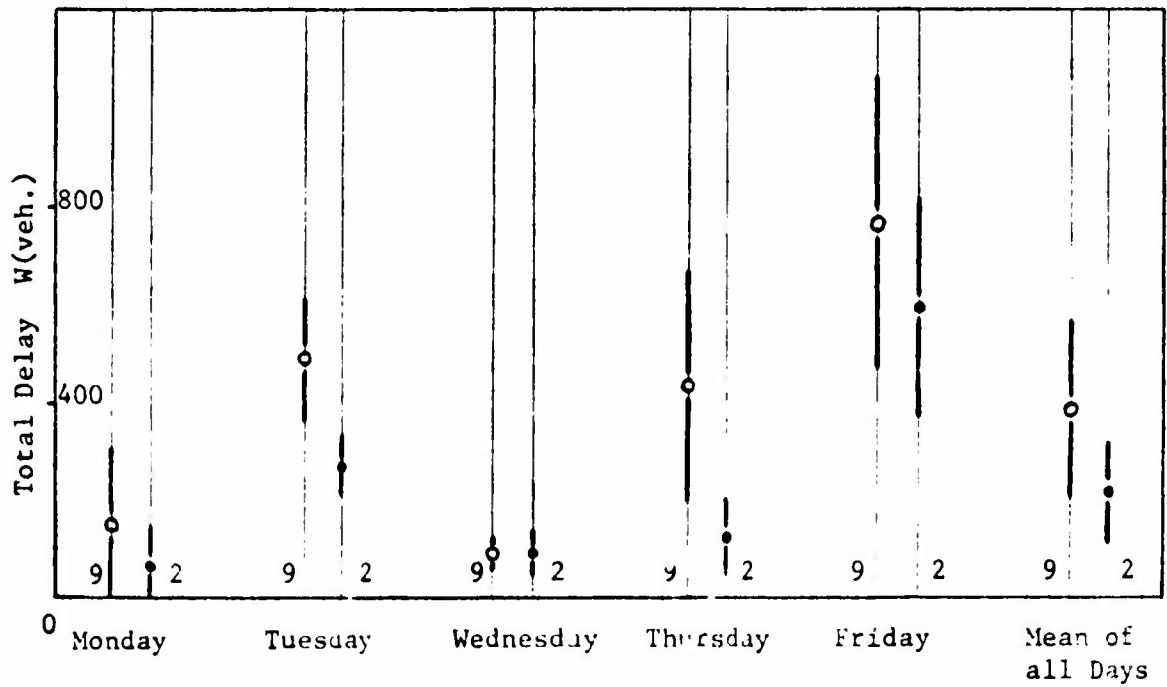


FIGURE 62: VARIATION OF TOTAL DELAY OVER THE DAYS OF THE WEEK FOR CANDIDATE SYSTEM 2 AND 9

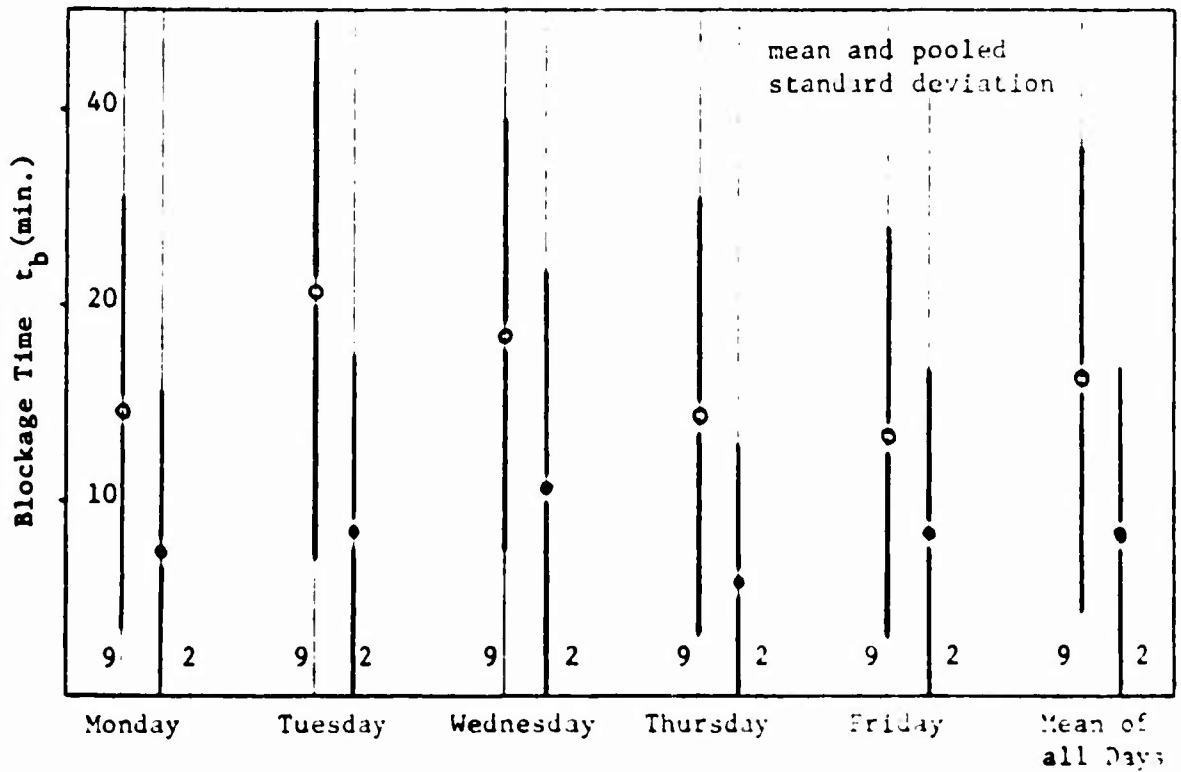


FIGURE 63: VARIATION OF BLOCKAGE TIME OVER DAYS OF THE WEEK FOR CANDIDATE SYSTEM 2 AND 9

The variance reduction achieved through this model is quite drastic for the six emergency service systems, which are largely deterministic in their model representation. The analysis of variance model gives larger variances for the candidate systems with mixed detection systems, i.e., where two detection systems interact. Here the advantage of the same array of random numbers is lost because the total delay is based on the minimum detection time computed from the two interacting detection systems.

The gain achieved with the analysis of variance model becomes obvious from Figure 61 where the reduced variances are superimposed on the pooled variances for the study period.

#### 6.4 QUANTITATIVE AND QUALITATIVE DIFFERENCES OF THE CANDIDATE SYSTEMS

The cost/effectiveness analysis quite clearly establishes that those emergency service systems which rely on the stranded motorist using either a call box or an emergency telephone are the dominating systems. In this subsection some quantitative and qualitative properties of various candidate systems are discussed which indicate the relative advantage of the different systems.

The group of candidate systems which appears to be most favorable from the cost/effectiveness diagram consists of discrete communication terminals as the detection subsystem and stationary police and mechanical service units. Call box and emergency telephone operations have been discussed in various studies and their pro and cons have been pointed out (see [72,73,81, 91,124]). As this study proves the detection via call boxes and emergency telephones is very fast and always available, but they have the large disadvantage that some motorists do not use these facilities because they either can't reach them or are afraid of possible extra charges. The cost per call is, therefore, very high for these terminals to the operating

agencies, and this is often reason enough to rule out these systems with the argument that the police patrol the freeway for law enforcement anyway, thereby detecting incidents on the freeways. The results of this analysis, however, show very strongly that this detection system is superior to others and that attempts should be made to encourage the use of the terminals. This could be done by proper spacing and signing of the boxes and by guaranteeing a fast and appropriate response to the request of service.

The question if call boxes are preferable to emergency telephones cannot clearly be seen from the study of the total delay. Emergency telephones appear to be preferable because of the possibility of transmitting a precise service need; nevertheless, they are more expensive. This advantage does not appear in the analysis because system 2 [box; stat. pol. + mech. (1 - 1 - 1)] causes 12 vehicle hours less delays than system 4 [phone, stat. pol. + mech. (1 - 1 - 1)], as Figure 60 indicates. One reason for this lies in the fact that for the emergency telephones one minute was added for communication on the phone, a time delay which does not exist for the call boxes. Another reason why the advantage of the emergency phone does not show up in this study is that the communication terminals are assumed to be monitored at the dispatch center of the mechanical service vehicles. The evaluation phase is, therefore, not critical because with the arrival of mechanical service no unnecessary delays occur. This would be quite different if the terminals would be monitored at the police communication center because then a request from a call box would have to be evaluated by a police officer, who is dispatched to the scene, and who only then requests mechanical service if required. However, the results of the study quite strongly recommend monitoring the terminals at the mechanical service dispatch center because more emergency stoppages require mechanical service than the service of police. For the data on the Bay Bridge only 10

12 per cent of all incidents the police were present.

Knowing that the emergency telephones provide the shortest detection time, (see Figure 57) with the least cost, it is interesting to find out which stationary service scheme can reasonably cope with the service demand and which is the optimal allocation of the service vehicles along the freeway. Because the detection time determined from the emergency telephones is independent of the service subsystem, this detection subsystem can be used in the performance of the suboptimization of the stationary service.

Candidate systems 3 to 6 reflect this approach. All four candidate systems have as a detection subsystem emergency telephones spaced at a 1/4 mile and stationary police vehicles (1 - 1). The effect of different service vehicle locations on the effectiveness measures can be used to obtain the optimal location and number of mechanical service vehicles.

The expenditure of an additional mechanical service vehicle to transfer system 3 [phone, stat. pol. + mech. (1 - 1)] to system 4 [phone, stat. pol. + mech. (1 - 1 - 1)] causes a reduction of total delay and the number of delayed vehicles as can be seen from the following table.

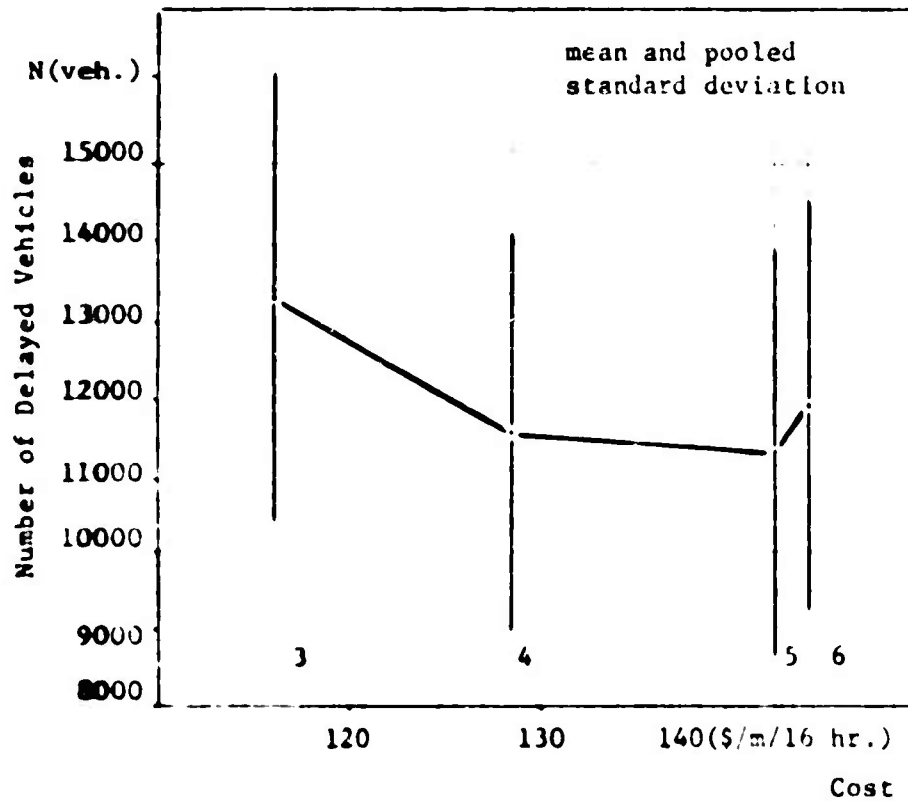
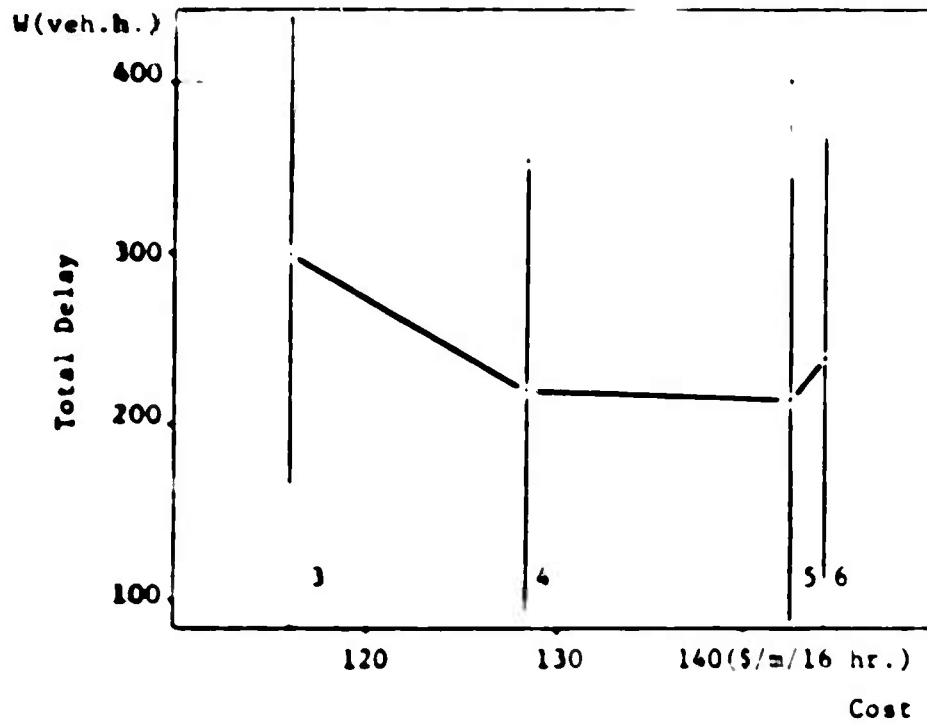
|                                                             | stat.<br>mech.<br>(1-1) | stat.<br>+ mech.<br>(1-1-1) | stat.<br>mech.<br>(1-1-1) | stat.<br>+ mech.<br>(1-2-1) | stat.<br>pol.<br>(1-1) | stat.<br>pol.<br>(1-1-1) |
|-------------------------------------------------------------|-------------------------|-----------------------------|---------------------------|-----------------------------|------------------------|--------------------------|
|                                                             | Candidate Systems r,s   |                             |                           |                             |                        |                          |
|                                                             | 1,2                     | 3,4                         | 9,10                      | 4,5                         | 11,12                  |                          |
| reduction of<br>delayed vehicles<br>$\Delta N_{r,s}$ (veh.) | 1836                    | 1689                        | 1707                      | 237                         | 220                    |                          |
| reduction of<br>total delay<br>$\Delta U_{r,s}$ (veh.h.)    | 78                      | 65                          | 75                        | 9                           | 26                     |                          |
| reduction of<br>arrival time<br>$\Delta t_a^{s,h}$ (min.)   | 4.7                     | 4.1                         | 4.9                       | 4.6                         | 2.8                    |                          |

If one more vehicle is added to the post half way of the freeway which corresponds to system 5 [phone, stat. pol. + mech. (1 - 2 - 1)] the gain is considerably less. Figures 64 a and b indicate that the location of 2 service vehicles at each end of the freeway system 6 [phone, stat. pol. + mech. (2 - 1)] results in higher costs and larger delays.

From this analysis and from the position of the systems 3 to 6 in the cost effectiveness diagram, figure 60 relative to the basic system, 1, it can be concluded that system 4 [phone, stat. pol. + mech. (1 - 1 - 1)] can reasonably cope with the service demand and achieves the lowest cost/ effectiveness\*. This is the reason why the subsystem [stat. mech. (1 - 1 - 1)] was used as the basic design for stationary mechanical service, when matched with detection and/or other service subsystems.

The provision of detection patrols does not warrant its expense as systems 7 [pat. det. (1), stat. pol. + mech. (1 - 1 - 1)] and 8 [pat. det. (1,1), stat. pol. + mech. (1 - 1 - 1)] indicate. Because it is assumed that the patrolling motorcycles do not provide any service, the patrol frequency has to be kept very high to achieve a short detection time and subsequently a fast arrival of service, which in turn increases the cost of the systems so that they are not competitive. The result of these two systems can also with some adjustments be used for other detection patrols (e.g. aircraft).

\* This conclusion was reinforced by the analysis of systems 1 [box, stat. pol. + mech. (1 - 1)] and 2 [box, stat. pol. + mech. (1 - 1 - 1)] as well as systems 9 [pat. pol., stat. mech. (1 - 1)] and 10 [pat. pol., stat. mech. (1 - 1 - 1)].

FIGURE 64a: VEHICLES DELAYED,  $N$  FOR CANDIDATE SYSTEMS 3,4,5,6FIGURE 64b: TOTAL DELAY,  $W$  FOR CANDIDATE SYSTEMS 3,4,5,6

Police service patrols only are not recommended from the results of this study, because the services of the police are required only for a few incidents. Systems 9 [pat. pol.; stat. mech. (1 - 1)] and 10 [pat. pol.; stat. mech. (1 - 1 - 1)] reflect this disadvantage, because both systems have a negative cost/effectiveness ratio relative to system 1. Because the police patrol the freeway for law enforcement anyway, one possibly should not take into account the full costs of this subsystem, but only those costs which are necessary to maintain a higher patrol frequency than that which the police considers as necessary for law enforcement. This would improve the relative position of systems 9 and 10 in the cost/effectiveness diagram but would not affect (reduce) the high delays caused by these systems. However, neither the psychological effect of the presence of the police, even when only mechanical services are required, should not be neglected, nor the fact that the police actually provides minor mechanical services when possible or justified.

Mechanical service patrols are superior to police patrols as systems 11 [pat. mech.; stat. pol.] and 12 [pat. mech.; stat. pol. (1 - 1 - 1)] demonstrate. It appears also to be slightly more advantageous to let two mechanical service vehicles patrol the freeway (system 11) than to keep the two vehicles stationary (system 1 [box; stat. pol. + mech. (1 - 1)] if one considers the total delay which both systems cause. However, the cost/effectiveness analysis proves that the stationary systems can be operated more cost/effective than the mobile service.

Emergency service systems with mixed detection subsystems (candidate systems 13, 14 and 15) are only economical if the subsystems matched are

complementary and proved to be cost/effective in the previous analysis. This is true for system 14 [phone + pat. pol.; stat. mech. (1 - 1 - 1)] where the directional dispatch of mechanical service vehicles is engendered by requests from emergency telephones or the police patrol. These two detection subsystems are ideal in their combination, because they compensate their disadvantages.

## 6.5 INDIVIDUAL EFFECTIVENESS MEASURES

The individual effectiveness measures, detection time and arrival time of service, reflect the effectiveness of the candidate systems to the stranded motorist. At the same time they give a good indication of the microscopic performance of the subsystems as can be seen in the following paragraphs. While the cost/effectiveness analysis based on the collective measure of effectiveness, total delay, provided a means to determine which candidate systems are the best and by how much they are better than others, the individual effectiveness measures give an indication why these systems are better. If one wants to improve the effectiveness of emergency service systems with the goal of reducing the total delay one has to investigate the detection time and arrival time of service, because only they describe the performance of the individual subsystems and components.

### 6.5.1 Detection Time

A comparison of the different detection methods can be based on the Figure 65 in which the mean detection times and their pooled standard deviations are plotted for the 15 candidate systems.

The detection time includes the time to evaluate the service need, which demonstrates the disadvantage of the call box as a means of detection. The detection time is in this case equal to the arrival of service, which is for system 2 [box; stat. pol. + mech. (1 - 1 - 1)] 5 minutes. The emergency

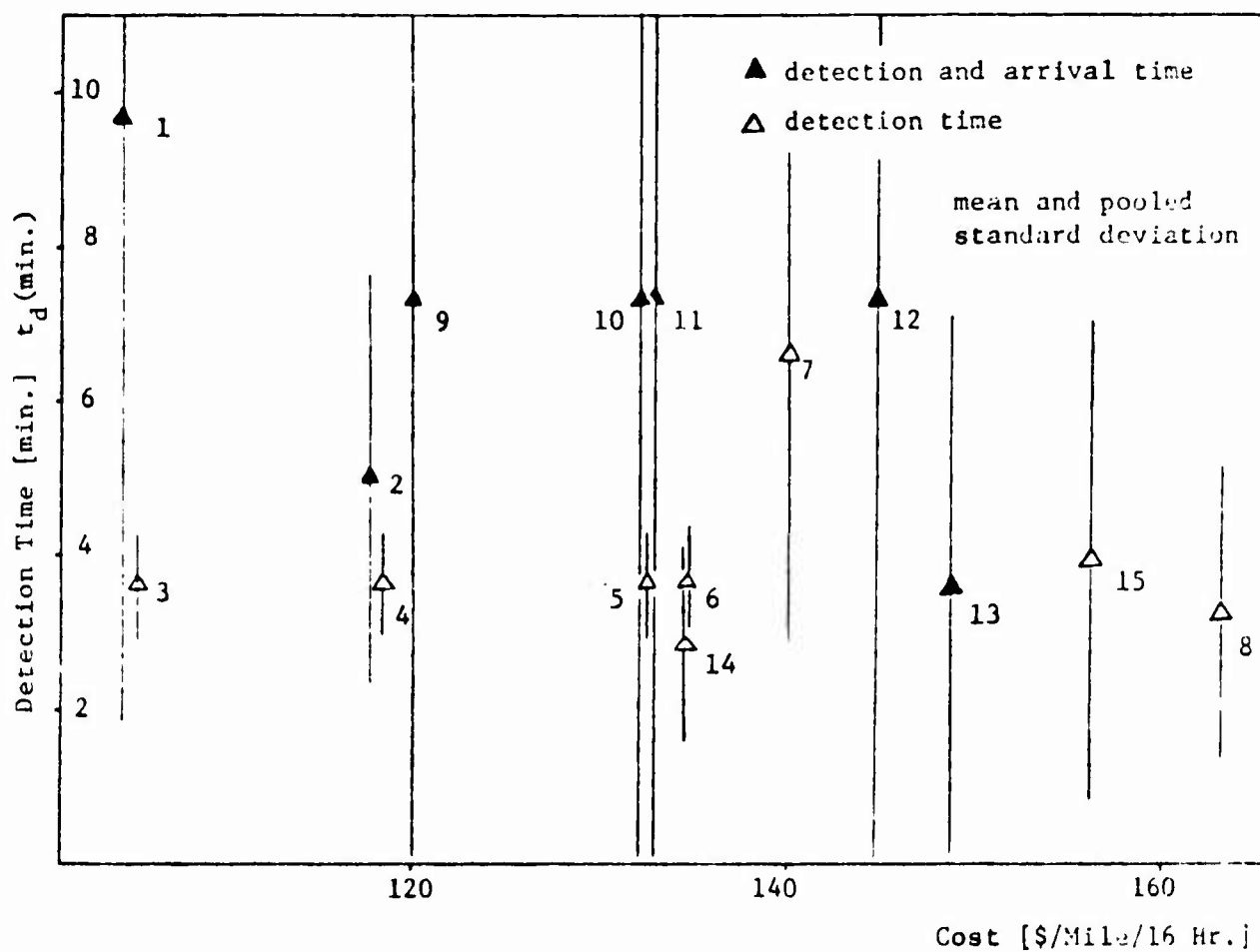


FIGURE 65: DETECTION TIME,  $t_d$  MEAN AND POOLED STANDARD DEVIATION FOR ALL CANDIDATE SYSTEMS

telephone shows with 3.7 minutes a clear advantage, system 4 [phone; stat. pol. + mech. (1 - 1 - 1)]. This time advantage is even 6.0 minutes for the emergency telephone (system 3) as compared with the call box (system 1), if the mechanical service subsystem consists of only one vehicle at each end of the freeway [stat. mech. (1 - 1)]. The shortest detection time is provided by system 14 [phone + pat. pol.; stat. mech. (1 - 1 - 1)], where this time is reduced to 2.8 minutes. The most efficient system appears to be 13 [pat. pol. + pat. mech.], with a detection time of 3.6 minutes, but where either the police or the mechanical service already arrives at this time. However, the cost/effectiveness analysis showed, that this system is expensive to install and not effective measured in the reduction of total delay relative to the basic system 1.

The disadvantage of the patrols as a means of detection is demonstrated in the generally higher means and considerably larger variances of the detection time as compared to the same statistics for discrete communication terminals.

#### 6.5.2 Arrival Time of Service

The arrival times for police and mechanical service are plotted in Figure 66. It is differentiated between the arrival of any service and the arrival of necessary service. The arrival of any service is of psychological importance to the stranded motorist, but is often actually part of the detection phase.

Figure 66 indicates the general trend of decreasing arrival times of service with higher system costs. The generally later arrival of the police service is due to the fact that only one police vehicle is stationed at each end of the 5 mile freeway. Comparing systems 11 [pat. mech.; stat. pol. (1 - 1)]

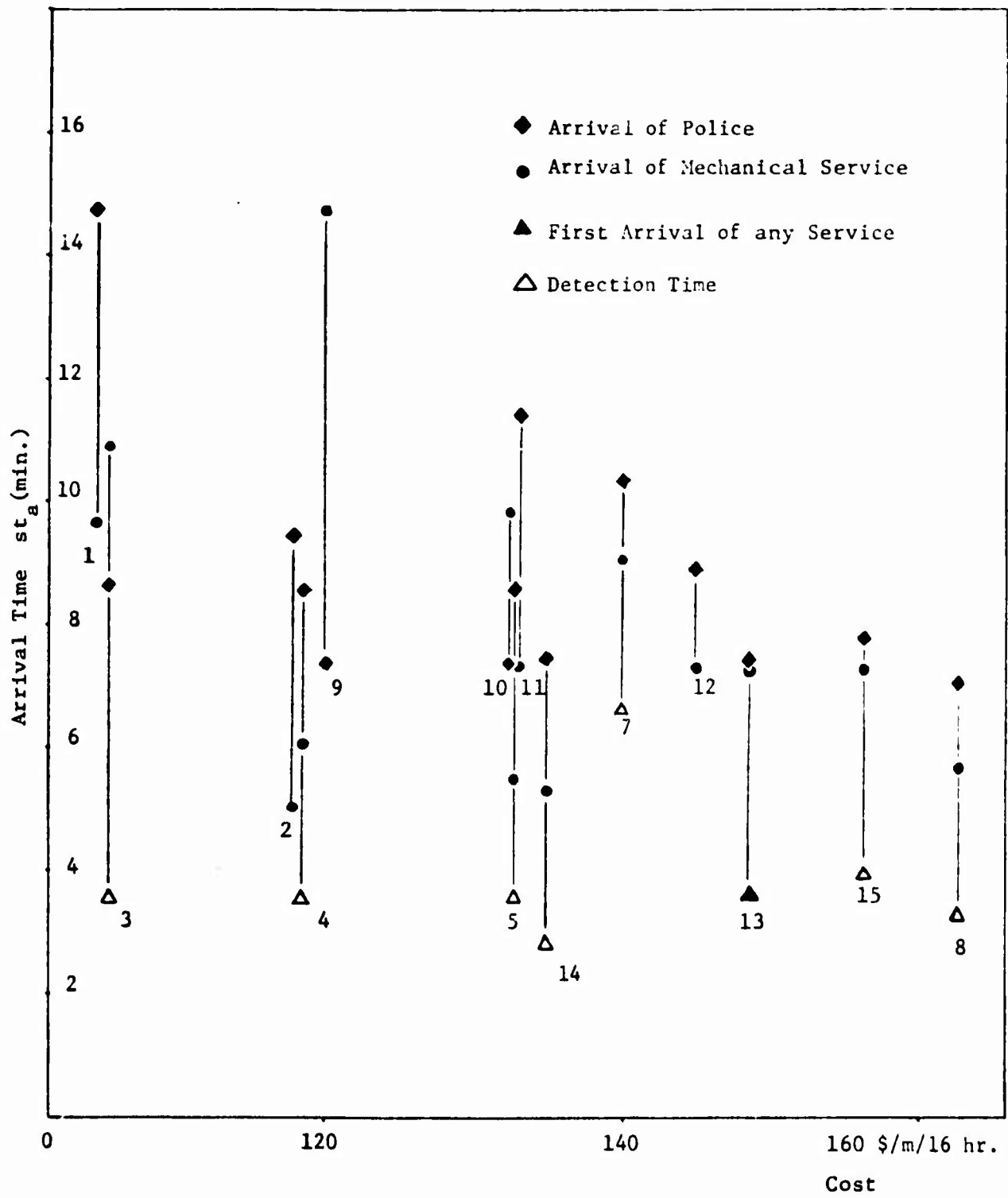


FIGURE 66: ARRIVAL TIME OF POLICE AND MECHANICAL SERVICE AT THE SCENE OF THE INCIDENT FOR ALL CANDIDATE SYSTEMS

with system 12 [pat. mech.; stat. pol. (1 - 1 - 1)], one realizes that the arrival of police is about 2.5 minutes earlier in the average, if one additional unit is stationed halfway at 2.5 miles of the freeway.

An analysis of the arrival times for systems 3,4,5 and 6 explains why system 4 [phone; stat. pol. + mech. (1 - 1 - 1)] was found to best cope with the service demand in Section 6.4. The arrival time of mechanical service varies from 10.9 minutes for system 3 [phone; stat. pol. + mech. (1 - 1)] to 5.5 minutes for system 5 [phone; stat. pol. + mech. (1 - 2 - 1)]. While in system 3 the average waiting time for an available service vehicle ( $t_{ay}$  in Subsection 5.1.3.2) amounted up to 7 minutes on Tuesday, this time was reduced to .6 minutes for system 4 [phone; stat. pol. + mech. (1 - 1 - 1)] and .1 minutes for system 5. The assignment of two units to each end of the freeway has the disadvantage of the highest cost and later arrivals due to the larger travel distances; system 6 [phone; stat. pol. + mech. (2 - 2)]. The adding of one car at midpoint of the freeway, system 5, causes a time reduction for the arrivals of 4.8 minutes, while the gain of having two cars at that position, system 5, is only .6 minutes at twice the cost.

The shortest arrival times are achieved with system 2 [box; stat. pol. + mech. (1 - 1 - 1)], 4 [phone; stat. pol. + mech. (1 - 1 - 1)], 5 [phone; stat. pol. + mech. (1 - 2 - 1)], and 14 [phone + pat. pol.; stat. mech. (1 - 1 - 1)], namely 5.1 and 6.1 minutes. Police and mechanical service patrols (systems 9, 10 and 11, 12) cause long detection times as already Figure 65 indicated,  $7.3 \pm 7.4$  minutes. This has its effect on the arrival of necessary service, if the detecting patrol does not at the same time provide the service need. Police patrols (systems 9, 10) generate the latest arrivals of mechanical service in comparison to all other candidate systems which explains the bad position of system 9, 10 in the cost/effectiveness analysis. Mechanical service patrols, systems 11, 12, have the same detection time, but because their arrival time is equivalent to their detection time, and because their service is always needed, they are more cost/effective.

## CHAPTER 7

### DISCUSSION AND FUTURE RESEARCH

In the course of this research a systematic approach was used to analyze freeway emergency service systems. The observation of the operation of existing detection and service systems showed that a coordinated effort of all related agencies is required to guarantee the necessary emergency services for the motorist. A schematic model of a systems analysis structure for responding to freeway incidents was therefore designed. The performance and operation of alternate emergency service systems being analyzed on the basis of cost and effectiveness.

The operation of an emergency service system was divided into a sequence of events and activities performed by the major components, the police, mechanical, fire, and medical services, of the detection and service subsystems. This activity model was then used as the basis for a next event simulation process.

In the framework of this study the research was limited to the analysis of the components police and mechanical service on an urban freeway. The costs were measured in dollars for the installation and operation of the system and two types of effectiveness measures were used. Individual effectiveness measures, detection time and arrival of first service and the collective measures, the total delay and the number of vehicles delayed, as a prediction of the hazard of a second incident. Fifteen candidate systems were subjected to an analysis of their performance, when responding to historical incidents which occurred during one week on a traffic facility. The candidate systems consisted basically of discrete communication terminals along a linear freeway and service patrols as detection subsystems and patrolling or stationary service units as service subsystems.

Submodels representing the activities in the activity model were developed to predict the completion time for the individual tasks and subsequently the overall response time and measures of effectiveness for the candidate systems.

A comparison of the candidate systems shows that the combination of discrete communication terminals along the freeway monitored at the dispatch center of mechanical service as detection subsystem and stationary service units can be operated with the least costs and the greatest effectiveness. Patrolling service units are more costly to operate and their use leads to greater delays to the motorists for the patrol frequencies analyzed. If patrolling service vehicles are matched with discrete communication links, the detection time is reduced, but the arrival of service is hardly affected. The advantage of the discrete communication terminals might be questioned if the motorist does not activate the detection system. But if he is informed properly about its use and for the type of emergency stops analyzed in this study, which are capacity reducing in their effects, the detection system can be assumed to be activated.

The results of this study also demonstrate that an investment in the mechanical service subsystem is much more effective for the motorist than an improvement of the police service. This is because in less than twelve per cent of the incidents analyzed the service of the police was requested. A big improvement can definitely be achieved, if the responsibilities and the services provided of the components police and mechanical service would be combined into one agency.

The stochastic properties of the incident occurrence and of the events and activities studied in the activity model are propagated also to the results of the analysis. The means of the effectiveness measures appear to give distinct differences for the various candidate systems, but the

consideration of the standard deviations of these means shows the complexity of the interpretation of the results.

Future research in this area should be concentrated on the improvement of the available submodels for the studied activities and should be directed toward the extension of the analysis to the medical emergency system. This will introduce a conflict in the evaluation, because the medical aspects for the survival of an individual are often contradictory to the desires of the collective of passing motorists. It will be then necessary to look at the efficient use of the time and not at the minimal activity times as done in this study.

The effectiveness measures total delay and the number of vehicles delayed are sensitive to changes in the traffic demand and capacity rate of the freeway. In the example analyzed here the demand and capacity rate are relatively constant over distance for undisturbed flows. But the effect of capacity reducing incidents on the transient behavior of the traffic flow rate over time and space remains to be studied and has to be considered if more complex systems are studied. Very little information is available on the amount of capacity reduction imposed by different types of incident at various levels of traffic flow.

The collective measures of effectiveness total delay and number of vehicles delayed are only useful as long as the capacity reduction caused by an incident reduces the capacity of the freeway below the demand rate. This is mostly only true during the morning and afternoon rush hours, so that during off peak hours nearly no contribution of delays is encountered. This fact suggests to evaluate emergency systems on urban freeways for peak and off peak hours separately. This should also be recommended because a more effective emergency system should be operated during rush

hours as compared to the other periods of the day.

The use of the measure total delay is very valuable, if one assigns a cost measure to time. An interesting study would be to determine if and when the increases of travel times due to incidents and accidents are larger than the tolerance which the motorist already takes into account due to the uncertainty in travel times in general.

The simulation of the operation of various detection and service systems proved to be very informative mainly with respect to the variation of the results. This approach permits the analysis of the effects of changes in various parameters relevant in emergency service systems. The simulation program has the potential to be applied to more complex transportation facilities, or with some adaptations, to different detection and service subsystems.

The decision of implementing such complex systems as an emergency service on highways is reached at various political levels, very often regardless of the cost and effectiveness of alternate systems. This research shows that a coordinated effort is necessary to improve existing and to install new emergency service systems on highways, for the survival of the individual motorist and the sake of the highway user in general. It appears not to be enough to provide a roadway designed for maximum safety and speed, but an integral part of an operating highway is an efficient and reliable emergency service system. Through continued research in transportation planning and traffic safety the decision maker can possibly be provided with an information base so that he can convince himself of the facts and knowledge available.

## LIST OF SYMBOLS

| <u>Symbol</u> | <u>Description</u>                                                                                                                       |
|---------------|------------------------------------------------------------------------------------------------------------------------------------------|
| $a$           | index or superscript used to identify police patrol                                                                                      |
| $b$           | index or superscript used to identify mechanical patrol                                                                                  |
| $c$           | index or superscript used to identify unidirectional communication terminals (call box with one single push button, signal)              |
| $c_{ac}$      | auxiliary equipment cost (\$/year)                                                                                                       |
| $c'_{ac}$     | auxiliary equipment cost (\$/unit/year)                                                                                                  |
| $c_{an}$      | manpower cost (\$/unit/year)                                                                                                             |
| $c'_{an}$     | auxiliary manpower cost (\$/year)                                                                                                        |
| $c_{eq}$      | equipment cost (\$/unit/year)                                                                                                            |
| $c_{in}$      | installation cost (\$/unit/year)                                                                                                         |
| $c_{op}$      | maintenance cost (\$/unit/year)                                                                                                          |
| $c'_{op}$     | maintenance and operating cost (\$/unit/mile)                                                                                            |
| $c_q$         | total cost for detection or service subsystem $q = a, b, c, e, f, g, h$<br>in \$/mile/time period, e.g., 16 hours or one day or one year |
| $c_g$         | capacity of freeway (Bay Bridge) East bound                                                                                              |
| $c_w$         | capacity of freeway (Bay Bridge) West bound                                                                                              |
| $d_q$         | distance (miles) travelled per unit per time period                                                                                      |
| $e$           | index or superscript used to identify bidirectional communication terminals (emergency telephone)                                        |
| $f$           | index or superscript used to identify detection patrol (motorcycle)                                                                      |
| $g$           | index or superscript used to identify police service units stationed at specified posts                                                  |

Symbol    Description

|          |                                                                                                                                                                                                                      |
|----------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| $s_{1j}$ | number of police vehicles stationed at post $j$                                                                                                                                                                      |
| $h$      | index or superscript used to identify mechanical service units stationed at specified posts                                                                                                                          |
| $h_1$    | post of the mechanical service vehicle which is dispatched to an incident                                                                                                                                            |
| $h_{2j}$ | number of mechanical service vehicles stationed at post $j$                                                                                                                                                          |
| $l_q$    | spacing between communication terminals (miles), or beat length for patrols (miles), or spacing between service posts (miles)                                                                                        |
| $a_{1j}$ | coefficient in matrix $M$ , the service available queue matrix,<br>$a_{1j} = s_{1j}$ and $a_{2j} = h_{2j}$                                                                                                           |
| $n_1$    | number of candidate systems                                                                                                                                                                                          |
| $n_j$    | number of iterations per day (16 hours period)                                                                                                                                                                       |
| $n_d$    | number of days (16 hour periods)                                                                                                                                                                                     |
| $n_q$    | number of units of type $q = a, b, c, e, f, g, h$ per study section of length $L$ (miles)                                                                                                                            |
| $o$      | indicates the number of the terminal which is used by the motorist or the post from which a service vehicle is dispatched<br>( $m = 1$ at $x = 0$ , $o = n_q + 1$ at $x = L$ )                                       |
| $q$      | general term to identify subsystem $a, b, c, e, f, g, h$                                                                                                                                                             |
| $q_o$    | number and location of communication terminal ( $q = c$ for call box, $q = e$ for emergency telephone) or service vehicle posts<br>( $q = g$ for police vehicle posts, $q = h$ for mechanical service vehicle posts) |
| $q_L(t)$ | traffic flow (vph) at time $t$ of day, East bound                                                                                                                                                                    |
| $q_U(t)$ | traffic flow (vph) at time $t$ of day, West bound                                                                                                                                                                    |

| <u>Symbol</u> | <u>Description</u>                                                                                                                  |
|---------------|-------------------------------------------------------------------------------------------------------------------------------------|
| $r_{1j,I}$    | coefficient in vector $r_{1,I}$ ; $r_{10,I} = 1$ , if police service unit $j = 0$ is busy during incident $I$ , zero otherwise      |
| $r_{2j,I}$    | coefficient in vector $r_{2,I}$ ; $r_{20,I} = 1$ , if mechanical service unit $j = 0$ is busy during incident $I$ , zero otherwise. |
| $t_{ar}$      | arrival time of first detection or service unit at the scene of an incident                                                         |
| $t_b$         | time of blockage of freeway due to incident, equal to time of reduced freeway capacity                                              |
| $t_c$         | communication time                                                                                                                  |
| $t_p$         | time period from dispatch til start of service vehicle                                                                              |
| $t_{re}$      | time during which the motorist recovers from the incident and evaluates his service needs                                           |
| $t^q$         | activity completion time the superscript signifies the detection or service system used for the activity                            |
| $t_a^q$       | travel time to the scene of the incident                                                                                            |
| $t_d^q$       | detection time                                                                                                                      |
| $t_e^q$       | evaluation time                                                                                                                     |
| $t_r^q$       | return time from scene of incident to original post                                                                                 |
| $t_s^q$       | on-site service time                                                                                                                |
| $t_t^q$       | towing time, time from freeway exit to garage and back to freeway entry                                                             |
| $st^q$        | time from incident occurrence til end of activity performed by service or detection unit $q$                                        |

Symbol    Description

|           |                                                                                                                                                                                                                                  |
|-----------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| $u$       | unit, e.g., communication terminal, patrol, service vehicle                                                                                                                                                                      |
| $v_q$     | speed (mph) for $q = a, b, g, h$ and $q = w$ for walking speed                                                                                                                                                                   |
| $w_q$     | walking time from incident to call box ( $q = c$ ) or to emergency telephone ( $q = e$ )                                                                                                                                         |
| $\bar{w}$ | average individual delay                                                                                                                                                                                                         |
| $x_{ijk}$ | effectiveness measure for incident $i$ , iteration $j$ , and day (16 hour period) $k$                                                                                                                                            |
| $y_{ijk}$ | effectiveness measure for system $i$ , iteration $j$ , and day (16 hour period) $k$                                                                                                                                              |
| $A(t)$    | cumulative arrivals of vehicles to time $t$                                                                                                                                                                                      |
| $CR$      | reduction of freeway capacity due to roadway blockage (in per cent)                                                                                                                                                              |
| $D(t)$    | cumulative departures of vehicles to time $t$                                                                                                                                                                                    |
| $I$       | number of incident, $I = 1$ for first incident analyzed<br>$I = NO$ total number of incidents analyzed per time period                                                                                                           |
| $INC$     | event of the occurrence of an incident                                                                                                                                                                                           |
| $K$       | type of service necessary<br>$K = P = 1$ police service necessary, $P = 0$ if not necessary<br>$K = S = 1$ mechanical service necessary, $S = 0$ if not necessary<br>$K = V = 1$ tow service necessary, $V = 0$ if not necessary |
| $L$       | length of study section (freeway)                                                                                                                                                                                                |
| $M_i$     | matrix of state of service available - request queues at time of incident $i$                                                                                                                                                    |
| $N$       | total number of vehicles delayed                                                                                                                                                                                                 |
| $Q(t)$    | number of vehicles in queuing system at time $t$                                                                                                                                                                                 |

Symbol   Description

|              |                                                                                                 |
|--------------|-------------------------------------------------------------------------------------------------|
| $Q_{\max}$   | maximum queue length or maximum number of veh. in queue                                         |
| R            | pseudo uniform (0,1) random number generated in the simulation routine                          |
| T            | time of day, when incident occurs (minutes), $T = 1$ at 12.01 a.m.,<br>$T = 1440$ at 12.00 p.m. |
| TQ           | queueing time                                                                                   |
| W            | total queueing time, total delay (veh. hours)                                                   |
| X            | location of incident on freeway, $X \leq 0$ West bound (miles)<br>$X > 0$ East bound            |
| $\lambda(t)$ | arrival rate of vehicles                                                                        |
| $\Delta t$   | discrete time interval used in queueing model                                                   |
| $\mu(t)$     | departure rate of vehicles                                                                      |

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## APPENDIX A

## COST OF INDIVIDUAL DETECTION AND SERVICE SYSTEMS

The costs derived for the various emergency service systems are adopted from [102], except for the detection patrol which are based on [68]. To facilitate the interpretation of the cost figures given in Figure 52 the assumptions made by [102] and for this study are presented in this appendix.

The costs shown are approximate and based on several estimates. The cost of equipment (unless specified otherwise) and its installation is amortized over ten years. Where no information on maintenance cost was available, a figure estimated to be high was chosen.

The assignment of personnel to monitoring stations was based on manning on 24-hour, 7-day week, 365-day-year basis. This requires five men per position per 24-hour day.

One operator for monitor and one maintenance technician at 4000 \$/year are deployed per 8 hours shift. A center for receiving emergency calls at \$10,000 and a structure worth \$20,000 to house the receivers and decoders is assumed.

Personnel to patrol and service vehicles is deployed on 24-hour, 7-day-week, 365-day-year manning, which requires five men per day and vehicle at 6000 \$/man/year.

The data listed here in Dollars/Mile/Year or Dollars/Unit/Year or Dollars/Year were linearly scaled down to a time period of 16 hours per day for this study (see Chapter 6).

#### Unidirectional Communication Terminal (Call Box)

Equipment cost = 100 \$/unit over ten years,  $c_{eq} = \underline{10}$  \$/unit/year.

Installation cost = 50 \$/unit (includes wire cost),  $c_{in} = \underline{60}$  \$/unit/year.

A.2

Maintenance cost: estimate 20 \$/year,  $c_{op} = 20$  \$/unit/year.

Auxiliary equipment cost: receiving center at \$10,000 over ten years and structures \$20,000 over ten years,  $c_{ac} = 3000$  \$/year.

Auxiliary personnel cost: 1 monitor and 1 maintenance technician at \$6,000,  $c_{ma} = 2 \cdot 5 \cdot 6000 = 60,000$  \$/year.

Bidirectional Communication Terminal (Emergency Telephone)

Equipment cost: 200-600 \$/unit over ten years,  $c_{eq} = 40$  \$/unit/year.

Installation cost:  $2 \cdot c_{eq}$  (includes wire cost),  $c_{in} = 80$  \$/unit/year.

Maintenance cost: estimate 40 \$/year,  $c_{op} = 40$  \$/unit/year.

Auxiliary equipment cost: see call box.

Auxiliary manpower cost: see call box.

Detection Patrol

Equipment cost: 3000 \$/vehicle, life one year,  $c_{eq} = 3000$  \$/unit/year.

Operating cost:  $c_{op} = .08$  \$/unit/mile.

Manpower cost: 1 man per vehicle 24 hours/day at 6000 \$/year,  
 $c_{ma} = 1 \cdot 5 \cdot 6000 = 30,000$  \$/unit/year.

Auxiliary equipment cost: spare vehicles, maintenance facilities 1/5 vehicle at 3000 \$/vehicle, life two years,  $c_{ac} = 3000/2/5 = 300$  \$/unit/year.

Receiving center and structures: see call box,  $c'_{ac} = 3000$  \$/year.

Auxiliary personnel cost: see call box.

Police Patrol and Police Service Unit

Equipment cost: 4000 \$/vehicle, life one year,  $c_{eq} = 4000$  \$/unit/year.

Operating cost  $c_{op} = .06$  \$/unit/mile.

Manpower cost: 1 man per vehicle 24-hours/day at 6000 \$/year,  
 $c_{ma} = 1 \cdot 5 \cdot 6000 = 30,000$  \$/unit/year.

Auxiliary equipment cost: spare vehicles, maintenance facilities 1/5 vehicle at 4000 \$/vehicle, life two years,  $c_{ac} = 4000/2/5 = \underline{400}$  \$/unit/year.

Communication center and structures: at \$30,000 over ten years,  $c'_{ac} = \underline{3000}$  \$/year.

Auxiliary manpower cost: maintenance and communication personnel assumed 2 per center, 24-hours a day at 6000 \$/year,  $c_{am} = 2 \cdot 5 \cdot 6000 = \underline{60,000}$  \$/unit/year.

#### Mechanical Patrol and Mechanical Service Unit

Equipment cost: 8000 \$/vehicle, life one year,  $c_{eq} = \underline{8000}$  \$/unit/year.

Operating cost:  $c_{op} = \underline{.12}$  \$/unit/mile.

Manpower cost: 1 man per vehicle 24-hours/day at 6000 \$/year,  $c_{ma} = 1 \cdot 5 \cdot 6000 = \underline{30,000}$  \$/unit/year.

Auxiliary equipment cost: spare vehicles, maintenance facilities 1/5 vehicle at 8000 \$/vehicle, life two years,  $c_{ac} = 8000/2/5 = \underline{800}$  \$/unit/year.

Communication center and structures: at \$30,000 over ten years,  $c'_{ac} = \underline{3000}$  \$/year.

Auxiliary manpower cost: see police patrol and service unit.

## APPENDIX B

### STATISTICS OF EFFECTIVENESS MEASURES

In this appendix the computations are summarized for the individual and collective effectiveness measures.

For each incident occurrence the detection time, the arrival time of service, the blockage time as well as the number of delayed vehicles and the total delay are computed. The general term used for these effectiveness data is  $x_{ijk}$  for the  $i$ -th incident, the  $j$ -th iteration and the  $k$ -th day.

The representative effectiveness measures for the total study period (five 16 hour periods) are the mean and pooled variance which are computed from the  $x_{ijk}$ .

- 1) For the detection time, the arrival time of service, and the blockage time the basis of the computations were the *mean* effectiveness per day  $k$  and iteration  $j$ , i.e., an average over the  $n_{1k}$  incidents, which occurred on day  $k$ ,  $x_{.jk}$ . The mean effectiveness measures and the pooled variance for the study period (five 16 hour periods) are then computed in the following form:

a) per day  $k$  and iteration  $j$

$$(1) \quad x_{.jk} = \frac{1}{n_{1k}} \sum_{i=1}^{n_{1k}} x_{ijk}$$

$$(2) \quad s_{jk}^2 = \frac{1}{n_{1k}-1} \sum_{i=1}^{n_{1k}} (x_{ijk} - x_{.jk})^2$$

b) per day k

$$(3) \quad x_{..k} = \frac{1}{n_j} \sum_{j=1}^{n_j} x_{.jk} = \frac{1}{n_j n_{1k}} \sum_{i=1}^{n_{1k}} \sum_{j=1}^{n_j} x_{ijk}$$

$$(4) \quad s_k^2 = \frac{1}{n_j (n_{1k} - 1)} \sum_{i=1}^{n_{1k}} \sum_{j=1}^{n_j} (x_{ijk} - x_{.jk})^2$$

c) per study period

$$(5) \quad x_{...} = \frac{1}{n_k} \sum_{k=1}^{n_k} x_{..k}$$

$$(6) \quad s^2 = \frac{1}{n_k \cdot n_j \cdot (n_{1k} - 1)} \sum_{k=1}^{n_k} \sum_{j=1}^{n_j} \sum_{i=1}^{n_{1k}} (x_{ijk} - x_{.jk})^2$$

d) variance between the five days

$$(7) \quad s_5^2 = \frac{1}{(n_k - 1)} \sum_{k=1}^{n_k} (x_{..k} - x_{...})^2$$

- 2) For the total delay and the number of delayed vehicles the computations were based on the sum of the effectiveness measures per day k and iteration j,  $x_{ijk}$ , where  $\Sigma$  indicates that the term is a sum over the  $\bar{n}_{1k}$  incidents which cause delays.
- For the collective effectiveness measures total delay and number of vehicle delayed the means and pooled variance are then computed from the following formulae:

### B.3

a) per day k and iteration j

$$(8) \quad x_{\bar{\tau},jk} = \frac{1}{\bar{n}_{jk}} \sum_{i=1}^{\bar{n}_{jk}} x_{ijk}$$

b) per day k

$$(9) \quad x_{\bar{\tau},\cdot k} = \frac{1}{n_j} \sum_{j=1}^{n_j} x_{\bar{\tau},jk} = \frac{1}{n_j} \sum_{j=1}^{n_j} \sum_{i=1}^{\bar{n}_{jk}} x_{ijk}$$

$$(10) \quad s_{\bar{\tau},k}^2 = \frac{1}{(n_j-1)} \sum_{j=1}^{n_j} (x_{\bar{\tau},jk} - x_{\bar{\tau},\cdot k})^2$$

c) per study period

$$(11) \quad x_{\bar{\tau},\dots} = \frac{1}{n_k} \sum_{k=1}^{n_k} x_{\bar{\tau},\cdot k}$$

$$(12) \quad s_{\bar{\tau}}^2 = \frac{1}{n_k(n_j-1)} \sum_{k=1}^{n_k} \sum_{j=1}^{n_j} (x_{ijk} - x_{\bar{\tau},\cdot k})^2$$

d) variances between the five days

$$(13) \quad s_{\bar{\tau},5}^2 = \frac{1}{(n_k-1)} \sum_{k=1}^{n_k} (x_{\bar{\tau},\cdot k} - x_{\bar{\tau},\dots})^2$$

## APPENDIX C

## RESULTS OF THE COST AND EFFECTIVENESS ANALYSIS

In this appendix the results cost and effectiveness analysis are summarized as they were obtained from the simulation routine "DESERV" for the 15 candidate systems.

The means and standard deviations for the cost and effectiveness measures for 16 hours/day are listed per system in the following way:

- first row (a) mean per day from Equations (B-5) and (B-11)
- second row (b) standard deviation between days from Equations (B-7) and (B-13)
- third row (c) pooled standard deviation per day from Equation (B-6)
- fourth row (d) pooled standard deviation per day from Equation (B-12)

| Candidate System | Detection Time [Min] | First Arrival of Any Service [Min] | Police Arrival Time [Min] | Mechanical Service Arrival Time [Min] | Blockage Time [Min] | Number of Vehicles Delayed [Veh.] | Total Delay (Veh.Hours) | Cost (\$/Mile/16 Hours) |
|------------------|----------------------|------------------------------------|---------------------------|---------------------------------------|---------------------|-----------------------------------|-------------------------|-------------------------|
| 1                | 5.67                 | 9.67                               | 14.78                     | 9.67                                  | 22.84               | 12923.55                          | 290.06(a)               | 105.4                   |
|                  | 3.10                 | 3.10                               | 5.30                      | 3.10                                  | 3.45                | 8738.10                           | 217.29(b)               |                         |
|                  | 7.74                 | 7.74                               | 10.86                     | 7.74                                  | 12.10               | 2198.98                           | 125.03(c)               |                         |
| 2                |                      |                                    |                           |                                       |                     | 2855.07                           | 145.72(d)               | 117.9                   |
|                  | 5.02                 | 5.02                               | 9.49                      | 5.02                                  | 17.91               | 11087.15                          | 212.62                  |                         |
|                  | .75                  | .75                                | 2.00                      | .75                                   | 2.03                | 7552.47                           | 186.53                  |                         |
| 3                | 2.69                 | 2.69                               | 5.49                      | 2.69                                  | 9.11                | 1906.73                           | 98.41                   | 106.0                   |
|                  |                      |                                    |                           |                                       |                     | 2646.97                           | 127.76                  |                         |
|                  | 3.59                 | 10.38                              | 8.65                      | 10.87                                 | 22.84               | 13252.88                          | 289.05                  |                         |
| 4                | .21                  | 2.84                               | 1.75                      | 3.21                                  | 3.13                | 8989.62                           | 210.86                  | 118.2                   |
|                  | .69                  | 7.66                               | 4.11                      | 7.98                                  | 10.93               | 2153.76                           | 117.32                  |                         |
|                  |                      |                                    |                           |                                       |                     | 2908.49                           | 147.73                  |                         |
| 5                | 3.59                 | 6.05                               | 8.65                      | 6.06                                  | 18.68               | 11563.28                          | 224.01                  | 132.6                   |
|                  | .21                  | .72                                | 1.75                      | .74                                   | 1.87                | 7799.28                           | 192.16                  |                         |
|                  | .69                  | 2.71                               | 4.11                      | 2.75                                  | 8.70                | 1910.68                           | 98.37                   |                         |
| 6                |                      |                                    |                           |                                       |                     | 2648.87                           | 130.58                  | 134.5                   |
|                  | 3.59                 | 5.51                               | 8.65                      | 5.51                                  | 18.23               | 11326.95                          | 215.20                  |                         |
|                  | .21                  | .45                                | 1.75                      | .45                                   | 1.80                | 7555.79                           | 191.19                  |                         |
|                  | .69                  | 1.62                               | 4.11                      | 1.62                                  | 8.50                | 1876.85                           | 96.65                   |                         |
|                  |                      |                                    |                           |                                       |                     | 2652.70                           | 130.47                  |                         |
|                  | 3.59                 | 7.33                               | 8.65                      | 7.41                                  | 19.72               | 11908.16                          | 236.42                  |                         |
|                  | .21                  | .87                                | 1.75                      | .97                                   | 1.85                | 8040.88                           | 196.63                  |                         |
|                  | .69                  | 2.83                               | 4.11                      | 3.01                                  | 8.59                | 1957.72                           | 100.74                  |                         |
|                  |                      |                                    |                           |                                       |                     | 2662.46                           | 129.90                  |                         |

| Candidate System | Detection Time [Min] | First Arrival of Any Service [Min] | Police Arrival Time [Min] | Mechanical Service Arrival Time [Min] | Blockage Time [Min] | Number of Vehicles Delayed [Veh.] | Total Delay [Veh.Hours] | Cost [\$ / Mile / 16 Hours] |
|------------------|----------------------|------------------------------------|---------------------------|---------------------------------------|---------------------|-----------------------------------|-------------------------|-----------------------------|
| 7                | 6.63                 | 9.04                               | 10.37                     | 9.06                                  | 21.52               | 13449.28                          | 296.20                  | 139.8                       |
|                  | .09                  | .53                                | 1.57                      | .58                                   | 1.86                | 8773.91                           | 249.57                  |                             |
|                  | 3.84                 | 4.34                               | 5.33                      | 4.38                                  | 9.07                | 2106.96                           | 114.74                  |                             |
| 8                | 3.31                 | 5.71                               | 7.11                      | 5.72                                  | 18.16               | 11394.21                          | 220.88                  | 163.6                       |
|                  | .04                  | .54                                | 1.51                      | .57                                   | 1.83                | 7796.87                           | 195.50                  |                             |
|                  | 1.92                 | 3.06                               | 4.24                      | 3.11                                  | 8.57                | 1913.42                           | 97.83                   |                             |
| 9                | 7.33                 | 7.33                               | 7.43                      | 14.69                                 | 26.12               | 2750.99                           | 132.73                  | 119.8                       |
|                  | .25                  | .25                                | .54                       | 2.87                                  | 2.89                | 15025.82                          | 384.12 (a)              |                             |
|                  | 7.40                 | 7.40                               | 7.55                      | 10.33                                 | 12.34               | 9841.01                           | 265.09 (b)              |                             |
| 10               | 7.33                 | 7.33                               | 7.43                      | 9.81                                  | 21.67               | 3808.05                           | 149.07 (c)              | 132.2                       |
|                  | .25                  | .25                                | .54                       | .55                                   | 1.41                | 2472.02                           | 217.30 (d)              |                             |
|                  | 7.40                 | 7.40                               | 7.53                      | 7.65                                  | 10.55               | 13318.37                          | 309.95                  |                             |
| 11               | 7.28                 | 7.28                               | 11.48                     | 7.28                                  | 20.06               | 8694.88                           | 243.20                  | 132.7                       |
|                  | .06                  | .06                                | 1.64                      | .06                                   | 1.96                | 2260.51                           | 127.44                  |                             |
|                  | 7.25                 | 7.25                               | 8.14                      | 7.25                                  | 11.43               | 3571.50                           | 201.15                  |                             |
| 12               | 7.28                 | 7.28                               | 8.93                      | 7.28                                  | 19.56               | 12429.72                          | 289.13                  | 145.0                       |
|                  | .06                  | .06                                | .71                       | .06                                   | 1.39                | 8300.67                           | 254.71                  |                             |
|                  | 7.25                 | 7.25                               | 7.27                      | 7.25                                  | 10.99               | 2396.53                           | 138.01                  |                             |
|                  |                      |                                    |                           |                                       |                     | 3678.13                           | 199.99                  |                             |
|                  |                      |                                    |                           |                                       |                     | 12209.67                          | 273.93                  |                             |
|                  |                      |                                    |                           |                                       |                     | 8237.87                           | 236.52                  |                             |
|                  |                      |                                    |                           |                                       |                     | 2311.87                           | 129.13                  |                             |
|                  |                      |                                    |                           |                                       |                     | 3695.52                           | 195.68                  |                             |

| Candidate System | Detection Time [Min] | First Arrival of Any Service [Min] | Police Arrival Time [Min] | Mechanical Service Arrival Time [Min] | Blockage Time [Min] | Number of Vehicles Delayed [Veh.] | Total Delay (Veh.Hours) | Cost (\$/Mile/16 Hours) |
|------------------|----------------------|------------------------------------|---------------------------|---------------------------------------|---------------------|-----------------------------------|-------------------------|-------------------------|
| 13               | 3.64                 | 3.64                               | 7.43                      | 7.28                                  | 19.61               | 12203.03                          | 270.26                  | 148.8                   |
|                  | .06                  | .06                                | .54                       | .06                                   | 1.42                | 8277.01                           | 231.49                  |                         |
|                  | 3.61                 | 3.61                               | 7.53                      | 7.25                                  | 10.80               | 2290.66                           | 121.00                  |                         |
| 14               |                      |                                    |                           |                                       |                     | 3543.91                           | 173.54                  | 134.8                   |
|                  | 2.85                 | 3.94                               | 7.43                      | 5.30                                  | 17.88               | 11086.74                          | 213.37                  |                         |
|                  | .14                  | .27                                | .54                       | .65                                   | 1.69                | 7620.04                           | 192.71                  |                         |
| 15               | 1.29                 | 2.44                               | 7.53                      | 2.87                                  | 8.84                | 1939.15                           | 100.69                  | 156.2                   |
|                  |                      |                                    |                           |                                       |                     | 2682.62                           | 131.61                  |                         |
|                  | 3.93                 | 6.84                               | 7.80                      | 7.28                                  | 19.58               | 12266.95                          | 273.60                  |                         |
|                  | .05                  | .26                                | 1.67                      | .06                                   | 1.60                | 8233.72                           | 231.23                  |                         |
|                  | 3.16                 | 6.87                               | 5.04                      | 7.25                                  | 10.73               | 2293.97                           | 121.59                  |                         |
|                  |                      |                                    |                           |                                       |                     | 3564.20                           | 173.98                  |                         |

## APPENDIX D

ANALYSIS OF VARIANCE FOR UNEQUAL  $\sigma_1^2$ 

In Subsection 6.3 an analysis of variance model was suggested which takes account of the property of the simulation program that the same array of random numbers was used to analyze alternative emergency service systems.

Considering this feature of the simulation process and taking into account the relation between the performance of candidate systems  $i$  and the days  $k$  analyzed the following analysis of variance model for a two-way layout was designed.

$$(1) \quad y_{ijk} = \alpha_i + \beta_{j(k)} + \gamma_{ik} + \epsilon_{ijk}$$

with the side conditions:

$$(2) \quad \sum_{j \in k} \beta_{j(k)} = 0$$

$$(3) \quad \sum_i \gamma_{ik} = 0$$

$$(4) \quad \sum_k \gamma_{ik} = 0$$

$y_{ijk}$  corresponds to the effectiveness measure, here total delay  $W$  for system  $i$ , iteration  $j$  and day  $k$ . ( $y_{ijk} = x_{i,j,k}$  of Equation (B-8).) There are  $n_i = 15$  systems,  $n_j = 100$  iterations per day and  $n_k = 5$  days. The estimates for  $\alpha_i$ ,  $\beta_{j(k)}$ ,  $\gamma_{ik}$  are

$$(5) \quad \hat{\alpha}_i = \frac{1}{n_j n_k} \sum_j \sum_k y_{ijk}$$

D.2

$$(6) \quad \hat{\beta}_{j(k)} = \frac{1}{n_i} \sum_i y_{ijk} - \mu$$

$$(7) \quad \hat{\gamma}_{ik} = \frac{1}{n_j} \sum_{j \in k} y_{ijk} - \frac{1}{n_j} \sum_{j \in k} \hat{\beta}_{j(k)} - \hat{\alpha}_i$$

and the grand mean is

$$(8) \quad \mu = \frac{1}{n_i n_j n_k} \sum_i \sum_j \sum_k y_{ijk}.$$

In contrast to the usual analysis of variance [111], where it is assumed that the random variables have equal variance  $\sigma^2$ , in this model it is taken into consideration that the variance  $\sigma_i$  of  $\alpha_i$  is not equal for all  $i$  ( $\sigma_i \neq \sigma_p$ , where  $p \neq i$ ).

The estimation of the variance  $\sigma_i^2$  of  $\alpha_i$  which is the mean total delay for system  $i$ , is then determined from the following analysis

$$(9) \quad \text{Var} [\hat{\alpha}_i] = \frac{1}{n_j n_k} \sigma_i^2$$

$$(10) \quad \text{Var} [\hat{\beta}_{j(k)}] = \frac{1}{n_i} \sigma_i^2$$

$$(11) \quad \text{Var} [\hat{\gamma}_{ik}] = \left[ \frac{1}{n_j} + \frac{1}{n_i^2 n_k} + \frac{1}{n_j n_k} - \frac{2}{n_i n_j} - \frac{2}{n_j n_k} + \frac{2}{n_i n_j n_k} \right] \sigma_i^2$$

$$(12) \quad \text{Cov} [y_{ijk}, \hat{\gamma}_{ik}] = \left[ \frac{1}{n_j} - \frac{1}{n_i n_j} - \frac{1}{n_i n_k} \right] \sigma_i^2.$$

Estimating the variance for  $\alpha_i$  from

$$(13) \quad \hat{e}_{ijk} = y_{ijk} - \hat{\alpha}_i - \hat{\beta}_{j(k)} - \hat{\gamma}_{ik}$$

$$(14) \quad \text{Var} [\hat{\epsilon}_{ijk}] = E[\hat{\epsilon}_{ijk}^2] - E^2[\hat{\epsilon}_{ijk}]$$

one obtains after inserting the variances and covariance

$$(15) \quad E \left[ \sum_j^{n_j} \sum_k^{n_k} (\hat{\epsilon}_{ijk}^2) \right] = \left[ n_j n_k \left( 1 - \frac{1}{n_1} \right)^2 - 3 \left( n_k + 1 + \frac{n_k}{n_1} \right) + \frac{n_k}{n_1} (n_j + 1) \right] \sigma_1^2$$

$$+ \frac{n_k}{n_1} (n_j + 1) \sum_{p \neq 1}^{n_1-1} \sigma_p^2.$$

For the given data this equation reduces to the following set of 15 simultaneous equations

$$(16) \quad \sum_j^{n_j} \sum_k^{n_k} (\hat{\epsilon}_{ijk})^2 = 2.24 \sigma_1^2 + 418.80 \sum_{p \neq 1}^{n_1-1} \sigma_p^2.$$

In Table D-1 the solution to these equations is given for the 15 sums

of squares  $\sum_j^{n_j} \sum_k^{n_k} (\hat{\epsilon}_{ijk}^2)$  for each system.

| Candidate<br>System<br>i | Mean Daily<br>Total Dela,<br>per System i<br>$\alpha_i$<br>Equ. (B-5)<br>Equ. (D-5) | Standard<br>Deviation<br>of Grand<br>Mean<br>$y_{...}$<br>— | Pooled<br>Standard<br>Deviation<br>for Study<br>Period<br>$\sigma_i$<br>Equ. (B-12) | Standard<br>Deviation<br>of $\alpha_i$<br>from<br>ANOVA Model<br>$\sigma_i$<br>Equ. (D-16) | Sums of<br>Squares<br>$\sum_j \sum_k e_{ijk}^2$<br>Equ. (D-15) |
|--------------------------|-------------------------------------------------------------------------------------|-------------------------------------------------------------|-------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------|----------------------------------------------------------------|
| 1                        | 290.06                                                                              | 242.72                                                      | 145.72                                                                              | 83.86                                                                                      | 3573345.98                                                     |
| 2                        | 212.62                                                                              | 209.96                                                      | 127.76                                                                              | 59.01                                                                                      | 2094606.88                                                     |
| 3                        | 289.50                                                                              | 239.36                                                      | 147.73                                                                              | 86.67                                                                                      | 3772830.43                                                     |
| 4                        | 224.01                                                                              | 215.67                                                      | 130.58                                                                              | 60.94                                                                                      | 2191173.20                                                     |
| 5                        | 215.20                                                                              | 214.91                                                      | 130.47                                                                              | 60.79                                                                                      | 2183514.27                                                     |
| 6                        | 236.42                                                                              | 218.47                                                      | 129.90                                                                              | 61.73                                                                                      | 2231442.40                                                     |
| 7                        | 296.20                                                                              | 273.84                                                      | 156.96                                                                              | 97.03                                                                                      | 4565535.28                                                     |
| 8                        | 220.89                                                                              | 219.36                                                      | 132.73                                                                              | 62.64                                                                                      | 2278320.57                                                     |
| 9                        | 384.12                                                                              | 321.21                                                      | 217.30                                                                              | 178.72                                                                                     | 13948804.64                                                    |
| 10                       | 309.95                                                                              | 296.12                                                      | 201.15                                                                              | 158.64                                                                                     | 11127643.78                                                    |
| 11                       | 289.13                                                                              | 302.79                                                      | 199.99                                                                              | 160.81                                                                                     | 11416413.58                                                    |
| 12                       | 273.93                                                                              | 280.96                                                      | 195.68                                                                              | 208.16                                                                                     | 18694175.72                                                    |
| 13                       | 270.26                                                                              | 272.87                                                      | 173.54                                                                              | 211.02                                                                                     | 19192748.71                                                    |
| 14                       | 213.37                                                                              | 219.46                                                      | 131.61                                                                              | 178.40                                                                                     | 13902078.02                                                    |
| 15                       | 273.60                                                                              | 266.42                                                      | 173.98                                                                              | 204.27                                                                                     | 18025809.40                                                    |

Grand Mean  $y_{...} = 265.77$  [veh. hours]

TABLE D-1: RESULTS OF ANALYSIS OF VARIANCE WITH UNEQUAL  $\sigma_i^2$

APPENDIX E  
INPUT AND INTERMEDIATE OUTPUTS OF THE SIMULATION  
PROGRAM "DESERV"

Input

The linear freeway is represented by a five mile section ( $L = 5$  miles) of the San Francisco-Oakland Bay Bridge between the call boxes number 512 (612) and 187 (387).

The basic design for the detection and service subsystems is shown in Figure 35. There the values are given for  $n_q$  and  $l_q$ ,  $q = a, b, c, e, f, g, h$  as well as for  $g_{1j}$  and  $h_{2j}$ .

The travel speeds for patrol and service vehicles are assumed to be  $v_f = 45$  mph and  $v_q = 43$  mph for  $q = a, b, g, h$ . The walking speed is set at 3 mph.

The activity times  $t_c$  and  $t_{re}$  are estimated to be 1 and 1.5 minutes respectively.

The traffic demand rate  $\lambda(t) = f(q(t))$  is approximated by the piecewise linear function of the traffic distribution over the time of day as given in Figure 25 from [63].

The capacity of the linear freeway (Bay Bridge),  $\mu(t)$  is 8600 vph East bound and 9000 vph West bound based on [113].

The  $n_i = 15$  candidate systems were analyzed on a set of 95 incidents, which occurred on  $n_k = 5$  days (Monday, October 7, to Friday, October 11, 1968) during the day and swing shifts (16 hours, from 6 a.m. to 10 p.m.). For each day and candidate system  $n_j = 100$  replications were made with the simulation program "DESERV".

LIST OF INCIDENTS AND THEIR CHARACTERISTICS  
FOR STUDY SECTION AND STUDY PERIOD

| Number of Incident               | Location<br><br>+ X<br>[Miles] | Time of Day<br><br>T<br>[Minutes] | Police Service<br><br>P<br>(0,1) | Mechanical Service<br><br>S<br>(0,1) | Tow Service<br><br>V<br>(0,1) | Capacity Reduction<br><br>CR<br>[%] |
|----------------------------------|--------------------------------|-----------------------------------|----------------------------------|--------------------------------------|-------------------------------|-------------------------------------|
| <b>Monday,<br/>10 incidents</b>  |                                |                                   |                                  |                                      |                               |                                     |
| 1                                | -2.26                          | 367                               | 0                                | 1                                    | 0                             | .10                                 |
| 2                                | 2.42                           | 415                               | 0                                | 1                                    | 0                             | .30                                 |
| 3                                | -4.25                          | 483                               | 1                                | 1                                    | 1                             | .30                                 |
| 4                                | -2.45                          | 647                               | 0                                | 1                                    | 1                             | .30                                 |
| 5                                | -2.93                          | 672                               | 1                                | 1                                    | 1                             | .30                                 |
| 6                                | -2.53                          | 1000                              | 0                                | 1                                    | 0                             | .10                                 |
| 7                                | 2.28                           | 1019                              | 0                                | 1                                    | 0                             | .10                                 |
| 8                                | 3.36                           | 1030                              | 0                                | 1                                    | 0                             | .10                                 |
| 9                                | -2.34                          | 1045                              | 0                                | 1                                    | 0                             | .10                                 |
| 10                               | -3.79                          | 1159                              | 0                                | 1                                    | 0                             | .30                                 |
| <b>Tuesday,<br/>26 incidents</b> |                                |                                   |                                  |                                      |                               |                                     |
| 1                                | .68                            | 407                               | 0                                | 1                                    | 0                             | .30                                 |
| 2                                | -3.87                          | 440                               | 0                                | 1                                    | 0                             | .30                                 |
| 3                                | 2.41                           | 441                               | 0                                | 1                                    | 0                             | .10                                 |
| 4                                | 2.86                           | 474                               | 0                                | 1                                    | 0                             | .30                                 |
| 5                                | -2.56                          | 475                               | 0                                | 1                                    | 1                             | .10                                 |
| 6                                | 2.84                           | 480                               | 0                                | 1                                    | 0                             | .30                                 |
| 7                                | 2.84                           | 501                               | 0                                | 1                                    | 0                             | .30                                 |
| 8                                | 2.85                           | 510                               | 1                                | 1                                    | 0                             | .30                                 |
| 9                                | .15                            | 540                               | 0                                | 1                                    | 0                             | .30                                 |
| 10                               | 4.40                           | 540                               | 0                                | 1                                    | 1                             | .10                                 |
| 11                               | -1.88                          | 555                               | 0                                | 1                                    | 0                             | .30                                 |
| 12                               | 2.24                           | 557                               | 0                                | 1                                    | 0                             | .10                                 |
| 13                               | 3.23                           | 585                               | 0                                | 1                                    | 0                             | .30                                 |
| 14                               | .77                            | 692                               | 0                                | 1                                    | 0                             | .30                                 |
| 15                               | 4.78                           | 781                               | 0                                | 1                                    | 1                             | .10                                 |
| 16                               | 1.00                           | 814                               | 0                                | 1                                    | 0                             | .30                                 |
| 17                               | -4.35                          | 831                               | 1                                | 1                                    | 1                             | .30                                 |
| 18                               | 4.83                           | 1023                              | 0                                | 1                                    | 0                             | .10                                 |
| 19                               | -1.33                          | 1030                              | 0                                | 1                                    | 1                             | .30                                 |
| 20                               | -1.61                          | 1034                              | 0                                | 1                                    | 1                             | .10                                 |
| 21                               | -.46                           | 1082                              | 0                                | 1                                    | 0                             | .30                                 |
| 22                               | -2.52                          | 1083                              | 0                                | 1                                    | 1                             | .10                                 |
| 23                               | -.96                           | 1096                              | 0                                | 1                                    | 1                             | .10                                 |
| 24                               | -.87                           | 1100                              | 1                                | 1                                    | 0                             | .40                                 |
| 25                               | 2.42                           | 1117                              | 0                                | 1                                    | 1                             | .10                                 |
| 26                               | .97                            | 1261                              | 0                                | 1                                    | 0                             | .30                                 |

| Number of Incident                 | Location<br>$\pm X$<br>[Miles] | Time of Day<br>T<br>[Minutes] | Police Service<br>P<br>(0,1) | Mechanical Service<br>S<br>(0,1) | Tow Service<br>V<br>(0,1) | Capacity Reduction<br>CR<br>[%] |
|------------------------------------|--------------------------------|-------------------------------|------------------------------|----------------------------------|---------------------------|---------------------------------|
| <b>Wednesday,<br/>12 incidents</b> |                                |                               |                              |                                  |                           |                                 |
| 1                                  | 2.92                           | 568                           | 1                            | 1                                | 1                         | .50                             |
| 2                                  | 2.72                           | 573                           | 1                            | 1                                | 0                         | .30                             |
| 3                                  | -3.04                          | 586                           | 0                            | 1                                | 1                         | .30                             |
| 4                                  | 2.94                           | 594                           | 1                            | 1                                | 0                         | .30                             |
| 5                                  | -1.81                          | 624                           | 0                            | 1                                | 1                         | .30                             |
| 6                                  | .21                            | 641                           | 0                            | 1                                | 0                         | .30                             |
| 7                                  | .43                            | 759                           | 1                            | 1                                | 1                         | .30                             |
| 8                                  | 3.55                           | 813                           | 0                            | 1                                | 0                         | .30                             |
| 9                                  | 2.48                           | 918                           | 0                            | 1                                | 1                         | .10                             |
| 10                                 | -.03                           | 998                           | 0                            | 1                                | 0                         | .10                             |
| 11                                 | -2.52                          | 1027                          | 0                            | 1                                | 0                         | .10                             |
| 12                                 | 2.50                           | 1199                          | 1                            | 1                                | 1                         | .10                             |
| <b>Thursday,<br/>32 incidents</b>  |                                |                               |                              |                                  |                           |                                 |
| 1                                  | 1.21                           | 385                           | 0                            | 1                                | 0                         | .30                             |
| 2                                  | 2.62                           | 392                           | 0                            | 1                                | 0                         | .30                             |
| 3                                  | -1.69                          | 536                           | 1                            | 1                                | 1                         | .30                             |
| 4                                  | -4.19                          | 588                           | 0                            | 1                                | 1                         | .30                             |
| 5                                  | -2.00                          | 592                           | 0                            | 1                                | 0                         | .30                             |
| 6                                  | .55                            | 604                           | 0                            | 1                                | 0                         | .30                             |
| 7                                  | -2.21                          | 640                           | 0                            | 1                                | 1                         | .10                             |
| 8                                  | 1.35                           | 741                           | 0                            | 1                                | 1                         | .30                             |
| 9                                  | .01                            | 763                           | 0                            | 1                                | 0                         | .30                             |
| 10                                 | -4.86                          | 802                           | 0                            | 1                                | 0                         | .10                             |
| 11                                 | .21                            | 810                           | 0                            | 1                                | 0                         | .30                             |
| 12                                 | 2.59                           | 816                           | 0                            | 1                                | 0                         | .10                             |
| 13                                 | .87                            | 828                           | 0                            | 1                                | 0                         | .30                             |
| 14                                 | .48                            | 831                           | 0                            | 1                                | 0                         | .30                             |
| 15                                 | -4.04                          | 854                           | 1                            | 1                                | 1                         | .40                             |
| 16                                 | 1.55                           | 901                           | 0                            | 1                                | 1                         | .30                             |
| 17                                 | -4.31                          | 928                           | 0                            | 1                                | 0                         | .30                             |
| 18                                 | .87                            | 937                           | 0                            | 1                                | 0                         | .30                             |
| 19                                 | .38                            | 950                           | 0                            | 1                                | 0                         | .30                             |
| 20                                 | 2.49                           | 961                           | 0                            | 1                                | 1                         | .10                             |
| 21                                 | 3.54                           | 973                           | 0                            | 1                                | 0                         | .30                             |
| 22                                 | 2.30                           | 991                           | 0                            | 1                                | 0                         | .10                             |
| 23                                 | -1.95                          | 999                           | 0                            | 1                                | 0                         | .30                             |
| 24                                 | -3.21                          | 1025                          | 0                            | 1                                | 0                         | .30                             |
| 25                                 | -4.06                          | 1066                          | 0                            | 1                                | 1                         | .30                             |
| 26                                 | .78                            | 1090                          | 0                            | 1                                | 0                         | .30                             |
| 27                                 | -.04                           | 1169                          | 0                            | 1                                | 1                         | .10                             |
| 28                                 | -.03                           | 1185                          | 0                            | 1                                | 1                         | .10                             |
| 29                                 | -4.31                          | 1237                          | 0                            | 1                                | 0                         | .30                             |
| 30                                 | -2.28                          | 1240                          | 0                            | 1                                | 0                         | .10                             |
| 31                                 | 4.18                           | 1259                          | 0                            | 1                                | 0                         | .30                             |
| 32                                 | 4.35                           | 1300                          | 0                            | 1                                | 1                         | .10                             |

E.4

| Number of Incident      | Location<br><br>+ X<br>[Miles] | Time of Day<br><br>T<br>[Minutes] | Police Service<br><br>P<br>(0,1) | Mechanical Service<br><br>S<br>(0,1) | Tow Service<br><br>V<br>(0,1) | Capacity Reduction<br><br>CR<br>[%] |
|-------------------------|--------------------------------|-----------------------------------|----------------------------------|--------------------------------------|-------------------------------|-------------------------------------|
| Friday,<br>15 incidents |                                |                                   |                                  |                                      |                               |                                     |
| 1                       | 2.04                           | 419                               | 0                                | 1                                    | 0                             | .30                                 |
| 2                       | .73                            | 474                               | 0                                | 1                                    | 0                             | .30                                 |
| 3                       | 2.88                           | 530                               | 1                                | 1                                    | 0                             | .30                                 |
| 4                       | .68                            | 559                               | 1                                | 1                                    | 1                             | .30                                 |
| 5                       | -2.91                          | 608                               | 0                                | 1                                    | 0                             | .30                                 |
| 6                       | 2.44                           | 611                               | 0                                | 1                                    | 0                             | .10                                 |
| 7                       | -1.03                          | 643                               | 0                                | 1                                    | 0                             | .10                                 |
| 8                       | .60                            | 727                               | 0                                | 1                                    | 0                             | .30                                 |
| 9                       | -4.53                          | 806                               | 0                                | 1                                    | 0                             | .10                                 |
| 10                      | -1.50                          | 979                               | 1                                | 1                                    | 0                             | .30                                 |
| 11                      | -.07                           | 1047                              | 0                                | 1                                    | 0                             | .10                                 |
| 12                      | -3.54                          | 1052                              | 0                                | 1                                    | 0                             | .30                                 |
| 13                      | -4.69                          | 1071                              | 0                                | 1                                    | 0                             | .10                                 |
| 14                      | .98                            | 1137                              | 0                                | 1                                    | 0                             | .10                                 |
| 15                      | -2.51                          | 1148                              | 0                                | 1                                    | 1                             | .10                                 |

Output

Of the 95 incidents analyzed per candidate system 14 to 15 incidents caused a capacity reduction which reduced the freeway capacity so that it was below actual demand rate at the time of the incident. The distribution of these incidents over the 5 days is presented in the following table

|                                                     | Monday | Tuesday | Wednesday | Thursday | Friday |
|-----------------------------------------------------|--------|---------|-----------|----------|--------|
| number of incidents<br>from 6 a.m. to 10 p.m.       | 10     | 26      | 12        | 32       | 15     |
| number of incidents,<br>where $\lambda(t) > \mu(t)$ | 1      | 7       | 1         | 4 or 5   | 1      |

The cost figures given in Appendix B and used in the cost effectiveness diagrams in Chapter 6 are computed with the formulae of Figure 52 and the following intermediate output of the simulation routine.

| Emergency Service Subsystem                        | Number of<br>Units, $n_q$ | Total Mileage for<br>the Five 16 Hour Periods<br>$n_q \cdot d_q$ |
|----------------------------------------------------|---------------------------|------------------------------------------------------------------|
| A Police Patrol                                    | 2                         | 10286.0                                                          |
| B Mechanical Patrol                                | 2                         | 10286.0                                                          |
| C Call Box                                         | 42                        | -                                                                |
| E Emergency Telephone                              | 42                        | -                                                                |
| F Detection Patrol (1)                             | 1                         | 5400.0                                                           |
| F* Detection Patrol (1,1)                          | 2                         | 10800.0                                                          |
| G Stationary Police Units (1-1)                    | 2                         | 154.3                                                            |
| G* Stationary Police Units (1-1-1)                 | 3                         | 77.6                                                             |
| H Stationary Mechanical<br>Service Units (1-1)     | 2                         | 1224.2                                                           |
| H* Stationary Mechanical<br>Service Units (1-1-1)  | 3                         | 675.2                                                            |
| H** Stationary Mechanical<br>Service Units (1-2-1) | 4                         | 675.2                                                            |
| H*** Stationary Mechanical<br>Service Units (2-2)  | 4                         | 1224.2                                                           |

Unclassified

Security Classification

| DOCUMENT CONTROL DATA - R & D                                                                                                      |                                                                             |                                                                                 |
|------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------|---------------------------------------------------------------------------------|
| (Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified) |                                                                             |                                                                                 |
| 1. ORIGINATING ACTIVITY (Corporate author)                                                                                         |                                                                             | 2a. REPORT SECURITY CLASSIFICATION                                              |
| University of California, Berkeley                                                                                                 |                                                                             | Unclassified                                                                    |
|                                                                                                                                    |                                                                             | 2b. GROUP                                                                       |
|                                                                                                                                    |                                                                             |                                                                                 |
| 3. REPORT TITLE                                                                                                                    |                                                                             |                                                                                 |
| AN ANALYSIS OF FREEWAY EMERGENCY SERVICE SYSTEMS                                                                                   |                                                                             |                                                                                 |
| 4. DESCRIPTIVE NOTES (Type of report and inclusive dates)                                                                          |                                                                             |                                                                                 |
| Research Report                                                                                                                    |                                                                             |                                                                                 |
| 5. AUTHOR(S) (First name, middle initial, last name)                                                                               |                                                                             |                                                                                 |
| Hartmut Keller                                                                                                                     |                                                                             |                                                                                 |
| 6. REPORT DATE                                                                                                                     | 7a. TOTAL NO. OF PAGES                                                      | 7b. NO. OF REFS                                                                 |
| August 1969                                                                                                                        | 170                                                                         | 145                                                                             |
| 8a. CONTRACT OR GRANT NO.                                                                                                          | 9a. ORIGINATOR'S REPORT NUMBER(S)                                           |                                                                                 |
| GK-1684                                                                                                                            | ORC 69-20                                                                   |                                                                                 |
| b. PROJECT NO.                                                                                                                     |                                                                             |                                                                                 |
| c.                                                                                                                                 | 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) |                                                                                 |
| d.                                                                                                                                 |                                                                             |                                                                                 |
| 10. DISTRIBUTION STATEMENT                                                                                                         |                                                                             |                                                                                 |
| This document has been approved for public release and sale; its distribution is unlimited.                                        |                                                                             |                                                                                 |
| 11. SUPPLEMENTARY NOTES                                                                                                            |                                                                             | 12. SPONSORING MILITARY ACTIVITY                                                |
| NONE                                                                                                                               |                                                                             | NSF-GK-1684-Shephard, The National Science Foundation<br>Washington, D.C. 20550 |
| 13. ABSTRACT                                                                                                                       |                                                                             |                                                                                 |
| SEE ABSTRACT.                                                                                                                      |                                                                             |                                                                                 |

DD FORM 1473

5/N 0101-807-6811

(PAGE 1)

Unclassified

Security Classification

A-31408

| KEY WORDS                 | LINK A |    | LINK B |    | LINK C |    |
|---------------------------|--------|----|--------|----|--------|----|
|                           | ROLE   | WT | ROLE   | WT | ROLE   | WT |
| Detection                 |        |    |        |    |        |    |
| Emergency Service         |        |    |        |    |        |    |
| Accident                  |        |    |        |    |        |    |
| Simulation                |        |    |        |    |        |    |
| Queueing                  |        |    |        |    |        |    |
| Cost/Effectiveness        |        |    |        |    |        |    |
| Traffic                   |        |    |        |    |        |    |
| Emergency Medical Systems |        |    |        |    |        |    |
| Freeway                   |        |    |        |    |        |    |
| Police                    |        |    |        |    |        |    |